ABSTRACT

KILONZO, OBADIAH. Process Control Modeling and Real-Time Error Compensation in Tube Hydroforming. (Under the direction of Gracious Ngaile.)

Tube Hydroforming (THF) is the metal forming process where metal tubes take the shape of a die cavity by being pressurized internally by a fluid in addition to axial material feed applied. This process has applications in automotive fields and household goods, offering benefits such as tight tolerances, lower part weight and fewer secondary operations. However, it is affected by long lead times due to loading path design and by process challenges related to errors such as the variation of tribological conditions that occur during hydroforming. The use of Finite Element Analysis (FEA) has greatly enhanced the THF field with the ability to simulate the process to generate loading paths (material feed versus pressure curve). However due to the nature of THF process being influenced by many variables such as material properties, tube geometry and tribological conditions, FEA leads to a lot of computation time.

This research presents the development of an interactive, real time Database Generated Loading Path Scheme (DGLPS) for various THF families. By classifying most of the asymmetric THF parts into families such as Bulge and Single Y-Shape THF parts; different loading paths are simulated and stored in the DGLPS. Interactivity with DGLPS is made available such that a user can request a loading path by providing input parameters. The DGLPS provides the material feed data by employing interpolation techniques and the pressure curve by multiplying the maximum pressure to a developed pressure profile with

unit amplitude. Loading path results from DGLPS for a variety of desired parameters for different THF families matched FEA simulations with minimum variation of less than 5%.

This research reviews errors occurring in THF by broadly categorizing based on association with material feed and with internal pressure. The dominant material feed error is identified as frictional error. This research introduces an error compensation scheme, the Database Back-Step (DBS) method to compensate the loading path due to the effect of the frictional error. In this method the forces at the cylinder-tube interface are monitored and compared to acceptable forces in a database. Variation in this force from the expected force is corrected by stepping back into the database for another loading path that compensates the difference based on the coefficient of friction established from this force. This is accomplished in real time during the forming process via a Data Dynamic Exchange link between the database and the control unit. Based on experimental results the friction tended to vary from 0.01 to 0.15 for a Double T-Shape THF family demonstrating the need for error compensation. This shows that the DBS method provides an assured error compensation effort by obtaining optimized loading paths.

Differences may occur when comparing the loading paths and the position of the press cylinder (stroke) after applying the loading paths. This indicates the possibility of errors associated with the equipment. This research proposes the Real Time Stroke (RTS) Controller method as a solution for improving the cylinder stroke by compensating for equipment errors. This method focuses on developing a plant model of the equipment involved, a closed loop system whereby the reference input is obtained from the DBS method and designing a controller. Simulations of the process control have been done with Think and Do Live software. The results from the RTS method show a close tracking of the reference input with reduced overshoots beyond the reference loading paths. Control with above approaches results in efficient and concerted control merging the loading path design flexibility with process and machinery dynamic response.

Process Control Modeling and Real-Time Error Compensation in
Tube Hydroforming

by
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DEDICATION

To God the Father and my Lord Jesus Christ for His unconditional love and support, wisdom and guidance, good health and many blessings including grace to complete this research.

Blessed be your Holy Name!

BIOGRAPHY

Obadiah Kilonzo received his B.S. degree in Mechanical Engineering from the University of Nairobi, Kenya; M.S degree in Mechanical Engineering from Rochester Institute of Technology, Rochester, New York and enrolled in graduate school at North Carolina State University, Raleigh, North Carolina in the Fall of 2006. His research interests include automated manufacturing systems, process control, modeling and automated hydraulic systems.

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CHAPTER 1:
INTRODUCTION AND RESEARCH OBJECTIVES

1.1 INTRODUCTION

Tube Hydroforming (THF) is the metal forming process where metal tubes take the shape of a die cavity by being pressurized internally by a fluid in addition to axial material feed applied. This process has applications in automotive fields and household goods, offering benefits such as tight tolerances, lower part weight, fewer secondary operations and part consolidation. However, it is affected by long lead times due to loading path design and by process challenges related to errors such as the variation of tribological conditions that occur during the hydroforming process. The use of Finite Element Analysis (FEA) tools has greatly enhanced the THF field with the ability to simulate the process to generate loading paths (material feed versus pressure curve). However due to the nature of THF process influenced by many variables such as material properties, tube geometry and tribological conditions, FEA leads to a lot of computation time.

The THF process is done in a press that houses the dies, pressure booster and control system. The inner pressure is supplied from a pressure booster into the tube. The hydraulic equipment of the press used for providing material feed to the tube is composed of the motor-pump system, valves and cylinders. The material feed and internal pressure together graphically form the loading path which is the guideline of material feed and pressure provided to the press. The use of FEA in developing loading paths has greatly enhanced the THF field enabling the ability to simulate the process for unique process conditions to generate loading paths. This loading path generation method requires a lot of computation time. Other methods for generating loading paths apart from FEA such as analytical and fuzzy logic are limited by how many parameters will be changed to obtain the loading path. This research focuses on developing Database Generated Loading Path Scheme (DGLPS) for parts developed by hydroforming straight tubes. Various parameters are considered including geometry, tribological conditions and material properties such as strength of material, and strain hardening exponent. Based on the request of a user, the inquisitive database with interpolation/extrapolation algorithms provides a loading path.

The development of the internal pressure and material feed is crucial requiring meticulous effort in order to inhibit THF failure modes such as wrinkling, bursting and buckling that are associated with too much feed (wrinkling and buckling) or too much pressure (bursting). Errors and uncertainties play a major role in the design of material feed and internal pressure. Types of errors include errors associated with the forming process such as the variation of friction, errors associated with the tube material such as change in strain hardening exponent during the process, errors associated with loading path design such as neglecting die elasticity and errors associated with equipment such as leakage. This research reviews errors occurring in THF broadly categorizing errors as associated with material feed and with internal pressure. The dominant material feed error identified is the frictional error. This research introduces an error compensation scheme whereby the Database Back-Step (DBS) method is used to compensate the loading path due to the effect of the frictional error.

In this method the forces at the cylinder-tube interface are monitored and compared to expected forces in a database. Variation in the cylinder force at the interface from the expected force is corrected by stepping back into the database for another loading path that compensates the difference based on the coefficient of friction established from the force at the cylinder-tube interface. This is accomplished in real time during the forming process via a communication link between the database and the control unit.

Though the loading path design is enhanced with the use of the DBS method, stroke control can be improved by considering the aspects of the equipment used. This research focuses on a study on errors and uncertainties that bound upon equipment and deriving a mathematical model of the equipment setup (plant model) with a controller that is designed to assist in tracking the stroke of the cylinder. The challenge being met in this research is developing a system with adjustable loading paths coupled with real-time error compensation during the THF process.

1.2 RESEARCH OBJECTIVES

The goal of this research is to develop real time error compensation in Tube hydroforming process that would enhance the development of quality parts. The particular objectives of this research are:

OBJ 1. Design and use of the Database Generating Loading Path scheme (DGLPS Method) for loading paths which involves the establishment of an adaptable pressure curve.

OBJ 2. Design and operate the Database Back-Step Method (DBS Method) in Real time control and compensation of errors associated in THF process congruent with identification of the dominant error.

OBJ 3. Develop a Real Time Stroke Controller (RTS Method) for error compensation of equipment bound errors and uncertainties subsequent to the development of a plant model.

1.3 DISSERTATION ORGANIZATION

The chapter outline in this research is as follows *Chapter 1: Introduction and Research Objectives* discusses the introduction and need for this research with objectives clearly stipulated. *Chapter 2: Literature Review –Tube Hydroforming, Process and Control* provides a review of Tube Hydroforming involving the process steps and parameters, insight to the loading path, design methods and Tube Hydroforming failure modes. A discussion on errors and uncertainty and the need for process control is provided. This chapter concludes with summary and key areas of future research. *Chapter 3: Database Development for Tube Hydroforming Loading Paths* provides the methodology of the Database Generated Loading Path Scheme (DGLPS) involving development of the pressure curve by analytical methods and development of the material curves using interpolation schemes. Case studies for various THF families are provided. This DGLPS will be further used in assisting in real time control. *Chapter 4: Error Compensation Using Database Back-Step (DBS) Method* begins with the identification of the dominant THF error and outlines the design of the DBS Method for error compensation.

Use of the database developed with the DGLPS method is discussed together with the real time control operation with Dynamic Data Exchange (DDE) communication. Analysis with simulation and experimentation is provided. Chapter *5: Error Compensation Using Real-Time Stroke (RTS) Controller Method* reviews equipment bound errors, discusses the THF hydraulic unit, develops a system model for the development of a plant model and provides the design of the Real Time Stroke (RTS) controller error compensation method. Analysis with simulation is provided at the end of the chapter. *Chapter 6: Conclusions and Future Work* provides concluding remarks and future areas of research. Reference and Appendix are appended after in support of this research.

CHAPTER 2:
LITERATURE REVIEW -TUBE HYDROFORMING, PROCESS AND CONTROL

2.1 INTRODUCTION IN TUBE HYDROFORMING

The two common types of hydroforming are Tube Hydroforming (THF) and Sheet Hydroforming with the former process used in various applications as automotive, electronics and biomedical fields and the latter process common in aerospace industry as well as the automotive sector. For automakers pursuing fuel efficient automobiles, reduction of automobile weight is a high priority and a beneficiary of THF research. Some of the parts that are hydroformed include automobile exhaust manifolds, exhaust connectors, chassis and piping. THF has also led to faster manufacturing processing in comparison to conventional metal forming processes and reduced tool cost [Koc, 2003]. Tube Hydroforming (THF) can be categorized into two types, based on the pressure - bearing tube surface, THF with internal pressure and THF with external pressure. Hydroforming tubes with inner hydraulic pressure where pressure is applied to the surface of the tube, is commonly used in production compared to hydroforming with outer hydraulic pressure.

2.1.1. Tube Hydroforming Process

The THF process involves a loading path i.e. a graph of internal pressure and axial displacement known as material feed. Effects of loading paths have been widely researched [Jirathearanat, 2004; Dohmann et.al., 1997; Koc et.al., 2001]. The tube is assumed to be in the state of plastic deformation throughout the process.

The process in tube hydroforming can be summarized in 10 steps as shown below

Step 1: The tube blank (workpiece) is inserted onto the lower die. The tube blank may be a tube that is straight or of a complex shape but be formed to the shape of the die cavity.

Step 2: Communication is established between the press and the source of the loading paths. The loading paths may be provided from a PC to a PLC via wire connection or remotely.

Step 3: The die is closed using hydraulic means, by bringing down the upper die to close in on the tube blank. Some designs may incorporate guide pins to ensure that the dies are well aligned and spacers to lock the upper die in position. The dies are clamped by engaging the press upper vertical cylinder to provide clamping force to clamp both dies together.

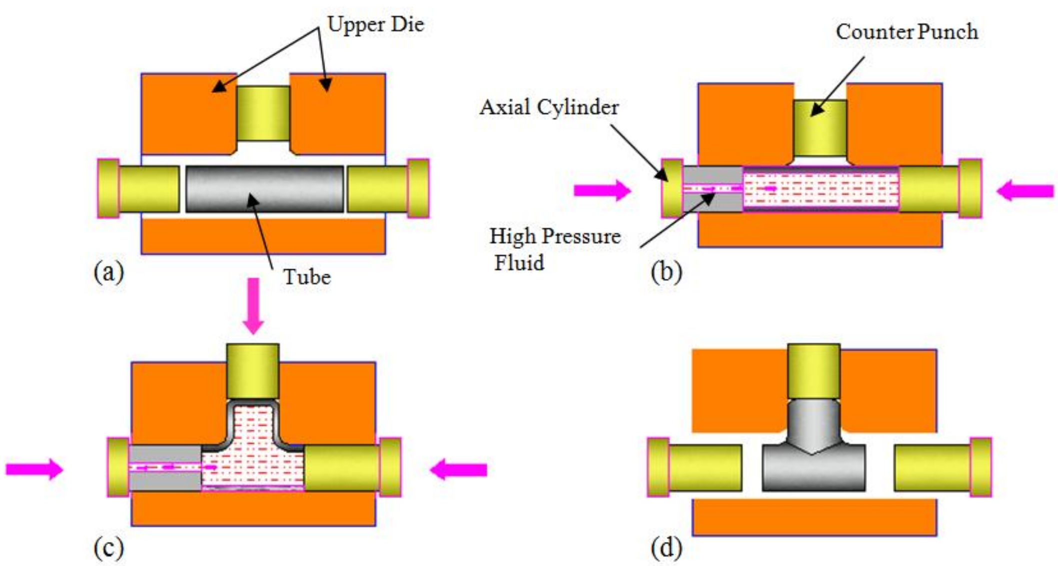


Figure 2 - 1 Sample of THF process

Step 4: The axial cylinders are adjusted to seal the tube ends as shown in Figure 2-1(a). During the forming process the cylinders provide the required axial force.

Step 5: Fluid is supplied into the tube at high pressure as shown in Figure 2-1(b). The fluid commonly used is hydraulic oil or water based fluid.

Step 6: Hydroforming of the tube takes place. The pressures may vary from about 600 bar (8700 psi) up to 2000 bar (30000 psi). The press capacities for hydroforming vary with high capacity recorded of 20,000 ton used by Sung Kwang Eng & Mfg Co., Ltd [Sung Kwang, 2010].

Step 7: Forming has been done as shown in Figure 2-1(c). Depressurization is done by stopping the pressure booster.

Step 8: The axial cylinders and counter punch are retracted, as shown in Figure 2-1(d) hence draining out the fluid.

Step 9: The upper vertical cylinder is moved upwards to unclamp the dies.

Step 10: The part is ejected from the dies and cycle begins again.

The THF process is influenced by various factors such as the type of tube blank material, product design and shape, tooling and equipment, tool - material interface and deformation zone. A review of the factors is discussed below.

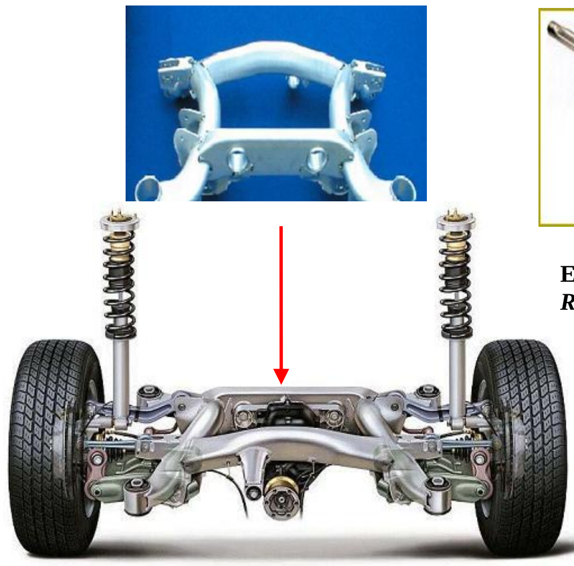
2.1.2. Factors Influencing Tube Hydroforming

2.1.2.1. Type of Tube Blank Material

Common materials used in THF are steels and aluminum. The various material parameters that are crucial in THF are: strain hardening, anisotropy, and strain rate effects. Parameters involved in developing simulation models are: Strength of the material, density, Young's modulus and Poisson's ratio. Other factors include the yield strength of a material which is at the initiation of plastic deformation and related to the material's ability to resist plastic deformation.

2.1.2.2. THF Product Design and Shape

Different secondary design processes can be added to the THF expansion process such as piercing, performing and bending. Various shapes can be obtained depending on the die cavity available. Parts such as exhaust manifolds require complex die shapes. The Figure 2-2 below shows sample of hydroformed parts.



(i) **(ii)**

Emergency door handle (i), Bathroom faucet (ii)
Ref (http www.h-htube.com)

Motor cycle and bicycle parts
Ref (http www. americanhydroformers.com)

Engine Cradle ***Ref (http://aluminium.matter.org.uk)***

Figure 2 - 2 Sample of Hydroformed parts

2.1.2.3. THF Tooling and Equipment

The hydraulic press is the common press used for THF purposes. Tools involved include the die holders, asymmetric die halves, oil drain plate and cylinder punch heads. Other equipment involves the control function equipment which includes the circuit board, PLC units and the desk computer. Figure 2-3 below shows a sample of the equipment set up.

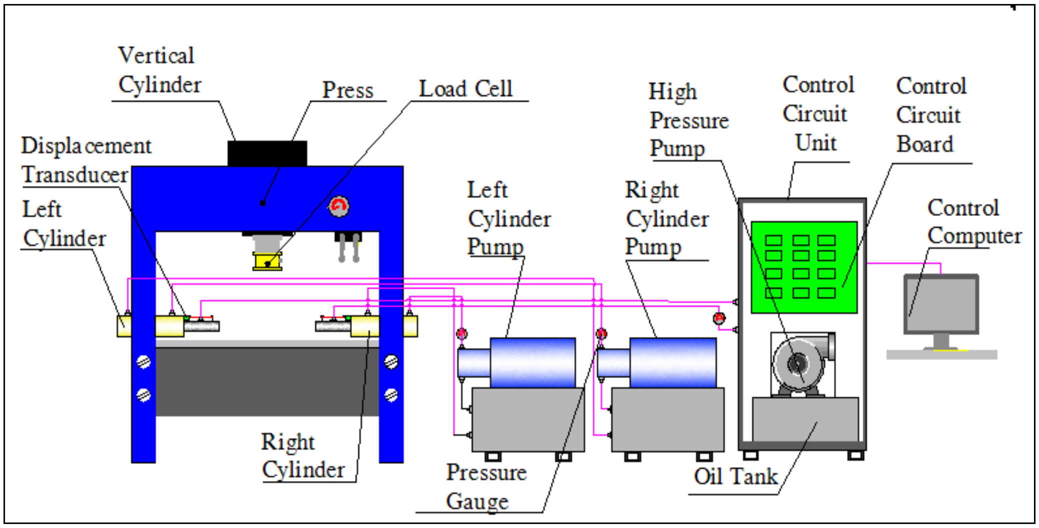


Figure 2 - 3 Sample Equipment for THF process

Equipment shown above contains following components: left and right cylinders connected to pump-motor systems, vertical cylinder, displacement transducers, high pressure system, pressure transducers, valves, control circuit unit and PC and hydraulic press.

2.1.2.4. Tool-material Interface and Deformation Zones

Apart from the material properties of the blank, the environment of the material plays an important role in THF. The interface of the tool and material will affect the axial force required while the deformation zones dictate the profile of the internal pressure. A THF family with deformation zone that has less tool-material interface such as Bulge shape will require less internal pressure towards the end of the THF process (pressure needed for calibration purposes due to corners).

All factors above are involved in shaping the loading path. The next section focuses on the loading path, design methods and THF failure.

2.2 LOADING PATH

The loading path is defined as the profile path of material feed and internal pressure supplied to the press to guide the forming process.

2.2.1. Loading Path Design

This path can be described as either force controlled loading path where the guidance provided is internal pressure and axial force and presented graphically as axial force versus pressure or as stroke controlled loading path where the guidance provided is internal pressure and displacement and presented graphically as material feed versus pressure.

2.2.2.1. Internal Pressure

Pressure is provided using a hydraulic fluid from a pressure booster system that is instructed from the control unit to act based on the loading path. The internal pressure for the loading path is developed from pressure curves (internal pressure versus time). This internal pressure is considered to be of substantial amount able to force the tube walls to deform plastically. Pressure assists in expanding the material outward towards the die cavity wall.

2.2.2.2. Material Feed

Material feed which involves pushing the tube material from the ends into the die expansion region in order to prevent excessive thinning from the internal pressure. Material feed is achievable via the axial hydraulic cylinders connected to a pump/motor system that is instructed from the control unit to act based on the loading path.

The material feed for the loading path is developed as either material feed curves (displacement versus time) or axial force curves (force versus time). The axial cylinders are required to deliver during the forward stroke a total axial force, F_a able to:

- Provide sealing force, F_{pt} needed to maintain contact with the punch hence avoiding leakage and overcome pressure reaction force during the process.
- Overcome friction force, F_L within the cylinder.
- Overcome friction force, F_{fr} in the die –tube interface and punch-tube interface.
- Provide forming force, F_{df} to cause yielding and plastic deformation of tube walls.

Figure 2-4 below shows the forces in THF process.

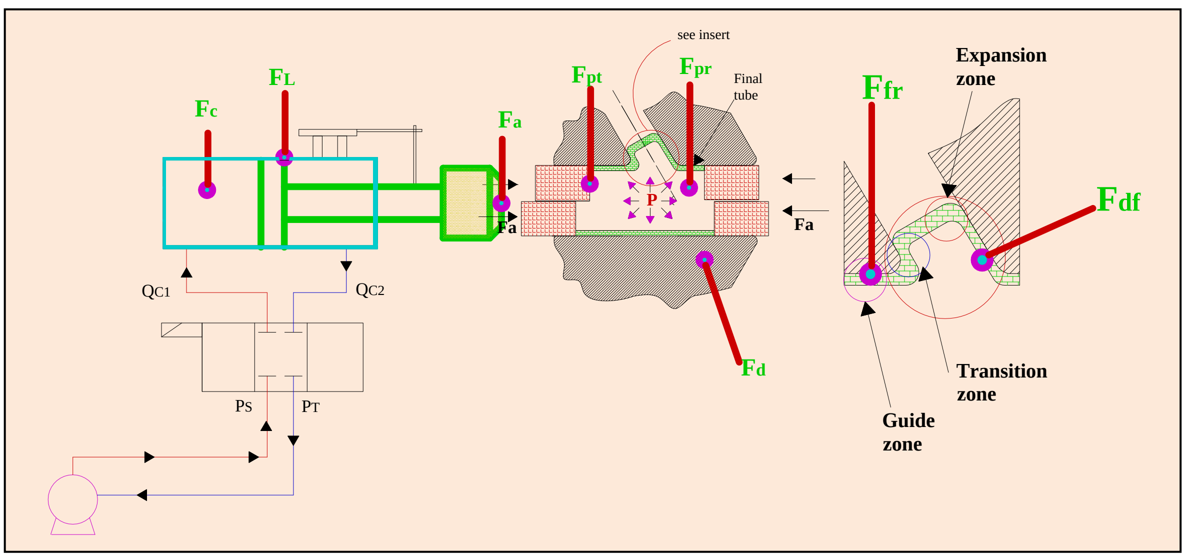


Figure 2 - 4 Forces in Single Y-Shape THF

Other Forces in THF are summarized below as:

- Clamping- Forces provided by the clamps to keep the die and set up in place during the THF process and is limited by the press tonnage.

- Pressure Forces- Forces supplied as the internal pressure on to the interior tube walls.
- Die reaction force- Force supplied by the die as a reaction to the force at the die-tube boundary applied onto the dies.

2.2.2. Loading Path Design Methods

Internal pressure can be determined by various means such as analytical, simulation and empirical ways. Jirathearanat, (2004) developed a pressure curve (pressure versus time) by using self-feeding simulation techniques. In this technique the first step involved calculating a maximum pressure value based on the pressure required to form a corner radius as shown in Eqn. 2.1 below:

$$p_{\max} = \frac{2}{\sqrt{3}}\sigma\left[\ln\frac{r_c}{r_c - t_o}\right] \qquad (2.1)$$

where σ is the flow stress of the material, r_c is the die corner radius and t_o is the initial tube wall thickness. In this step, no axial feeds are applied and the die–tube interface friction coefficient is set to zero. The next step involved modifying the pressure curve based on the velocity of the nodes at the tube ends. The profile of the pressure curve is developed with segments of different gradients till the maximum pressure value. In this method the pressure curve gradients have to be estimated and results in a large material feed requirement when applied to a loading path. This method is also limited to the bulge type (more discussion on part types in section 3.2).

Yang and group [Yang et.al. 2001] developed an optimization scheme to come up with the pressure curve. The optimization scheme is developed with an objective (cost) function to be minimized, design variable(s) to be optimized and constraint functions determining the design constraints. The objective function involved the element thickness variations after the forming process with pressure as the design variable while the constraint function represented the distance of the desired shape from the final part. This method is limited in that the objective function tends to be complex and requires many simulation runs. Gelin and group [Gelin et al., 2005] compared a numerical scheme and an optimization scheme for the pressure curve. The numerical scheme involved considering the fluid in the die cavity, the momentum and mass conservation equations and motion of the fluid nodes at the tube surface. The optimization scheme involved an objective function which took into account the variations of the volume of fluid injected into the tube. Though the numerical scheme took less time than the optimization scheme, it relatively took long time (14 hours) to develop and hence a method providing the loading paths in a shorter time would improve the THF process.

The maximum pressure allowable $P_{(\max)}$ may be obtained by analytical methods [Asnafi, 1999; Koc et. al., 2000; Hwang et. al., 2005] that involve modeling the tube as a thin cylindrical vessel, or by the finite element modeling methods in conjunction with the available equipment limits. The analytical method for the pressure curve may be a linear function such as from 0 to p_{max} (developed using Eqn. 2.1) or by adaptive methods.

The linear pressure function method observed by Jirathearanat, (2004) leads to the need for high nodal velocity at the tube ends to overcome excessive thinning. Aue-U-Lan and group [Aue-U-Lan et al., 2004] developed an adaptive pressure curve that is made of segments of increasing pressure and constant pressure. Upon the detection of excessive thinning, the pressure is held constant while increasing material feed until the detection of wrinkling, and then pressure is increased. The adaptive method provides a corrective measure to the linear function but requires advance knowledge of predicting bursting and wrinkling such as to know when to maintain a constant pressure due to the onset of bursting.

Aydemir and group [Aydemir et al. 2005] designed a fuzzy based incremental pressure curve similar to the adaptive method but that took into effect the prediction of THF failure based on fuzzy logic. The wrinkling criterion uses an energy-based indicator inspired on the plastic bifurcation theory. For necking, followed by bursting, a criterion based on the forming limit curve is employed. Applying these two criteria, the process parameters (pressure and material feed) are adjusted during the simulation via a fuzzy knowledge based controller. This leads to the pressure curve profile with increasing pressure segments with varying gradients. The limitation in this method is not being a ‘ready to use’ scheme and its dependence on the Engineers experience. Though a knowledge base is used to provide information on failure, a ‘database’ knowledge base developed with simulations would enhance the loading path development. The analytical methods above are also limited in that there has to be a change in the design of the pressure curve whenever there is a change in the geometry variables of the part or change in the overall shape of the part.

Material feed curves have been developed by methods such as adaptive, fuzzy logic and analytical. The adaptive method discussed by Aue-U-Lan and group, [Aue-U-Lan et al., 2004] uses the principle where the material feed is increased till the onset of wrinkling (effect due to excess material feed) is detected and maintained at a constant till the onset of bursting (effect due to excess pressure) is detected. This interchange of material feed and pressure goes on till the end of the forming time. This method takes time in adjusting the process parameters and is suitable for simple bulge shapes as mentioned by Jirathearanat, (2004).

Shu-hui and group [Shu-hui et. al., 2008] developed loading paths using a knowledge database that operated with fuzzy logic algorithm from a simulation database library with necking and wrinkling indicators obtained from simulation results, which are used as the input for the fuzzy logic control. The output sets of the fuzzy logic control were used for adjusting the loading path. Ray and MacDonald [Ray et. al., 2004] developed an intelligent fuzzy load control algorithm that operated by bringing much axial feed as possible to the ends of the tube while simultaneously keeping internal pressure low. The fuzzy methods above are time consuming in designing a loading path in response to a slight change in geometry or change in the family type and further assumes that the coefficient of friction is a constant value whereas it varies during the hydroforming process. The analytical method of determining the maximum material feed (total stroke) discussed by Asnafi (2004) develops the stroke as a function of the length of the tube and yield strength. This is limited by the number of variables that can be changed and does not provide detail on the profile required.

Potential ways of improving the loading path to reduce design time include developing the pressure curve that is adaptable to various THF parts. This can be in the form of a polynomial curve with end of the polynomial with a value of one. The maximum pressure values that are mapped to this polynomial profile can be determined based on various variables. The development of a database with the ability to adjust the loading path with various parameters that vary during the process such as the friction coefficient would enhance the accuracy of the loading path. The database also has the capability of storing various simulations, suitable for establishing searches for the optimal loading paths whenever there is a change in the variables used to develop the simulations. This close examination in the development of the loading paths is necessary to avoid part failures discussed below.

2.2.3. THF Failure Modes

The three failure modes below discuss the forming limits in THF.

- **Wrinkling-** is commonly observed in short tubes with relatively thin walls (i.e. high diameter/thickness ratios) according to Koc and Altan, [Koc et. al., 2002] and is as a result of much material feed and less pressure. Initiation and growth of wrinkles are influenced by many factors such as stress ratio, material properties, geometry of work piece and contact conditions. In the study by Koc and Altan [Koc et al., 2002], the critical axial compressive stress and force for wrinkling to occur are directly affected by the strength of the material strain hardening, thickness and effective strain. In order to reduce wrinkling internal pressure has to be increased during the process and more so when the tube is in contact with the die cavity.

- **Buckling –** similar to wrinkling this occurs where the internal pressure is less and is observed in long tubes with relatively thick walls (i.e. low diameter/thickness ratios) [Koc et al., 2002] during the initial stages of deformation when strain level is very small. To avoid buckling, the free length has to have a certain relation with twice the outer diameter based on the ratio of the original outer diameter to thickness [Asnafi, 1999]. The critical axial compressive stress and force for buckling [Koc et al., 2002] for tubes are dependent on the length, (inversely proportional to the square of the length).

- **Bursting-** is due to excessive pressure that leads to excessive thinning. Bursting is irrecoverable and hence detecting onset of bursting (referred to as 'necking') is very important. In order to avoid bursting material feed is provided during the process and maximum internal pressure should be attained when the tube wall is resting against the die cavity wall.

For best results of Tube Hydroforming, Dohmann and Hartl [Dohmann et al., 1997] proposed designing the loading path within the process window as shown in Figure 2-5. The process window occurs above the yield zone which is the limit where the material begins to deform plastically. The material feed necessary should provide a force above the force needed for sealing as shown in Figure 2-5.

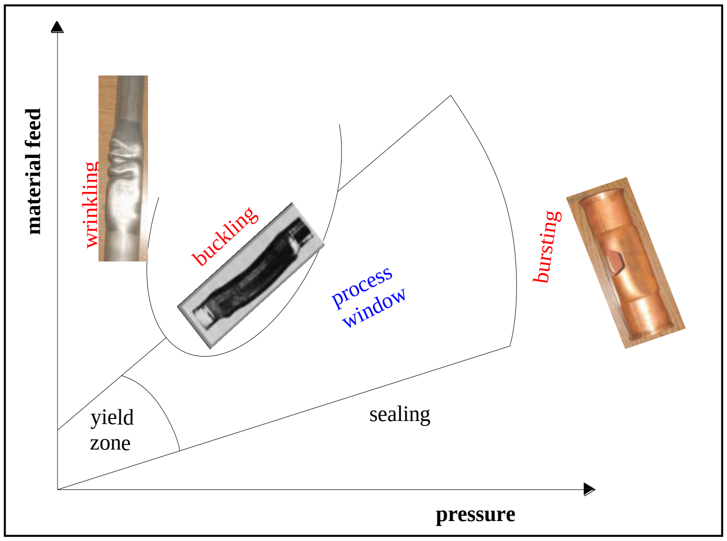


Figure 2 - 5 Process Window and Failure Modes

2.3 ERRORS AND UNCERTAINTIES

Errors and uncertainty occur in manufacturing and vary with the manufacturing equipment and operations performed. Press machinery has various sources of error and uncertainty depending on the type of press and function performed. Vibration is more prevalent in mechanical presses than hydraulic presses. Qin and group [Qin et al., 2004] discuss dimensional errors associated with forward extrusion. Balendra and groups [Balendra et al., 2000; Balendra et al., 2004] have done considerable research into errors in forming processes including die deflection that arises from neglect of die elasticity during FE simulation of dies. Vibration errors due to ram motion [Badrinarayan et. al., 2004], thermal errors in precision machining [Hao et. al., 2008] and force induced errors in milling [Ratchev et. al., 2005] are some of the common errors that lead to dimensional and form errors [Zhou et. al., 2004] in the final component. The presence of friction is a common source of error [Ou et. al., 2002] in most metal manufacturing processes.

The undetected variation of friction leads to underestimating the effect of friction. Large amounts of frictional force during a machine process lead to the work tool experiencing large forces that can lead to tool wear. Some of these errors occurring in manufacturing affect the THF process as discussed below.

2.3.1. THF Process Sources of Errors and Uncertainty

Common errors and sources associated with THF are categorized based on the area of occurrence are shown in Table 1. The 'occurrence' is the general term to show category of the error. As shown in Table 1 errors can be generally classified as process errors that occur due to inappropriate amounts of the forming inputs, loss errors that are associated with decrease in the effect of applicants (that are subject to loss), equipment errors that are associated with the working of tools and equipment, material errors that are associated with the material blank and indirect errors associated with preprocessing stages such as Finite Element Analysis (FEA) results. This makes THF a highly nonlinear system.

The Figure 2-6 shows the different stages in the process. The stages shown involve:

- The generation of simulated results with FEM for material curve where errors include dies being considered rigid neglecting die elasticity.
- Development of pressure curves where analytical designs consider various parameters that may include imperfections due to inhomogeneous and anisotropic materials [Koc et. al., 2002].

Table 1 Sources of Error in Tube Hydroforming

Occurrence	Errors	Sources
Process	Buckling	Excess material feed
	Bursting	Excess Internal pressure
	Wrinkling	Excess of material feed and pressure
Losses	Leakage	Broken seals, Imperfect tool-punch contact
	Friction	Poor lubricant application
	Lubricant loss/thinning	Environmental effects, i.e. temp on lubricant
Equipment	Cylinder seal friction/valve friction	Broken seal/quality & quantity of lubrication
	Inaccurate position of sensor	Measurement inaccuracies
	Tool wear /poor surface quality	Friction
	Vibration	Environmental effects/foundation
	Heat increase-high cycle time	Lack of coolant
	Actuator nonlinearities	Positioning error/ motion nonlinearity
	Machine frame deflections	Assembly errors/ poor guiding systems
	Controller variations	Control errors such as electrical noise
	Flow saturation in valves	Flow nonlinearity
	Tool position error	Alignment issues with repeatability
Material	Change in properties	Presence of high stresses
	History defects	Material imperfections-tube ends not perpendicular to longitudinal axis
	Weld line weakness	Weld line properties differing from other part
	Localized deformation	Incorrect material flow-inaccuracy of flow
	Poor surface quality	Poor ejection methods.
Indirect, i.e. Software Issues	FEA solution errors	Arithmetic tolerances, lower bound solutions
	Modeling Inaccuracies	Limited Simulation power
	FEA Assumptive errors	Neglecting effect of die elasticity [48]

- Controller communication between the press and the loading path where remote communication may be affected by electrical noise or heavy communication traffic on the network hence lowering the performance efficiency.
- Hydraulic equipment to carry out instruction from the PLC where uncertainties and leakage losses can occur.

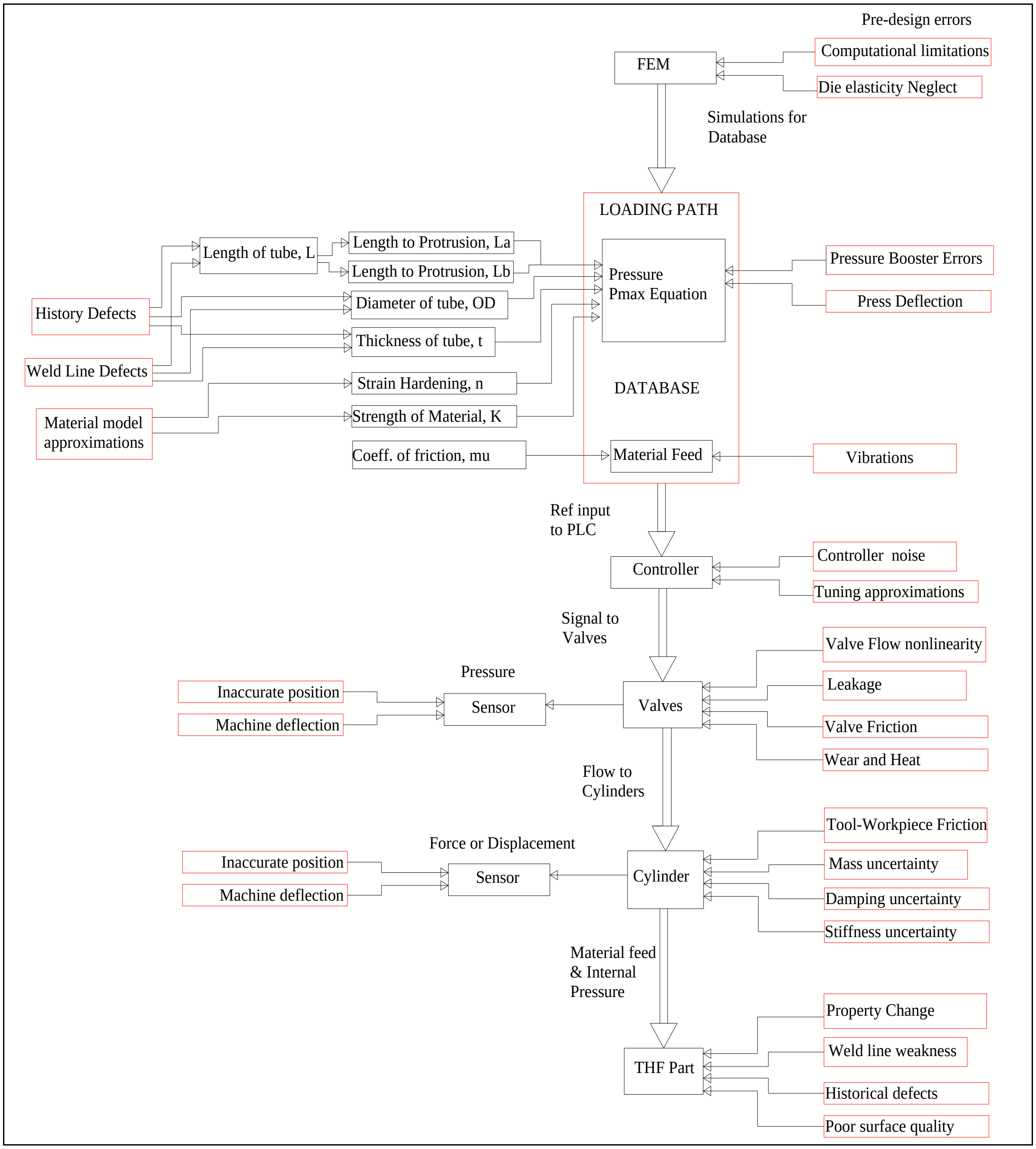


Figure 2 - 6 Errors and THF associated Stages

Other errors are related to process set up where misalignment and tube imperfect edge conditions may lead to eccentric loading [Koc et. al., 2002]. These errors require compensation.

2.3.2. Introduction to Error Compensation

Error compensation is the event of offsetting a variable or a process path in order to achieve a desired result where the difference between the desired result and the outcome is due to errors. Error compensation is used to assist correct the difference with the goal of increasing the quality of products and reduce the costs of production.

2.3.3. Methods to Error Compensation

Error compensation models studied by Zhou and group and Ramesh and group [Zhou et. al., 2004 and Ramesh et. al., 2000] are categorized as either online models where errors detected are compensated within the same process operation or offline models where errors are measured before or after a process to be utilized in subsequent operations. Database libraries that contain knowledge for comparison to predict the amount of error anticipated (offline model) have been developed [Balendra et. al., 2000; Hao et. al., 2008]. Other database libraries have been developed involving compensation algorithms for virtual processes [Chen et. al., 2004; Ratchev et. al., 2005] (online model). Other efforts ventured to compensate errors involve numerical methods [Holecek et. al., 2005], feedback systems [Hao et. al., 2008], Fuzzy control [Park et. al., 1992], optimization schemes [Gelin et. al., 2006] and adaptive methodology [Xia, 2000]. The challenge is to develop a system with real-time error compensation involved during actual process.

Errors, particularly frictional errors, in hydraulic cylinders have been researched. Sohl and group [Sohl et. al., 1999] discussed the effect of friction and developed compensation by taking friction within the axial cylinder as a disturbance to the system and hence using controllers to reject the disturbance. Olsson and group [Olsson et. al., 1996] studied actuators based on velocity tracking, developed friction compensation for actuators by taking the force applied to be proportional to the control signal. Compared to THF process this internal cylinder frictional error is less than the frictional error occurring at the interfaces between tube and die. Process control provides enlightenment on the effect of errors in manufacturing processes and the need for compensation. This is crucial for THF processes where proper process control is required in applying the loading path in order to inhibit part failure modes.

2.4 PROCESS CONTROL

2.4.1. Process Control in Manufacturing

Process control has been utilized in various manufacturing sectors such as wastewater plants, distillation processes, and aerodynamic systems. The common control methods are open-loop and closed-loop control. Open loop control is limited in that it does not track the difference between actual and desired values. This limitation does not exist with closed-loop control. Nachtwey [Nachtwey, 2007] comments that open-loop control can be used in combination with closed-loop control for different parts of the machine cycle such as open loop used in the retract direction to quickly open a press to eject a part and closed loop used in forming the part. Closed loop control is favorable for applications that require following a profile path, synchronization, a high degree of flexibility, accuracy, and speed; or the ability to maintain precision with changing loads [Nachtwey, 2007].

Closed-loop control makes use of a controller to adjust the signal to correct the difference between actual and desired values. Common controllers used are the Proportional-Integral-Derivative (PID) controller, Proportional-Integral (PI) and Proportional- Derivative (PD) controllers.

Some of the advances in process control in manufacturing involve the ability to compensate for variations in the machine's hydraulic characteristics without manual intervention. This has been done for the injection molding industry and used in companies such as JVH Engineering, Inc in Michigan, US [JVH, 2010]. This compensation is done during each machine cycle by comparing actual machine process variables with the desired set points and then adjusting the control output to the hydraulic valve amplifiers to compensate for any differences or errors that may have occurred in the previous cycle of operation.

Databases have been used as libraries for storing experience information, material and tool knowledge. ThyssenKrupp [Thyssen Krupp, 2001] developed a material database library with the benefit of assisting the user in selecting a material for an application before simulation or prototyping. Much is desired regarding the use of databases online for information during the manufacturing process. Cylinder positioning has been done such as by Delta computer systems [Delta motion, 2009] with controllers and feedback from displacement transducers mounted along the hydraulic piston axes.

2.4.2. Process Control Methods- Feedback System

The feedback system has been crucial in the advancement of control in manufacturing. This method of control is commonly appropriated for adjusting input parameters via a controller based on the measurement of the output parameters. Sensors are used to measure the output and provide feedback to the control unit, which then compares the obtained signal (output) versus the desired (reference) signal and provides a corrective action. Block diagrams are commonly used to represent the schematics for feedback control as shown Figure 2-7 below where ***r*** is the reference signal, ***e*** is the error, ***u*** is the control signal, ***y*** is the actual output.

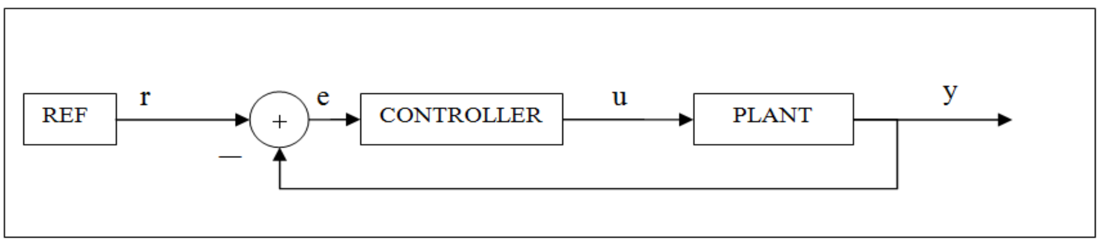


Figure 2 - 7 Block Diagram with Closed Loop model in THF

Some of the kinds of feedback for dynamic systems are position, velocity, force and pressure feedback where displacement sensors are for position feedback, tachometers are for velocity feedback, load cells for force feedback and pressure transducers for pressure feedback. Though placing a load cell in most metal forming processes is difficult due to the high forces and/or pressure, force sensors have been used in processes such as the deep-drawing press [Wagener et. al., 2001] where sensors are connected to connecting rods or placed under the die. In the absence of load cells, pressure providing differential cylinder motion can be converted to force by multiplying the pressure by the area of the cylinder punch.

The controller which provides a signal to the plant in response to the difference of the output and reference has been designed for cylinder motion with various techniques such as PI controllers [Lazic et. al., 2007], PID controllers [Zhao et. al., 2005], controllers based on loop shaping approach [Tsai et. al., 2009] and $H\infty$ techniques [You et. al., 2006]; for the purpose of position tracking [Mihajlov et. al., 2002] and force tracking [Sohl et. al., 1999; Zhang et. al., 2007]. In the above designs the focus was on general motion of the cylinder. Some have further discussed the motion of the cylinder in relation to the environment being acted upon. Niksefat and group [Niksefat et. al., 2001] discuss the need for controllers involved in motion control of cylinder actuators interacting with manufacturing automation platforms and material handling environments. This interaction leads to variations in operating conditions and component degradation resulting in design parameter change. Tar and group [Tar et. al., 2005] designed a PID controller for an electric servo-valve operated hydraulic cylinder under unknown external disturbance forces The above researchers designed the forces with a spring (operating within the elastic range) and less is known about the effect of a PID controller in a system interacting with a deformable body (beyond the elastic range). The THF process poses the challenge and below is a discussion on control for the THF.

2.4.3. Process Control in THF – The Hydraulic Unit

The THF process involves introducing the work piece (tube) to the die, providing reference loading path instruction to the press control system using software programs. The control system instructs the equipment by sending signals (such as voltage) to the flow source which supplies fluid from the pump to the cylinder.

The equipment used for THF mainly the hydraulic press, suitable for its capability to provide internal fluidic pressure into the work piece and provide material feed via valves and axial cylinders. The Figure 2-8 shows the sample schematic of the THF control system. The control task involved in the Figure 2-8 is tracking the position of the cylinder, *xref*, using a controller, *Gv*, desired to reduce errors, e_r, the difference between the reference signal *Ref*, and output of the cylinder.

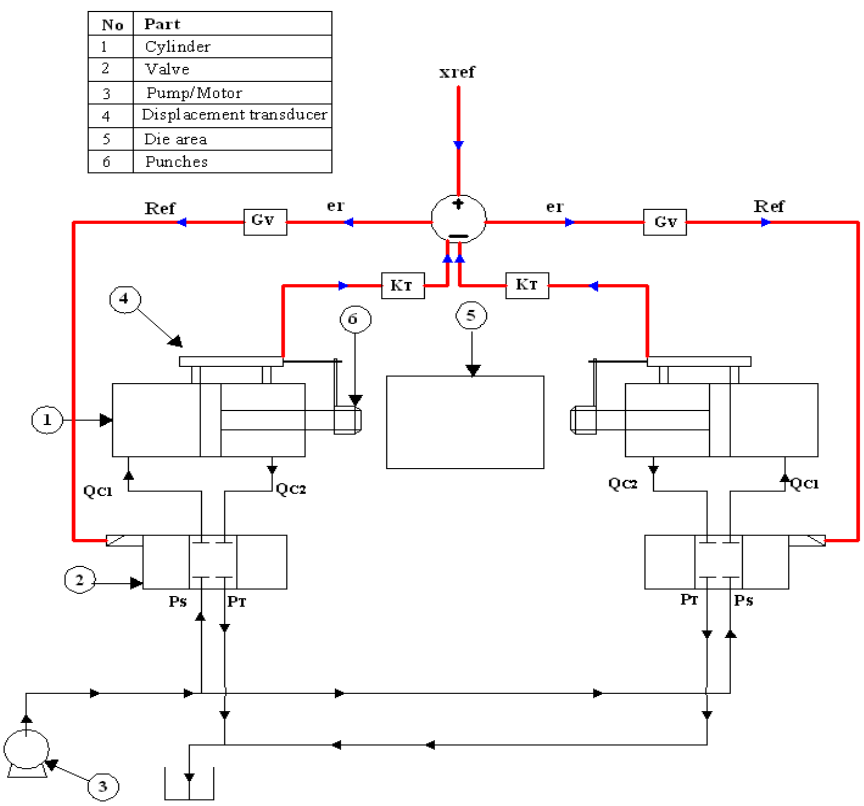


Figure 2 - 8   Sample Control System for a THF Press

In the industrial sector different companies involved with THF have developed various algorithms and software to address their control needs.

Interlaken [Interlaken, 2010] developed a system with various features including: the ability to switch between stroke controlled and force controlled loading paths within an operation cycle, the ability to control the velocity of the cylinder or pressure flow rate from the booster, complex actuator motion including ramp and sinusoidal and sequence control which includes guiding forming steps by events or by time. These advances show the growth of process control in THF. Error compensation during process control is desired to realize better THF performance. Suggested methods of THF error compensation are discussed below.

2.5 SUMMARY AND FUTURE AREAS OF RESEARCH

Tube hydroforming process has been reviewed and discussion carried out on the loading path. This path is prone to failures due to the dual application of material feed and internal pressure. Various errors affect the THF process and can be broadly categorized into three parts: errors affecting the design of the loading path (affecting the design of the material feed and pressure), errors associated with the application of the loading path (discussed as the failure modes) and errors associated with the result of the application of the loading path (discussed as equipment errors affecting the output of the loading path). This work proposes handling the above issues by focusing on the need to:

i. Develop an interactive database scheme for generating loading paths with less computing time.
ii. Study the dominant errors in material feed and effects on the loading path
iii. Analyze the equipment errors associated with internal pressure

iv. Study the application of database systems and potential for use in real time processes.

v. Develop real-time error compensation methods that address the dominant loading path errors and equipment errors during the process.

vi. Develop tube hydroforming system models involving the equipment parameters.

vii. Study the effect of the different controller designs and applications in Tube Hydroforming

viii. Develop feedback process control to enhance the error compensation schemes and review the effect of position, velocity and force control

ix. Analyze the performance of real time communication between the loading path and the press. This involves reviewing the comparisons of remote control and the alternatives to Data Dynamic Exchange (DDE).

This work focuses on specific items listed above. Item (i) is handled by developing an analytical approach for the pressure curve and generating material feed curves by the development of a database with interpolation schemes. These two items are developed into a Database Generating Loading Path Scheme (DGLPS) with a user interface for parameter inputs. This method is suitable for reducing computation time in developing loading paths, and hence cutting back on costs and proving efficient for mass production systems. Item (ii) is achieved using Design of Experiments (DOE) technique to compare the errors due to material, geometrical and tribological properties. Item (iv) is performed by using the database developed from DGLPS and applying to real time Tube hydroforming process. This is coupled with Item (v) to form the Database Back-Step (DBS) method.

Item (vi) is addressed with a spring model representing the environment and a PID controller proposed to handle Item (vii). Item (viii) is tackled with the design of the Real-Time Stroke controller which is a PID structured controller that in a closed loop and for position control.

CHAPTER 3:
DATABASE DEVELOPMENT FOR TUBE HYDROFORMING LOADING PATHS

This section of the research focuses on obtaining a loading path from a database based on various variables. The loading path is formed by plotting the material feed curves and pressure curves against each other. This chapter will review the use of databases in loading path design and discuss the Database Generated Loading Path Scheme methodology and operation. An analysis for developing the maximum internal pressure is discussed based on the geometrical and material variables of the Bulge Shape. This maximum pressure is mapped to a pressure profile to develop the pressure curve (pressure vs. time). Material feed case studies are developed with the Database Generated Loading Path Scheme and compared to FEA simulations.

3.1 DATABASE USE FOR LOADING PATH DESIGNAND GENERATION

Methods to design the loading path have been mentioned in section (2.2.2). The database employs an analysis to develop the maximum value of pressure and interpolation schemes to develop the material feed curve. A comparison between the methods mentioned in section (2.2.2) for developing loading paths and the database is given in Table 2. In the Table 2 the term ‘Method’ refers to the type of design used to obtain the loading path. ‘Maximum pressure’ is related to the scheme used to obtain the maximum pressure. ‘Pressure Curve Profile’ and ‘Material Curve Profile’ show the type of path of pressure and material feed.

'Material Feed Profile' is the scheme used to obtain the material feed and 'Loading Path Request' is the computation time required to generate a loading path.

Table 2 Summary of Loading Path Design Methods

Method	EMPIRICAL	ANALYTICAL	ADAPTIVE	DATABASE
Maximum Pressure	Use of FEM/ Trial and error	Use of Equations	Use of Equations / FEM	Use of Equations / FEM
Pressure Curve Profile	Linearly to Maximum value	Linearly to Maximum value	Linear and constant profiles	Polynomial
Material Curve Profile	Linear to a Maximum value	Linear to a Maximum value	Linear and constant profiles	Non-linear
Material Feed Profile	Use of FEM	Use of Fuzzy logic or FEM	Use of FEM	Interpolation Scheme
Loading Path Request	Fast but limited to few variables	Slow	Slow	Fast and efficient for multiple variables

The database contains sets of simulated data, established based on three classifications of variables given below (more discussion in section (3.2)):

- Geometric parameters – these include the geometrical aspects of the tube such as tube length, tube diameter and tube wall thickness (t).
- Material properties (strength of material (K) and strain hardening exponent (n))
- Tribological parameter (coefficient of friction (μ)).

These variables form the set variables required during the performance of the database. The database is further developed with Microsoft Excel macros that perform various functions in the database such selection of the type of family, requesting the set variables from the user using input boxes, developing the pressure curve, performing interpolation algorithms for the material feed curves and force curves and output the results in a graphical format.

The macros also gather the data from the simulation and store the loading path for use in the real-time error compensation scheme. More discussion on the use of macros in the error compensation scheme is in Chapter 4.

3.2 DATABASE GENERATED LOADING PATH SCHEME METHODOLOGY

The parts used for this database can be broadly grouped into 'families' based on the final shape obtained. This leads to bulge type and protrusion type such as Single and Double T-Shape with the protrusion of the tube at right angle to the tube axis (angle of protrusion to tube axis is α); and Single and Double Y-Shape with the protrusion of the tube at an angle less or greater than right angle to the tube axis. The database contains sets of simulated data for various THF families. Figure 3-1 shows the cross-section of the families.

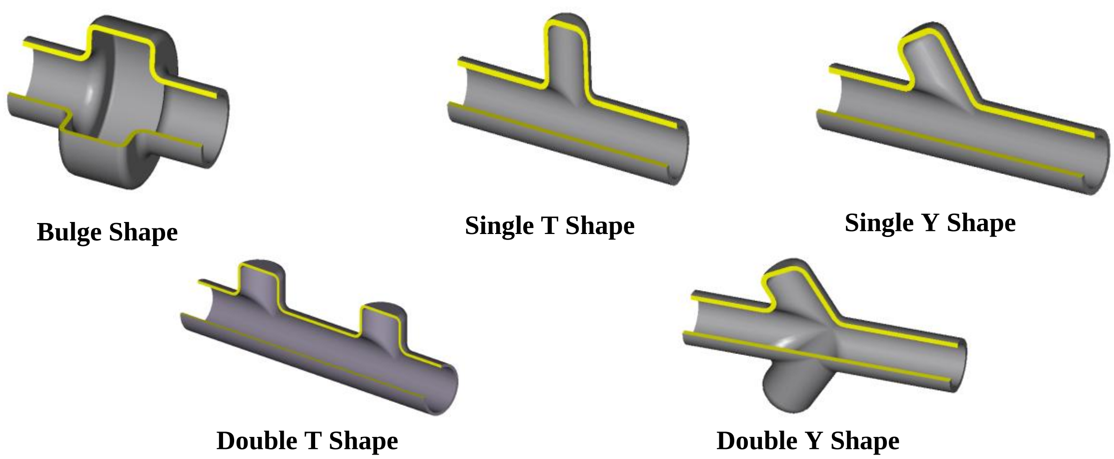


Figure 3 - 1 THF Families in the Database

The classification of variables i.e. geometrical, material and tribological variables are referred to as 'input parameters' since they are provided by the user into the database in order to generate a loading path. All input parameters apart from μ are used in the analysis for developing the maximum pressure for the pressure curve as further discussed in section (3.5). Thus variations in the coefficient of friction will not affect the pressure. The material feed curves are developed based on simulations available in the database. Each simulation is created with a unique set of 10 variables i.e. a set of (Lt, La, Lf, h, OD, t, K, n, μ, α) the geometric parameters are illustrated in Figure 3-2.

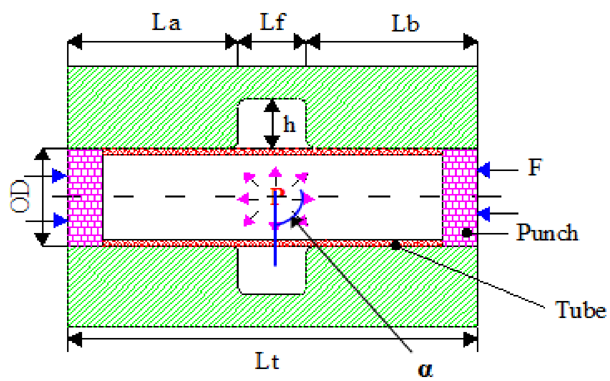


Figure 3 - 2 Input parameters used in Simulation

3.2.1. <u>Development of Simulated Sets of Loading Paths from FEA</u>

The THF family shape models are simulated with ABAQUS Explicit, with the die modeled with solid elements and the deformable tube with shell type elements. The simulation process time is 0.01s. Steps involved are:

1. Creating a loading path model design where the initial tube geometry is based on the following constraints:

- Outer Diameter (OD) of the tube should be between 25mm to 40 mm for Single T and Y families and between 30mm and 40 mm for Bulge, Double T and Y Families.
- Protrusion heights of up to 40 mm.

- Thickness of tube should be between 1 mm to 3mm.
- The length of the tubes should be between 150mm and 200mm.
- For Y-Shape families (Single and Double), the die angle(s) to the protrusion(s) from the tube axis, should be between 45̊ to 60̊ and for T-Shape families (Single and Double) and the Bulge Shape the angle is 90̊.

2. Establishing material properties for stainless steel SS 304 with Ludwick-Holoman hardening law $\sigma=K\varepsilon^n$, where σ is the effective stress, K is the strength of the material ranging from 150 MPa to 1500 MPa, ε is the strain, n is the strain hardening exponents ranging from 0.4 to 0.6.
3. Establishing Tribological conditions with the friction coefficient between 0.01 and 0.3.
4. Creating the material feed curve which is developed by providing a velocity profile to the axial punches. The conditions involved in the material feed curve design are:

- Ensuring that there is no loss of contact between the punches and tube. This is achieved by visual inspection of the forming history and observing the forming force profile which should not be zero.
- Maintaining a final thinning of 30%
- Ensuring that the material in the expansion zone reaches the die cavity wall.

5. Developing a pressure profile for the Tube families – more discussion in § 3.5
6. Once the simulation is done and conditions mentioned in step 4 above are satisfied, the simulated material feed together with the unique variable set used are stored in an Excel file. A force curve (forming force versus time) with the same variable set is also stored.

3.2.2. <u>Database Generated Loading Path Scheme Performance Steps</u>

The steps involved in the scheme are as follows:

- Open the database Excel workbook and enable macros. Amongst the list of macros select and run the **CreateToolbar** macro. This macro adds a Toolbar button with the list of THF families: Single and Double T-Shape, Single and Double Y-Shape, X-Shape and Bulge Shape. The sample of code for this macro and the list box created are shown in Figure 3-3 below. The whole code is in Appendix A

```
' Add a list box
Set cbctl = cbar.Controls.Add(Type:=msoControlDropdow

' Add a tag so macro can find it
cbctl.Tag = "THF-FamilyList"
cbctl.Visible = True
cbctl.Caption = "ListCaption"

' Set list properties of the list box
With cbctl
    .AddItem "Double T-Shape", 1
    .AddItem "Single T-Shape", 2
    .AddItem "Double Y-Shape", 3
    .AddItem "Single Y-Shape", 4
    .AddItem "X-Shape", 5
    .AddItem "Bulge Shape", 6
    .DropDownLines = 0
    .DropDownWidth = 500
     'select nothing to start
    .ListIndex = 0
End With

' Set macro to execute when an item is selected
cbctl.OnAction = "HydroformListMacro"
```

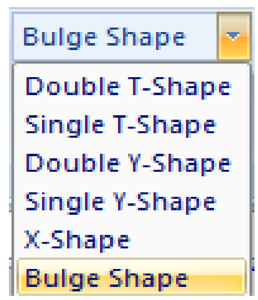


Figure 3 - 3 Sample of Create Toolbar Code and List box created

- Selection of choice of the THF family from the list developed from step above. Once the THF Family is chosen, a query is done to check if the database for the family is available. If available, a message is created as follows "(THF) is available" where '(THF)' represents the THF Family selected. A message to proceed, "Press the START button to begin" is created for guidance. The START is a button on the user interface Figure 3-5. For the current database the X-Shape family is not available.

- User provides input parameters (set of variables) as directed by the Active Control input boxes operated by a macros for every variable. This information is gathered and stored in specified cells regions on the user interface as shown in Figure 3-5. Sample of code for the input box is shown in Figure 3-4 below

```
    Sheets("START").Select
      Range("G16").Select
    InputTitle = "Kvalue"
    Kvalue = InputBox("What is the Kvalue input?", InputTitle, "1426", 6000, 800)
  ActiveCell.FormulaR1C1 = Kvalue

If ((Range("G16") <> Empty) And (Range("G16") >= 500) And (Range("G16") <= 1500)) Then
   'Code that handles the user's input
   'Message if K value has been entered
  MsgBox "Do you want to continue? "
   'Rename the cell containing the Kvalue
   Range("G16").Select
   ActiveWorkbook.Names.Add Name:="Kvalue", RefersToR1C1:="='START'!R16C7"
  inputn

 ElseIf (Range("G16") <> Empty) And (Range("G16") < 500) And (Range("G16") > 1500) Then
  'Message if K value has been entered and more than 500.
   MsgBox "Please input a value between to 500 and 1500"
   inputK
   Else
   'Message if K value has been entered and want to cancel
    MsgBox "Do you want to cancel?"
   End If
```

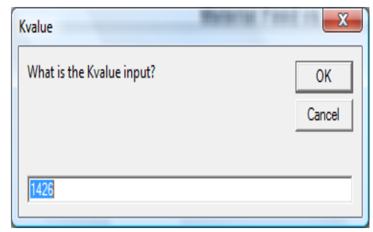


Figure 3 - 4 Input Box for K value

The input boxes collect data for variables as described below

- mu value Frictional coefficient
- K value Strength coefficient, K
- n value Strain hardening component, n.
- L tube Length of the tube, Lt
- Odvalue outer diameter, OD
- t value tube thickness, t
- Lf value Length of the bulge region
- La value Length from free end to left punch, La.
- Lb value Length from free end to right punch, Lb.
- α-,β-angles Angles of protrusion height to die.

- Upon completion of providing variable user has to click on the SUBMIT button (Ref Figure 3-5) to send the data for database operation. In a situation where a correction has to be done during data collection, the user can use the CANCEL or RESET Buttons to begin again. The RESET button will clear all previous data and start an input box to begin data entry. CANCEL Button will clear all previous data without beginning an input box for data entry and the user will have to begin with the START button.

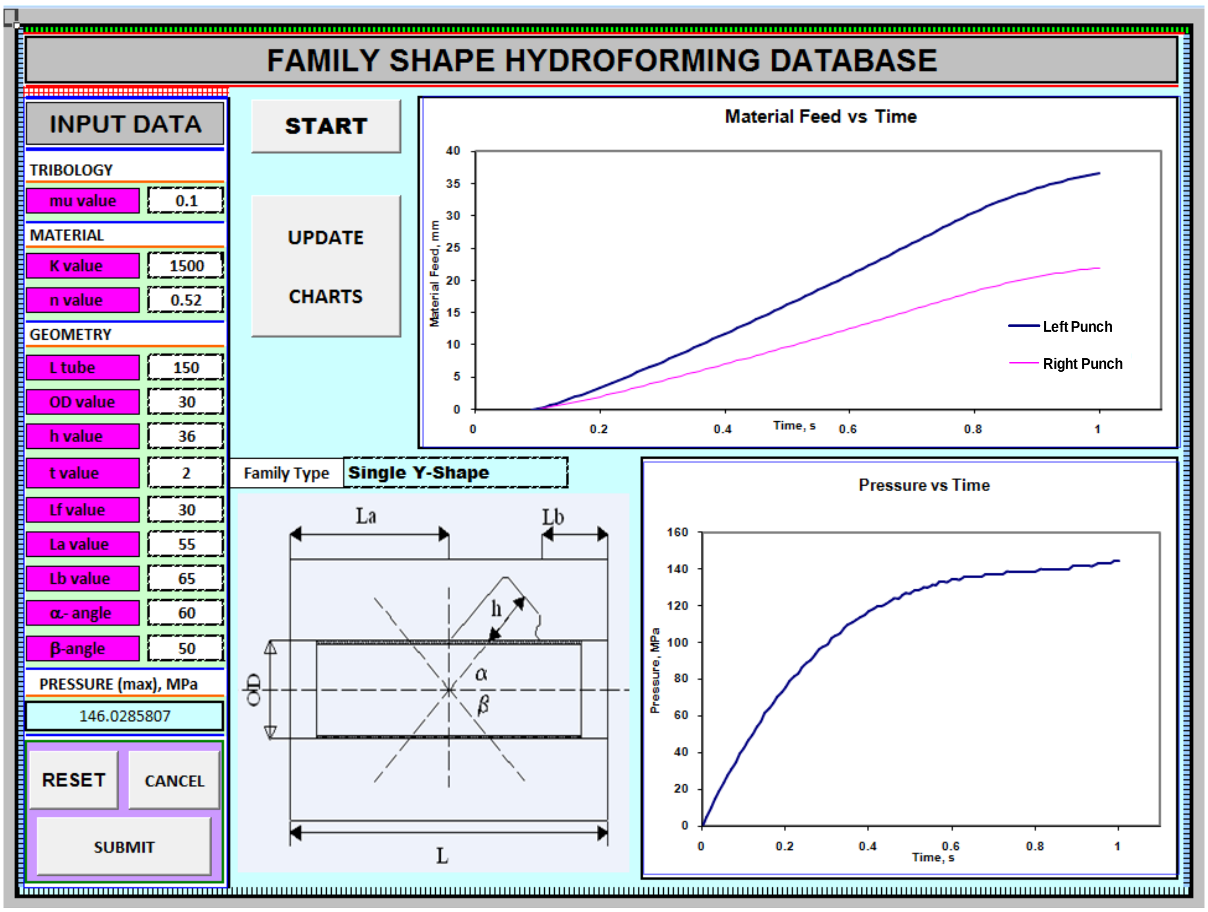


Figure 3 - 5 THF Graphic User Interface Display

- To view the output results, user will click on the UPDATE CHARTS button. The outputs are the material feed and internal pressure curves. The output curve for pressure is obtained by analysis discussed in section (3.5). The curve for material feed is based on the interpolation scheme. In this scheme a query is initially made in the database to check if the variables provided by the user match any of the simulated data in the database. If the set of variables is available then the simulated data set will be used for material feed, otherwise an interpolation has to be done. For example, if the variable of μ provided by the user is 0.07 and the database has simulated data for μ equal to 0.05 and 0.1, an interpolation will be done between 0.05 and 0.1. Extrapolation is acceptable within the variable constraints discussed in item (1) in section (3.2.1). The flowchart showing the steps of operation is shown in Figure 3-6 below

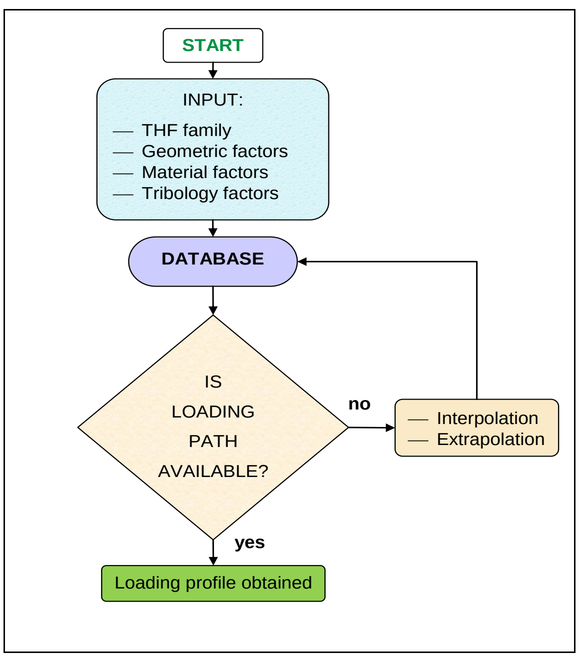


Figure 3 - 6 Database Operation Flowcharts

The Interpolation scheme for the developing material feed is shown in the Figure 3-7 where a query is done for all variables. Currently there is no interpolation for the protrusion height, h. The length of tube, *Lt*, variable is used for determining the length *Lb*, which is the length from the right edge of die to the protrusion.

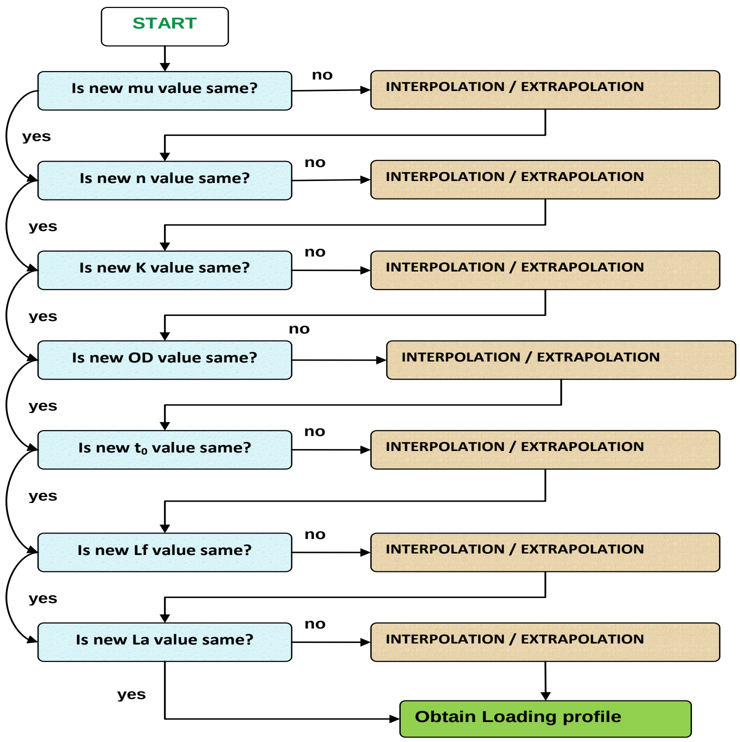


Figure 3 - 7 Interpolation Flowchart

The interpolation is done for all the time steps provided in the simulation set. The time unit used in the simulation is 0.01sec intended to match the maximum time of 100 sec for the complete THF process.

The material feed curve is developed along the following steps:

a) Based on the parameters provided in section (3.2), the database will perform interpolation between each parameter and the simulated data to develop a set of material feed curves (material feed versus time) and force curves (force versus time).

b) The interpolation calculation used to obtain material feed loading path is carried out using Eqn. 3.1:

$$\delta_2 = \delta_1 + \frac{(\delta_1 - \delta_0)}{(\mu_1 - \mu_0)}(\mu_{est} - \mu_0) \tag{3.1}$$

where δ represents the stroke (cylinder position) and μ is the coefficient of friction. Subscripts '*0*' and '*1*' represent simulated data sets and '*2*' is the new data obtained, '*est*' is the value provided by the user. Details on the operation are discussed in the next section.

3.3 DATABASE GENERATED LOADING PATH SCHEME OPERATION

This section investigates the operation of the database and the how the interpolation scheme responds to the variables. The first investigation involves the set of variables provided by the user where one variable does not match amongst the sets used for the simulated data. The next investigation involves the case where all variables provided by the user do not match any set of variables used for the simulated data in the database.

3.3.1. Investigation on the Effect of One Variable Interpolated

This section shows how the interpolation handles the need for one variable to be interpolated. Suppose the variable μ (coefficient of friction) obtained from the user is different from the database sets. Let the name of the variable obtained from the input box from the user estimated value be *μvalue*. Then linear interpolation using the Newton Forward Difference equation, Eqn. (3.2), will be used to obtain the material feed data for *μvalue*. Defining *sim set 1* in the Figure 3-8 as the column the loading path model set (This is the first set of loading paths) with material feed data set $x1$ corresponding to coefficient of friction as $\mu1$.

	sim set 1	*sim set 2*	*sim set 3*	*sim set 4*	*sim set 5*	*sim set 6*	*sim set 7*
	Original	*new_μ*	*new_n*	*new_K*	*new_OD*	*new_t*	*new_La*
Kvalue	1500	1500	1500	750	1500	1500	1500
nvalue	0.5	0.5	0.6	0.5	0.5	0.5	0.5
tvalue	2	2	2	2	2	1	2
Odvalue	30	30	30	30	36	30	30
hvalue	13	13	13	13	13	13	13
rvalue	90	90	90	90	90	90	90
Lavalue	85	85	85	85	85	85	115
Lfvalue	30	30	30	30	30	30	30
mu	0.1	0.25	0.1	0.1	0.1	0.1	0.1
Lbvalue	85	85	85	85	85	85	55
Time (sec)							
0	0	0	0	0	0	0	0
0.01	0.003064	0.003688	0.005715	0.003168	0.00326	0.003471	0.004085
0.02	0.016875	0.021824	0.025525	0.015212	0.01843	0.019884	0.025099
0.03	0.045603	0.056622	0.060285	0.036785	0.04916	0.052262	0.063292
0.04	0.086084	0.100395	0.109656	0.067308	0.08747	0.097806	0.111218
0.05	0.132397	0.162215	0.166286	0.102295	0.14183	0.150156	0.178877
	x1	x2					

Figure 3 - 8 Sample Sets in the Database for Bulge Shape

Also defining *sim set 2* in Figure 3-8 as another set of simulated data with material feed data set $x2$ and coefficient of friction as $\mu2$. The desired material feed data set *xvalue* corresponding to *μvalue* provided by the user, which lies between $\mu1$ and $\mu2$ is obtained from:

$$xvalue = x_1 + \frac{(\mu value - \mu_1)}{(\mu_2 - \mu_1)}(x_2 - x_1) \tag{3.2}$$

This interpolation is done for the entire time. The graph Figure 3-9 shows a sample case for the change of *μvalue* from the variable 0.002 to 0.1. The profiles of the simulated and interpolated data were approximately the same.

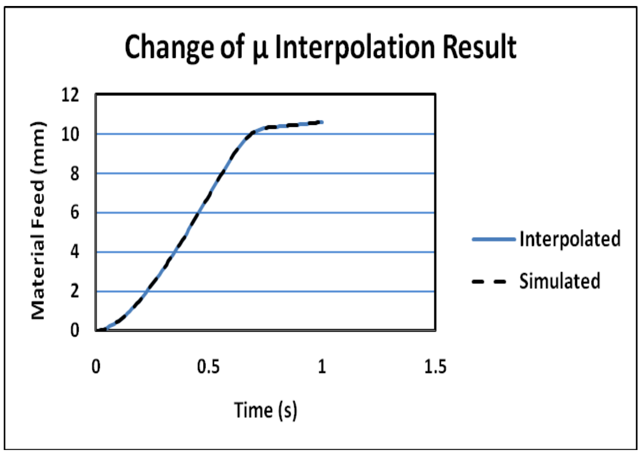


Figure 3 - 9 Change in One Parameter for Bulge Shape THF

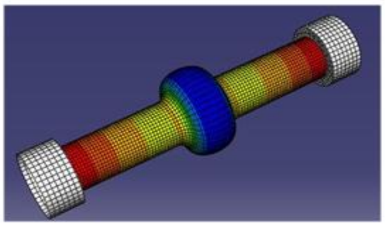
3.3.2. Investigation on the Effect of All Variables Interpolated

This section shows how the interpolation handles the need for all variables to be interpolated. Interpolation steps will be carried out according to Figure 3-7.

Bulge Shape

The 'new' variables provided by the user (refer to Figure 3-10) are used in the interpolation scheme and also in a separate simulation for comparison purposes.

The final interpolated result was a close match to the separate simulation done with minimal difference appearing during the calibration stage. Figure 3-11 shows the interpolation steps for all parameters except change in the h value.



Parameter	New values
n-value	0.55
K-value	1300
OD value	32
t- value	1.5
Friction Coeff μ	0.15
La/Lb value	95

Figure 3 - 10 Bulge Shape Part and Variables used

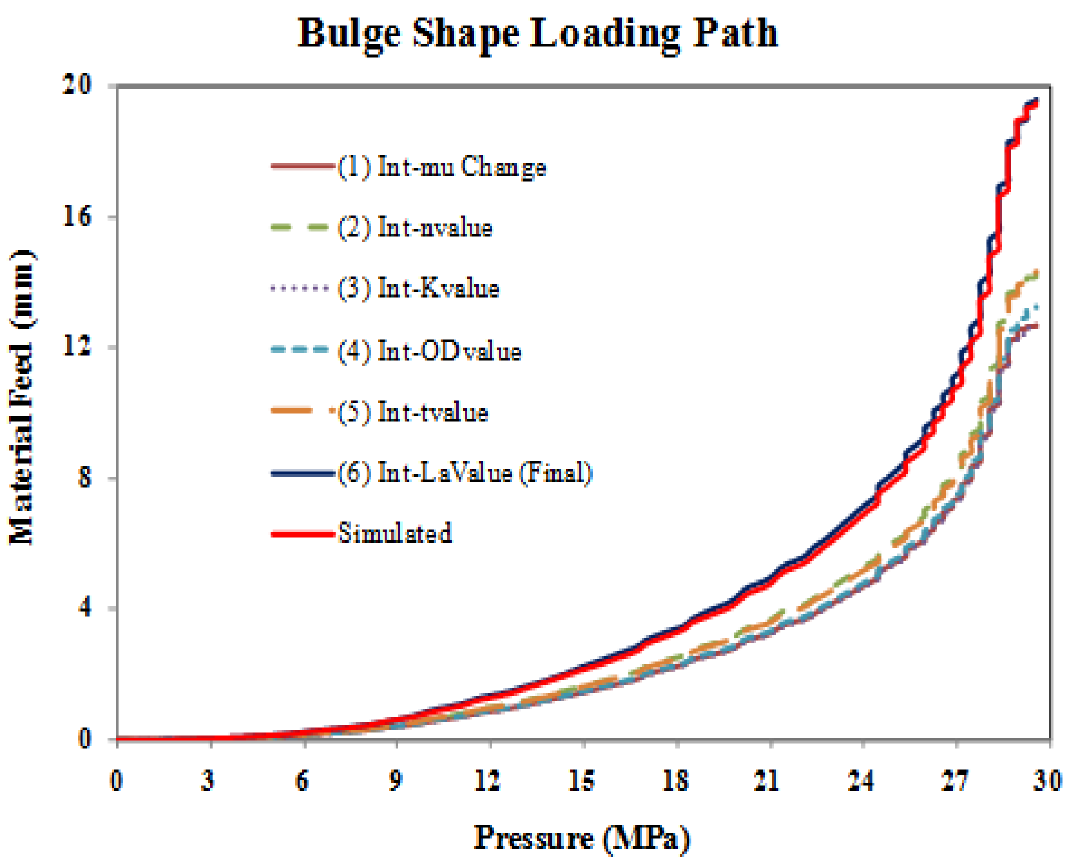
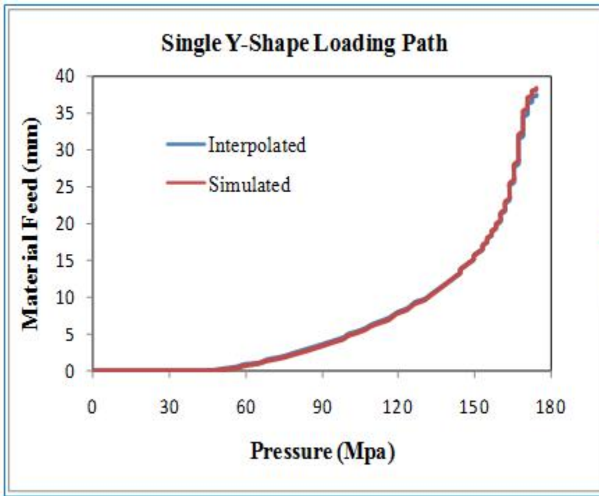


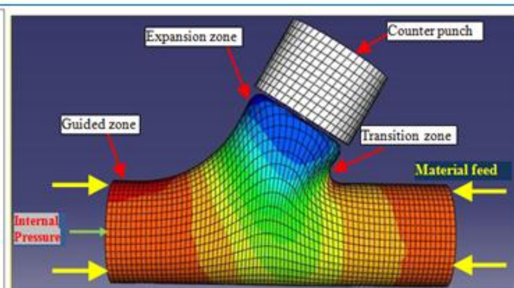
Figure 3 - 11 Bulge Shape Simulated-Interpolation Comparison

The investigations in sections (3.3.1) and (3.3.2) were done for Bulge Shape THF family. The development of the pressure curve used for the loading path in Figure 3-11 is discussed in section 3.5.The next section investigates the operation of the database for other families.

3.4 OTHER THF FAMILY CASE STUDIES

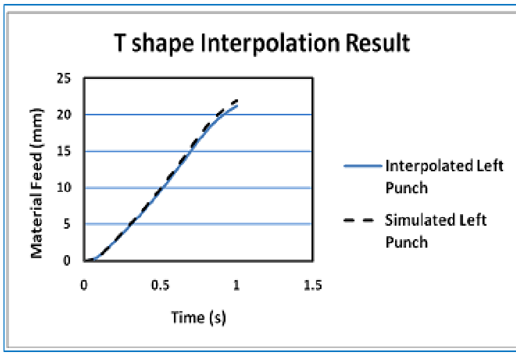
This section investigates how the interpolation handles the need for all variables to be interpolated with respect to the other families such as Single and Double T-Shape families and Single and Double Y-Shape families. The variables used for interpolation and a separate simulation for comparison, and the results of both interpolation and simulation are shown together with the figure of the part. Single Y-Shape is shown in Figure 3-12, Single T-Shape in Figure 3-13, Double T-Shape in Figure 3-14, and Double Y-Shape in Figure 3-15.





Parameter	New values
n-value	0.6
K-value	1250
OD value	35
t- value	3
Friction coeff	0.05
La/Lb value	45
Die angle	50

Figure 3 - 12 Single Y-Shape Simulation-Interpolation Comparison



Parameter	New values
n-value	0.6
K-value	1000
OD value	32
t-value	2.5
Friction coeff	0.05
La value	75

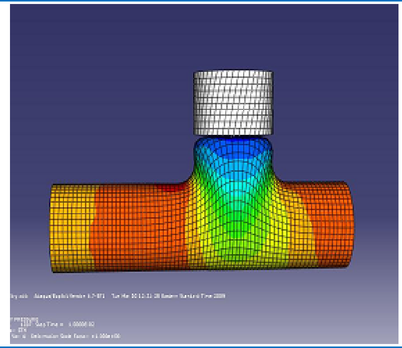
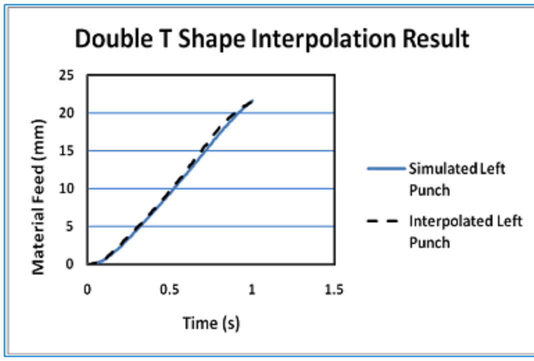


Figure 3 - 13 Single T-Shape Simulation-Interpolation Comparison



Parameter	New values
n-value	0.6
K-value	1250
OD value	36
t-value	3
Friction coeff	0.01
La value	110

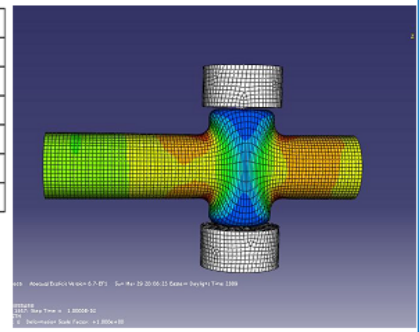
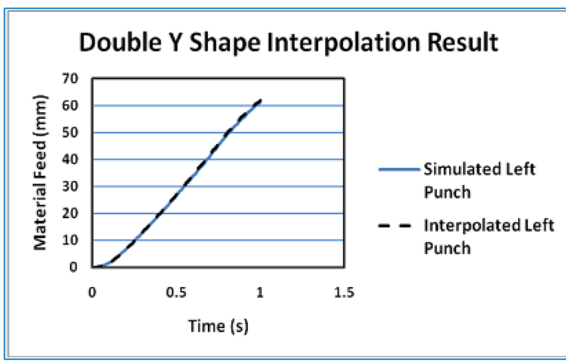


Figure 3 - 14 Double T-Shape Simulation-Interpolation Comparison



Parameter	New values
n-value	0.6
K-value	1000
OD value	34
t- value	1.5
Friction	0.08
La/Lb value	120
Die angle	50

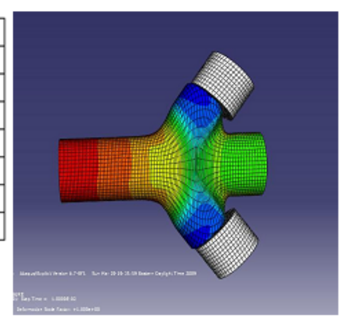


Figure 3 - 15 Double Y-Shape Simulation-Interpolation Comparison

Next section addresses the development of the pressure curve for the loading path. The pressure curve from the discussion below is part of the database user interface in Figure 3-5.

3.5 PRESSURE CURVE GENERATION FOR BULGE SHAPE

The loading path pressure curve is obtained by graphing the internal pressure versus time and may be developed to be a linear or nonlinear profile.

3.5.1. Pressure Curve Development

The method proposed here is the development of a pressure curve using a polynomial function related to the process time. This pressure curve is developed by observing various pressure curves from researchers and developing a polynomial curve with certain design features such as the main stages (refer to Figure 3-16) in THF process – Yielding, Expansion and Calibration:

- Yielding Stage: period when material is yielding and the pressure profile is linear
- Expansion: During this stage the gradient is reduced.
- Calibration: During this stage, the profile increases positively in slope to its maximum value.

Design Constraint-The maximum value of the curve is designed to be unity and this allows mapping to a maximum pressure value by multiplying the polynomial to the maximum pressure value. The curve that meets the above criteria sufficiently is a third degree polynomial chosen as:

$$p = 1.66t^3 - 4t^2 + 3.33t \qquad (3.3)$$

where t is the time step and p is the unit instantaneous pressure. The relation of the maximum pressure value and the pressure curve is given in Eqn. (3.4).

$$P = P_f \left(1.66t^3 - 4t^2 + 3.33t\right) \tag{3.4}$$

P_f is the maximum pressure value, P is the instantaneous pressure at the final geometry achievable and is assumed to be the maximum pressure applicable to obtain the THF part.

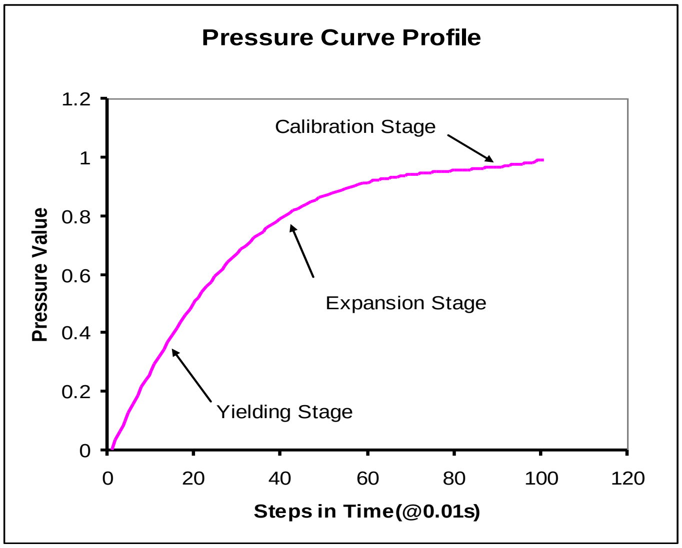


Figure 3 - 16 Pressure Curve Profile for THF

3.5.2. Determination of the Maximum Pressure

The maximum pressure is determined by an analysis of a free bulge THF family during the final forming stage. Figure 3-17 shows a Bulge Shape part within a die where material feed, *F*, is supplied by the punches. The balance equation, Eqn. 3.5 can be derived based on the stress state in the element of the bulge tube in Figure 3-17 above.

$$\frac{\sigma_\theta}{\rho_z} + \frac{\sigma_z}{\rho_\theta} = \frac{P}{t_i} \tag{3.5}$$

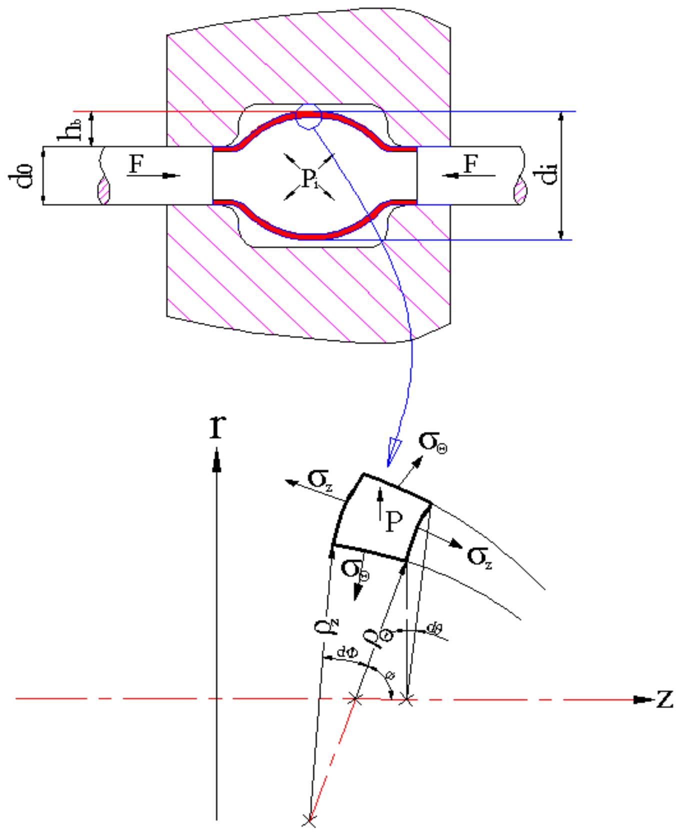


Figure 3 - 17 Bulge Shape THF

Where ρ_θ is the hoop curvature, ρ_z is the axial curvature σ_θ is hoop stress, σ_z is the axial stress, P is the instantaneous internal pressure and t_i is the instantaneous thickness. In the apex of the bulging, the stress status can be assumed to be in biaxial tension state where the hoop curvature is approximately equal to the axial curvature, i.e. $\sigma_\theta \approx \sigma_z$ for $\rho_\theta \approx \rho_z$ and hence reducing equation (3.5) to Eqn. 3.6

$$P = \frac{2\sigma_\theta t_i}{\rho_\theta} = \frac{4\sigma_\theta t_i}{d_i} \tag{3.6}$$

Where d_i is the final diameter

The P_f prediction equation is derived using Eqn. (3.6). The radial stress is assumed to be negligible compared to the other stresses. Thinning of the tube after forming is assumed to be 30 % of the original tube as derived below:

$$\textit{Thinning } x\% = \frac{t_i - t_0}{t_0}\% \tag{3.7}$$

where t_o is the initial thickness. The final diameter in the expansion region is given by:

$$d_i = {}^{d_0}\!/_2 + h \sin(\phi) \tag{3.8}$$

d_o is the initial diameter, h is height of protrusion from middle of the tube and ϕ the angle of protrusion in die for Bulge Shape the angle is assumed to be at right angles. Considering the state of plane stress and defining the radial strain ε_ρ and hoop strain ε_θ as given by equations 3.9 and 3.10 respectively:

$$\varepsilon_\rho = \ln\left(\frac{t_i}{t_0}\right) \tag{3.9}$$

$$\varepsilon_\theta = \ln\left(\frac{d_i - t_i}{d_0 - t_0}\right) \tag{3.10}$$

The relations of strain with effective strain, $\bar{\varepsilon}$ and stress with effective stress, $\bar{\sigma}$ are established from Von Mises yield criterion for plane stress [Asnafi, 1999]

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}}\varepsilon_\theta\left(1+\beta+\beta^2\right)^{1/2} \tag{3.11}$$

$$\bar{\sigma} = \left(1-\alpha+\alpha^2\right)^{1/2}\sigma_\theta \tag{3.12}$$

where $\alpha = {}^{\sigma_z}\!/_{\sigma_\theta} \approx 1$ and $\beta = {}^{\varepsilon_z}\!/_{\varepsilon_\theta} = {}^{-\varepsilon_r}\!/_{\varepsilon_\theta} - 1$

Assuming the flow stress of the material obeys the power law $\bar{\sigma}=\mathrm{K}\left(\bar{\varepsilon}\right)^{n}$, with K the strength of the material and n the strain hardening exponent, and combining Eqns. (3.6), (3.11) and (3.12) the expression for P_f can be obtained.

$$p = P_f = \frac{4\sigma_\theta t_i}{d_i} = 4K\left(\frac{2}{\sqrt{3}}\right)^n \left(1+\beta+\beta^2\right)^{n/2} \left(\ln\left(\frac{d_i - t_i}{d_0 - t_0}\right)\right)^n \frac{t_i}{d_i} \tag{3.13}$$

3.5.3. Comparison of Maximum Pressure Equation and Maximum Pressure from FEA

The maximum pressure P_f obtained from Eqn. (3.13) is developed without consideration of the tube length. The tube length is crucial for determining the volume of the tube. The volume of the tube changes during THF process. This makes the value of maximum pressure from Finite Element Analysis (FEA) larger than the analytical value.

Therefore due to this underestimation, the pressure given in Eqn. (3.13) will have to be scaled up to obtain sufficient pressure for deformation in the expansion zone (ensuring that the tube material touches the die wall) and calibration stage (ensuring that the corners are formed). The pressure from Eqn. (3.13) is suitable for providing an initial guide to designing the maximum pressure for THF simulations. The scaling factor adopted for Bulge Shape family which assisted in satisfactorily forming the part, and with less than 30% thinning is 1.35. The equation for maximum pressure for the Bulge Shape is Eqn. (3.14).

$$P_{fb} = 5.4K\left(\frac{2}{\sqrt{3}}\right)^n \left(1+\beta+\beta^2\right)^{n/2} \left(\ln\left(\frac{d_i - t_i}{d_0 - t_0}\right)\right)^n \frac{t_i}{d_i} \tag{3.14}$$

where P_{fb} is the final pressure for the Bulge Shape

The pressure equation for the other families is scaled up based on Eqn. (3.14) of the Bulge family as the initial pressure value and running FEA simulations to determine the scaling factors. The pressure equation for the other THF families is given by Eqn. (3.15):

$$P_{fo} = CP_{fb} \tag{3.15}$$

where C is the scaling factor. The scaling factors are developed by FEA simulations under the conditions that the part is successfully formed and the thinning is less than 30%. The scaling factors for the various THF families are given in Table 3 below.

Table 3 Scaling Factors for Various Families

THF Family	Scaling factor, C
Single Y-Shape	1.8
Single T-Shape	1.74
Double T-Shape	1.8
Double Y-Shape	1.33

A sample pressure curve is considered here. Beginning with Eqn. (3.14) for Bulge Shape THF and with properties shown below the value of the maximum pressure is obtained as 77.2 MPa and the pressure curve is shown in the Figure 3-18:

K 1426 d_0 34.9 mm h 6.55mm n 0.502 t_0 1.65 mm φ 90°

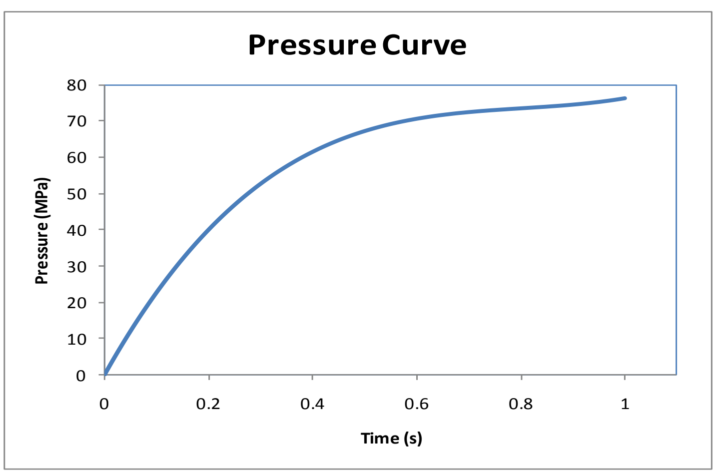


Figure 3 - 18 Bulge Shape Pressure Curve

3.6 EFFECT OF PARAMETER CHANGE IN DATABASE

This section reviews the effect of the strength of the material, strain hardening exponent and friction coefficient in the development of loading paths.

a) <u>Effect of Strength of Material, K</u>- acts as a scaling factor to the maximum pressure value in Eqn. (3.14) and hence any increase on K increases the area under the loading path. High values of K which lead to high pressures require faster axial cylinder feed to supply more material into the expansion zone to avoid bursting and ensure that the material is in contact with the die wall during calibration stage.

b) <u>Effect of strain hardening exponent, n</u>- As the value of n increases the punch has to travel at a longer distance inorder to deform the tube. The tube yields faster to pressure applied and hence the axial material feed velocity has to be higher to maintain contact with the tube and avoid bursting.

c) <u>Effect of friction coefficient</u>- Change in the coefficient of friction based on the database methodology does not affect the internal pressure curve. Any change will affect the material feed curves where increase in the coefficient of friction will require higher axial force and hence higher cylinder speed to overcome it. More details on the effect of friction in the next Chapter.

This chapter provided an understanding of the database operation and development of the pressure curve. Case studies on material feed curve generation for different THF families are presented. The loading paths developed are provided to the THF press machinery to guide the forming. Though the loading path provided to the THF machinery is ideal, errors and uncertainty issues arise before a final part is obtained. The next chapter provides analysis leading to identifying the dominant errors associated with THF and introduces the Database Back-Step error compensation scheme.

CHAPTER 4:
ERROR COMPENSATION USING DATABASE BACK-STEP (DBS) METHOD

The purpose of error compensation is to achieve better quality of THF products and enhance safety in forming by ensuring that forming forces are within the acceptable limits. This chapter introduces the Database Back-Step (DBS) method which is developed to compensate for the dominant error. The dominant error in THF is identified by applying variation analysis with focus on tube wall thickness, strain hardening exponent and friction. A study on the effect of these errors is provided. Operation of the DBS Method is provided to compensate for the dominant error. This method provides a concretive error compensation method to deal with errors in real time, with communication between loading path database and the Programming Logic Controller (PLC) achieved with Data Dynamic Exchange (DDE).

4.1 DOMINANT ERROR IDENTIFICATION

Errors need to be identified and controlled to reduce risk of product failure and minimize the overall cost of production. A reliability assessment of the THF process is achieved by considering the uncertain variables due to errors as probabilistic variables with mean values and standard deviation. The variables in THF with uncertainty probability include:

- The tubular material properties (K , n), if power law of the flow stress is applied
- The tribological conditions such as the coefficient of friction, μ
- The geometrical size of the tool and tube such as tube wall thickness, t.

4.1.1. Review on the Parameters and Causes of Uncertainty

The selected uncertain parameters are material strain hardening exponent n, the tube thickness t and the coefficient of friction μ.

4.1.1.1. Variation of Strain Hardening

This is the mechanism whereby a material undergoing deformation reaches the plastic domain and hardens. The strain hardening is influenced by multiple factors including the presence of grain boundaries and the motion of dislocations. The grain boundaries may interfere with the motion of dislocations leading to higher dislocation density. This increase leads to increase of strain hardening. Since the strain hardening exponent in tubes is affected by the process during manufacturing, it is common to find different strain hardening exponents for the same material. The effect of this variation is evident in the change in the deformation characteristic of the material.

4.1.1.2. Variation of Thickness

Thickness variation is due to manufacturer tolerance. This tolerance for welded stainless tubes is about +/- 1%.

4.1.1.3. Variation of Friction

The frictional error varies with the location of the tube commonly referred to as the friction zones which are characterized by the effects of the axial material feed and the geometrical conditions of the die. The friction zones are shown in Figure 4-1 below.

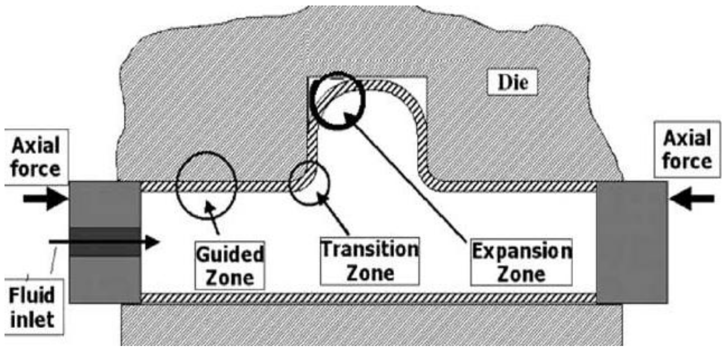


Figure 4 - 1 Friction zones in THF (Ref [Ahmetoglu et. al., 2000])

The guided zone is the location where the tube is in contact with the die and minimal expansion takes place. Due to the contact of the die, the flow of the material behavior is 'guided'. Yielding mainly occurs within the guide zone and friction is very critical due to large die-tube interface. The lower the friction, the better the material flow into the transition zone. The transition zone is where the flow of the material experiences a transition from guided to free. The flow of the material is along the contour of the die cavity due to the pushing from internal pressure. The contact with the die is less and hence the friction in this region is less than the guided zone. Expansion zone is the region where the flow of the material is free to expand until reaching the either a die wall, counter punch or a certain height desired by the Engineer (in the absence of a counter punch). Less friction occurs in this region unless an interface contact is established.

Variation of Friction due to Lubrication Mechanisms

A lubrication system may be viewed in four regimes as shown in Figure 4-2, which shows the lubrication mechanisms between the tool and the workpiece.

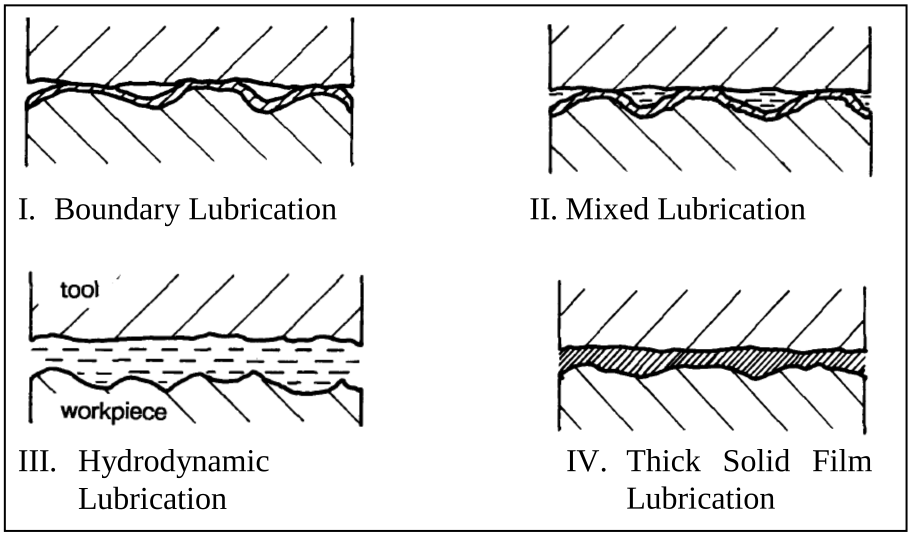


Figure 4 - 2 Lubrication Mechanisms

In the Boundary Lubrication Regime the metal-metal contact results in increase in the interface friction. Partial Fluid Lubrication Regime experiences some metal-to-metal contact though friction is reduced due to presence of some lubricant. The mixed lubrication regime is prevalent in THF processes causing friction to vary due to the intermittent interface contact. Hydrodynamic Regime and Thick solid film lubrication regime are where the lubricant is between the interfaces possibly at all times since metal-to-metal contact is eliminated. This regime hardly occurs in metal forming, with the exception of steady state process such as rolling where a constant lubricant intake is possible.

<u>Study on the Coefficient of Friction</u>

Since frictional error is directly related to the friction force, the analysis will involve force control. The amount of friction for the guiding zone can be expressed analytically using the coefficient of friction such as [Ngaile et. al., 2009]:

$$\mu = \frac{cF_f}{P_i \pi d_i L} \tag{4.7}$$

Where μ is the coefficient of friction, F_f is the friction force, P_i is the internal pressure in the tube, D_i is the internal diameter of the tube, L is the effective length of the tube, and c is a constant which varies with the ratio of tube diameter to thickness. The coefficient of friction is a dimensionless quantity representing the ratio between the frictional force and the force that is causing contact of the bodies (in the Eqn.4.7 above the force is pressure). This quantity can be obtained by various ways such as calculation using geometrical data from the deformed tube and material properties using the tube upsetting test [Plancak et. al., 2005], experimentally by measuring the frictional force from the difference in axial force [Imaninejad et. al., 2004], thickness comparison of FEA and experimental results [Koc et. al., 2000] and Tribotests [Ngaile et. al., 2009; Ngaile et. al., 2008] which are used together with FEA to determine the coefficients of friction (μ) using calibration charts developed with analytical methods.

4.1.2. Design of Experiments Technique for Identifying Dominant Error

The higher uncertain variables among thickness, strain hardening exponent and friction are identified using design-of-experiments (DOE) techniques. A response surface model (RSM) is developed to represent the process behavior and analyze the process response variation. The axial forming load of Single Y-Shape THF is considered as the process response. The factorial design method is used to identify the contribution of the each uncertain variable to the process response. The response surface model is used to approximate the right hand load, *Fr*, and left hand load, *Fl*, shown in Figure 4-3, as in the following equations:

$$Fr = \alpha_1 + \alpha_2 t + \alpha_3 n + \alpha_4 \mu + \alpha_5 tn + \alpha_6 n\mu + \alpha_7 \mu t + \alpha_8 tn\mu \tag{4.1}$$

$$Fl = \beta_1 + \beta_2 t + \beta_3 n + \beta_4 \mu + \beta_5 tn + \beta_6 n\mu + \beta_7 \mu t + \beta_8 tn\mu \tag{4.2}$$

The coefficients α_i and β_i in equations (4.1) and (4.2) are evaluated by a two-level fraction factorial DOE, which are listed in the Table 4.

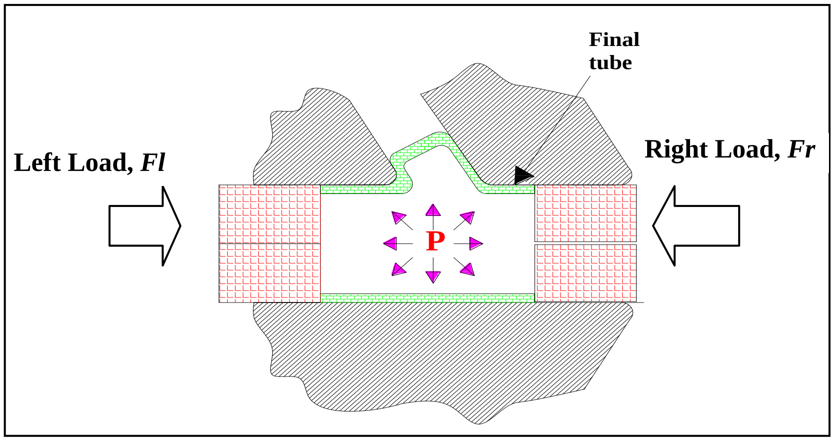


Figure 4 - 3 Axial forces in the Single Y-Shape

Other parameters used in the simulation are strength of material *K*=1450Mpa, tube length *L*=180mm, tube outer diameter *D0*=34.95mm.

Table 4 Two-level fraction factorial DOE matrix

Evaluation Num	t	n	μ
1	1.5	0.4	0.05
2	1.5	0.4	0.15
3	1.5	0.6	0.05
4	1.5	0.6	0.15
5	1.8	0.4	0.05
6	1.8	0.4	0.15
7	1.8	0.6	0.05
8	1.8	0.6	0.15

The variance of the uncertainty variable *x* and response function *f(x)* contributed by *x* can be computed from Eqn. (4.3) and (4.4) respectively.

$$Var(x) = \sigma(x)^2 \qquad (4.3)$$

$$\sigma(f)_{x_i} = \sqrt{Var(f)_{x_i}} = \sqrt{(\frac{\partial f}{\partial x_i})^2 Var(x_i)} \qquad (4.4)$$

The total variance of the response function is the sum of the variance contributed by all uncertainty variables as shown in Eqn. (4.5), which can be used to compute the standard deviation of the response function.

$$\sigma(f) = \sqrt{Var(f)} = \sqrt{\sum_i (\frac{\partial f}{\partial x_i})^2 Var(x_i)} \qquad (4.5)$$

The contribution ratio (CR) of each uncertain variable to total standard deviation of the axial forming load is expressed as the ratio of the standard deviation component of forming load $\sigma(f)_{x_i}$ due to each variable to the total standard deviation, $\sigma(f)$:

$$CR = {\sigma(f)_{x_i}}\big/{\sigma(f)} \qquad (4.6)$$

Where *x* represents the variables *t, n, μ* and *i* is the number of evaluations. The variables for uncertainty analysis and other parameters used in the simulation of the DOE matrix are shown in Table 5. Covariance factors for n and μ are established from experiments and covariance for t is established from manufacturer tolerance.

Table 5 Standard deviation of uncertainty variables in the Single Y-Shape THF process

Parameter	**t (mm)**	**n**	**μ**
Mean value u	1.65	0.56	0.10
Standard deviation σ	0.0198	0.0168	0.01
Covariance	0.012	0.015	0.10

Figure 4-4 shows the contribution ratio of the uncertain variables t, n, μ for the left and right cylinders. Though the forces of the Single Y-Shape for the right cylinder differ in magnitude from the left cylinder, the contribution of the uncertain variables t, n and μ are the same. The contribution from friction coefficient μ to the deviation of the axial forming force is more than 0.8 (where the possible maximum is 1.0) and the contribution from the thickness t and strain hardening exponent n is less than 0.4 most of the time. The analysis above shows that the friction coefficient μ is the most critical uncertainty source among these three uncertain variables. Carleer and group [Carleer et. al., 2000] discussed the effect of different material parameters, such as the anisotropy (r-value) and the strain hardening exponent (n), on the hydroformability of tubes. Results of the discussion showed a comparison of the effect of change of anisotropy (r), n and μ on the axial feed where r had the largest effect followed by μ then n. Li and group [Li et. al., 2006] discussed the effect of geometry parameters such as the length of tube, thickness, die entry radius and bulge width; material parameters such as the strain hardening exponent and process parameters such as the internal pressure, stress ratio and friction coefficient.

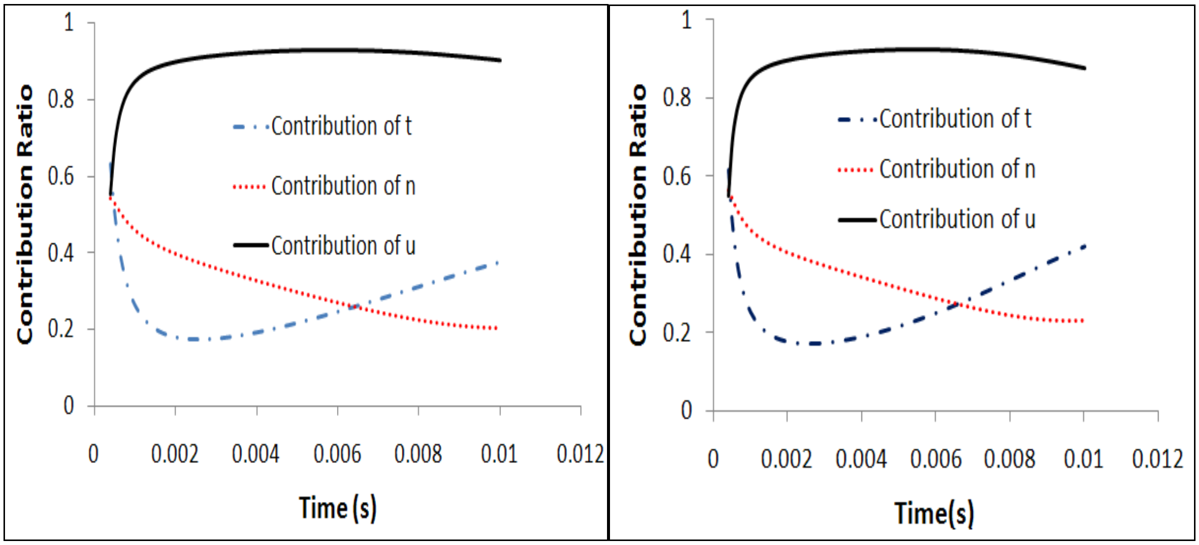


Figure 4 - 4 Contribution ratio of the uncertain variables to Left and Right hand axial loads

Process parameters had the biggest effect and friction coefficient had a greater effect than stress ratio. Zadeh and group [Zadeh et. al., 2006] compared the effect of fillet radius, strain hardening and coefficient of friction with results showing friction having the highest effect. Hence in considering the errors and uncertainties, friction coefficient has the greatest effect in the THF process as the dominant error. Frictional error at the tube-die interface potentially affects the flow of the material, axial forming forces and quality of the part surface. Next section focuses on error compensation in stroke controlled THF by tracking the force at the cylinder-environment (cylinder-tube) interface and readjusting the loading path online from a database using the Database Back-Step (DBS) method.

4.2 DATABASE BACK-STEP METHOD

Databases in metal forming systems have been used to assist with control by providing estimations of friction [Siegert et. al., 2000] or providing the errors to the controller [Ferreira et. al., 2006]. In the Database Back-Step (DBS) method changes in the tracked force (measured from the sensor) due to friction are corrected by stepping back into the database (source of the loading paths) for another loading path that compensates the change. The DBS method incorporates interpolation algorithms. In this method the forces at the cylinder-tube interface are monitored and compared to expected forces in a database. Variation in the cylinder force at the interface from the expected force is corrected by stepping back into the database for another loading path that compensates the difference based on the coefficient of friction established from the cylinder force at the interface. In the absence of a force sensor at the cylinder-tube interface, the force is estimated from the pressure in the cylinder obtained from pressure transducers multiplied by the area of the cylinder punch in contact with the tube.

There are three main interpolations involved in the Database Back-Step Method, 1) Interpolation to extract the data from the database that matches the current time in the PLC, 2) Interpolation to obtain the current coefficient of friction based on the force monitored at the tube-cylinder interface, 3) Interpolation to obtain the compensated stroke (cylinder position) based on the current coefficient of friction

4.2.1. Database Back- Step Flowchart

The database is used in the DBS method to provide the initial loading path requested to the Control unit via a PLC program called Think and Do Live. Figure 4-5 shows the Database Back- Step method flowchart.

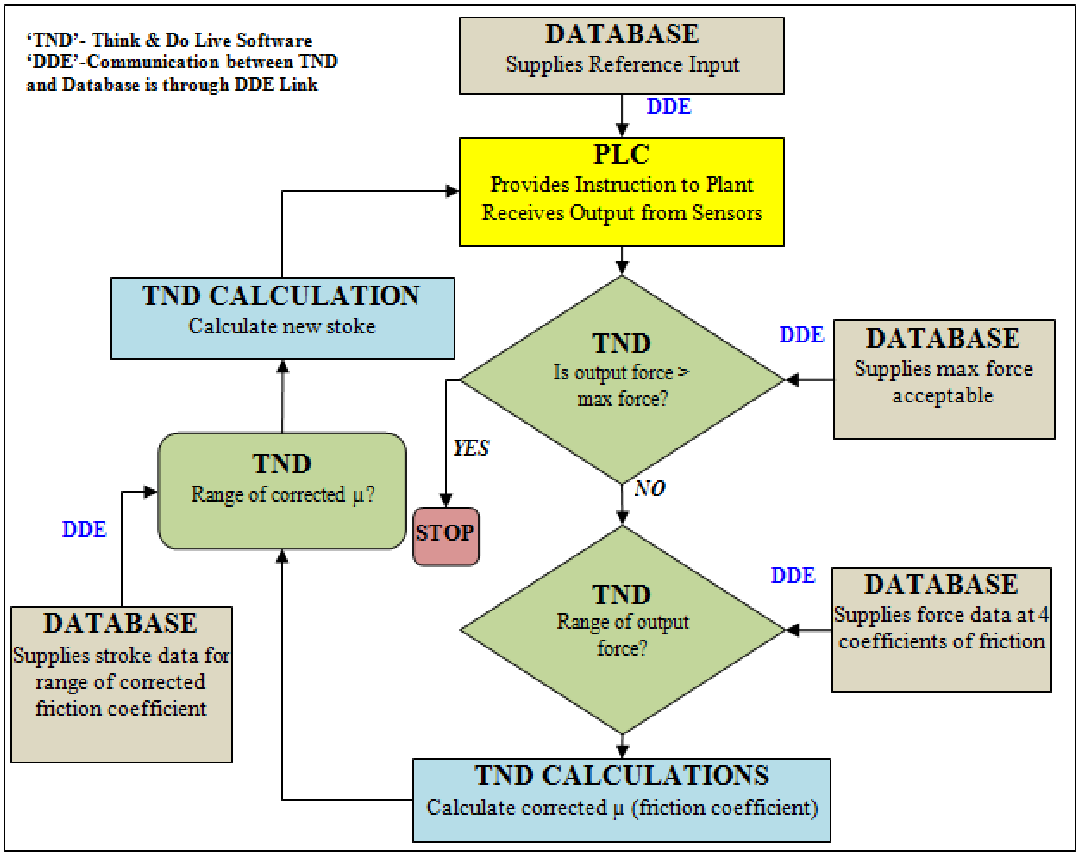


Figure 4 - 5 Database Back- Step Method Flowchart

The feedback force from the press is compared with other forces from the database generated with a unique coefficient of friction. The database supplies 4 forces with coefficient of friction 0.01, 0.05, 0.1 and 0.2. The feedback force is compared with these forces. Based on the upper and lower bounds of the feedback force interpolation is done to obtain the coefficient of friction for the feedback force. The database also supplies 4 stroke data with unique coefficients of friction. The coefficient of friction from the feedback force is compared and interpolation is carried out to establish the new loading path.

4.2.2. Control Software (TND) and Data Dynamic Exchange (DDE) Link

Online adjustment is made possible for the Database Back-Step method with the Dynamic Data Exchange (DDE) link for communication between the Database client program and the PLC program and to feed the reference loading path in real time. The force of the cylinder developed from the differential pressure is the input to the PLC. This is compared to threshold forces (a force curve in the database with maximum acceptable coefficient of friction) for two reasons: to provide safety where only acceptable forces are allowed and to establish the correct coefficient of friction.

4.3 FRICTION EFFECTS ON LOADING PATH

This section provides an investigation of the effects of varying friction on a Single Y-Shape part. The Single Y-Shape model is simulated with ABAQUS Explicit, with the die, left and right punches modeled as rigid bodies and discretized with rigid shell elements. The tube is modeled as a deformable tube and discretized with integration-reduced shell elements. The material used is stainless steel SS 304 with Ludwick-Holoman hardening law. Geometrical parameters – length and thickness of the tube and the friction coefficient are varied as shown in the Table 6 below.

Table 6 Parameter Data for Single Y-Shape model

Work piece Material	SS 304
Thickness, t (mm)	1.245mm, 1.65mm
Outer Diameter, OD (mm)	34.9mm
Length, L (mm)	150mm, 185.3mm
Strength of material, K	1500
Strain hardening exponent, n	0.52
Friction coefficient, μ	0.01, 0.05, 0.1, 0.2

4.3.1. Effects of Friction on Loading Path

FEA simulation with different friction coefficients is carried out for the Single Y-Shape to analyze the effect of friction on the loading path. This is done by having a set of variables used in simulation and changing the value of the friction coefficient. In order to have the same goal of thinning range and for material reaching the top of the protrusion height at the end of the cycle time, the material feed velocity is increased to overcome the effect of friction. Figure 4-6 shows the loading path effect of the change of friction coefficient for a specified length and tube thickness.

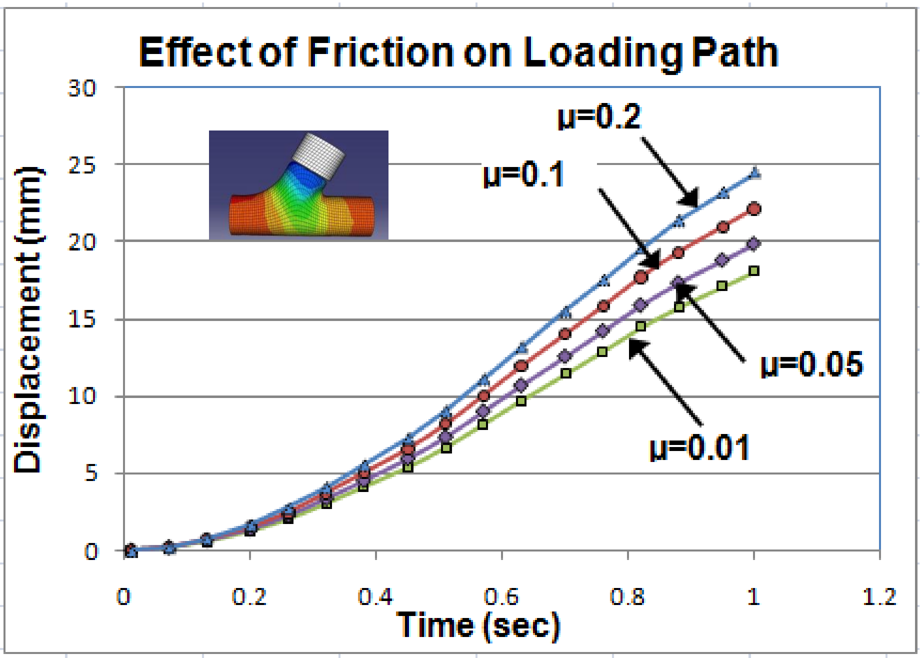


Figure 4 - 6 Friction Effect on loading path (L1-185.3mm, T1- 1.245mm)

The axial feeding increases with the increase of the friction coefficient when the maximum thinning range of the hydroformed part is kept the same. The increasing of the friction hinders the consistency of material flow, which leads to the increasing of the localized thinning. More material is fed into the forming zone to compensate for the localized thinning.

4.3.2. Effects of Friction and Guiding Zone Length on Loading Path

The FEA simulations on different guiding-zone lengths L1 for 185.3mm and L2 for 150mm are shown in Figures 4-7 and 4-8, comparing two coefficients of friction for a tube thickness of 1.65mm. Figure 4-5 shows the effect for μ of 0.01 and Figure 4-6 for μ of 0.2.

4.3.3. Effects of Friction and Tube Thickness on Loading Path

Figures 4-9 and 4-10 show the effect of μ on the loading path for friction values of μ= 0.05 and μ = 0.2 respectively. The length of the tube for both cases was 185.3mm. Both Figures 4-9 and 4-10 show that the more the thickness of the tube, the more the material feed to obtain the desired thinning.

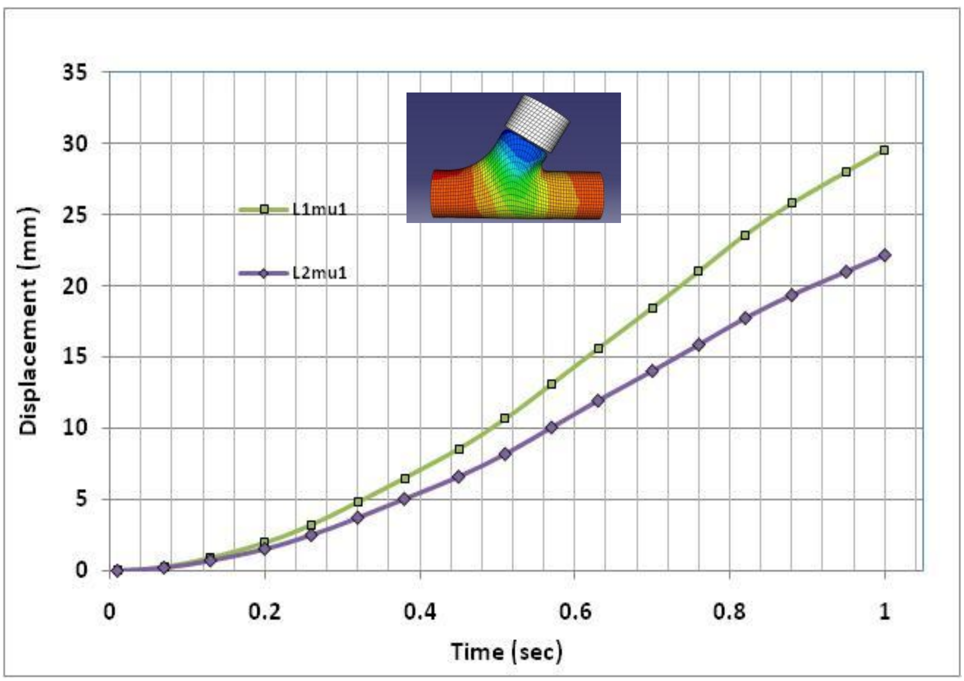


Figure 4 - 7 Effect of the length change on material feed with μ=0.01; T2=1.65mm

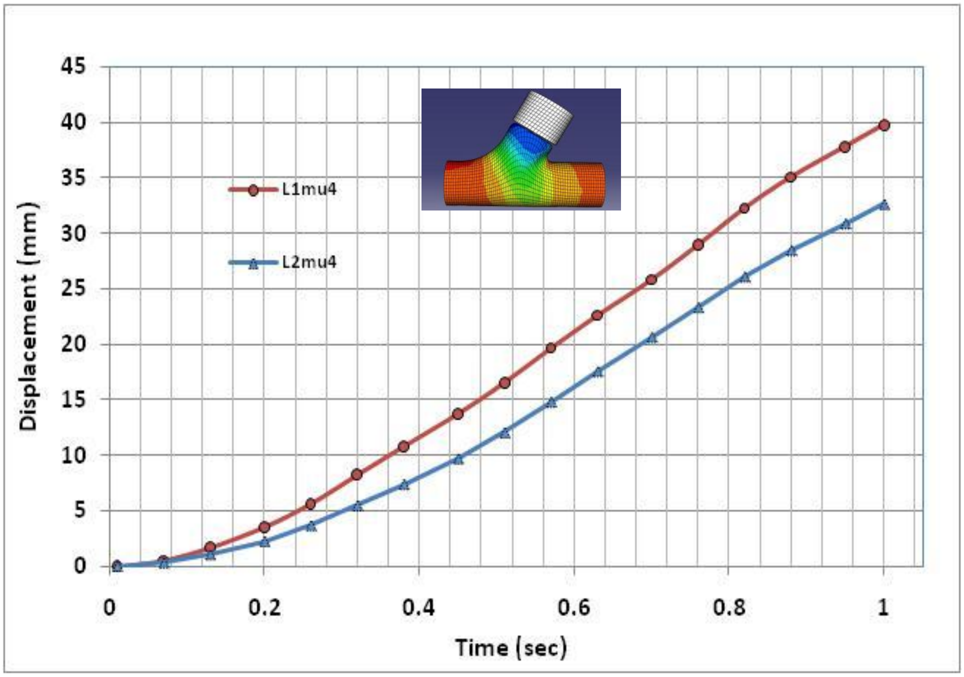


Figure 4 - 8 **Effect of the length change on material feed with μ=0.2; T2=1.65mm**

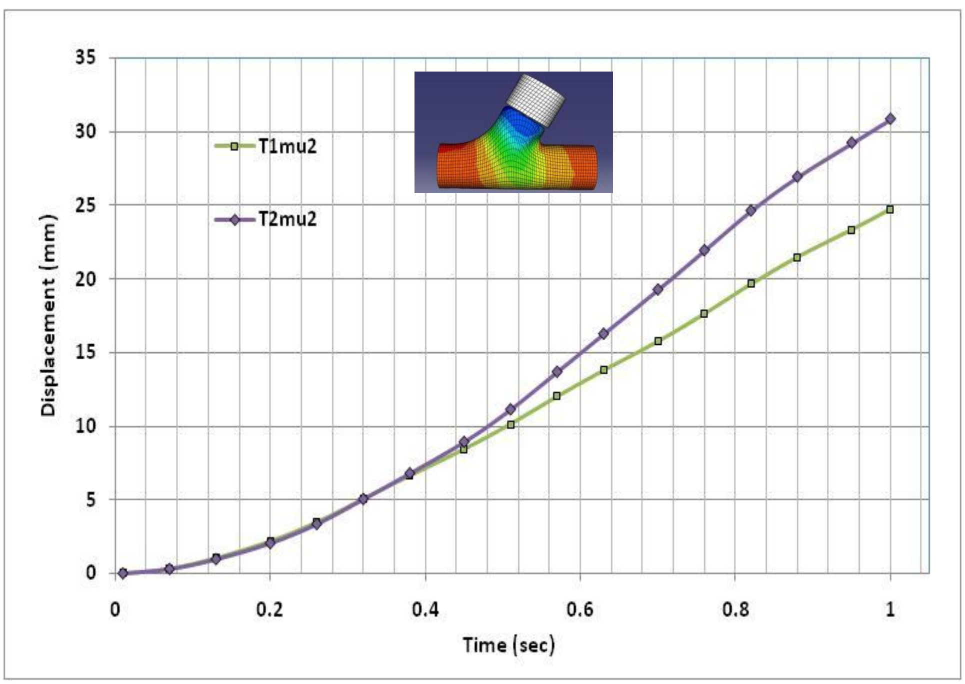


Figure 4 - 9 **Effect of thickness change on Material Feed with μ=0.05; L1=185.3**

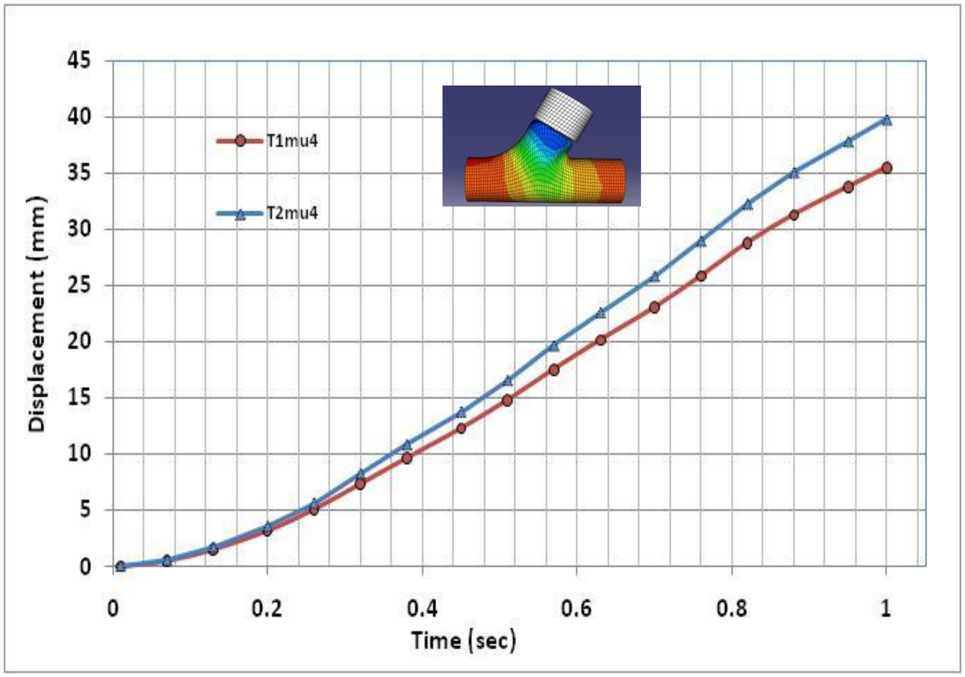


Figure 4 - 10 Effect of thickness change on Material Feed with μ=0.2; L1=185.3

4.3.4. Effects of Friction on Force Profile

Figure 4-11 shows the punch force profiles for different friction conditions. As expected the punch load increases with increase in the interface friction.

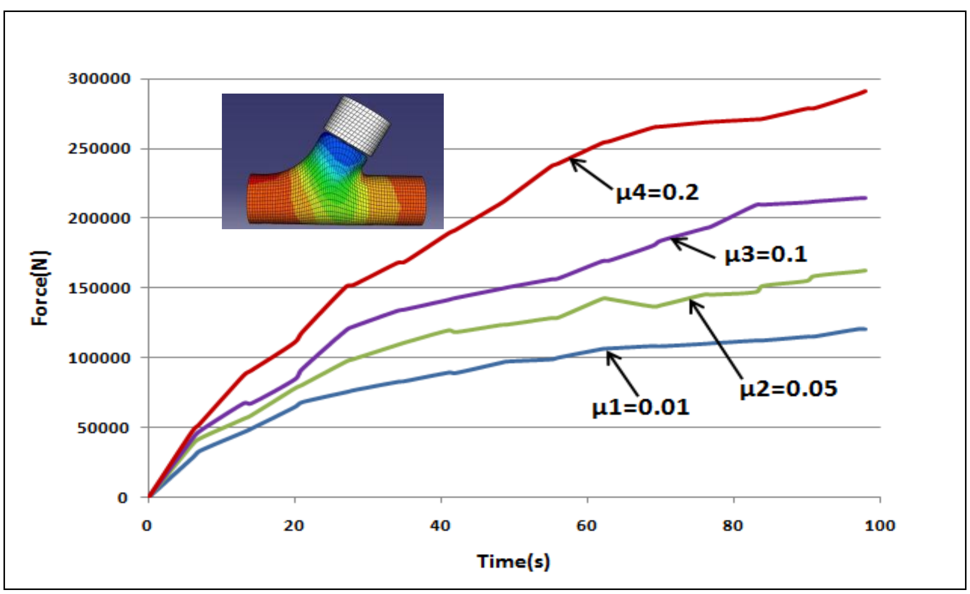


Figure 4 - 11 Friction Effect on Force (Length 150mm, Thickness 1.65mm)

4.4 DATABASE BACK-STEP METHOD ALGORITHMS

The model used for the DBS method is the linear input-output model interpolation. The steps involved in DBS algorithm are:

I. The database has to have the simulated sets of force curves developed during the development of material feed curves e.g. F_1, F_2, F_3 and F_4 that correspond to the coefficient of friction μ_1, μ_2, μ_3 and μ_4 respectively.

II. The feedback force F_{tr} which is the force monitored at the cylinder-tube interface has to be less than the threshold force, F_{thr}(acceptable maximum force) If the feedback force is higher than the threshold force then a stop relay is triggered and the system shuts down to avoid destroying the punches.

Condition to be satisfied at all times: $F_{tr_1} \le F_{thr}$

III. The feedback force is compared with other forces by stepping back into the database to check the range and interpolation is carried out between forces mentioned in I to obtain coefficient of friction μ_{tr} corresponding to the tracked feedback force. Hence for the case when $F_1 \le F_{tr} < F_2$, the interpolation equation is:

$$\mu_{tr} = \mu_2 + \frac{(\mu_2 - \mu_1)}{\left(F_2(t) - F_1(t)\right)}\left(F_{tr}\left(t^*\right) - F_1(t)\right) \tag{4.8}$$

Where t^* is the specific time that might differ from t.

Since the desired forming time from the press t^* may not be exact in the database timescale, an interpolation is done to obtain the data at time t^*.

This is achieved by observing the range of t^* i.e. $t-1 < t^* < t+1$ and collecting the data. The database has data for the left and right cylinder. A sample for the data used in the interpolation is shown in Figure 4-12 for $\mu 1$ and $\mu 2$. Hence when $t^* \neq t$, the interpolation is carried out as shown below

$$
\begin{aligned}
F_{1(t)} &= F_{1(t-1)} + \frac{F_{1(t+1)} - F_{1(t-1)}}{(t+1)-(t-1)}\left(t^* - (t-1)\right) \\
F_{2(t)} &= F_{2(t-1)} + \frac{F_{2(t+1)} - F_{2(t-1)}}{(t+1)-(t-1)}\left(t^* - (t-1)\right)
\end{aligned}
\tag{4.9}
$$

The forces obtained from Eqn. (4.9) are substituted into Eqn. (4.8) to obtain the Eqn. (4.10):

$$
\mu_{tr}(t^*) = \mu_1 + \frac{F_{tr}(t^*)\left((t+1)-(t-1)\right) - F_1(t+1)\left(t^* - (t-1)\right) - F_1(t-1)\left((t+1)-t^*\right)}{\left(F_2(t+1)-F_1(t+1)\right)\left(t^* - (t-1)\right) - \left(F_2(t-1)-F_1(t-1)\right)\left((t+1)-t^*\right)}\left(\mu_2 - \mu_1\right) \tag{4.10}
$$

IV. The new coefficient of friction is used to adjust the stroke loading path for the next time step in the reference loading path. The equation with interpolation for *(t)* is obtained as:

$$
D\left(t^*\right) = D_1(t) + \frac{\left(D_2(t) - D_1(t)\right)}{\left(\mu_2 - \mu_1\right)}\left(\mu_{tr}\left(t^*\right) - \mu_1(t)\right) \tag{4.11}
$$

Where the model stroke used for comparisons are obtained by interpolation as in Eqn. 4.12:

$$
\begin{aligned}
D_{1(t)} &= D_{1(t-1)} + \frac{D_{1(t+1)} - D_{1(t-1)}}{(t+1)-(t-1)}\left(t^* - (t-1)\right) \\
D_{2(t)} &= D_{2(t-1)} + \frac{D_{2(t+1)} - D_{2(t-1)}}{(t+1)-(t-1)}\left(t^* - (t-1)\right)
\end{aligned}
\tag{4.12}
$$

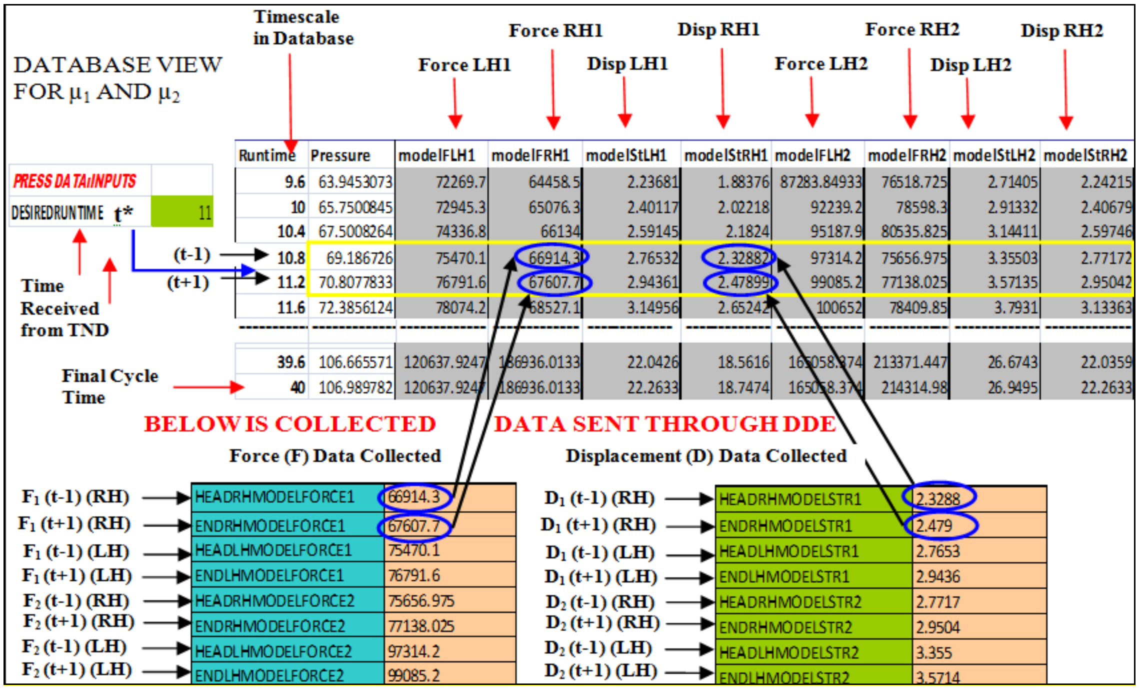


Figure 4 -12 DBS Method Data Collection for μ1 and μ2 (sample for time 11s); LH=Left side, RH=Right Side

$$D(t^{**}) = \frac{D_1(t+1)\big(t^* - (t-1)\big) + D_1(t-1)\big((t+1) - t^*\big)}{\big((t+1) - (t-1)\big)} + \frac{\big(D_2(t+1) - D_1(t+1)\big)\big(t^* - (t-1)\big) - \big(D_2(t-1) - D_1(t-1)\big)\big((t+1) - t^*\big)}{\big(\mu_2 - \mu_1\big)\big((t+1) - (t-1)\big)}\big(\mu_{tr}(t^*) - \mu_1\big) \quad (4.13)$$

Eqn. (4.13) is used to determine the displacement that is sent to the PLC based on the tracked feedback force.

V. The force output from the next scan undergoes the same procedures as given above.

All the calculations carried out using Eqns. (4.8) to (4.13) are performed in Think and Do software. More description on the data sent to Think and Do Live, portions of the flow charts for these calculations and macros used are given in Appendix B.1, B.2 and B.3.

4.5 SIMULATION CASE STUDY USING DATABASE BACK-STEP METHOD

This section's objective is to verify the operation of the algorithm of the Database Back-Step method before being implemented into the Experiment process. The Initial step involved obtaining the loading path for a particular family by operating the database as discussed in Chapter 3. A brief outline on the database operation is given below with more details given in section (3.2.2). Sample macro codes based on Visual Basic used for generating the database are given in Appendix A.

4.5.1. Procedure for Database Operation

(1) Decide on the selection of the THF family, geometric and material properties. The THF family used is the Single Y-Shape and the data variables are (Lt=185.3mm, La=65.2mm, Lf= OD=34.9mm, t=1.65mm, K=1426, n=0.502, μ=0.01, α=60)

(2) Open Database Excel sheet and enable macros and run **CreateToolbar** macro.

(3) Select a THF Family from the list. Press the START button to begin data entry.

(4) Press the SUBMIT button to begin database analysis. (To view the material and pressure curves press the UPDATE CHARTS button).

(5) Verify by checking the Excel sheet that will be used for real time communication to ensure the loading path is loaded. Save and Close the Excel file.

4.5.2. Simulation for Single Y-Shape

The feedback force obtained from the cylinder –tube interface that is developed from the differential pressure monitored by the pressure transducer is simulated by developing a force with changing coefficients of friction. The model forces in the database and the simulated forces are in Appendix B.2 in Table A-1 (left cylinder) and A-2 (right cylinder).This simulated force was provided to Think and Do Live (PLC software) from the database using macros shown in Appendix B.3.The simulated force is compared to the model forces to determine the range of the force and obtain the coefficient of friction.

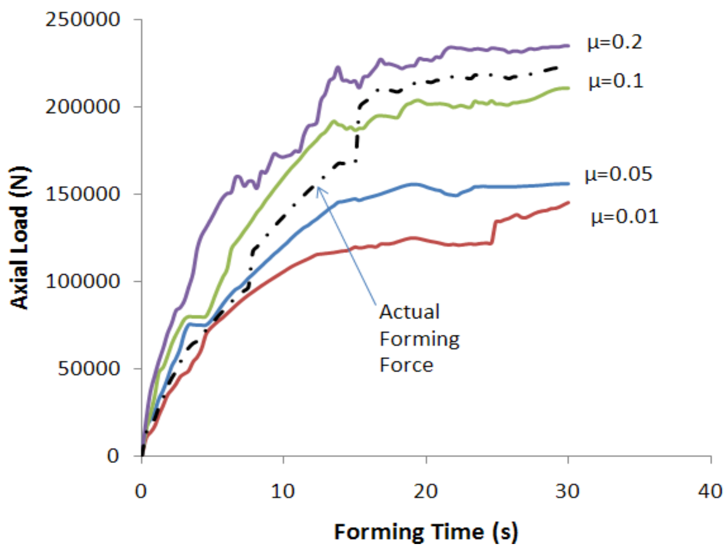


Figure 4 -13 Axial Load for Single Y-Shape

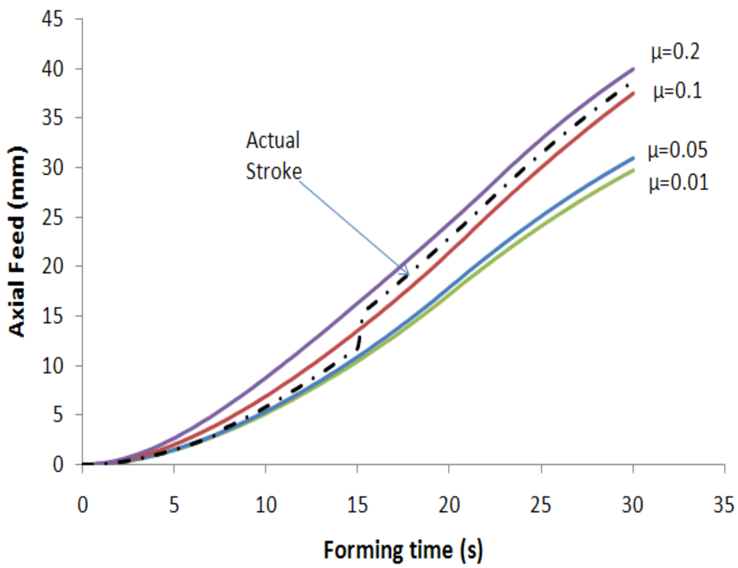


Figure 4 -14 Axial Feed for Single Y-Shape

This shows that the frictional error affects the loading path and the evidence of variation of the coefficient of friction with time verifying that the algorithm was operational in real time. The DBS method therefore compensates the stroke with another loading path. The algorithms are further applied in the experimental validation discussed below.

4.6 EXPERIMENTAL VALIDATION

In order to validate the proposed methodology, THF experiments for the Double T-Shape family were carried out. The loading paths used in the experiments were obtained by the Database Back-Step method.

4.6.1. Test Set-up and Experimental Procedures

The experimental set-up for THF is shown in the Figures 4-15 and Figure 4-16. The tooling set-up consists of split dies and die holders, two axial cylinders (50 ton capacity each) to provide the axial feed, and a 150 ton hydraulic press which is used to clamp the split dies during the operation. The maximum fluid pressure that can be attained in this hydroforming test rig is 20,000 PSI (140MPa). The split dies were made of A2 steel and hardened to 62 HRC. The tubular material used for the tests was stainless steel SS304 with material strength coefficient K = 1426MPa and the strain hardening exponent n = 0.502.

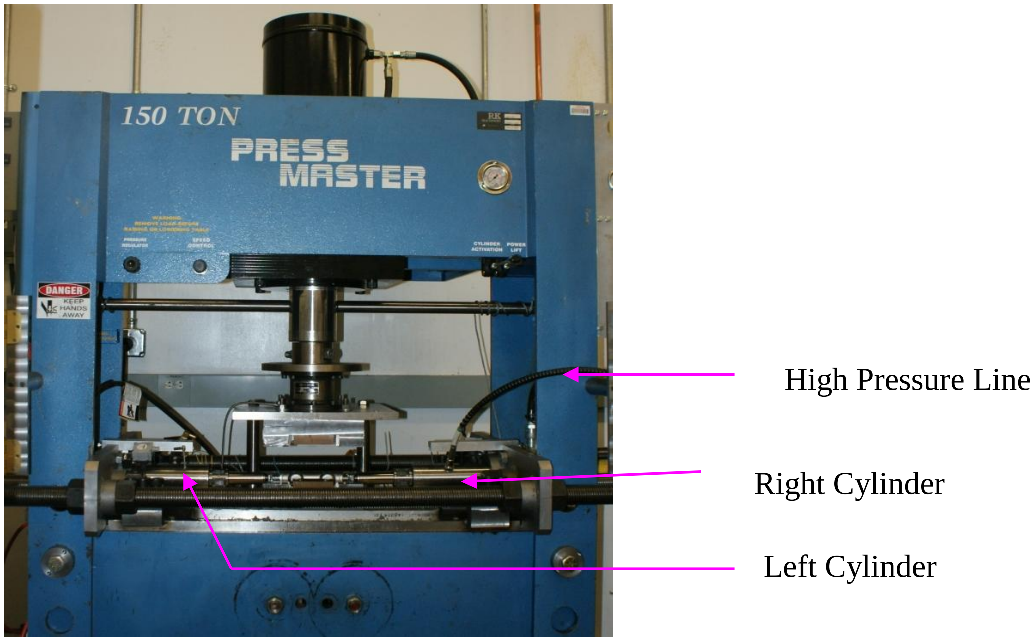


Figure 4 -15 Hydroforming Test Rig

Prior to the experiments, the tube and the dies surfaces were cleaned by acetone. Lubrication was provided by a Teflon sheet which was wrapped around the tube. The loading paths used for these experiments were obtained from the DBS database. All the experiments were carried out in 40 seconds. It should be noted that all the loading paths residing in the database were obtained at a simulation time of 0.01seconds. The difference in the process time should not account for any errors because the loading path for cold forming is independent of the process time.

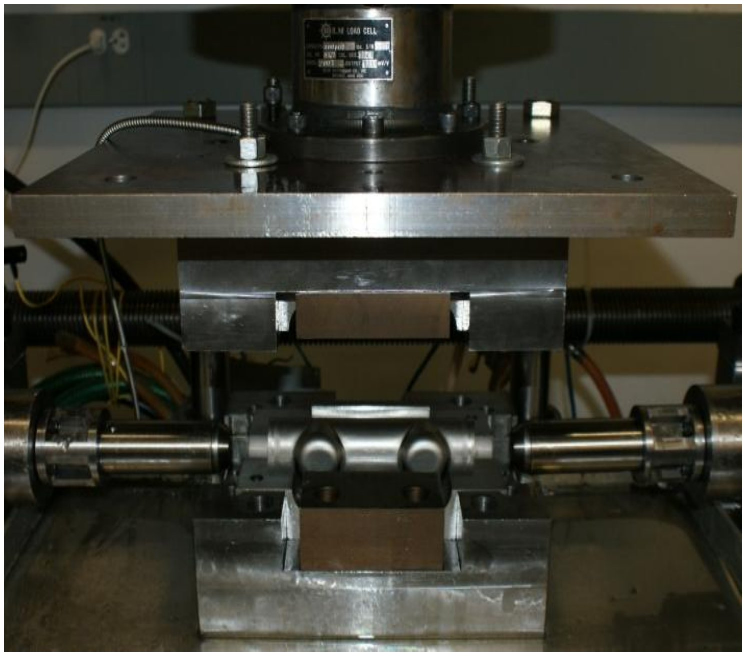


Figure 4 -16   Hydroforming Test Rig - Die area

4.6.2. <u>Press Control Module Description</u>

The PLC parts are Automation direct modules: D2-06B-1 base, H2-EBC Ethernet Base Controller, D2-16ND3-2 16-channel discrete inputs, D2-16TD1-2 16-channel discrete outputs, F2-02DAS-2 (2) 2-channel analog outputs, F2-08AD-1 8-channel analog input and F2-04AD-1 4-channel analog input. Other parts involve power supplies, motor, pump, 2 double acting cylinders and directional valves, sensors (position and pressure) and high pressure equipment. Database operation is done with Microsoft Excel and the machine operation begins with Think and Do Live (TND) control software. For position control the output of material curve of the loading path provided to the cylinder is monitored via a sensor. Each material curve (material feed versus time) in the database is developed with a specific coefficient of friction.

The algorithm used to develop the compensated material feed has been as discussed in section (4.4). Running the Think and Do Live project begins by peering into the database via a DDE link to access data. The Database supplies data that is further manipulated in the Think and Do Software. Sample of the communication code between the Database and Think and Do Live is shown in the Appendix B.3. The database used in the validation of the developed method contains the pressure development curve of the loading paths, axial feeding curve and the loading path and punch load at different friction conditions as shown in Figures 4-17, Figure 4-18 and Figure 4-19 respectively.

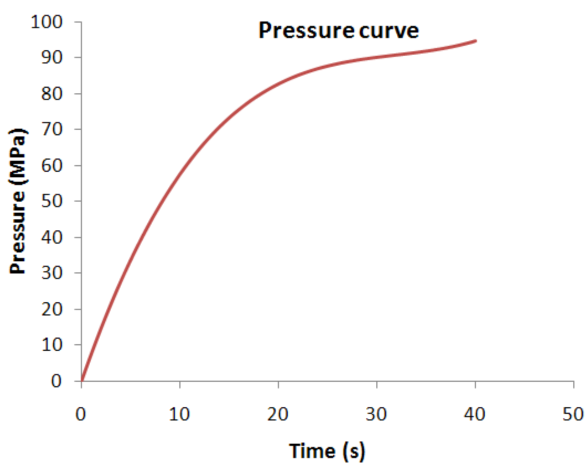


Figure 4 -17 Pressure development Curve for double T-Shape

4.6.3. Hydroforming Equipment Description

Motors drive the left and right cylinder pumps which provide the oil for actuation force. The oil is returned to the tank through the valve at atmospheric pressure. The high pressure from the loading path sent out as an analog signal to the regulator. The regulator and accessories are responsible for providing low air pressure to the 'liquid' (air /oil) pump.

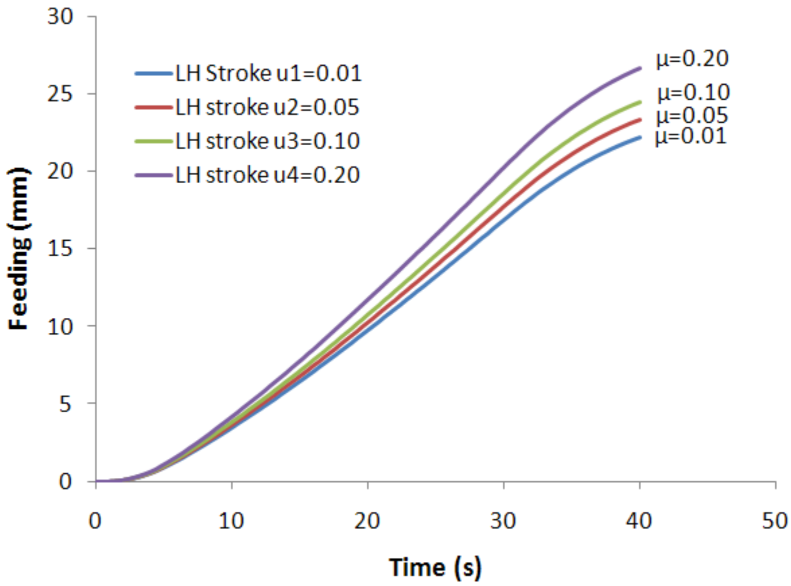


Figure 4 -18 Material feed profiles for double T-Shape at different friction conditions

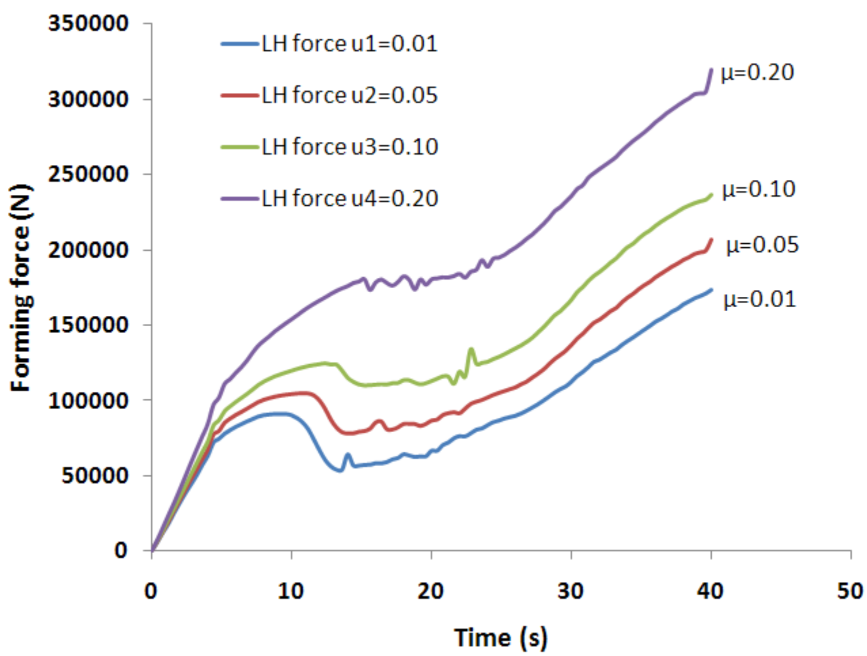


Figure 4 -19 Left and Right side Punch force for different friction conditions

The pump operation is based on the principle of differential areas where the area on the air side is large compared to the oil side. Hence the air side piston moves the oil piston which in turn pushes the fluid into a small opening generating high pressure. The high pressure system which supplies high pressure to the tube in the cylinder region involves the dumping valve and bleeding valve. The dumping valve is used to ‘dump’ (remove) all the high pressure instantly when open while the bleeding valve is used to ‘bleed’ (reduce) the high pressure enabling the capability to perform pulsating functions. A relief valve is used to maintain constant supply pressure from the output of the pump. A desk computer is employed to edit the main control procedure using programming logic control (PLC) language, execute sequences for operation phases of the machine, monitor the current status of the machine, communicate with other modules inside and outside the machine, and store and retrieve useful data in the memory module.

4.6.4. Experimental Results

The die set and hydroformed Double T-Shape are shown in Figure.4-20 (a) and Figure.4-20(b), respectively.

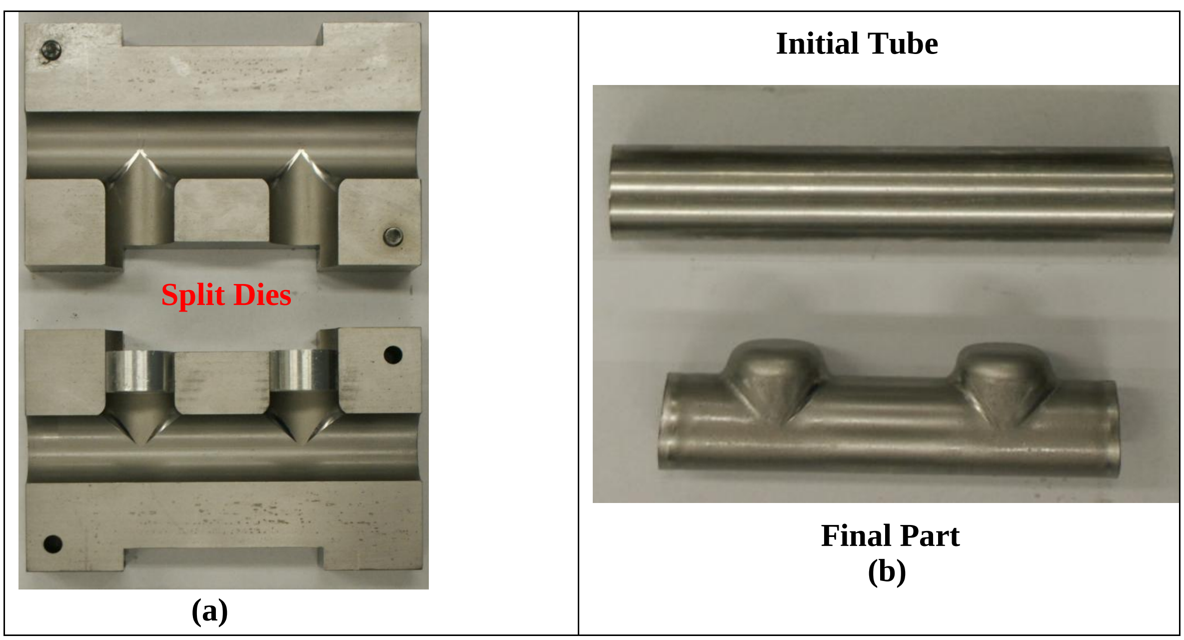


Figure 4 -20 Split dies and hydroformed Double T-Shape hydroformed part

As seen in Figure 4-20(b), the part was successfully formed. To examine the system response, input variables and output variables were assessed. Figure 4-21 shows the input hydraulic pressure curve to the hydroforming machine and the actual pressure from the press. The high pressure output matches the pressure loading path well after 5 seconds. The pressure difference in the first 5 seconds is due to slow response of the pressure booster. Figure.4-22 shows the cylinder punch loads (forces) for the left and right cylinders. The cylinder punch loads are almost identical. This is expected as the part is symmetric and the feeding rate is the same for both sides. It should be noted that the cylinder punch load profiles given in Figure.4-22 exclude the sealing pressure.

The sealing pressure has been excluded because it does not contribute to the friction force and also the cylinder punch loads (model forces) residing in the database have been established without considering the sealing pressure. To examine whether non-linear friction condition is exhibited at the die-tube interface as deformation progresses, the cylinder punch loads obtained from the experiment are plotted as shown in Figure.4-23 together with the punch loads (model forces) from the database for different friction conditions. As seen in Figure.4-24 when Teflon lubricant was used the friction varies from μ=0.03 to 0.15 as the process progresses. When Teflon and oil were used to lubricant the tube the coefficient of friction varied from μ= 0.02 to 0.12 as seen in Figure.4-24.

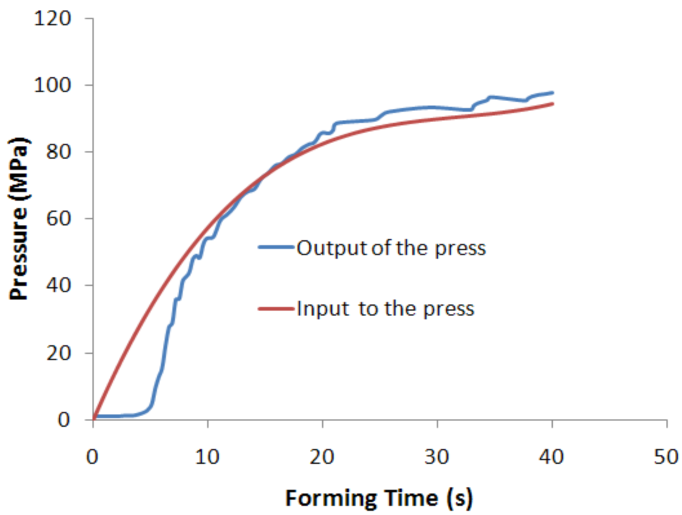


Figure 4 -21 Input pressure and output presure from the hydroforming machine.

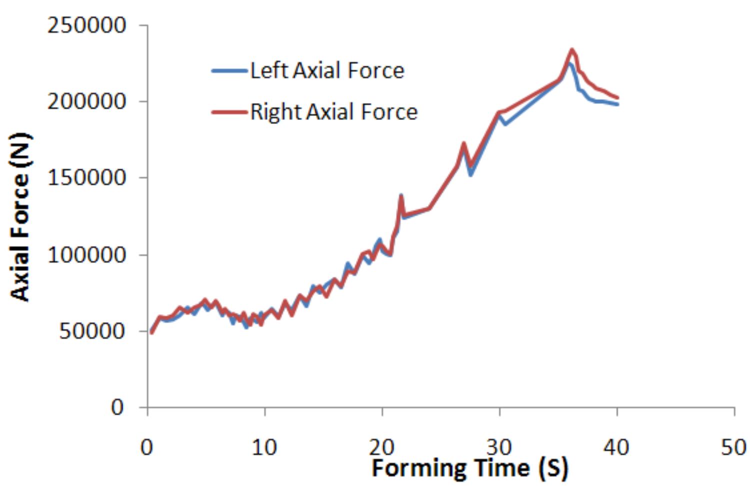


Figure 4 -22 Punch load for the left and right cylinder [Teflon lubricant].

Figure 4-24 is developed for the forming time after 13 s when the pressure booster output is close to the desired pressure.

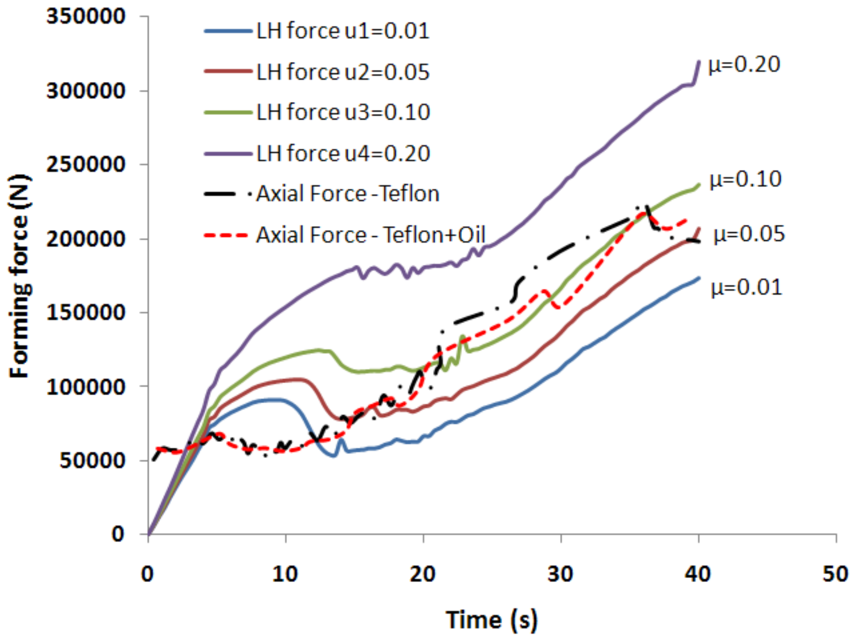


Figure 4 -23 Comparison of punch load from the database and that obtained from experiment [Teflon lubricant] and [Teflon + Oil lubricant]

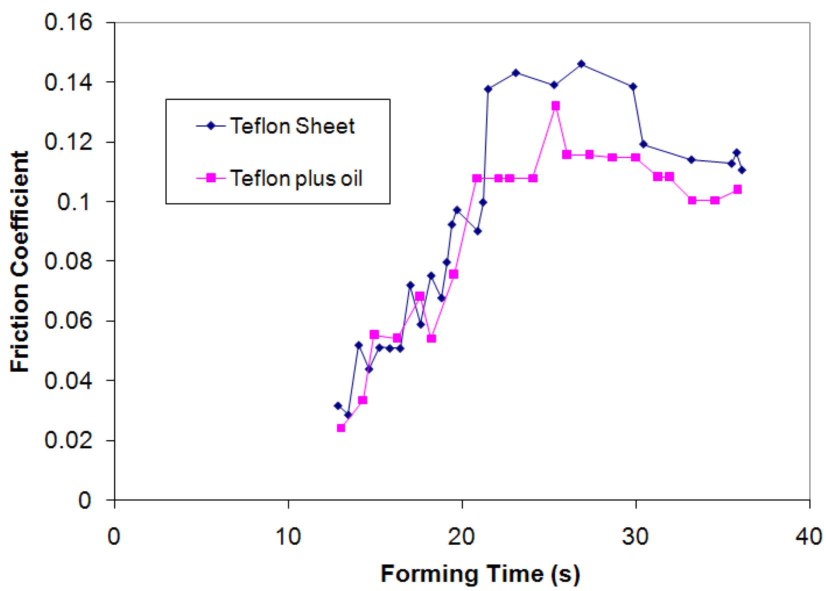


Figure 4 -24 Non-linear friction characteristic for different lubrication conditions

Figure 4-25 shows the displacement of the cylinder for the different lubricants.

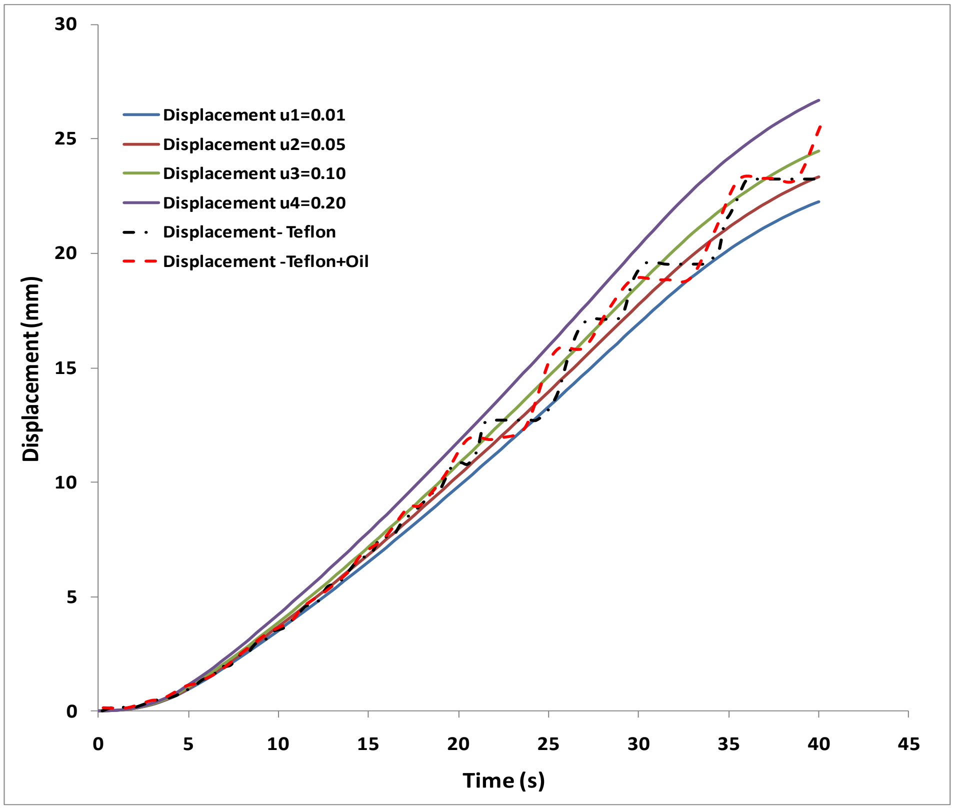


Figure 4 -25 Comparison of punch displacement from the database and that obtained from experiment [Teflon lubricant] and [Teflon + Oil lubricant]

Concluding Remarks

The database back step method has proven to be sufficient for providing frictional error compensation and establishing a correct loading path to correct for errors. The results have shown that the interface friction can increase considerably as the deformation process progresses. This implies that lubricant performance may depreciate as deformation progresses. This may be caused by numerous reasons as discussed earlier in this chapter.

The challenge faced by the database back step method include the lag response of the equipment leading to a stepwise motion of the cylinder as shown beyond 20 s in Figure 4-25. Moreover the cylinder position overshoots the desired loading path. In the next chapter errors associated with the THF equipment will be discussed.

CHAPTER 5:
ERROR COMPENSATION USING REAL-TIME STROKE (RTS) CONTROLLER METHOD

5.1 INTRODUCTION

Control for tube hydroforming is an area that is relatively new and most research is involved for its importance in curbing the common THF failure modes being buckling, bursting and wrinkling. Application of control techniques lead to ensure product profitability is maximized. Apart from frictional error compensation using the Database Back-Step Method errors can arise from the equipment creating the need for controller design.

Stroke is the motion of the cylinder in response to a command to move to a certain position at a certain velocity under the influence of a certain cylinder differential pressure. In an ideal situation, the motion of the cylinder observed from the displacement transducer will match the provided reference command. This is not usually the case as shown in Figure 5-1. The cylinder position has intermittent overshoots creating a stepwise profile motion about the reference loading path. Figure 5-1 shows a simulation study of the motion of the press cylinder without a forming load. In the study, the loading path (reference) was provided from a database to the Press via Think and Do live software. The position of the cylinder was monitored and compared to the loading path resulting in Figure 5-1 with overshoots. This is due to errors associated with the press equipment and can lead to poor forming performance and compromising the quality of the part.

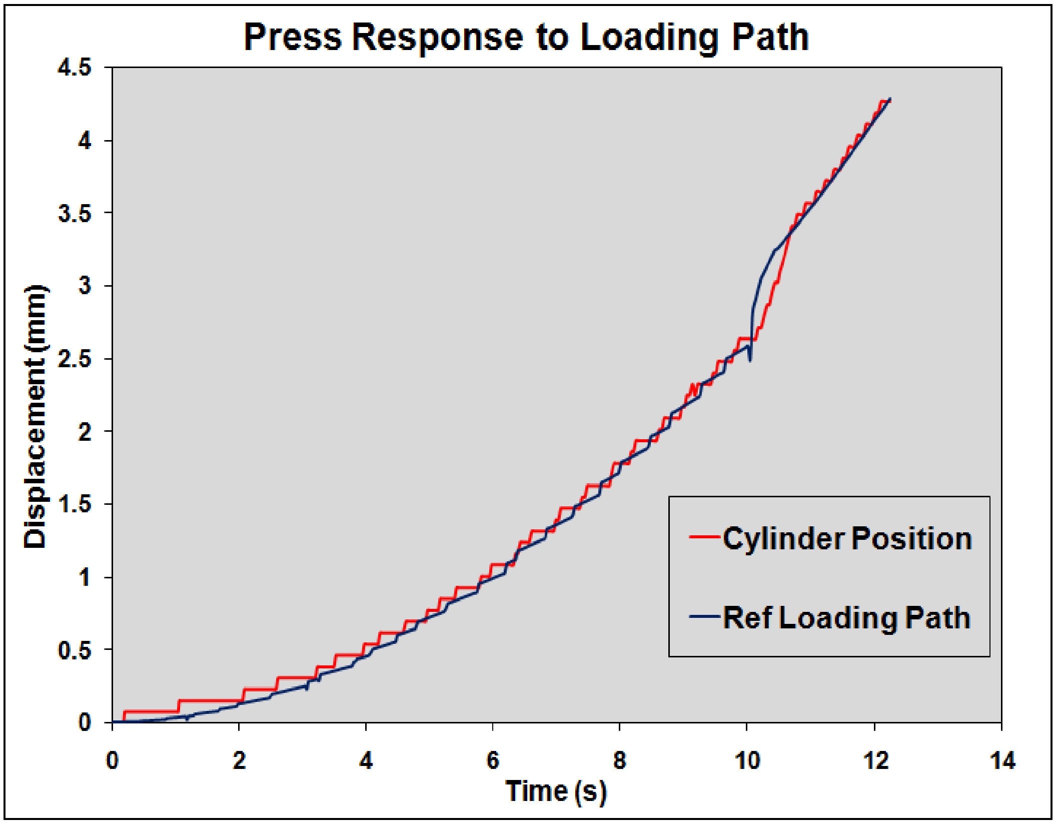


Figure 5 - 1 Cylinder Motion with Overshoots

Uncertainties such as nonlinear relationships between flow and pressure of the orifices, mechanical constraints of the moving parts and flow forces acting on the valve spool [Jelali et. al., 2003] cannot be captured by the Database Back-Step method because the DBS is developed to compensate for friction errors occurring at the tube-die interface. Errors associated with internal pressure are due to fluid incompressibility, air trapped in the die cavity, rapid change in volume flow rate in the tube area. The high pressure is monitored by pressure transducer which is currently not located to detect the pressure inside the tube. This poses the challenge of establishing the high pressure inside the tube. This remoteness of the tube discourages the use of a control feedback since the sensor is away from the tube leading to approximations that can be erroneous. Other errors associated with the equipment include cylinder uncertainties and leakage, controller tuning approximations, machine deflections, neglect of tooling characteristics such as die-elasticity and inaccurate sensor response. Stroke control is where feedback from the sensors is compared to the desired stroke and the difference provided to a controller that sends an output to correct the difference.

This chapter introduces the Real-Time Stroke (RTS) Controller method that involves developing stroke improvement to the Database Back-Step control method by addressing the overshoot error. A review of the stroke control is done beginning with a view of the parameters that are controlled and equipment. Some of the equipments involved in the hydraulic system for stroke control include the motor driven pump, directional control valves, pressure relief valves, cylinders, sensors- pressure and displacement transducers and Programmable Logic Controller (PLC) unit. Figure 5-2 shows the set up of the press and errors associated with the equipment. The plant model is developed and used in a feedback loop to design the RTS controller. Results from the DBS method are used for simulation purposes to show the effectiveness of the RTS controller method.

5.2 EQUIPMENT AND CONTROLLED PARAMETERS IN THF

The parameters controlled are position, velocity and pressure. In the THF process the desired position signal sent from the PLC to the cylinder is provided by the loading path obtained from the database. Communication between the PLC and the database is achieved using a Data Dynamic Exchange link. Cylinder velocity is derived from the stroke (material feed) and sent out to the motor as an analog signal (analog out) which drives the pump.

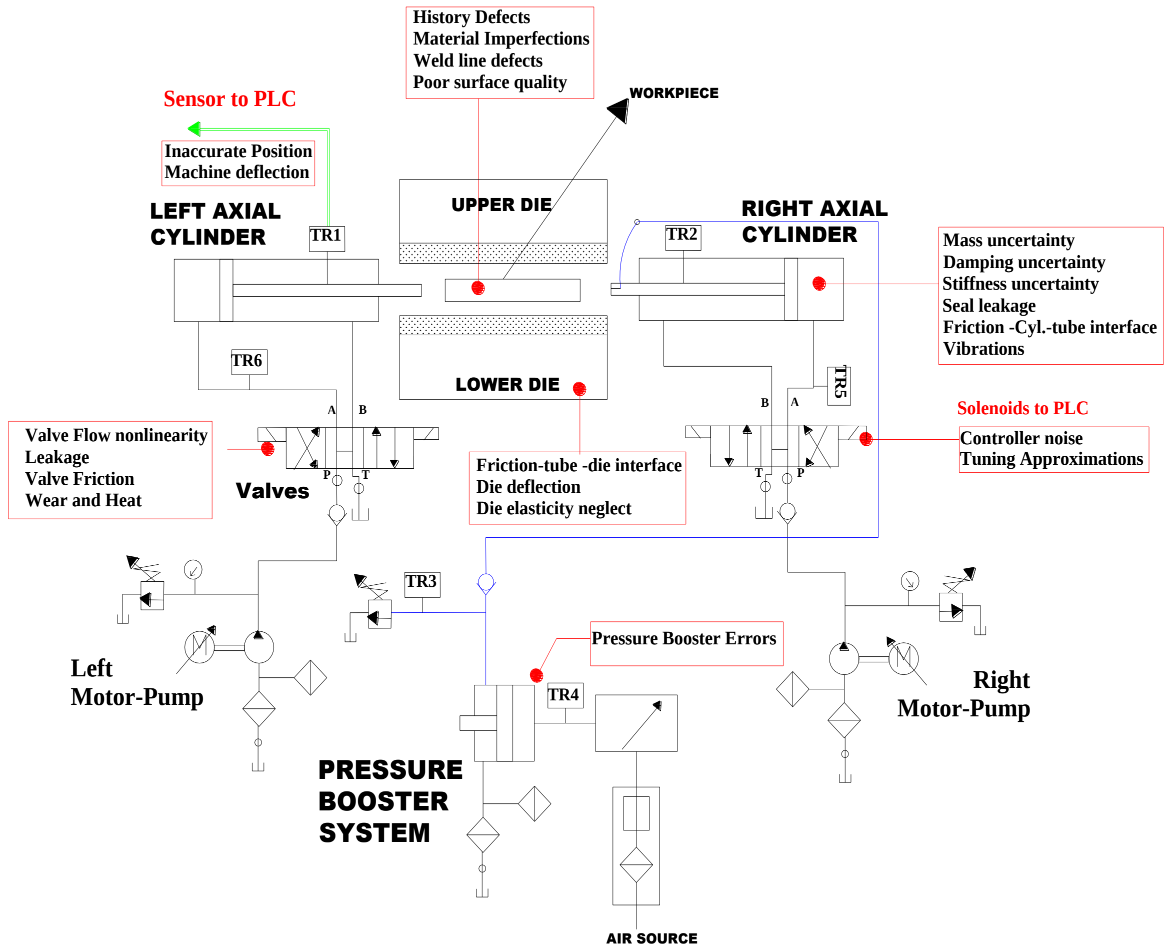


Figure 5 - 2 THF Press Set Up and Errors

Figure 5-3 shows PLC unit modules that involve Discrete and Analog inputs and outputs and the various equipments and sensors that are involved in receiving and sending signals. The electric motor receives voltage and current which leads to exciting the magnetic fields and hence rotation of the shaft that is coupled to the pump.

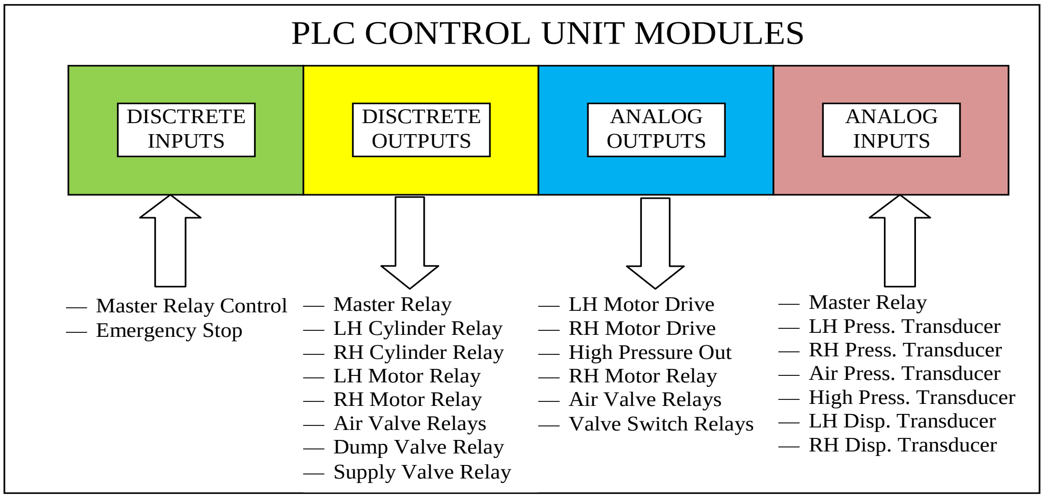


Figure 5 - 3 THF Press Set Up and Errors

The motor is a constant torque variable speed motor hence provides the same amount of torque to the pump though its speed is variable. The motor converts electrical energy into mechanical energy. The electrical power, $Pe = IV$ where I is the current and V is the voltage, and mechanical energy, $Pm = TN$ where T is the torque produced and N is the speed (rpm). Since the torque is constant, the power of the pump can be varied by varying the speed and the power of the motor is varied by the voltage.

$$
\begin{aligned}
&P_m = \eta_m P_e \\
&T_m N = \eta_m IV \\
&\eta_m - \text{motor efficiency} \\
&Pe, Pm - \text{Power input, output of motor}
\end{aligned}
\qquad (5.1)
$$

The motor displays velocity variation by operating under Volts/Hertz control where changing speed leads to changing both the frequency and the voltage together. This ensures constant flux and hence constant torque (since current is constant). This further changes the power of the motor while maintaining a constant torque.

$$
\begin{aligned}
&Torque, T_m = K_m BI \\
&Speed, N = f/P \\
&Flux, B = K_f\, V/f \\
&where \\
&I - \text{current} \\
&P - \text{Poles} \\
&V/f - \text{Volts-frequency ratio} \\
&K_f, K_m - \text{constants}
\end{aligned}
\tag{5.2}
$$

The torque supplied to the fixed displacement piston pump provides a displacement to the hydraulic fluid which is channeled to the directional valves. This positive displacement pump is a constant torque load. The pump upon rotation of its shaft converts mechanical energy into hydraulic energy. The power input to the pump is the shaft power that is equivalent to the power into the motor excluding the motor losses. The motor losses are due to electrical and mechanical losses. In the coupled system, the motor power output is equal to the pump power input. The overall efficiency of the system is the motor efficiency multiplied by the pump efficiency. The flow from the pump to the valve is obtained from:

$$
\begin{aligned}
&T_m = \Delta PD/\eta_{pm} \\
&Q_p = ND - C_k \Delta P \\
&where \\
&Q_p - \text{Valve flow} \\
&\eta_{pm} - \text{Pump efficiency} \\
&C_k - \text{leakage coefficient} \\
&D - \text{pump displacement (in}^3\text{/rev)} \\
&\Delta P - \text{pump pressure difference of inlet and outlet ports (Supply pressure, } P_s\text{)}
\end{aligned}
\tag{5.3}
$$

Considering leakage as part of the efficiency factor, the motor –pump coupled system produces a supply pressure as derived below:

$$Q_p = ND - C_k P_s = \eta_{pv} ND$$
$$\eta_{pv} - \text{volumetric efficiency} \tag{5.4}$$
$$P_s = \frac{ND\left(1 - \eta_{pv}\right)}{C_k}$$

The flow from the pump is delivered to the valves at a supply pressure, *Ps*, and further is sent to the cylinder head. Pressure relief valves are suited to provide relief and send back oil to the tank when a certain level of pressure is reached. The directional valves supply oil to and from the cylinder serving as a medium between the cylinder and the pump. The valve is a four way, three position valve whereby the spool moves when the solenoid is activated.

The valve has two solenoids such that when one solenoid is energized, flow is allowed from the pump to the cylinder head and when the other solenoid is energized, flow flows back to the tank hence retracting the cylinder. The differential pressure built up in the cylinder provides force to advance or retract the piston hence obtaining stroke. The displacement sensors on the piston rod provide feedback by analog signal, inputs to PLC. The pressure sensors located between the valves and the cylinder provide detail of the force developed in the cylinder head from the pressure differential. The control unit has algorithm calculations to determine the input reference to the pump. The next section discusses the design of the plant model.

5.3 SYSTEM MODELING

The system model for the plant is the transfer function representation of the system made of the motor, pump, valve and cylinder. This section begins with a study on the cylinder and the interaction with the environment.

5.3.1. Cylinder Interaction with Environment

Cylinders have been used in various functions such as to providing force, clamping, motion and material handling. This leads to interaction with various kinds of environments. The term 'environment' refers to the external surface upon which the cylinder is interacting. The external surfaces may be in motion such as in material handling or immovable such as when providing support. This interaction with the environment leads to the cylinder experiencing external reaction and opposing forces. The forces considered are in the same direction axis as the cylinder motion. This external force, F_e has been modeled as a spring opposing the cylinder motion [Popp, 2005; Niksefat et. al., 1999] where force applied is equal to the spring stiffness multiplied by the cylinder piston displacement. Other models such as a second order system have been used when a force sensor is placed between the cylinder and the environment [Wu et. al., 1998].

In THF the external force is of significant importance regarding the position of the cylinder. The external force defines the resistance 'stiffness' of the environment to deform. The spring model for THF is sufficient for the cylinder since the environment is between the cylinder and a fixed end. More discussion on the THF model fixed ends in the next section.

Hence adopting the approach of the spring model the environmental stiffness is obtained as:

$$K_e = \frac{F_e}{y_p} \tag{5.5}$$

where K_e is the 'environment stiffness' and y_p is the cylinder displacement.

5.3.2. Estimation of External Force

The external force is the forming force obtained from FEA during the establishment of the loading paths. The contact force obtained between the cylinder and the tube is treated as the external force. The environmental stiffness in THF is obtained from Eqn. (5.5). Figure 5-4 shows the axial force and stroke from which the stiffness is derived for the Double T-Shape.

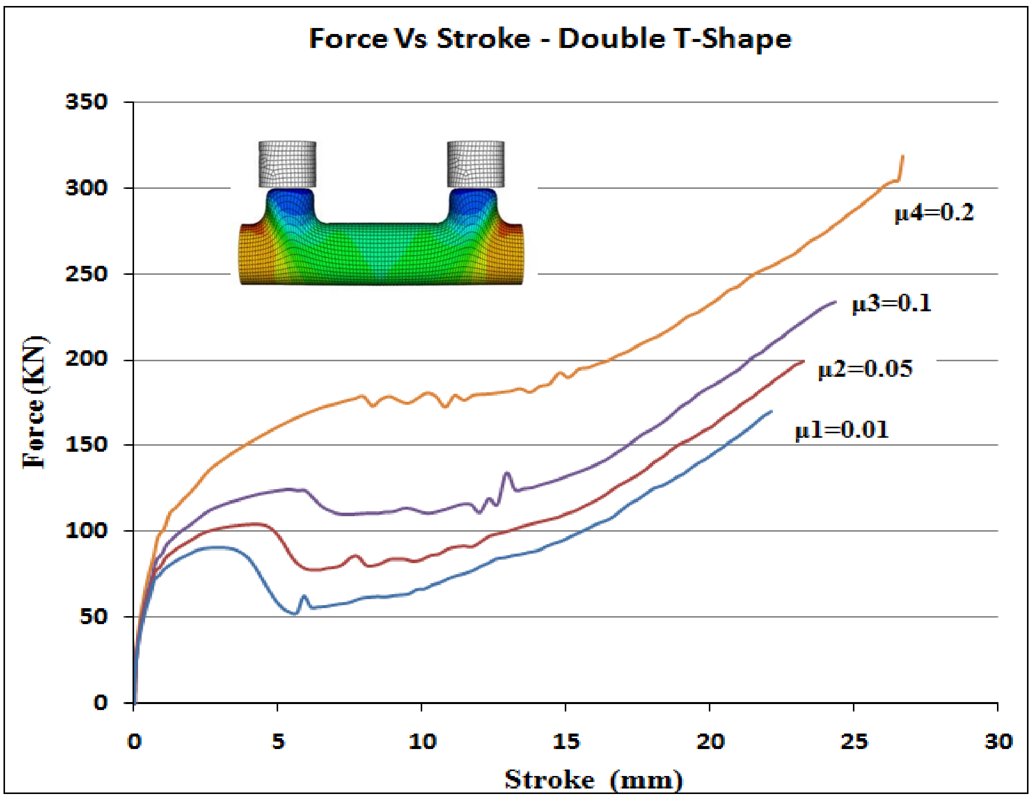


Figure 5 - 4 Axial force and Stroke –Double T-Shape

The stiffness varies with the stroke and the coefficient of friction. The stiffness in this work is obtained by dividing the each profile (different coefficient of friction) into linear segments of the stroke from 0-4mm, 4-6.5mm, 6.5-13mm and 13 mm till end of the forming cycle.

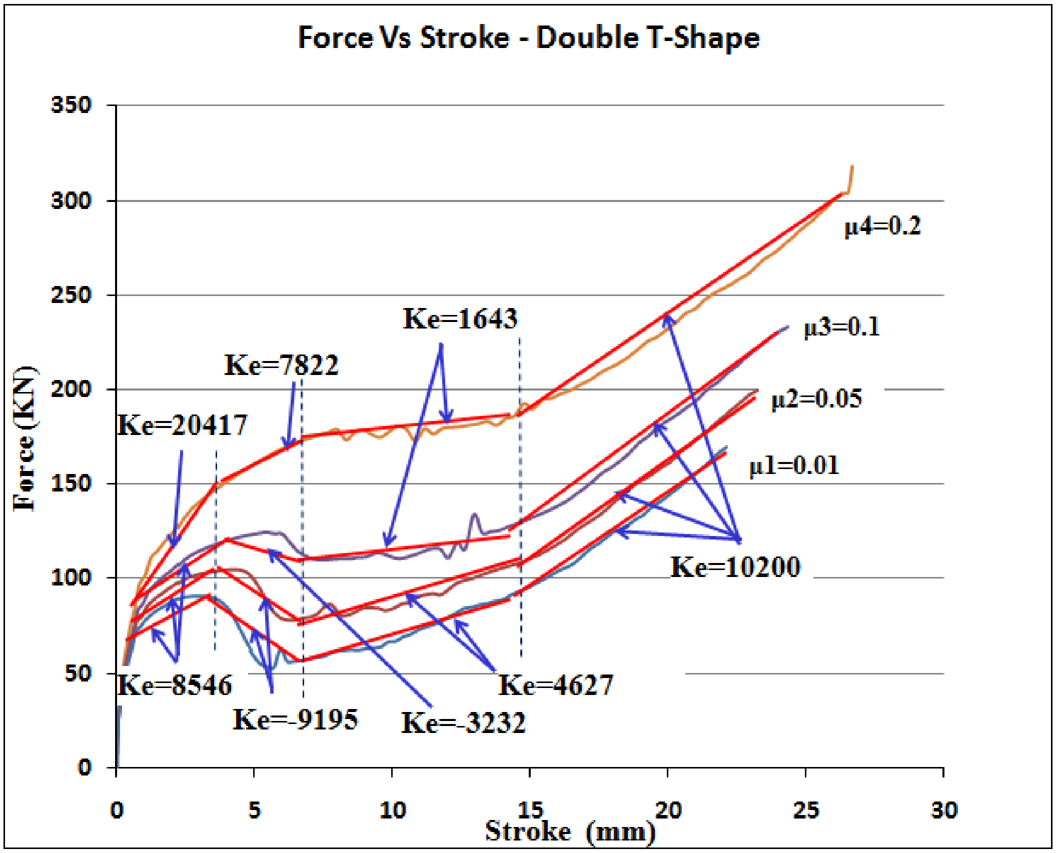


Figure 5 - 5 Axial force and Stroke with Stiffness Analysis–Double T-Shape

The results of the stiffness are shown in the Table 7 below:

Table 7 Stiffness Analysis (N/mm)

Double T-Shape THF Family				
Stroke region	**μ1**	**μ2**	**μ3**	**μ4**
0-4 mm	8546	8546	8546	20417
4mm-6.5mm	-9195	-9195	-3232	7822
6.5mm-13mm	4627	4627	1643	1643
13mm~27mm	10200	10200	10200	10200

5.3.3. System Modeling Steps

This section focuses on developing a system model that will be used to define the plant model with equations obtained from analyzing forces involved in the system. Beginning with the tube area and focusing on the cylinders and the environment, modeling will be done based on motion of parts and forces involved.

1) Parts:

a. Parts in Motion

The solid parts that are in motion in THF die area are the axial cylinders and the tube. The tube is in motion under the impact of the axial cylinders. Common cylinder modeling involves the mass-spring damper system. The motion of the tube is the material flow occurring beyond the yielding point. The material flow takes place in the guide, transition and expansion zone as the tube expands in the expansion zone (Refer to Figure 4-1). The tube is modeled as a mass with a spring.

b. Parts Not in Motion

These form the fixed boundaries of the system model. The parts are the press frame which houses the axial cylinders providing a fixed boundary and the ‘Expansion zone Limit’. The ‘Expansion zone Limit’ is zone whereby there is a limit of the amount of axial material feed into the expansion zone. More material feed beyond this limit causes more thickening at the tube edge and possible wrinkling in the guide zone. The limit is due to the strain hardening in the expansion zone and acts like a fixed boundary.

2) Forces

The forces involved include the External force in the tube area as discussed in §5.3.2 and the pressure differential on the cylinder piston. Considering an asymmetric cylinder as shown in Figure 5-6, where *A*, *V*, *P* represent the area, volume and pressure of the sections of the cylinder. Q_A and Q_B is the rate of flow into and out of the cylinder from and to the valve, P_1 is pressure in chamber with area A_1, P_2 is pressure in chamber with area A_2, and CP_L is the leakage pressure between chambers. The pressure differential develops a force F_c that is:

$$F_c = P_1A_1 - P_2A_2 = P_LA_2$$
$$where$$
$$P_L = \alpha P_1 - P_2 ; \alpha = {A_1}/{A_2} \tag{5.10}$$

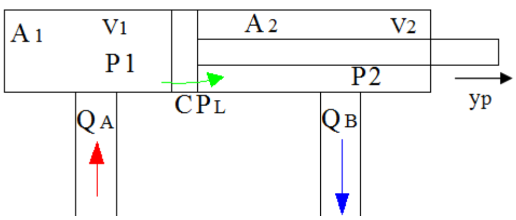


Figure 5 - 6 Cylinder Sections

The model proposed in this research for the cylinder involves a single rod, double acting cylinder and the environment design is based on the spring model. Due to symmetry in the setup one cylinder is considered for modeling purposes. The model is shown in Figure 5-7 where m and m_e are masses of the cylinder piston (including hydraulic fluid contained) and tube respectively, K_1 is the stiffness in cylinder due to the hydraulic fluid, K_e is the environment stiffness, F_e is the external force, F_a is the axial force and y_p is the displacement of the piston based on the Database back-Step method

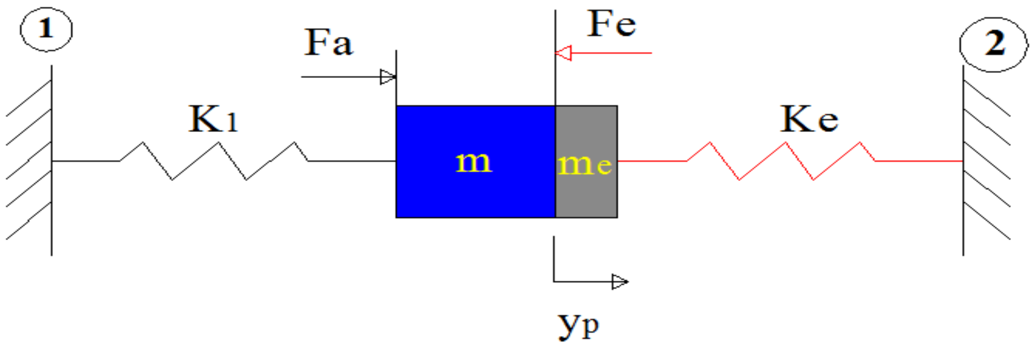


Figure 5 - 7 Diagram of the System Model

Fixed boundaries are labeled '*1*' and '*2*' where '*1*' is the press providing a fixed end on the cylinder side and '*2*' is the fixed end as the result of the expansion zone limit. The dies assumed to be rigid and immovable due to clamping provided by the vertical pressure cylinder. Next section focuses on an analysis of the system model.

5.4 PLANT DESIGN

The equation of motion that governs the system model is derived as:

$$\left(m+m_e\right)\ddot{y}_p+K_1y_p-F_e=F_a \tag{5.11}$$

Assuming that cylinder internal friction is negligible compared to the cylinder force due to pressure F_c, then the axial force $F_a = F_c$. Substituting the external force from Eqn. (5.5) and axial force from Eqn. (5.10) leads to

$$\left(m+m_e\right)\ddot{y}_p+\left(K_1+K_e\right)y_p=P_LA_2 \tag{5.12}$$

The stiffness in the cylinder is given Eqn. (5.13) [Jelali et. al., 2003]:

$$K_1 = \beta\left(\frac{A_1{}^2}{V_1} + \frac{A_2{}^2}{V_2}\right) \tag{5.13}$$

Where β is the effective bulk modulus of the hydraulic fluid is assumed to be constant. To simplify further the mass of the tube is added to the mass of the piston to form one mass term, m, and with Laplace transform Eqn. (5.12) becomes Eqn. (5.14):

$$\left(ms^2 + K_1 + K_e\right)Y_p(s) = A_2 P_L(s) \tag{5.14}$$

The continuity equation [Jelali et. al., 2003] is obtained by considering the mass flow rate, the leakages between the cylinder chambers and external leakage and the effect of fluid compressibility to obtain Eqn. 5-15. The continuity equation with leakage between the chambers of the cylinder is (Refer to Figure 5-6):

$$Q_L = \frac{V}{2\beta}\dot{P}_L + CP_L + A_2\dot{y}_p \tag{5.15}$$

The directional valves do not provide control of the flow or pressure but provide direction to the flow. From the calculations of the flow characteristics [Jelali et. al., 2003] the flow load is obtained as:

$$Q_L = C_d A_v \operatorname{sgn}(P_s - P_L)\sqrt{\frac{2}{\rho}\left|P_s - P_L\right|} \tag{5.16}$$

Where:

P_S – Supply pressure $\quad$ ρ – Fluid density

P_L – Load pressure $\quad$ A_v – Orifice Area

C_d – Coefficient of Discharge

From Eqn. (5.16), *sgn*(P_s-P_L) depends on the position of the valve. The sign is positive when flow of fluid is to the cylinder for forward motion. Analysis is done assuming that the orifice of the valve is open (no flow control since the port is fully open) and that the flow is a function of the pressure only, then the load pressure can be expressed as:

$$Q_L \approx K_q P_s$$
$$\textit{where} \tag{5.17}$$
$$K_q = \frac{C_d A_v}{2\sqrt{\rho(P_s - P_L)}}$$

Combining Eqns. (5.15) and (5.17) gives the relation between the pressure load and the position of the cylinder as expressed In Laplace transform in Eqn. 5.18:

$$\left(\frac{sV + 2\beta C}{2\beta}\right) P_L(s) = K_q P_s(s) - A_2 s Y_p(s) \tag{5.18}$$

Substituting for load pressure from Eqn. (5.14) leads to

$$\left(\frac{sV + 2\beta C}{2A_2\beta}\left(ms^2 + K_1 + K_e\right) + A_2 s\right) Y_p(s) = K_q P_s(s) \tag{5.19}$$

The transfer function between the cylinder position and the supply pressure becomes:

$$\frac{Y_p(s)}{P_s(s)} = \frac{2A_2 K_q \beta}{\left((sV + 2\beta C)\left(ms^2 + K_1 + K_e\right) + 2sA_2{}^2\beta\right)} \tag{5.20}$$

The supply pressure from the pump is a function of the pump flow as shown in Eqn. (5.4) where

$$\frac{P_s(s)}{U(s)} = \frac{2\pi D\left(1-\eta_{pm}\right)}{60C_k} \tag{5.21}$$

$U(s)-$is speed in radians, $\dot{\theta}$

Since the motor operates as a variable frequency device that is to change the speed of the motor, the frequency and voltage are changed. The motor speed input from the user changes the voltage supplied. The transfer function between the motor speed input and the cylinder position is:

$$\frac{Y_p(s)}{U(s)} = \frac{4\pi D\left(1-\eta_{pm}\right)A_2 K_q \beta}{60C_k\left(mVs^3 + 2m\beta Cs^2 + \left(V\left(K_1+K_e\right)+2A_2{}^2\beta\right)s + 2\beta C\left(K_1+K_e\right)\right)} \tag{5.22}$$

This forms the open plant model. The next section focuses on the design of the controller to be used with the plant model in a closed loop system

5.5 RTS CONTROLLER

5.5.1. <u>Introduction</u>

The RTS controller is designed to do either position or velocity control. Closed loop position control is achieved by sending stroke loading path data from the database, converting into velocity within Think and Do Live, sending velocity (speed) data to the motor and obtaining position feedback from the cylinder via the displacement transducers. Figure 5-8 shows position control where ‘SP’ is the reference Set point (loading path), ‘EP’ is the position error (difference of the set point and feedback), , ‘OV’ is the output variable from the PID controller to adjust the voltage of the motor, ‘PV’ is the feedback process variable obtained from the displacement transducer and ‘POS’ refers to position.

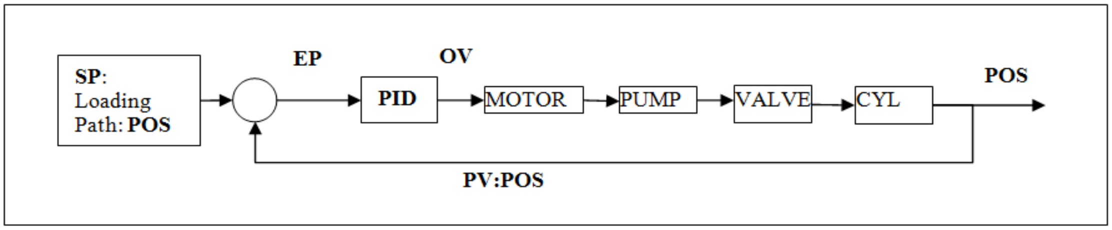


Figure 5 - 8 Position Control in THF Process

5.5.2. <u>RTS Methodology and Controller Operation</u>

Focus in this section will begin on developing the controller position control. The process loop uses a controller with the terminologies:

a. *SP*: Set Point is the desired amount of stroke for position control provided from the database to the controller.

b. *OV*: is the output from the Controller to the plant model.

c. *PV: POS*: Process Variable is the actual displacement from the transducer.

Since this method involves improving the stroke control obtained from the database, the procedure involved in obtaining the reference position and DDE communication is based on the Database Back-Step method in Chapter 4. Simulation tools from MATLAB (code is in Appendix C.1) are used to develop the controller based on the model in Eqn. (5.22). The data in Table 8, 9 are collected from the manufacturer specifications of the equipment and applied to the Eqn. (5.22) to obtain the plant model.

Table 8 **System Data**

Symbol	Description	Value	Units
m	Mass of cylinder	35	kg
y_t	Stroke	300	mm
A_1	Effective push area	7.6×10^3	mm^2
A_2	Effective pull area	3.8×10^3	mm^2
β	Bulk modulus of hydraulic fluid	1.72×10^3	MPa
ρ	Density of hydraulic fluid	8.6×10^{-7}	kg/mm^3
Ps	Supply pressure	68.95	MPa
C	Cylinder Leakage coefficient	2×10^3	mm^3/s MPa
C_k	Pump Leakage coefficient	1×10^4	mm^3/s MPa
C_d	Discharge Coefficient	0.61	
A_v	Orifice area	27.74	mm^2
η_{pm}	Volumetric efficiency	0.8	
Q_p	Pump output flow	6.3×10^4	mm^3/s
N	Pump shaft max speed	1800	rpm

The data below is obtained from calculations and conversions.

Table 9 **Calculated data**

Symbol	Description	Value	Units
V	Volume of the cylinder	2.23×10^5	mm^3
D	Pump displacement	6.814×10^2	$(mm^3/s)/rad$
K_1*	Cylinder Stiffness	8.735×10^5	N/mm
K_q	Flow proportionality	1.55×10^4	mm^3s/kg

* Based on:

$$K_1 = 2\beta \frac{A^2}{V}$$

Since the variation of *Ke* from section (5.3.2) affects the plant model its effect needs investigation. The step response of the closed loop model is proposed to assist in this study. The effect of *Ke* is studied by observing the overshoot and settling time of the step response.

The *Ke* for the regions based on cylinder displacement (stroke) are obtained by taking the average of the stiffness for the different coefficients of friction for particular stroke range. The first step involved in selecting the controller was considering using sisotool in Matlab. The Ziegler- Nichols PID tuning (closed loop method) method was used to obtain the controller. The challenge of this controller was that the PID gains were beyond the limits of the PID block in Think and Do Live. Second step involved using a Proportional gain (Pgain) and the plant model in a closed loop. The step function response with the Pgain only led to noisy signals with small amplitudes (0.007). Third step involved adding an Integral gain (Igain) which showed good response to step function. Fourth step involved adding a derivative gain (Dgain) which led to noisy signals. Hence the Proportional-Integral (PI) controller was adopted and tuned by providing one similar Pgain and I gain to all stroke segments. The results obtained are shown in Table 10. The 'model name' is a name of the system used for a stroke range, given for easy reference. The stroke ranges are 0-4mm, 4-6.5mm, 6.5-13mm and 13mm-~27mm (end of forming cycle). The PI controller gains are K (Pgain) =10 and K_I (Igain) =20000. The RTS Controller is developed as a PI controller using MATLAB tools and can be expressed in the Laplace format below with K_P, and K_I as the PI gains:

$$D_{PI} = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_I s}\right) \quad T_I = \frac{K_p}{K_I}; \tag{5.23}$$

where T_I is the reset time in minutes.

Figure 5-9 shows a sample step response of the closed loop system 'Syscl4' with overshoot (at 0.248s) and settling time (at 0.681s).

Table 10 Stiffness to Step response with a PI controller (K=10, K_I=20000)

Model name	Time region	Stiffness	Overshoot	Settling time (s)
Syscl1	0-4 mm	11006	1.14	0.681
Syscl2	4-6.5mm	-3786.1	1.15	0.677
Syscl3	6.5-13mm	3135	1.14	0.679
Syscl4	13-~27mm	10200	1.14	0.681

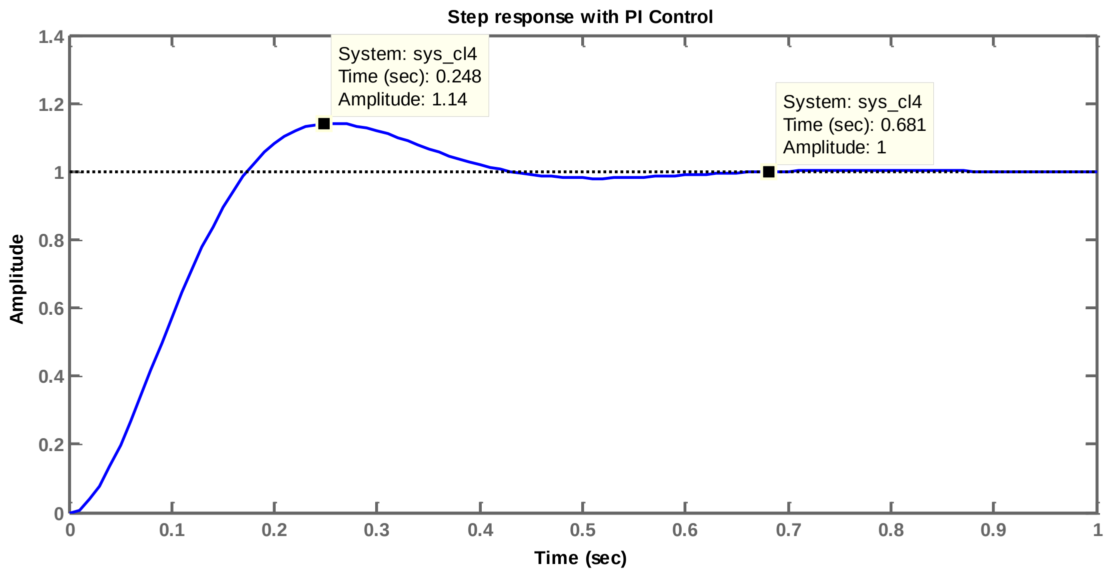


Figure 5 - 9 Step Response of Syscl4

The results of the step response from Table 10 show equal response for the system Syscl1 and Syscl4. This shows that choosing Syscl1 would be sufficient to cover both stroke ranges. Therefore the adopted models are Syscl1 for time segment 0-4mm and 13-27mm, Syscl2 for 4 -6.5mm and Syscl3 for 6.5-13mm. Further tuning the PI controller to reduce the overshoot in the step response leads to the PI gains of K =0.1, K_I =7270 for Syscl1, K =0.1, K_I =7115 for Syscl2 and K =0.1, K_I =7190 for Syscl3. The PLC software Think and Do program has the capability of monitoring event- changes hence the plant models are converted to discrete type models using MATLAB ‘c2d’ function.

Double T-Shape Plant Model for Time region 0-4mm and 13-27mm

The plant model transfer function named *sysGP1* is obtained

$$\text{sysGP1} = \frac{Y_p(s)}{U(s)} = \frac{910.4}{s\wedge 3 \ + \ 30.1\, s\wedge 2 \ + \ 8.79\text{e}4\, s \ + \ 1.331\text{e}6} \tag{5.24a}$$

The discrete plant model is:

$$\text{sysGPdis1} = \frac{4.493e\text{-}5\, z^3 \ + \ 1.348e\text{-}4\, z^2 + \ 1.348e\text{-}4\, z \ + \ 4.493e\text{-}5}{z^3 + 0.2467\, z^2 + 0.07137 z - 0.7926} \tag{5.24b}$$

This is further modified to difference equations to obtain:

$$\begin{aligned} y_{p_n} &= 4.493e\text{-}5\ u_n \ + 1.348e\text{-}4\ u_{n-1} \ + 1.348e\text{-}4\, u_{n-2} \ + 4.493e\text{-}5\, u_{n-3} \\ &\quad - 0.2467\, y_{p_{n-1}} \ - 0.07137\, y_{p_{n-2}} \ + 0.7926 y_{p_{n-3}} \end{aligned} \tag{5.24c}$$

The controller gains are: K (Pgain) =0.1 and T_I (reset time) = 2.29e-007. Figure 5-10 is the step response of Syscl1:

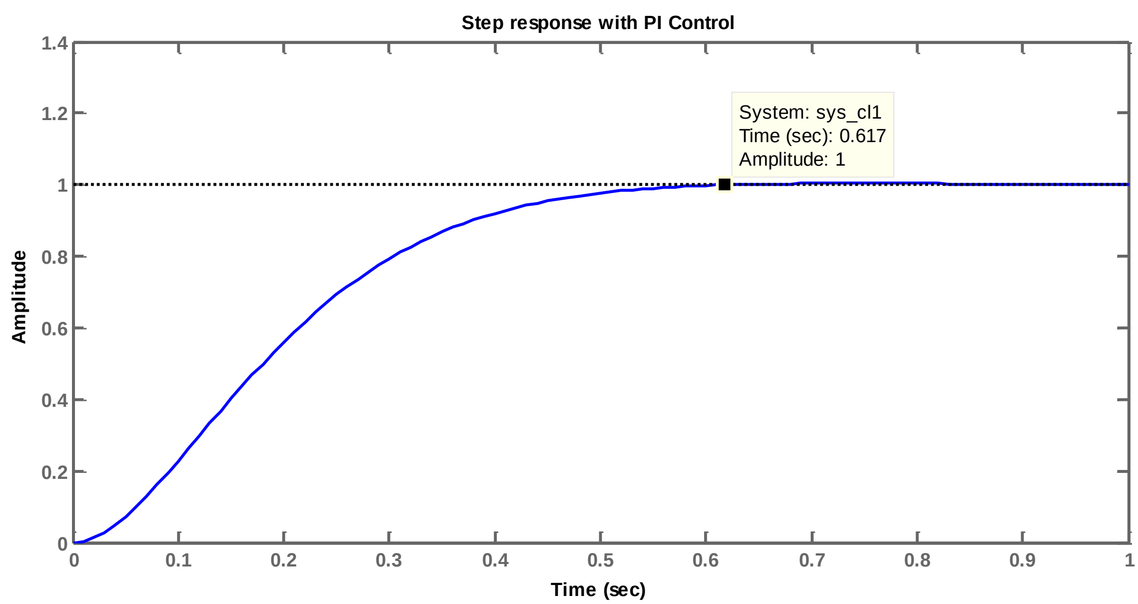


Figure 5 - 10 Step response for Double T-Shape (0-4mm, 13-27mm)

Double T- Shape Plant Model for Time region 4mm-6.5mm

The plant model transfer function named *sysGP2* is obtained

$$\text{sysGP1} = \frac{Y_p(s)}{U(s)} = \frac{910.4}{s\wedge 3 \ + \ 30.1\, s\wedge 2 \ + \ 8.716\text{e}4\, s \ + \ 1.309\text{e}6} \tag{5.25a}$$

The discrete plant model is:

$$\text{sysGPdis2} = \frac{4.525e\text{-}5\, z^3 \ + \ 1.357e\text{-}4\, z^2 + \ 1.357e\text{-}4\, z \ + \ 4.525e\text{-}5}{z^3 + 0.2393\, z^2 \ + 0.07443z \text{ - } 0.7933} \tag{5.25b}$$

This is further modified to difference equations to obtain:

$$\begin{aligned} y_{p_n} = {} & 4.525e\text{-}5\, u_n \ + \ 1.357e\text{-}4\ u_{n-1} \ + \ 1.357e\text{-}4\, u_{n-2} \ + \ 4.525e\text{-}5 u_{n-3} \\ & - \ 0.2393\ y_{p_{n-1}} \text{ - } 0.07443\, y_{p_{n-2}} + 0.7933 y_{p_{n-3}} \end{aligned} \tag{5.25c}$$

The controller gains are: K (Pgain) =0.1 and T_I (reset time) = 2.34e-007. Figure 5-11 is the step response of Syscl2

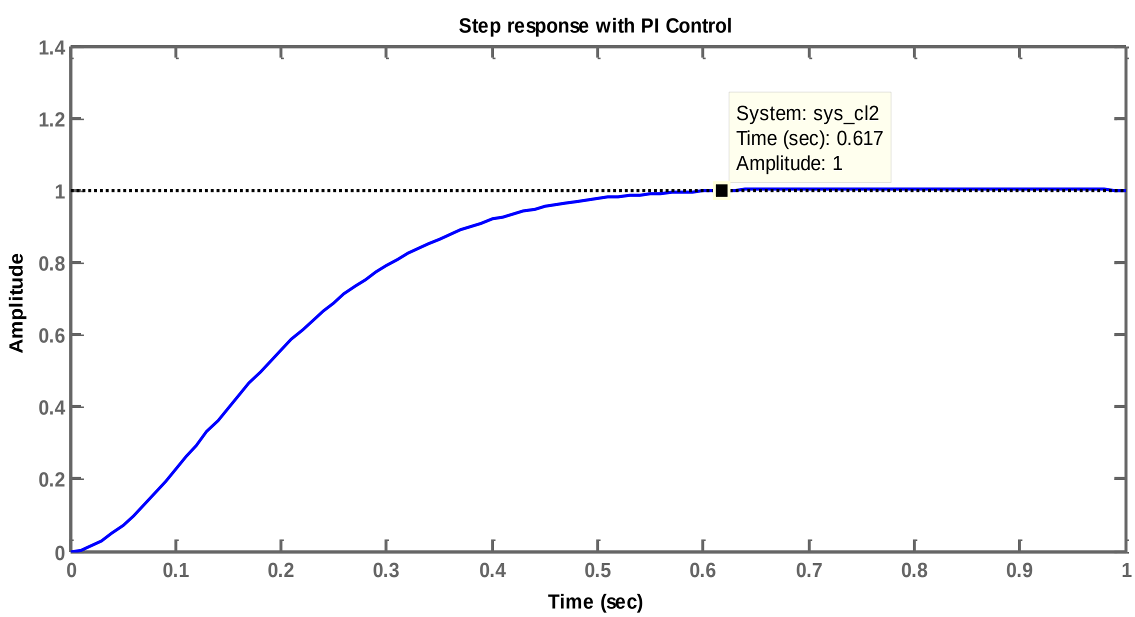


Figure 5 - 11 Step response for Double T-Shape (4-6.5mm)

Double T-Shape Plant Model for Time region 6.5-13mm

The plant model transfer function named *sysGP3* is obtained

$$\text{sysGP3} = \frac{Y_p(s)}{U(s)} = \frac{910.4}{s^3 + 30.1\,s^2 + 8.751e4\,s + 1.319e6} \tag{5.26a}$$

The discrete plant model is:

$$\text{sysGPdis3} = \frac{6.512e\text{-}5\,z^3 + 1.953e\text{-}4\,z^2 + 1.953e\text{-}4\,z + 6.512e\text{-}5}{z^3 + 0.6324\,z^2 - 0.1282\,z - 0.7493} \tag{5.26b}$$

This is further modified to difference equations to obtain:

$$\begin{aligned} y_{p_n} &= 6.512e\text{-}5\;u_n + 1.953e\text{-}4\;u_{n-1} + 1.953e\text{-}4\,u_{n-2} + 6.512e\text{-}5\,u_{n-3} \\ &\quad - 0.6324\,y_{p_{n-1}} + 0.1282\,y_{p_{n-2}} + 0.7493y_{p_{n-3}} \end{aligned} \tag{5.26c}$$

The controller gains are: K (Pgain) =0.1 and T_I (reset time) = 2.318e-007. Figure 5-12 is the step response of Syscl3:

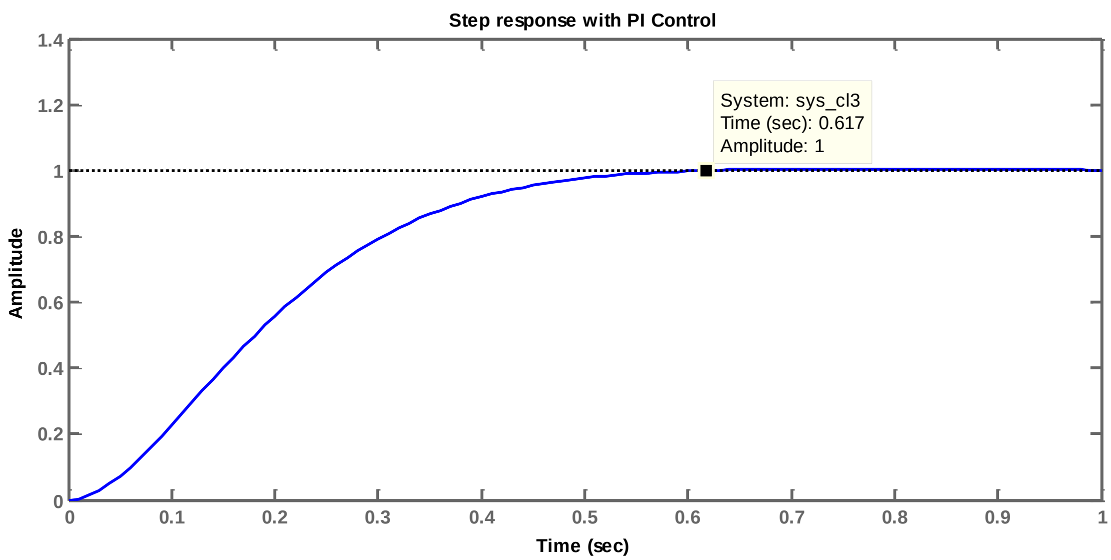


Figure 5 - 12 Step response for Double T-Shape (6.5-13mm)

Next section shows the simulation with Think ad Do Live.

5.6 SIMULATION WITH THINK AND DO PROGRAM

Think and Do is a process software that uses flowcharts methodology and in current research used for THF process. The PID block in Think and Do is used to perform controller actions by calculating the error and giving the output control signal. The reference point also referred to as the setpoint is the desired point obtained from the DBS method. The value from the displacement feedback also called process variable is the output from the plant monitored by the displacement sensor. The output value from the controller is directed to the plant. The Figure 5-14 shows the initial set up in the PID block for the setpoint, process variable and the output. The PI gain values of the controller are on the 'Tuning' tab of the PID block.

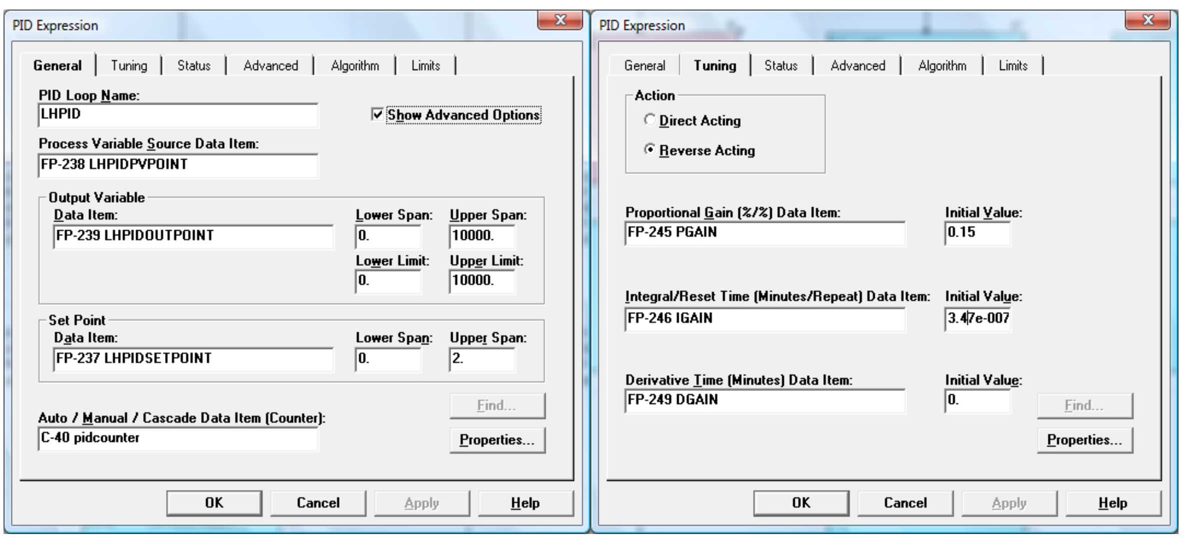


Figure 5 - 13 Sample PID General and Tuning Tab for Syscli2

Based on the difference equations of the plant model, the current generation position step is dependent on preceding generations of position and control output. The use of arrays in Think and Do will assist in capturing previous positions and controller outputs. The SHIFT function in Think and Do moves the array element of the 'current step' in the current scan to the 'previous step' for the next scan. The displacement and output arrays are made of 4 elements. The block diagram in Figure 5-15 below shows the position control with the PID controller.

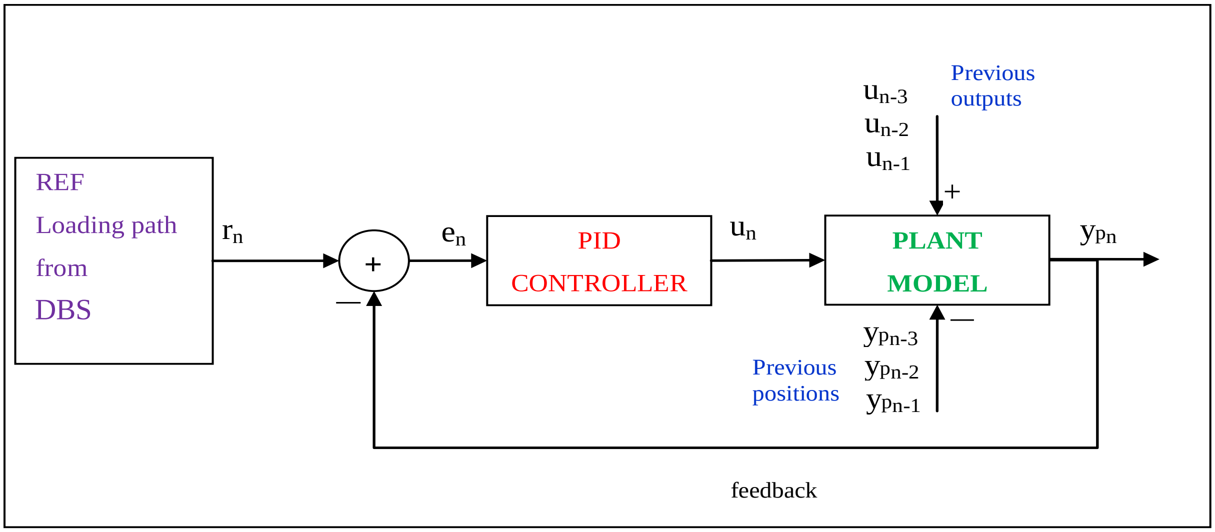


Figure 5 - 14 Block Diagram with Position in THF

Using arrays to store the data, the current output and position are moved to the first cell of the array. In the next scan the values in the cell are shifted to the next array cell, hence capturing 'n-1' data where 'n' represents the current scan. The sample flowcharts for the PID logic and plant are in Appendix C.2.

5.7 SIMULATION FOR THE DOUBLE T-SHAPE FAMILY

The diagram Figure 5-16 shows the experimental displacement of the cylinder based on the Database Back-Step method results for a Double T-Shape THF part obtained in section (4.6) with the lubricant as Teflon plus oil. The profile labeled 'DBS Method' is the anticipated material feed profile developed from the interpolation results of coefficient of friction from

Figure 4-24 (Teflon plus oil). This profile is part of the loading path providing guidelines to the press on the position of the cylinder. The profile labeled 'Cylinder Position' is the actual motion of the cylinder. The profiles are shown beginning from 13 s due to the response of the pressure booster. The cylinder position overshoots the DBS method which is causes the overshoot error discussed in section (5.1). The source of this error is proposed in this research as equipment related. The suggested corrective measure is the use of the Real-time Stroke controller developed in previous sections.

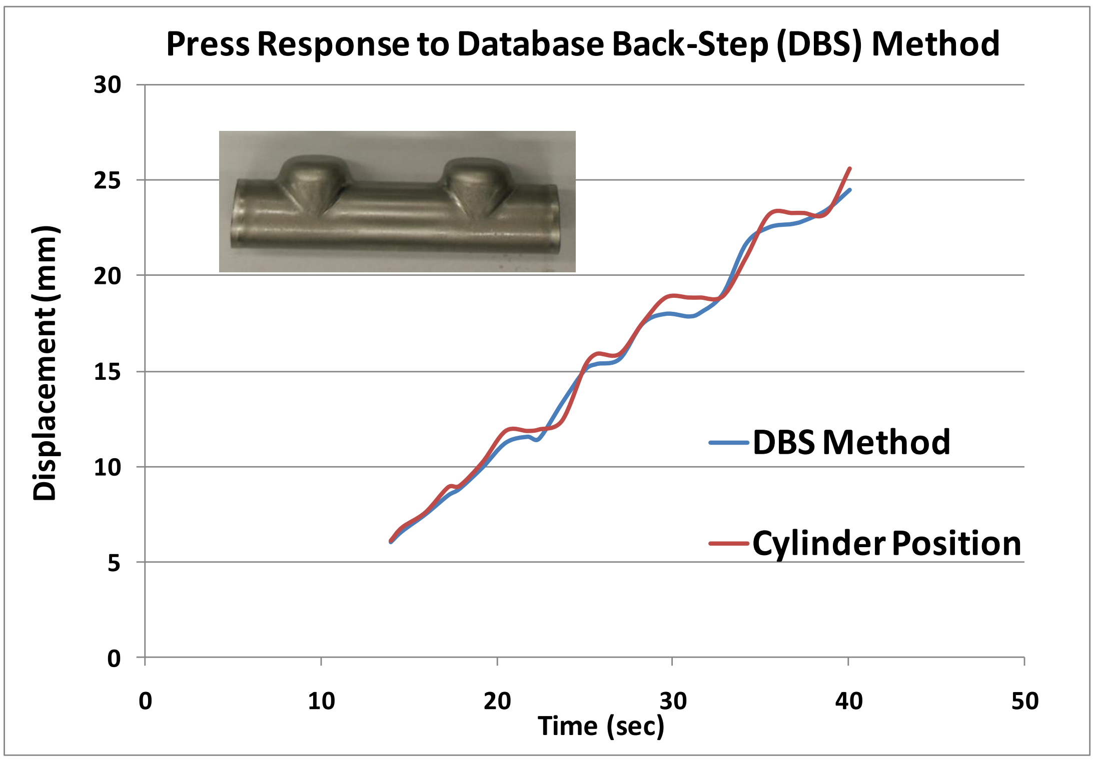


Figure 5 - 15 Results of Press Response to the Experimental DBS Method for Double T-Shape

In the Real Time Stroke controller Method the stroke from the Database Back-Step method is used as the reference (set point) for the controller loop. The output from the controller is sent to the plant model. The position obtained from the plant model is used to send instruction to the motors, i.e. speed of rotation. The feedback position of the cylinder is the process variable to be compared to the reference. The difference of the process variable and reference, is sent to the controller for corrective action. Figure 5-17 shows simulation results of the RTS method used with a simulated DBS reference. In this simulation the DBS loading path for the Double T-Shape (after friction compensation) is provided to the RTS controller, and the plant sends instruction to the press (without the forming setup). The position of the cylinder based on the sensor is monitored and the profile is shown in Figure 5-17 as 'RTS Cylinder position'. Possible reasons why the RTS Cylinder position profile is not equal to the DBS Method profile are such as i) the estimations of the stiffness matrix as discussed in section (5.3.2), ii) the plant model parameter values are based on manufacturer data thus not taking into account the current wear which lowers the efficiency and performance, and iii) need for further tuning of the PI controller

Figure 5-18 shows the response of the cylinder with the RTS method with DBS method obtained from experimental results. The 'DBS Method' profile is the same as the profile in Figure 5-16. The 'RTS Cylinder Position' profile is obtained by mapping from Figure 5-17. This is achieved by mapping the Simulated DBS profile in Figure 5-17 to the Experimental DBS Method in Figure 5-18. The difference between the Simulated and Experimental DBS method profiles is obtained and applied to the Simulated RTS Cylinder position in Figure 5-17. This results in the RTS profile in Figure 5-18.

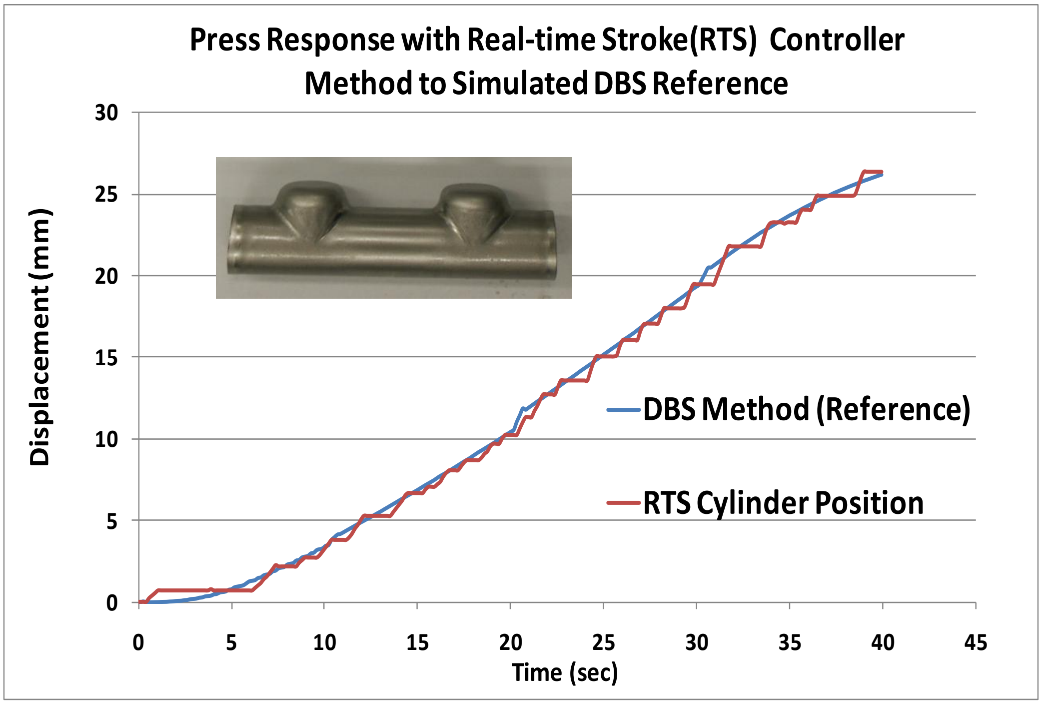


Figure 5 - 16 **Results for Double T-Shape with Simulated DBS Reference**

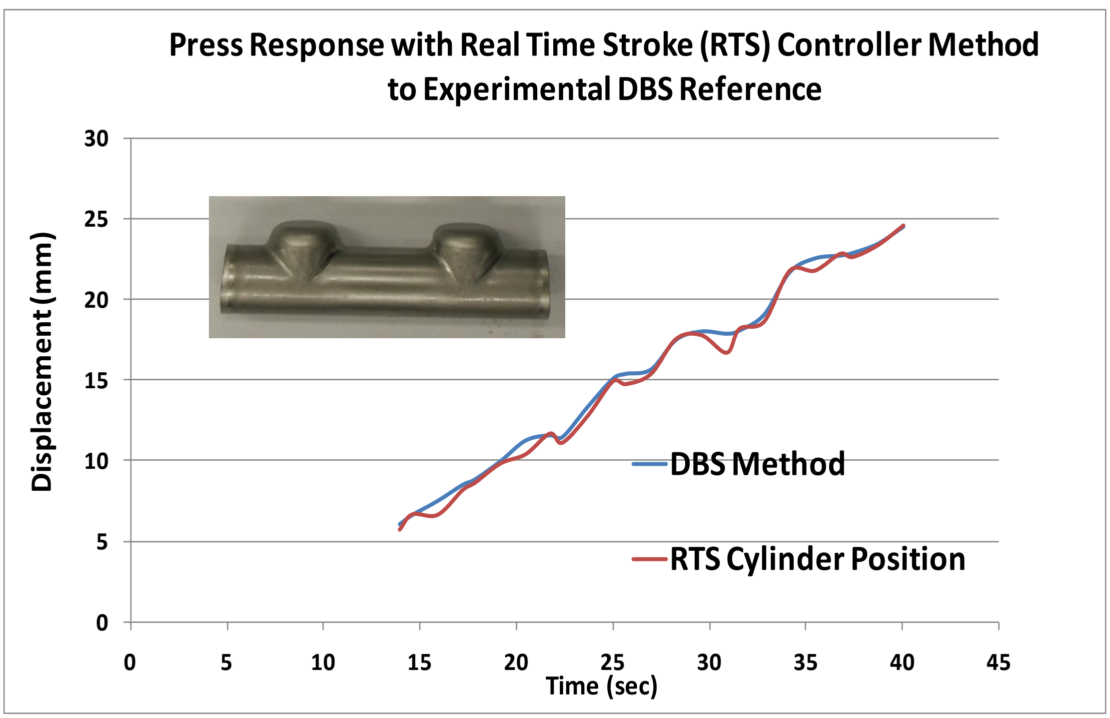


Figure 5 - 17 **Results for Double T-Shape with Experimental DBS Reference**

Comparing the RTS Cylinder position in Figure 5-17 to the actual cylinder position with Experimental DBS only, in Figure 5-16, shows much improvement in reducing the overshoot error. Moreover the error between the desired loading path and actual position is minimized. This shows that the hybrid of DBS and RTS method would produce better results though it must be noted that this is based on simulations. This improvement provides compensation for the equipment error. The advantage of the plant model is that it is applicable to any press for tube hydroforming so long as the values to the variables are available. Though RTS method requires finer tuning of the PI variables, the advantages of the hybrid (RTS with DBS) over the DBS only method are the ability to keep the cylinder position under the desired set point and provide close tracking of the loading path. This is desirable for situations where the only tolerance allowed is for values less than a desired value.

CONCLUDING REMARKS

Development of the RTS controller method to improve the Database Back-Step method has been obtained with results based on a simulation for a Double T-Shape THF family. The output of the system closely matches the desired material feed curve (from the DBS method), showing that the system model is sufficiently modeled.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

In this dissertation, the objectives were (i) to develop an interactive database scheme for generating loading paths with less computing time, (ii) to study the dominant errors in material feed and effects on the loading path, (iii) to study the application of database systems and potential for use in real time processes, (iv) to develop real-time error compensation method that addresses the dominant loading path errors, (v) to develop a system model for tube hydroforming process involving the equipment parameters that will be used to design a controller for closed loop control, (vi) to develop a closed loop system for improving the error compensation scheme with focus on position control. (vii) to conduct experiments to observe the performance of the error compensation scheme in process control.

The following are the contributions of this work and further suggestions:

1. Development of a real time interactive database. This database has the ability to provide loading paths in a timely manner reducing time in computation and prototyping. This database has the potential of providing loading paths in real time. This becomes crucial for use in process control. This has been achieved by focusing on two parts: i) the design of the pressure profile scheme. In this scheme, the maximum pressure during tube hydroforming is determined analytically and mapped to a polynomial function to obtain the pressure profile. ii) the design of the interpolation scheme. In this scheme a variable set comprising of variables representing the geometry, material properties and tribological forming conditions are gathered.

A query is done in the database to check if there is any match of the variables. Interpolation is done for closely matching variables in order to produce the material feed curve. The results from the interpolation scheme agreed well with finite element simulations. Only a minimal difference of less than 5 % was observed.

2. Design of a database error compensation method. In this method referred to as Database Back-Step method, errors during the real time tube hydroforming process are compensated by stepping back into a database for a better path profile. In this method the loading path provided to the press is continually being updated to compensate for errors. These errors are identified by comparing the feedback force of the cylinder piston to the desired range of forces. This comparison provides information by identifying the coefficient of friction available at the die-tube interface and acts as an indicator for the need for compensation. The database provides material feed profiles developed with coefficients of friction that closely match the coefficient of friction identified from the feedback force. Interpolation algorithms are applied to obtain a material feed curve that has a coefficient of friction equal to the one identified from the feedback force. This material feed is provided to the press in for the next position step. This method has shown experimentally that the coefficient of friction varies i.e. between 0.01 and 0.15. This variation demonstrates the importance of having a friction error compensation scheme in establishing accurate loading paths for THF.

3. Development of a Feedback loop to improve the error compensation scheme. This closed loop is developed with a tube hydroforming plant model and a controller. The reference set point for the feedback is the material feed curve obtained from the Database Back-Step method. The plant model is designed to involve the equipment functions and capture the interaction of the cylinder with the tube hydroforming environment. The controller designed is a PI controller. This method provides improvement to the error compensation by reducing the amounts of cylinder overshoot past the reference values.

For future research, the following are several suggested directions:

A. Develop the database scheme to provide loading paths for the X-Shape THF Family.

B. Optimize the hydroforming process compensating for errors associated with the internal pressure equipment.

C. Consider other controller designs such as gain scheduling and loop shape for the feedback system.

D. Review real-time communication systems between the loading path and the press such as alternatives to Data Dynamic Exchange (DDE).

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APPENDICES

APPENDIX A: SAMPLE MACRO CODES FOR DATABASE

APP A .1 MODULE FOR CREATING A TOOLBAR WITH LIST OF FAMILIES

This is the code that is used to generate the list of THF families and indicates if the family type is currently available in the database or not. The code add in creates a toolbar in Excel.

```
Module10 - 1

Sub CreateToolbar()
Dim cbar As CommandBar, cbctl As CommandBarControl

'This helps delete anything on the new toolbar
'On Error Resume Next
'Application.CommandBars("Worksheet Menu Bar").Controls("Custom").Delete
'On Error GoTo 0

' Delete if it exists
For Each cbar In Application.CommandBars
   If cbar.Name = "THF FAMILY" Then cbar.Delete
Next

' Create a floating toolbar
Set cbar = Application.CommandBars.Add(Name:="THF FAMILY", _
 Position:=msoBarFloating)
cbar.Visible = True

' Add a list box
Set cbctl = cbar.Controls.Add(Type:=msoControlDropdown)

' Add a tag so macro can find it
cbctl.Tag = "THF-FamilyList"
cbctl.Visible = True
cbctl.Caption = "ListCaption"

' Set list properties of the list box
With cbctl
    .AddItem "Double T-Shape", 1
    .AddItem "Single T-Shape", 2
    .AddItem "Double Y-Shape", 3
    .AddItem "Single Y-Shape", 4
    .AddItem "X-Shape", 5
    .AddItem "Bulge Shape", 6
    .DropDownLines = 0
    .DropDownWidth = 500
     'select nothing to start
    .ListIndex = 0
End With

' Set macro to execute when an item is selected
cbctl.OnAction = "HydroformListMacro"


End Sub

Sub HydroformListMacro()
   Dim cbctl As CommandBarControl
'    Find the list box control
 ' To enter the family name
    Sheets("Start").Select
    Range("K28").Select
    ActiveWorkbook.Names.Add Name:="FamilyType", RefersToR1C1:="='START'!R28C11"

   Set cbctl = CommandBars("THF FAMILY"). _
        FindControl(Tag:="THF-FamilyList")
   'If Not cbctl Is Nothing Then
  ' If cbctl.ListIndex = "1" Then
     ' MsgBox "You selected " & cbctl.List(cbctl.ListIndex)
```

Module10 - 2

```
If cbctl.ListIndex = "0" Then
MsgBox cbctl.List(cbctl.ListIndex) & " Choose a family"

ElseIf cbctl.ListIndex = "1" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = "Double T-Shape"
MsgBox cbctl.List(cbctl.ListIndex) & " is currently available"

Sheets("dde2load").Select
Application.WindowState = xlMinimized
Range("G2:AC102").Select
Selection.ClearContents

screenadjust

ElseIf cbctl.ListIndex = "2" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = "Single T-Shape"
MsgBox cbctl.List(cbctl.ListIndex) & " is not currently available"
CreateToolbar

ElseIf cbctl.ListIndex = "3" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = ""
MsgBox cbctl.List(cbctl.ListIndex) & " is not currently available"
CreateToolbar

ElseIf cbctl.ListIndex = "4" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = "Single Y-Shape"
MsgBox cbctl.List(cbctl.ListIndex) & " is currently available"


Sheets("dde2load").Select
Application.WindowState = xlMinimized
Range("G2:AC102").Select
Selection.ClearContents

screenadjust

ElseIf cbctl.ListIndex = "5" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = ""
MsgBox cbctl.List(cbctl.ListIndex) & " is not currently available"
CreateToolbar

ElseIf cbctl.ListIndex = "6" Then
Range("K28").Select
ActiveCell.FormulaR1C1 = "Bulge Shape"
MsgBox cbctl.List(cbctl.ListIndex) & " is currently available"

Sheets("dde2load").Select
Application.WindowState = xlMinimized
Range("G2:AC102").Select
Selection.ClearContents

screenadjust
End If
```

```
End Sub

Sub screenadjust()
'
' screenadjust Macro
'
'
    Sheets("START").Select
'    ActiveWindow.DisplayGridlines = False
'    ActiveWindow.DisplayHeadings = False
    Application.DisplayFullScreen = True
    Range("A1:V53").Select
    ActiveWindow.Zoom = True
    Range("A1").Select
    MsgBox " Press the START button to begin"
End Sub
```

APP A .2 MODULE FOR GATHERING VARIABLES FROM THE USER

This is a sample code showing how the variables are requested by the user and stored in the database. The variables in the code below are coefficient of friction, strength of material and strain hardening exponent.

```
Module1 - 1

Sub FirstStart()
'INPUT FRICTION COEFFICIENT
'input_mu()
' This will request for mu value

' Bulge interpolation

    Sheets("START").Select
    Range("G12").Select
    InputTitle = "muvalue"
    muvalue = InputBox("What is the muvalue input?", InputTitle, "0.01", 6000, 800)
    ActiveCell.FormulaR1C1 = muvalue

If ((Range("G12") <> Empty) And (Range("G12") <= 1)) Then
   ' Code that handles the user's input
   'Message if mu value has been entered and less than 1.
   MsgBox "Do you want to continue? "
   'Rename the cell containing the mu value
   Range("G12").Select
   ActiveWorkbook.Names.Add Name:="muvalue", RefersToR1C1:="='START'!R12C7"
  inputK
ElseIf (Range("G12") > 1) Then
  'Message if mu value has been entered and more than 1.
   MsgBox "Please input a value less than or equal to 1."
   FirstStart
Else
   'Message if mu value has been entered and want to cancel
    MsgBox "Do you want to cancel?"
End If


' Single Y interpolation

'Sheets("START").Select
    'Range("G12").Select
   ' InputTitle = "muvalue"
   ' muvalue = InputBox("What is the muvalue input?", InputTitle, "0.001", 6000, 800)
   ' ActiveCell.FormulaR1C1 = muvalue

'If ((Range("G12") <> Empty) And (Range("G12") <= 1)) Then
  ' ' Code that handles the user's input
   ''Message if mu value has been entered and less than 1.
  ' MsgBox "Do you want to continue? "
   'Rename the cell containing the mu value
  ' Range("G12").Select
  ' ActiveWorkbook.Names.Add Name:="muvalue", RefersToR1C1:="='START'!R12C7"
  'inputK
'ElseIf (Range("G12") > 1) Then
 ' 'Message if mu value has been entered and more than 1.
   'MsgBox "Please input a value less than or equal to 1."
  ' FirstStart
'Else
   'Message if mu value has been entered and want to cancel
   ' MsgBox "Do you want to cancel?"
'End If


End Sub

Sub inputK()
```

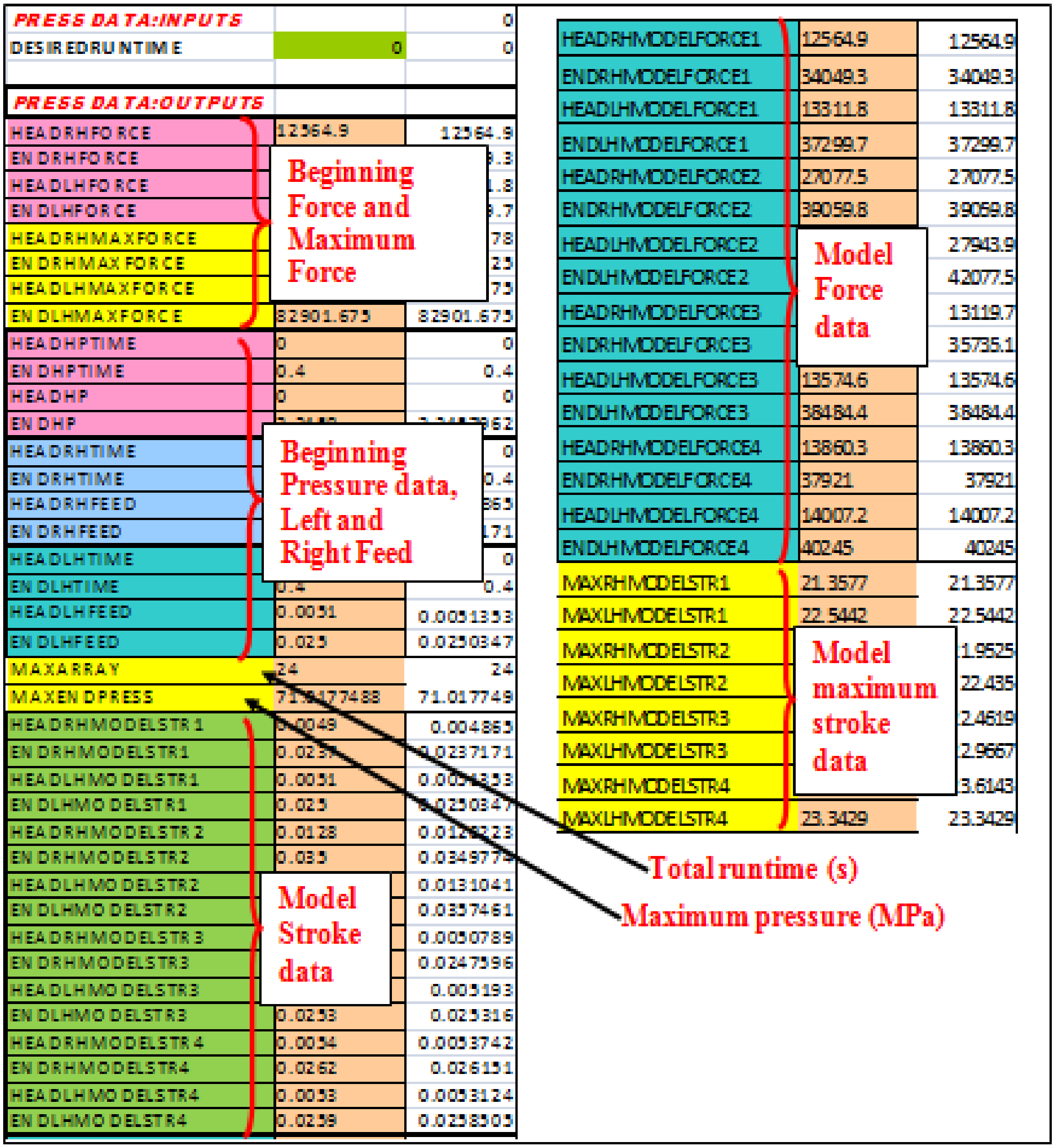
```
'INPUT STRENGTH OF MATERIAL,K
'This will request for K value
'
    Sheets("START").Select
      Range("G16").Select
    InputTitle = "Kvalue"
    Kvalue = InputBox("What is the Kvalue input?", InputTitle, "1426", 6000, 800)
  ActiveCell.FormulaR1C1 = Kvalue

If ((Range("G16") <> Empty) And (Range("G16") >= 500) And (Range("G16") <= 1500)) The
n
   'Code that handles the user's input Message if K value has been entered
  MsgBox "Do you want to continue? "
   'Rename the cell containing the Kvalue
   Range("G16").Select
   ActiveWorkbook.Names.Add Name:="Kvalue", RefersToR1C1:="='START'!R16C7"
  inputn

 ElseIf (Range("G16") <> Empty) And (Range("G16") < 500) And (Range("G16") > 1500) Th
en
  'Message if K value has been entered and more than 500.
   MsgBox "Please input a value between to 500 and 1500"
   inputK
   Else
   'Message if K value has been entered and want to cancel
    MsgBox "Do you want to cancel?"
   End If


End Sub


Sub inputn()
'INPUT STRAIN HARDENING CONSTANT
'This will request for n value

    'Single Y-Shape & T Shape
Sheets("START").Select
    Range("G18").Select
    InputTitle = "nvalue"
    nvalue = InputBox("What is the nvalue input?", InputTitle, "0.502", 6000, 800)
    ActiveCell.FormulaR1C1 = nvalue

If ((Range("G18") <> Empty) And (Range("G18") <= 0.6) And (Range("G18") > 0.4)) Then
   ' Code that handles the user's input
     MsgBox "Do you want to continue? "
   'Rename the cell containing the n value
   Range("G18").Select
   ActiveWorkbook.Names.Add Name:="nvalue", RefersToR1C1:="='START'!R18C7"
   input_Ltube

ElseIf (Range("G18") < 0.4) Then
  'Message if n value has been entered and less than 0.4.
   MsgBox "Please input a value greater than or equal to 0.4"
   inputn

Else
   'Message if n value has been entered and want to cancel.
    MsgBox "Do you want to cancel?"
End If

End Sub
```

APPENDIX B: DATABASE BACK-STEP METHOD

APP B .1 AUTOMATION IN TND LIVE

The database is involved in automation for the press by providing the loading path and data that is used for interpolation in Think and Do Live. To achieve real time control, the loading path from the database is provided to Think and Do Live during each scan. The "DesiredRuntime" which is the current process time from Think and Do Live is sent to the Excel database. Based on the "DesiredRuntime", various values are sent back to Think and Do via DDE link. The values sent from the database include the current and maximum values of loading path - pressure and material feed, force and stroke data at various coefficients of friction as shown in Figure A-1. The tables that contain data from the database, specified for the Single Y-Shape THF family are shown in Tables A-1 and A-2 showing the data of the left and right cylinder.

Figure A-1 shows the sets of data collected and sent to Think and Do Live. The beginning and maximum force and feed data, total runtime and maximum pressure are provided before the hydroforming process begins. This establishes the limit of the forming time and pressure to be finally developed. The model force data and model stroke data are provided during the hydroforming process and assist with obtaining the coefficient of friction of the force at the cylinder-tube interface and establishing the new stroke to be sent to the press.



PRESS DATA:INPUTS		0
DESIREDRUNTIME	0	0
PRESS DATA:OUTPUTS		
HEADRHFORCE	12564.9	12564.9
ENDRHFORCE	[illegible]	[illegible]
HEADLHFORCE	[illegible]	[illegible]
ENDLHFORCE	[illegible]	[illegible]
HEADRHMAXFORCE	[illegible]	[illegible]
ENDRHMAXFORCE	[illegible]	[illegible]
HEADLHMAXFORCE	[illegible]	[illegible]
ENDLHMAXFORCE	82901.675	82901.675
HEADHPTIME	0	0
ENDHPTIME	0.4	0.4
HEADHP	0	0
ENDHP	[illegible]	[illegible]
HEADRHTIME	[illegible]	0
ENDRHTIME	[illegible]	0.4
HEADRHFEED	[illegible]	[illegible]
ENDRHFEED	[illegible]	[illegible]
HEADLHTIME	[illegible]	0
ENDLHTIME	0.4	0.4
HEADLHFEED	0.0051	0.0051353
ENDLHFEED	0.025	0.0250347
MAXARRAY	24	24
MAXENDPRESS	71.0177488	71.017749
HEADRHMODELSTR1	0.0049	0.004865
ENDRHMODELSTR1	0.0237	0.0237171
HEADLHMODELSTR1	0.0051	0.0051353
ENDLHMODELSTR1	0.025	0.0250347
HEADRHMODELSTR2	0.0128	0.0128223
ENDRHMODELSTR2	0.035	0.0349774
HEADLHMODELSTR2	[illegible]	0.0131041
ENDLHMODELSTR2	[illegible]	0.0357461
HEADRHMODELSTR3	[illegible]	0.0050789
ENDRHMODELSTR3	[illegible]	0.0247596
HEADLHMODELSTR3	[illegible]	0.005193
ENDLHMODELSTR3	0.0253	0.025316
HEADRHMODELSTR4	0.0054	0.0053742
ENDRHMODELSTR4	0.0262	0.026151
HEADLHMODELSTR4	0.0053	0.0053124
ENDLHMODELSTR4	0.0259	0.0258505

HEADRHMODELFORCE1	12564.9	12564.9
ENDRHMODELFORCE1	34049.3	34049.3
HEADLHMODELFORCE1	13311.8	13311.8
ENDLHMODELFORCE1	37299.7	37299.7
HEADRHMODELFORCE2	27077.5	27077.5
ENDRHMODELFORCE2	39059.8	39069.8
HEADLHMODELFORCE2	[illegible]	27943.9
ENDLHMODELFORCE2	[illegible]	42077.5
HEADRHMODELFORCE3	[illegible]	13119.7
ENDRHMODELFORCE3	[illegible]	35735.1
HEADLHMODELFORCE3	13574.6	13574.6
ENDLHMODELFORCE3	38484.4	38484.4
HEADRHMODELFORCE4	13860.3	13860.3
ENDRHMODELFORCE4	37921	37921
HEADLHMODELFORCE4	14007.2	14007.2
ENDLHMODELFORCE4	40245	40245
MAXRHMODELSTR1	21.3577	21.3577
MAXLHMODELSTR1	22.5442	22.5442
MAXRHMODELSTR2	[illegible]	1.9525
MAXLHMODELSTR2	[illegible]	22.435
MAXRHMODELSTR3	[illegible]	2.4619
MAXLHMODELSTR3	[illegible]	2.9667
MAXRHMODELSTR4	[illegible]	3.6143
MAXLHMODELSTR4	23.3429	23.3429

Figure A - 1 Data involved in DDE Link from Database to Think and Do Live

Since the runtime from the press may not match the values in the database time column in Tables A-1 and A-2 by the name "Time", interpolation is done between the rows. Hence as shown in Figure A-1 the label "HEAD*" refers to the value in the same column closest and less than the runtime while the label "END*" refers to the value in the same column closest and more than the runtime i.e. “HEAD*”< runtime <“END*. Interpolation is done in Think and Do Live between “HEAD” and “END” to obtain force, stroke components at the desired runtime. The ‘Beginning’ stroke and force refer to the loading path established for the experiment before compensation has been done. Once compensation begins the beginning values will not be necessary. For Pressure data, compensation is not involving the interpolation scheme and hence the data will be supplied during the forming cycle.

The columns inside Tables A-1 and A-2 are described as follows:

“Time”: Column for the forming time

“P”, Hydroforming pressure

“F1”, “S1”: axial force and stroke with friction coefficient μ =0.01, which supplies to the labels ending with“…MODELFORCE1” and “…MODELSTR1” respectively

“F2”, “S2”: axial force and stroke with friction coefficient μ =0.05, which supplies to the labels ending with “…MODELFORCE2” and “…MODELSTR2” respectively

“F3”, “S3”: axial force and stroke with friction coefficient μ =0.1, which supplies to the labels ending with “…MODELFORCE3” and “…MODELSTR3” respectively

“F4”, “S4”: axial force and stroke with friction coefficient μ =0.2, which supplies to the labels ending with “…MODELFORCE4” and “…MODELSTR4” respectively

“F”: the axial force obtained as feedback from the press.

“μ”: the updated friction coefficient based on the axial force “F”.

The forces used in interpolation depend on the value of the actual forming force “F”. If “F1”< “F”< “F2” then “F1”and “F2” are used in the interpolation, if “F2”< “F”< “F3” then “F2”and “F3” are used in the interpolation and if “F3”< “F”< “F4” then “F3”and “F4” are used in the interpolation.

“S” is the adjusted stroke for the actual forming based on the value of the friction coefficient “μ” obtained from actual forming force. If “μ1”< “μ”< “μ2” then “S1”and “S2” are used in the interpolation, if “μ2”< “μ”< “μ3” then “S2”and “S3” are used in the interpolation and if “μ3”< “μ”< “μ4” then “S3”and “S4” are used in the interpolation.

The next section shows how the algorithms are carried out in Think and Do Live flowcharts.

APP B .2 FLOWCHARTS IN DATABASE BACK-STEP METHOD

Figure A-2 shows the calculation steps in Think and Do Live. Block 2 calculates the feedback force at the cylinder-tube interface. Blocks 1-4 and 8-11 calculate the model force and feed based on the forming time. Blocks 6-12 calculate the maximum acceptable force and feed during the cycle based on highest possible coefficient of friction, 0.4. A comparison of the force feedback and maximum force is done with Blocks 6-7 to check if the feedback is suitable to continue. If inappropriate then the process will stop.

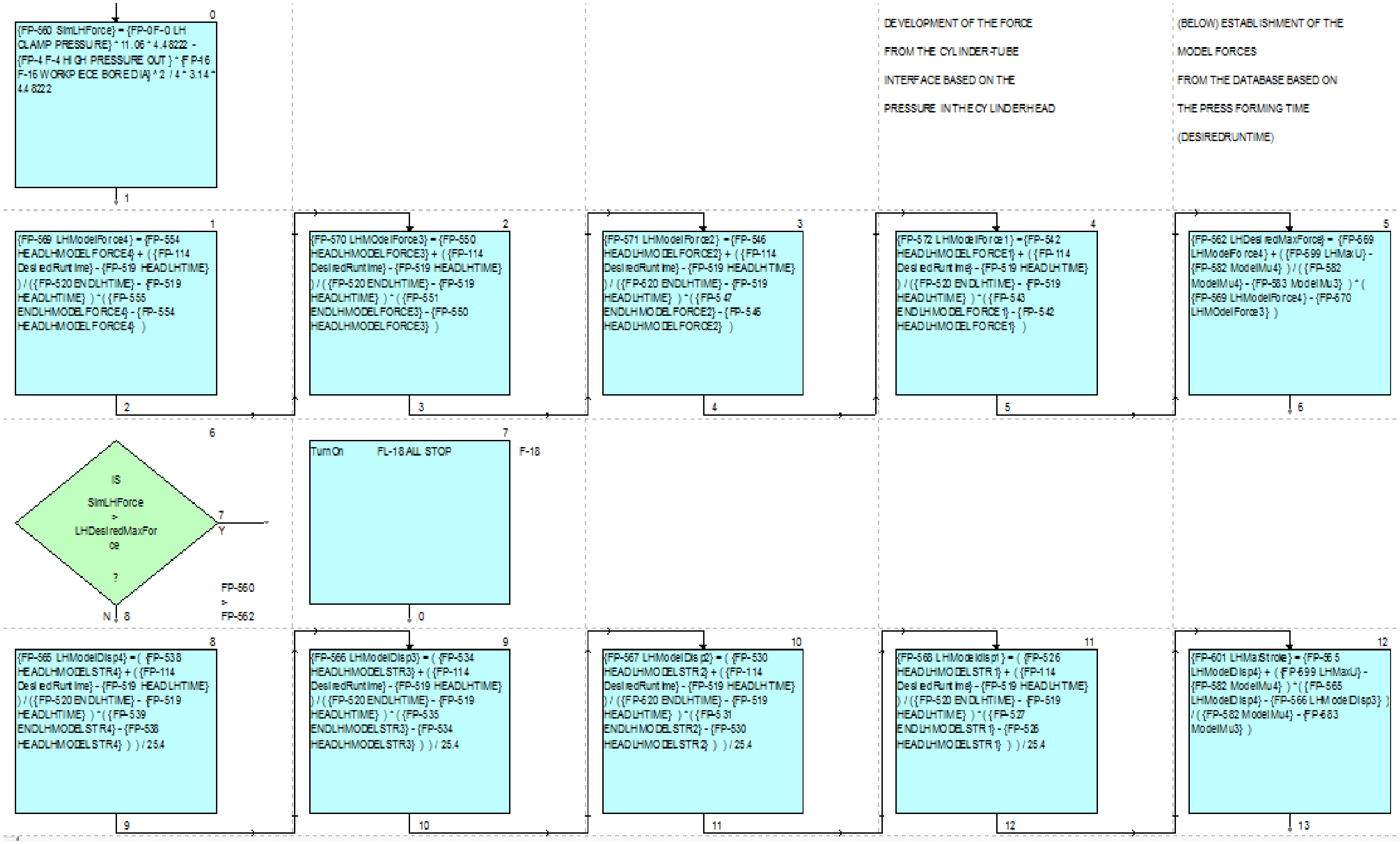


Figure A - 2 Calculations in Think and Do for Desired Force and Feed and Maximum Force and Feed

Figure A-3 shows the comparisons for the Feedback force to expected model values from the database which are also data used for interpolation to obtain the coefficient of friction. The updated friction coefficient is based on the axial force “F”.

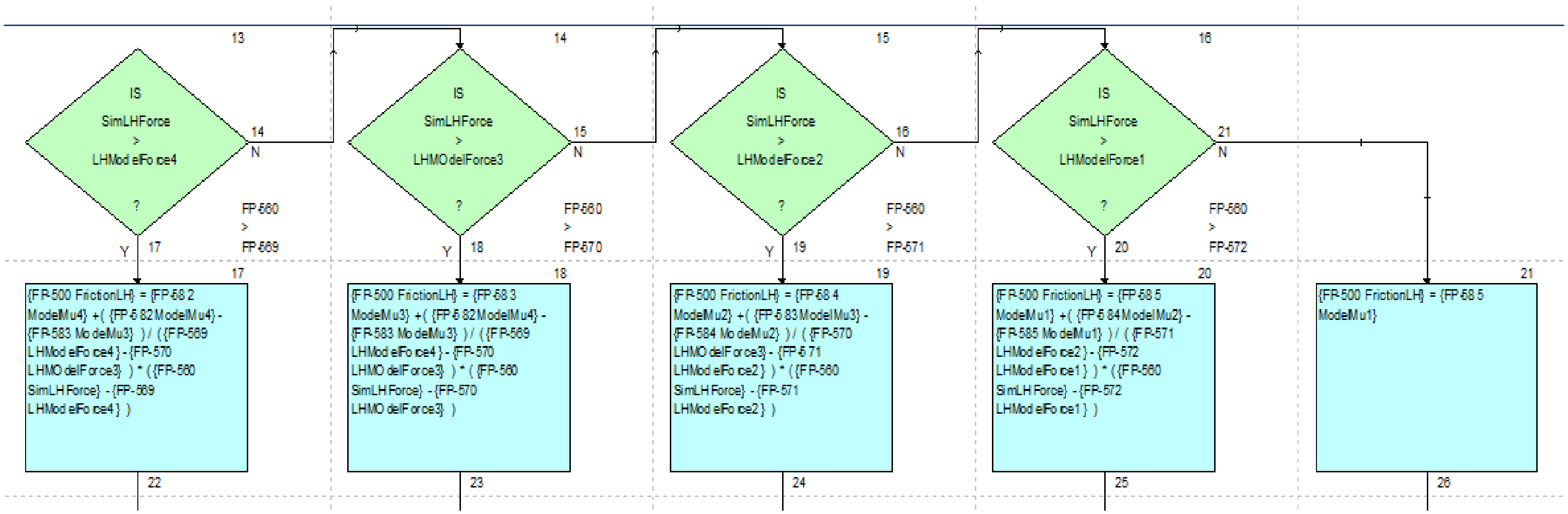


Figure A - 3 Calculations in Think and Do for Friction coefficient

Figure A-4 shows the final interpolation to obtain the new stroke position based on the friction coefficient “µ”. If “µ1”< “µ”< “µ2” then “S1”and “S2” are used in the interpolation, if “µ2”< “µ”< “µ3” then “S2”and “S3” are used in the interpolation and if “µ3”< “µ”< “µ4” then “S3”and “S4” are used in the interpolation.

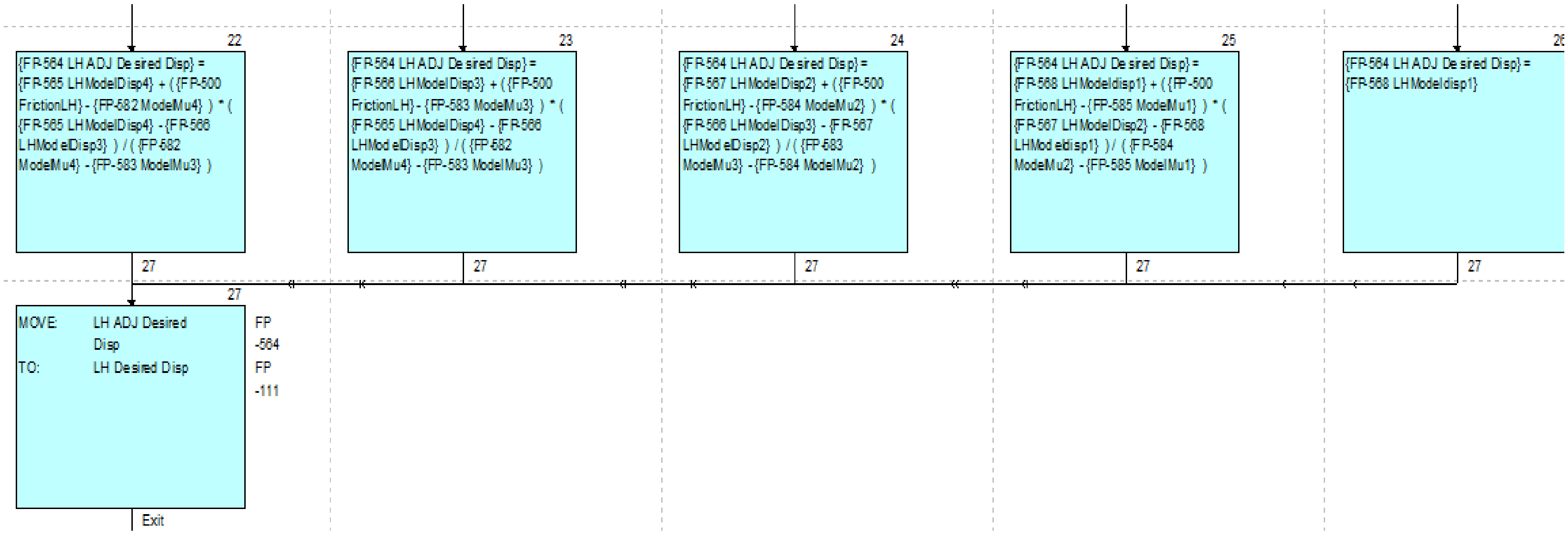


Figure A - 4 Calculations in Think and Do for new stroke based on corrected Friction coefficient

Tables A-1 and A-2 provide data from the database for a Single Y-Shape THF part. The force and feed data are shown based on the coefficient of friction. The actual forming data is obtained by simulating the force for varying coefficients of data and the stroke is obtained by using the algorithms in the flow charts with the simulated force.

Table A - 1 Loading Path of Left Cylinder of the Single Y-Shape THF

		FRICTION COEFFICIENTS										
		μ =0.01		**μ=0.05**		**μ =0.1**		**μ =0.2**		**Actual Forming**		
	Pressure	Force	Stroke	Force	Stroke	Force	Stroke	Force	Stroke	Force	FRICTION	STROKE
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
0	0	0	0	0	0	0	0	0	0	0	0.03	0
0.3	3.555519	10376.8	0.006414	16201.2	0.006684	14763.4	0.009055	20491.5	0.012397	13289	0.03	0.006549
0.6	7.024582	13538.18	0.02374	20737.7	0.024794	23995.08	0.033426	36610.1	0.045772	17137.94	0.03	0.024267
0.9	10.40719	17068.9	0.053183	25527.84	0.05521	34176.16	0.076626	45809.96	0.104417	21298.37	0.03	0.054197
1.2	13.71414	23456.84	0.093696	32744.9	0.099644	47891.76	0.133936	54437.76	0.179297	28100.87	0.03	0.09667
1.5	16.93465	28988.3	0.149121	37710.88	0.152246	50855.31	0.208553	61657.62	0.275941	33349.59	0.03	0.150684
1.8	20.0795	34941.84	0.209912	44223.38	0.217369	57071.31	0.292486	70057.06	0.400113	39582.61	0.03	0.213641
2.1	23.13789	38010.2	0.278926	51447.4	0.298068	64237.19	0.392162	76011.32	0.531845	44728.8	0.03	0.288497
2.4	26.10983	41304.24	0.363683	55841.56	0.384931	69538.62	0.503481	83314.82	0.68562	48572.9	0.03	0.374307
2.7	29.01693	45439.26	0.453746	61710.62	0.478837	74089.35	0.637786	85078.84	0.865149	53574.94	0.03	0.466292
3	31.84837	47219.92	0.56077	70560.64	0.581136	78456.35	0.773793	89171.3	1.04363	58890.28	0.03	0.570953
3.3	34.59336	48987.68	0.670763	75227.02	0.706951	79981.62	0.933453	96859.5	1.25775	62107.35	0.03	0.688857
3.6	37.27351	53993.2	0.797854	75209.24	0.829582	79796.99	1.09515	104724	1.46934	64601.22	0.03	0.813718
3.9	39.8672	56724.38	0.918422	74995.93	0.9657	79726.99	1.28199	118738	1.70362	65860.16	0.03	0.942061
4.2	42.40686	61404.6	1.06232	74993.24	1.10199	79717.77	1.46364	126269.4	1.95482	68198.92	0.03	1.082155
4.5	44.86006	69439.04	1.21661	74939.82	1.2618	80024.77	1.67553	130490.6	2.23149	72189.43	0.03	1.239205
4.8	47.24842	72966.68	1.36376	76890.9	1.41492	84409.52	1.87506	134813	2.49886	74928.79	0.03	1.38934
5.1	49.57193	75329.42	1.51803	79824.06	1.5957	90902.72	2.11027	139326.5	2.77398	77576.74	0.03	1.556865
5.4	51.8198	77468.9	1.69986	83493.18	1.76425	97070.22	2.32857	144142.2	3.09468	80481.04	0.03	1.732055
5.7	54.00282	79325.54	1.86865	86981.84	1.96227	102492.7	2.5841	148041.9	3.40956	83153.69	0.03	1.91546
6	56.121	81709.72	2.06637	90152.36	2.14554	107221	2.8197	150425.5	3.70661	85931.04	0.03	2.105955
6.3	58.17434	83885.62	2.24888	92949.7	2.35961	118596	3.094	151200.3	4.05231	88417.66	0.03	2.304245
6.6	60.16284	86185.32	2.46159	95436.26	2.55675	122252	3.34571	159638	4.41071	90810.79	0.03	2.50917
6.9	62.08649	88407.14	2.65708	96817.4	2.78604	125345	3.63737	159641.2	4.72933	92612.27	0.03	2.72156

Table A-1 (Continued)												
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
7.2	63.94531	90373.78	2.88403	99204.3	2.99632	128884	3.90381	154634.7	5.10015	94789.04	0.03	2.940175
7.5	65.75008	92226.2	3.09185	101836	3.2399	132172	4.21138	157359.3	5.47743	97031.1	0.03	3.165875
8.1	69.18673	95704.1	3.55188	106366	3.71986	139627	4.81381	153445.4	6.24123	119854.5	0.075	3.977035
8.4	70.80778	97418.36	3.80526	108572	3.95439	142515	5.14351	162826.6	6.62535	122996.5	0.075	4.266835
8.7	72.38561	99036.12	4.03608	110992	4.22471	146249	5.44259	162191.3	7.01648	125543.5	0.075	4.54895
9	73.8986	100650.2	4.30187	113185	4.47058	149397	5.78555	167464.4	7.41624	128620.5	0.075	4.83365
9.3	75.36836	102156.6	4.5434	115584	4.75334	152709	6.09589	173114.6	7.81471	131291	0.075	5.128065
9.6	76.77327	103657.6	4.821	117514	5.04241	155814	6.45096	172018.6	8.25974	134146.5	0.075	5.424615
9.9	78.13496	105226	5.07289	119853	5.30457	158917	6.81213	171189.9	8.66024	136664	0.075	5.746685
10.2	79.43181	106786.4	5.36184	121947	5.60528	161978	7.13808	171851.2	9.09081	139385	0.075	6.05835
10.5	80.69623	108314.2	5.65665	124501	5.87762	164926	7.5101	172637.7	9.53623	141962.5	0.075	6.37168
10.8	81.89582	109602.4	5.92356	126816	6.18954	167424	7.88756	174851.2	9.94771	144713.5	0.075	6.69386
11.1	83.06298	110734.8	6.22917	128765	6.50723	170040	8.27024	174602.6	10.4118	147120	0.075	7.03855
11.4	84.1761	111850	6.50553	130716	6.79443	173127	8.6147	183837.2	10.8225	149402.5	0.075	7.388735
11.7	85.246	112953.8	6.82163	132018	7.1228	176156	9.00695	188835.8	11.268	151921.5	0.075	7.704565
12	86.26186	114175.4	7.14312	134009	7.41932	178463	9.40408	189626.2	11.7271	154087	0.075	8.064875
12.3	87.2453	115388.4	7.43338	135627	7.75808	180959	9.80587	190962.8	12.1821	156236	0.075	8.4117
12.6	88.18552	115688.8	7.76498	137701	8.10221	183866	10.1668	203525.7	12.6272	158293	0.075	8.781975
12.9	89.0825	115967.1	8.06415	139603	8.41258	185613	10.577	207473.9	13.0653	160783.5	0.075	9.134505
13.2	89.93626	116226.6	8.40488	141655	8.76677	188909	10.9916	214937.3	13.5272	162608	0.075	9.49479
13.5	90.7576	116517.6	8.74814	143216	9.12626	191797.8	11.4039	216654.7	13.9975	165282	0.075	9.879185
13.8	91.5357	116956.6	9.05559	145212	9.45021	189896.8	11.8206	222823.8	14.4669	167506.9	0.075	10.26508
14.1	92.27058	117425.6	9.40411	145585.9	9.81819	189366.1	12.2529	215472.4	14.9278	167554.4	0.075	10.63541
14.4	92.98385	117594.9	9.75434	146125.7	10.1905	187360.6	12.6783	215236.7	15.4061	167476	0.075	11.03555
14.7	93.65388	118498.4	10.1062	146673.1	10.566	188450.6	13.0875	214074.6	15.8912	166743.1	0.075	11.4344
15	94.2915	119719.3	10.4597	147149.5	10.9255	186603.4	13.5498	214894.8	16.3487	167561.9	0.075	11.82675
15.3	94.89669	119162.8	10.8145	146281.1	11.2915	187734.3	13.9518	210947.9	16.806	199341.1	0.15	15.3789
15.6	95.46947	119398.3	11.201	147166.1	11.6679	187827.8	14.422	216965	17.2774	202396.4	0.15	15.8497

Table A-1 (Continued)												
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
15.9	96.00982	120048.8	11.5902	147851.7	12.0929	190728.2	14.8545	217488.3	17.7576	204108.2	0.15	16.30605
16.5	97.01488	119811.2	12.3441	149148.7	12.8622	194705.7	15.7716	223230.9	18.72	208968.3	0.15	17.2458
16.8	97.46877	121400.2	12.7013	149925.9	13.2922	194932.9	16.2061	227269.6	19.173	211101.2	0.15	17.68955
17.1	97.90105	121471.8	13.1035	150805	13.6809	194856.5	16.6811	224555.6	19.6563	209706	0.15	18.1687
17.4	98.31172	121475.8	13.5071	151630.3	14.1146	194488.8	17.1679	224681.6	20.1627	209585.2	0.15	18.6653
17.7	98.68997	121905.4	13.9123	152500.5	14.5058	194047.9	17.6074	223988.2	20.636	209018	0.15	19.1217
18	99.05741	122729.8	14.3191	153354	14.9416	194000.2	18.0934	223085.1	21.1356	208542.7	0.15	19.6145
18.3	99.39243	123499.6	14.7494	154214.1	15.379	198157.7	18.5958	221963.7	21.62	210060.7	0.15	20.1079
18.6	99.70583	124254.2	15.1493	154946.5	15.8184	201164.6	19.0613	223056	22.1063	212110.3	0.15	20.5838
18.9	100.0084	124819.6	15.596	155378.6	16.2598	202081.4	19.5602	223495.3	22.5951	212788.3	0.15	21.07765
19.2	100.2894	124881.8	16.0024	155535.1	16.702	203403.6	20.0631	223676.3	23.0848	213540	0.15	21.57395
19.5	100.5488	124502.1	16.45	155292.5	17.1884	203706	20.5737	227560.7	23.5948	215633.3	0.15	22.08425
19.8	100.7865	123909.4	16.8941	154631.7	17.6305	202599.6	21.1033	227121.2	24.0868	214860.4	0.15	22.59505
20.1	101.0243	123312.2	17.3307	153706.3	18.1156	201507.4	21.623	226974.9	24.5826	214241.1	0.15	23.1028
20.4	101.2404	122811.2	17.7954	152966.9	18.5499	201581.7	22.1459	226529	25.0812	214055.4	0.15	23.61355
20.7	101.435	122390.8	18.2472	152207.9	19.0151	201776.9	22.6327	228602.4	25.573	215189.7	0.15	24.10285
21	101.6295	121830.4	18.6859	151861.3	19.5033	201863.3	23.1695	228345.2	26.103	215104.2	0.15	24.63625
21.3	101.8024	121170	19.1117	150294.1	19.9341	201548.2	23.7402	232008	26.6075	216778.1	0.15	25.17385
21.6	101.9753	120891.7	19.5261	149610.4	20.3898	201018.1	24.2532	233936.7	27.1154	217477.4	0.15	25.6843
21.9	102.1374	121256	19.9618	149228.1	20.833	199742.5	24.7901	234049.9	27.6275	216896.2	0.15	26.2088
22.2	102.2887	120855.9	20.3787	149137.2	21.2635	200329.3	25.3189	233567.3	28.1657	216948.3	0.15	26.7423
22.5	102.4292	120887.4	20.8081	150696.9	21.6981	200805.4	25.829	233542.8	28.6829	217174.1	0.15	27.25595
23.1	102.6994	121572.8	21.6119	152448.5	22.5576	199643.2	26.8395	232542.6	29.7496	216092.9	0.15	28.29455
23.4	102.8399	121159.2	22.0306	154046.3	22.983	203214.2	27.3682	233142.2	30.2789	218178.2	0.15	28.82355
23.7	102.9588	121577.9	22.4117	154107.3	23.4052	202414.7	27.8448	233222.6	30.7588	217818.6	0.15	29.3018
24	103.0884	121853.9	22.821	154396.4	23.8091	202355.8	28.372	232802	31.2839	217578.9	0.15	29.82795
24.3	103.2181	121947.9	23.1963	154149.8	24.197	201715.8	28.852	232431.3	31.7799	217073.5	0.15	30.31595
24.6	103.3478	122070	23.5889	154034.2	24.6202	203510.2	29.3434	233663.8	32.2652	218587	0.15	30.8043

Table A-1 Continued

Time	P	F1	S1	F2	S2	F3	S3	F4	S4	F	μ	S
24.9	103.4775	133980	23.9715	153988.6	25.0034	201717.1	29.8372	233436.3	32.7419	217576.7	0.15	31.28955
25.2	103.6072	134277	24.343	154034.5	25.4024	201803.5	30.3001	233048.7	33.2355	217426.1	0.15	31.7678
25.5	103.7369	135317	24.7042	154032.6	25.7927	201263.5	30.7809	232590	33.704	216926.8	0.15	32.24245
25.8	103.8882	135996	25.0813	154047.6	26.172	201107.7	31.2792	231156.3	34.1713	216132	0.15	32.72525
26.1	104.0287	137256	25.4264	154103.1	26.5399	202357.1	31.7253	231930.8	34.6313	217144	0.15	33.1783
26.4	104.1799	138188	25.7856	154186.6	26.9201	202435.7	32.1964	232003.8	35.0763	217219.8	0.15	33.63635
26.7	104.3421	136700	26.136	154350.6	27.2883	203008.1	32.6558	231377.9	35.5128	217193	0.15	34.0843
27	104.515	136501	26.4995	154449.1	27.648	203294.3	33.105	232266.6	35.9567	217780.5	0.15	34.53085
27.3	104.6987	137542	26.8347	154546.1	27.9992	203933.1	33.5677	233378	36.3791	218655.6	0.15	34.9734
27.6	104.8932	138845	27.1627	154678.5	28.3619	204735.1	34.0161	232966.3	36.8135	218850.7	0.15	35.4148
27.9	105.0985	139783	27.4996	154861.2	28.6951	205825.9	34.4533	233290.7	37.2216	219558.3	0.15	35.83745
28.2	105.3255	140387	27.8273	155004.5	29.041	206962.1	34.9036	233993.4	37.649	220477.8	0.15	36.2763
28.5	105.5524	140682	28.1469	155265.8	29.3788	208212.5	35.3387	233893.4	38.0413	221053	0.15	36.69
28.8	105.8118	141694	28.4764	155457.9	29.7057	209225.7	35.7606	234342.3	38.441	221784	0.15	37.1008
29.1	106.0712	141836	28.7955	155602.8	30.0411	210091.7	36.1952	234349.3	38.8329	222220.5	0.15	37.51405
29.4	106.363	142676	29.1051	155700.4	30.3677	210529.7	36.6187	234384.7	39.2265	222457.2	0.15	37.9226
29.7	106.6656	143988	29.4067	155814.3	30.6866	210707.3	37.0301	234934.4	39.6041	222820.9	0.15	38.3171
30	106.9898	145115	29.6994	155814.3	30.9912	210707.3	37.4393	234934.4	39.9696	222820.9	0.15	38.70445

Figure A-5 shows the Axial load and feed for left hand side cylinder for Single Y- Shape. The dotted lines show the actual path.

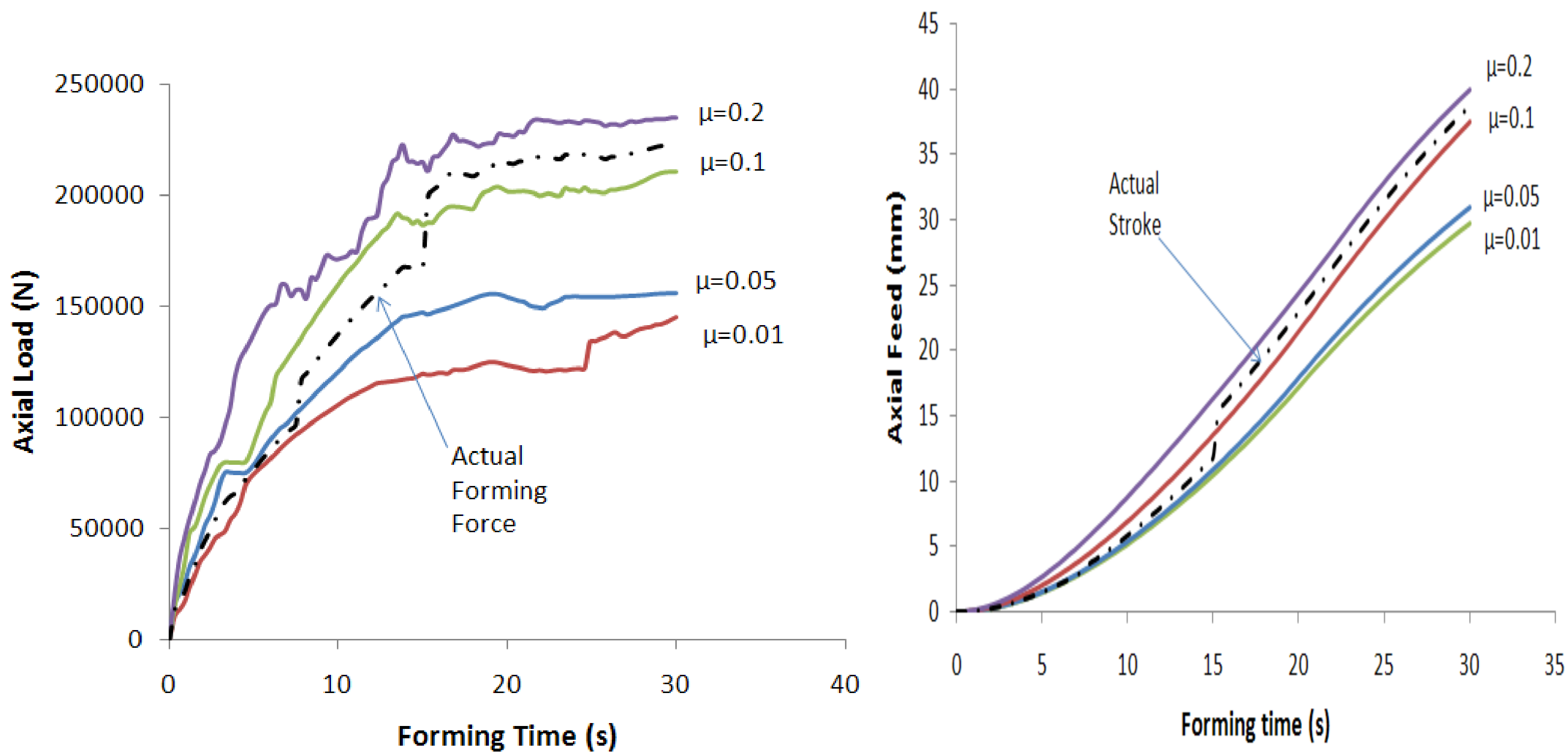


Figure A - 5 Axial Load and Feed for Single Y-Shape (Left Cylinder)

Table A - 2 Loading Path of Right Cylinder of the Y-Shape THF												
		μ =0.01		**μ =0.05**		**μ =0.1**		**μ =0.2**		**Actual Forming**		
	Pressure	Force	Stroke	Force	Stroke	Force	Stroke	Force	Stroke	Force	FRICTION	STROKE
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
0	0	0	0	0	0	0	0	0	0	0	0.03	0
0.3	3.555519	9052.42	0.005606	10171.5	0.006145	12198.7	0.007438	16118.5	0.009702	9611.96	0.03	0.005875
0.6	7.024582	21227	0.020728	21886.9	0.022736	25436.9	0.027504	31210.5	0.035885	21556.95	0.03	0.021732
0.9	10.40719	25652.9	0.046339	29854	0.05061	31863.8	0.063099	33917.4	0.081941	27753.45	0.03	0.048474
1.2	13.71414	34018	0.081538	36534.96	0.091353	43639.72	0.110261	43692.18	0.140715	35276.48	0.03	0.086445
1.5	16.93465	37616.2	0.129724	40758.68	0.139533	45961.82	0.171703	51212.9	0.216539	39187.44	0.03	0.134629
1.8	20.0795	40042.64	0.182566	41179.56	0.199219	48140.88	0.240841	59869.23	0.313975	40611.1	0.03	0.190893
2.1	23.13789	42525.22	0.24256	44644.48	0.273232	54373.34	0.322912	66296.93	0.41735	43584.85	0.03	0.257896
2.4	26.10983	45994.92	0.316259	50613.65	0.35287	59150.57	0.414558	73988.13	0.537979	48304.29	0.03	0.334565
2.7	29.01693	48123.86	0.394607	53558.65	0.438923	63312.44	0.525137	75595.58	0.678771	50841.26	0.03	0.416765
3	31.84837	50002.52	0.487707	57754.11	0.532709	68523.64	0.637105	79597.43	0.818757	53878.32	0.03	0.510208
3.3	34.59336	50112.94	0.583357	60046.87	0.648057	70435.53	0.768568	85853.8	0.986762	55079.91	0.03	0.615707
3.6	37.27351	50418.28	0.693919	60030.35	0.760435	70201.5	0.901751	89599.48	1.15279	55224.31	0.03	0.727177
3.9	39.8672	50618.76	0.798806	59730.57	0.885201	70104	1.05562	90114.28	1.33661	55174.67	0.03	0.842004
4.2	42.40686	52559.96	0.923921	59713.99	1.01013	70072.51	1.20523	102582.6	1.53373	56136.98	0.03	0.967026
4.5	44.86006	55276.98	1.05808	59633	1.1566	70061.7	1.37974	109853	1.75079	57454.99	0.03	1.10734
4.8	47.24842	57172.08	1.18605	61252.38	1.29695	72770.28	1.54407	117925	1.96061	59212.23	0.03	1.2415
5.1	49.57193	60623.12	1.32021	63859.42	1.46271	77206.28	1.7378	126198	2.17652	62241.27	0.03	1.39146
5.4	51.8198	63360.38	1.47831	67282.56	1.61729	88764.2	1.91757	134878	2.42815	65321.47	0.03	1.5478
5.7	54.00282	65264.26	1.62508	70564.84	1.79884	93650.8	2.12797	142050.2	2.6752	67914.55	0.03	1.71196
6	56.121	66834.16	1.79701	73568.6	1.96688	98881.8	2.32197	146169.2	2.90823	70201.38	0.03	1.881945
6.3	58.17434	68218.74	1.95573	84986.5	2.16318	104028	2.54783	146649.2	3.17944	76602.62	0.03	2.059455
6.6	60.16284	69577.32	2.14073	89006.6	2.34393	107456	2.75509	151550.8	3.46066	79291.96	0.03	2.24233
6.9	62.08649	78745.8	2.31077	91702.4	2.55412	110156	2.99525	151411	3.71066	85224.1	0.03	2.432445
7.2	63.94531	80229.8	2.50814	93993	2.74686	113097	3.2147	151016.1	4.00161	87111.4	0.03	2.6275
7.5	65.75008	81285.7	2.68885	96250.6	2.97017	115687	3.46801	152310.6	4.29767	88768.15	0.03	2.82951

Table A-2 (Continued)												
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
7.8	67.50083	83051.6	2.89796	98010.1	3.17428	118466	3.69863	152237.1	4.59554	105968.8	0.075	3.21909
8.1	69.18673	84617.2	3.0889	100258	3.4101	121344	3.96403	149574.8	4.89704	108238.1	0.075	3.436455
8.4	70.80778	86089.5	3.30927	101948	3.62511	123767	4.23552	155271.5	5.19843	110801	0.075	3.687065
8.7	72.38561	87463.9	3.50997	104094	3.87291	127031	4.48179	155184.9	5.50531	112857.5	0.075	3.930315
9	73.8986	88940.4	3.74107	106098	4.09828	130114	4.76418	158608.9	5.81895	115562.5	0.075	4.17735
9.3	75.36836	90277	3.95113	108653	4.35742	132854	5.01973	161594.2	6.13157	118106	0.075	4.43123
9.6	76.77327	91651.1	4.19251	110717	4.6224	135717	5.31213	161586.5	6.48069	120753.5	0.075	4.688575
9.9	78.13496	93511.8	4.41149	113041	4.86275	138117	5.60954	160874.9	6.79491	123217	0.075	4.967265
10.2	79.43181	94915.5	4.66277	114618	5.13842	141049	5.87797	161272.2	7.13276	125579	0.075	5.236145
10.5	80.69623	95429.4	4.91914	116480	5.38807	143885	6.18431	162115	7.48225	127833.5	0.075	5.508195
10.8	81.89582	96671.6	5.15122	118641	5.67402	146053	6.49514	163044.8	7.80508	130182.5	0.075	5.78619
11.1	83.06298	97937.1	5.41696	120239	5.96529	149172	6.81034	162766	8.16923	132347	0.075	6.08458
11.4	84.1761	98819	5.65725	122182	6.22855	151286	7.09401	168380.7	8.49146	134705.5	0.075	6.387815
11.7	85.246	99971.1	5.93208	123921	6.52956	152733	7.41698	172001	8.84096	136734	0.075	6.66128
12	86.26186	100523	6.21163	125731	6.80138	155309	7.74397	172470.3	9.2012	138327	0.075	6.97327
12.3	87.2453	100938	6.46403	126932	7.11192	158390	8.07484	174143.2	9.55815	140520	0.075	7.272675
12.6	88.18552	103072	6.7524	128328	7.42736	160796.5	8.37206	180732.4	9.90737	142661	0.075	7.59338
12.9	89.0825	103614	7.01257	130854	7.71185	162051.6	8.7099	183603.5	10.2511	144562.3	0.075	7.89971
13.2	89.93626	104285	7.30883	133161	8.0365	160785	9.0514	187065.8	10.6135	146452.8	0.075	8.210875
13.5	90.7576	105559	7.60731	134223	8.36599	165440.9	9.39091	186660.7	10.9826	146973	0.075	8.54395
13.8	91.5357	106243	7.87466	135596.9	8.66294	164998.6	9.73407	190864.2	11.3508	149831.9	0.075	8.87845
14.1	92.27058	108170	8.17766	135810.4	9.00029	164848.5	10.0901	190266.8	11.7124	150297.8	0.075	9.198505
14.4	92.98385	108259.6	8.4822	136191.6	9.34167	162727.9	10.4404	189983	12.0877	150329.4	0.075	9.545195
14.7	93.65388	109834.1	8.78815	137832.8	9.68579	164689.3	10.7774	189793	12.4682	149459.7	0.075	9.891035
15	94.2915	111270.7	9.09551	139402.8	10.0153	164195.6	11.1582	189791.6	12.8272	151261	0.075	10.2316
15.3	94.89669	110469.1	9.40406	137116.2	10.3509	165910.9	11.4892	189095.4	13.186	177503.2	0.15	12.3376
15.6	95.46947	110730.9	9.74016	140589.2	10.6959	166004.4	11.8764	197596.4	13.5559	181800.4	0.15	12.71615
15.9	96.00982	111574.5	10.0785	143004.6	11.0854	170229.4	12.2326	199553.8	13.9327	184891.6	0.15	13.08265

Table A-2 (Continued)												
Time	P	F1	S1	F2	S2	F3	S3	F4	S4	F	μ	S
16.2	96.52856	111471.1	10.3908	148373	11.4372	173300.4	12.5913	203063	14.2911	188181.7	0.15	13.4412
16.5	97.01488	111453.1	10.734	149697	11.7905	175685.9	12.9879	207771.5	14.6878	191728.7	0.15	13.83785
16.8	97.46877	113600.8	11.0445	151943	12.1847	176408.1	13.3458	212121.2	15.0432	194264.7	0.15	14.1945
17.1	97.90105	113606.1	11.3943	154537	12.5409	176612.7	13.737	211740.9	15.4224	194176.8	0.15	14.5797
17.4	98.31172	113822.8	11.7452	155956	12.9384	176285.3	14.138	211670.4	15.8197	193977.8	0.15	14.97885
17.7	98.68997	114531.3	12.0976	157654	13.297	175952.6	14.4999	211632.1	16.1911	193792.3	0.15	15.3455
18	99.05741	115511.2	12.4513	160060	13.6965	176237.5	14.9002	210957.4	16.5831	193597.5	0.15	15.74165
18.3	99.39243	116506.6	12.8255	162518	14.0974	182448.5	15.3139	210523.3	16.9632	196485.9	0.15	16.13855
18.6	99.70583	118349.4	13.1733	164354	14.5002	186809.5	15.6972	211388.9	17.3448	199099.2	0.15	16.521
18.9	100.0084	119346.1	13.5617	164609.8	14.9048	188129.2	16.1081	212395.1	17.7283	200262.1	0.15	16.9182
19.2	100.2894	119168.8	13.9151	164712.2	15.3102	190442.4	16.5222	213685	18.1125	202063.7	0.15	17.31735
19.5	100.5488	118563	14.3043	164705.5	15.756	190441.6	16.9428	221467.3	18.5128	205954.5	0.15	17.7278
19.8	100.7865	117800.5	14.6905	164545.5	16.1612	190143.8	17.3788	220961.8	18.8988	205552.8	0.15	18.1388
20.1	101.0243	116909.1	15.0702	164107.4	16.6058	189830	17.8068	222585.7	19.2879	206207.8	0.15	18.54735
20.4	101.2404	116490.4	15.4743	163780.4	17.0039	190009.8	18.2374	222262	19.6791	206135.9	0.15	18.95825
20.7	101.435	116004	15.8672	163498.5	17.4304	189925.5	18.6383	224716.9	20.065	207321.2	0.15	19.35165
21	101.6295	115529.2	16.2486	161427.4	17.8779	190617.3	19.0803	223277.9	20.4809	206947.6	0.15	19.7806
21.3	101.8024	114783	16.6189	160329.8	18.2728	190601.6	19.5503	231268.3	20.8768	210935	0.15	20.21355
21.6	101.9753	113996.5	16.9793	159949.4	18.6906	190520.6	19.9727	231993.1	21.2753	211256.9	0.15	20.624
21.9	102.1374	115194.1	17.3581	159090.3	19.0968	188894	20.4148	233423.7	21.677	211158.9	0.15	21.0459
22.2	102.2887	115121.1	17.7207	158985.5	19.4915	189656.2	20.8503	233113.4	22.0993	211384.8	0.15	21.4748
22.5	102.4292	115096.1	18.0941	160095.4	19.8899	190372.6	21.2704	233067.3	22.5052	211720	0.15	21.8878
23.1	102.6994	117060.2	18.793	161740.6	20.6777	191205.7	22.1025	234527.9	23.3421	212866.8	0.15	22.7223
23.4	102.8399	116154.2	19.1571	162799.2	21.0676	197331.4	22.5379	237828.7	23.7574	217580.1	0.15	23.14765
23.7	102.9588	116900	19.4885	163130.4	21.4547	197707.4	22.9304	239982.1	24.134	218844.8	0.15	23.5322
24	103.0884	117846.1	19.8444	163388.7	21.8249	198033.3	23.3645	240467.7	24.546	219250.5	0.15	23.95525
24.3	103.2181	118310	20.1707	163297.6	22.1805	197696.4	23.7598	238353	24.9351	218024.7	0.15	24.34745
24.6	103.3478	118985	20.5121	163231	22.5684	200764.1	24.1645	242723.1	25.3159	221743.6	0.15	24.7402

Table A-2 (Continued)												
Time	**P**	**F1**	**S1**	**F2**	**S2**	**F3**	**S3**	**F4**	**S4**	**F**	**μ**	**S**
24.9	103.4775	119719.1	20.8448	163289.7	22.9197	200444.8	24.5711	242464.8	25.6899	221454.8	0.15	25.1305
25.2	103.6072	120445.9	21.1679	163336.7	23.2854	200425.8	24.9523	243698.5	26.0772	222062.1	0.15	25.51475
25.5	103.7369	121183.8	21.4819	163444.9	23.6432	200541.9	25.3482	243157.5	26.4448	221849.7	0.15	25.8965
25.8	103.8882	122151.5	21.8098	163613.6	23.9909	201195.9	25.7585	242532.3	26.8115	221864.1	0.15	26.285
26.1	104.0287	122841.6	22.11	163787.2	24.3282	201651	26.1259	245970.1	27.1723	223810.5	0.15	26.6491
26.4	104.1799	123687.2	22.4223	163983.1	24.6766	201809.1	26.5138	246787.8	27.5215	224298.4	0.15	27.01765
26.7	104.3421	124709.3	22.727	164211.4	25.0142	202264.7	26.8922	245770.5	27.864	224017.6	0.15	27.3781
27	104.515	125677.2	23.0431	177632	25.3439	202919.9	27.2621	248738.8	28.2123	225829.3	0.15	27.7372
27.3	104.6987	142297	23.3346	178757	25.6658	203632.3	27.6431	251594.8	28.5437	227613.5	0.15	28.0934
27.6	104.8932	142429	23.6198	181573	25.9983	204559.6	28.0124	250335.4	28.8846	227447.5	0.15	28.4485
27.9	105.0985	144852	23.9127	182611	26.3037	205565.8	28.3724	251588.4	29.2048	228577.1	0.15	28.7886
28.2	105.3255	147585	24.1977	184257	26.6208	206795.5	28.7432	254509.8	29.5401	230652.6	0.15	29.14165
28.5	105.5524	149427	24.4756	186634	26.9304	208109.7	29.1014	254120.1	29.8479	231114.9	0.15	29.47465
28.8	105.8118	151978	24.7621	188260	27.2301	209188	29.4489	255135.2	30.1615	232161.6	0.15	29.8052
29.1	106.0712	154450	25.0397	190144	27.5376	210026	29.8068	255275.6	30.469	232650.8	0.15	30.1379
29.4	106.363	157147	25.3089	192731	27.837	210648.6	30.1555	254854.2	30.7778	232751.4	0.15	30.46665
29.7	106.6656	160108	25.5711	195455	28.1293	210971.3	30.4943	255839.9	31.0741	233405.6	0.15	30.7842
30	106.9898	163751	25.8256	200748	28.4085	210971.3	30.8312	255839.9	31.3608	233405.6	0.15	31.096

Figure A-6 shows the Axial load and feed for right hand side cylinder for Single Y-Shape. The dotted lines show the actual path.

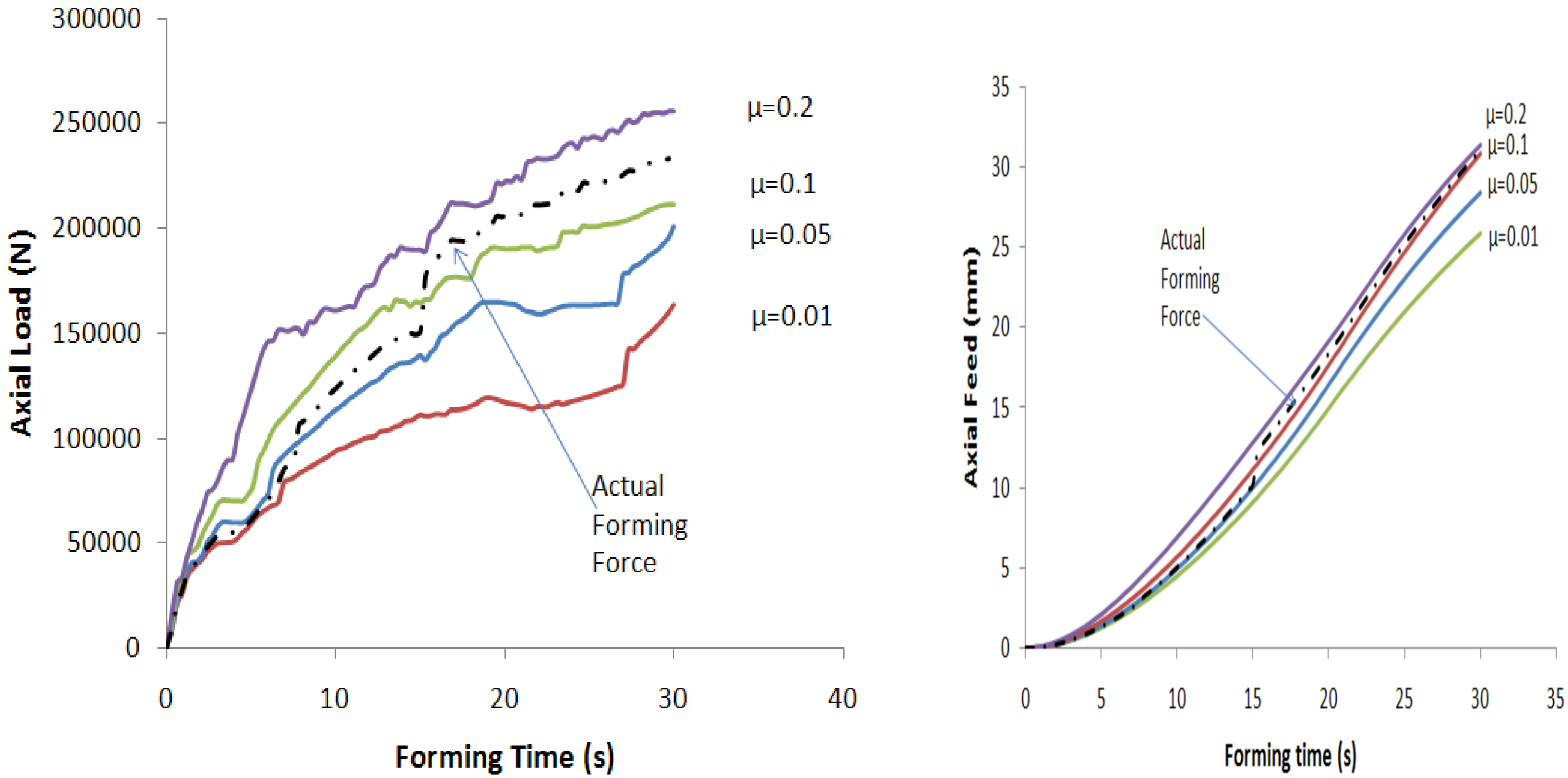


Figure A - 6 Axial Load and Feed for Single Y-Shape (Right Cylinder)

APP B .3 EXCEL MACRO FOR SENDING/RECEIVING DATA

```
Module8 - 1

Sub Auto_Open()
'---------------------------------------------------------------
 'This opens the macros once the Excel sheet is opened from TND
Sheets("dde2load").Select

Application.WindowState = xlMinimized

TND2VB

End Sub

Sub TND2VB()
'---------------------------------------------------------------'
'The following 2 lines help open the program without a user response

Dim mytnd2dde
mytnd2dde = Shell("C:\THINKNDO\BIN\TND2DDE.exe", 1)

If (mytnd2dde = Empty) Then

mytnd2dde = Shell("C:\THINKNDO\BIN\TND2DDE.exe", 1)

End If

Application.WindowState = xlMinimized

Namenames

End Sub

Sub Namenames()
'----------------------------------------------------------------------------
-
'Give some names

'Maxarray- The maximum runtime for the loading path
Range("B33").Select
    ActiveWorkbook.Names.Add Name:="maxarray", RefersToR1C1:="=dde2load!R33C2"

'DESIRED Runtime- Current Runtime from Think and Do
Range("B3").Select
    ActiveWorkbook.Names.Add Name:="DesiredRuntime", RefersToR1C1:="=dde2load!R3
C2"

DataRequest

End Sub

Sub DataRequest()
'---------------------------------------------------------------
' Begin Requests:
'REQUEST FOR THE DATA- DESIRED RUNTIME

DDE_channel = Application.DDEInitiate("tnd2dde", "data")
Worksheets("dde2load").Range("C3").Formula = "=tnd2dde|data!DesiredRuntime"

SendData
```

```
End Sub

Sub SendData()
'-------------------------------------------------------------------
'This is the macro that sends the values of the
'loading path from the database to Think & Do Live as input

'Establish Channel
DDE_channel = Application.DDEInitiate("tnd2dde", "data")

'SEND original Muvalue
Set muvalue = Worksheets("dde2load").Range("A5")
Set Munumber = Worksheets("dde2load").Range("B5")
Application.DDEPoke DDE_channel, muvalue, Munumber

'SEND VARIABLES OF  HEADRHFORCE
Set HEADRHFORCE = Worksheets("dde2load").Range("A13")
Set RHFORCEHEAD = Worksheets("dde2load").Range("B13")
Application.DDEPoke DDE_channel, HEADRHFORCE, RHFORCEHEAD

'SEND VARIABLES OF  ENDRHFORCE
Set ENDRHFORCE = Worksheets("dde2load").Range("A14")
Set RHFORCEEND = Worksheets("dde2load").Range("B14")
Application.DDEPoke DDE_channel, ENDRHFORCE, RHFORCEEND

'SEND VARIABLES OF  HEADLHFORCE
Set HEADLHFORCE = Worksheets("dde2load").Range("A15")
Set LHFORCEHEAD = Worksheets("dde2load").Range("B15")
Application.DDEPoke DDE_channel, HEADLHFORCE, LHFORCEHEAD

'SEND VARIABLES OF  ENDLHFORCE
Set ENDLHFORCE = Worksheets("dde2load").Range("A16")
Set LHFORCEEND = Worksheets("dde2load").Range("B16")
Application.DDEPoke DDE_channel, ENDLHFORCE, LHFORCEEND

'SEND VARIABLES OF MAX HEADRHFORCE
Set HEADRHMAXFORCE = Worksheets("dde2load").Range("A17")
Set RHMAXFORCEHEAD = Worksheets("dde2load").Range("B17")
Application.DDEPoke DDE_channel, HEADRHMAXFORCE, RHMAXFORCEHEAD

'SEND VARIABLES OF MAX ENDRHFORCE
Set ENDRHMAXFORCE = Worksheets("dde2load").Range("A18")
Set RHMAXFORCEEND = Worksheets("dde2load").Range("B18")
Application.DDEPoke DDE_channel, ENDRHMAXFORCE, RHMAXFORCEEND

'SEND VARIABLES OF MAX HEADLHFORCE
Set HEADLHMAXFORCE = Worksheets("dde2load").Range("A19")
Set LHMAXFORCEHEAD = Worksheets("dde2load").Range("B19")
Application.DDEPoke DDE_channel, HEADLHMAXFORCE, LHMAXFORCEHEAD

'SEND VARIABLES OF MAX ENDRHFORCE
Set ENDLHMAXFORCE = Worksheets("dde2load").Range("A20")
Set LHMAXFORCEEND = Worksheets("dde2load").Range("B20")
Application.DDEPoke DDE_channel, ENDLHMAXFORCE, LHMAXFORCEEND

'SEND VARIABLES OF HEADHPTIME
```

Module8 - 3

```
Set HEADHPTIME = Worksheets("dde2load").Range("A21")
Set headtimeHP = Worksheets("dde2load").Range("B21")
Application.DDEPoke DDE_channel, HEADHPTIME, headtimeHP

'SEND VARIABLES OF ENDHPTIME
Set ENDHPTIME = Worksheets("dde2load").Range("A22")
Set endtimeHP = Worksheets("dde2load").Range("B22")
Application.DDEPoke DDE_channel, ENDHPTIME, endtimeHP

'SEND VARIABLES OF HEADHP
Set HEADHP = Worksheets("dde2load").Range("A23")
Set HPhead = Worksheets("dde2load").Range("B23")
Application.DDEPoke DDE_channel, HEADHP, HPhead

'SEND VARIABLES OF ENDHP
Set ENDHP = Worksheets("dde2load").Range("A24")
Set HPend = Worksheets("dde2load").Range("B24")
Application.DDEPoke DDE_channel, ENDHP, HPend

'SEND VARIABLES OF HEADRHTIME
Set HEADRHTIME = Worksheets("dde2load").Range("A25")
Set headtimeRH = Worksheets("dde2load").Range("B25")
Application.DDEPoke DDE_channel, HEADRHTIME, headtimeRH

'SEND VARIABLES OF ENDRHTIME
Set ENDRHTIME = Worksheets("dde2load").Range("A26")
Set endtimeRH = Worksheets("dde2load").Range("B26")
Application.DDEPoke DDE_channel, ENDRHTIME, endtimeRH

'SEND VARIABLES OF HEADRHFEED
Set HEADRHFEED = Worksheets("dde2load").Range("A27")
Set RHheadfeed = Worksheets("dde2load").Range("B27")
Application.DDEPoke DDE_channel, HEADRHFEED, RHheadfeed

'SEND VARIABLES OF ENDRHFEED
Set ENDRHFEED = Worksheets("dde2load").Range("A28")
Set RHendfeed = Worksheets("dde2load").Range("B28")
Application.DDEPoke DDE_channel, ENDRHFEED, RHendfeed

'SEND VARIABLES OF HEADLHTIME
Set HEADLHTIME = Worksheets("dde2load").Range("A29")
Set headtimeLH = Worksheets("dde2load").Range("B29")
Application.DDEPoke DDE_channel, HEADLHTIME, headtimeLH

'SEND VARIABLES OF ENDLHTIME
Set ENDLHTIME = Worksheets("dde2load").Range("A30")
Set endtimeLH = Worksheets("dde2load").Range("B30")
Application.DDEPoke DDE_channel, ENDLHTIME, endtimeLH

'SEND VARIABLES OF HEADLHFEED
Set HEADLHFEED = Worksheets("dde2load").Range("A31")
Set LHheadfeed = Worksheets("dde2load").Range("B31")
Application.DDEPoke DDE_channel, HEADLHFEED, LHheadfeed

'SEND VARIABLES OF ENDLHFEED
Set ENDLHFEED = Worksheets("dde2load").Range("A32")
Set LHendfeed = Worksheets("dde2load").Range("B32")
```

```
Application.DDEPoke DDE_channel, ENDLHFEED, LHendfeed

'SEND MAXIMUM ARRAY NUMBER
Set maxarray = Worksheets("dde2load").Range("A33")
Set Maxarraynum = Worksheets("dde2load").Range("B33")
Application.DDEPoke DDE_channel, maxarray, Maxarraynum

'SEND MAXIMUM END PRESSURE
Set MAXENDPRESS = Worksheets("dde2load").Range("A34")
Set Maxpressure = Worksheets("dde2load").Range("B34")
Application.DDEPoke DDE_channel, MAXENDPRESS, Maxpressure

'SEND VARIABLES OF MODEL HEADRHFEED 1
Set HEADRHMODELSTR1 = Worksheets("dde2load").Range("A35")
Set RHMODELSTRHEAD1 = Worksheets("dde2load").Range("B35")
Application.DDEPoke DDE_channel, HEADRHMODELSTR1, RHMODELSTRHEAD1

'SEND VARIABLES OF MODEL ENDRHFEED 1
Set ENDRHMODELSTR1 = Worksheets("dde2load").Range("A36")
Set RHMODELSTREND1 = Worksheets("dde2load").Range("B36")
Application.DDEPoke DDE_channel, ENDRHMODELSTR1, RHMODELSTREND1

'SEND VARIABLES OF MODEL HEADLHFEED 1
Set HEADLHMODELSTR1 = Worksheets("dde2load").Range("A37")
Set LHMODELSTRHEAD1 = Worksheets("dde2load").Range("B37")
Application.DDEPoke DDE_channel, HEADLHMODELSTR1, LHMODELSTRHEAD1

'SEND VARIABLES OF MODEL ENDLHFEED 1
Set ENDLHMODELSTR1 = Worksheets("dde2load").Range("A38")
Set LHMODELSTREND1 = Worksheets("dde2load").Range("B38")
Application.DDEPoke DDE_channel, ENDLHMODELSTR1, LHMODELSTREND1

'SEND VARIABLES OF MODEL HEADRHFEED 2
Set HEADRHMODELSTR2 = Worksheets("dde2load").Range("A39")
Set RHMODELSTRHEAD2 = Worksheets("dde2load").Range("B39")
Application.DDEPoke DDE_channel, HEADRHMODELSTR2, RHMODELSTRHEAD2

'SEND VARIABLES OF MODEL ENDRHFEED 2
Set ENDRHMODELSTR2 = Worksheets("dde2load").Range("A40")
Set RHMODELSTREND2 = Worksheets("dde2load").Range("B40")
Application.DDEPoke DDE_channel, ENDRHMODELSTR2, RHMODELSTREND2

'SEND VARIABLES OF MODEL HEADLHFEED 2
Set HEADLHMODELSTR2 = Worksheets("dde2load").Range("A41")
Set LHMODELSTRHEAD2 = Worksheets("dde2load").Range("B41")
Application.DDEPoke DDE_channel, HEADLHMODELSTR2, LHMODELSTRHEAD2

'SEND VARIABLES OF MODEL ENDLHFEED 2
Set ENDLHMODELSTR2 = Worksheets("dde2load").Range("A42")
Set LHMODELSTREND2 = Worksheets("dde2load").Range("B42")
Application.DDEPoke DDE_channel, ENDLHMODELSTR2, LHMODELSTREND2

'SEND VARIABLES OF MODEL HEADRHFEED 3
Set HEADRHMODELSTR3 = Worksheets("dde2load").Range("A43")
Set RHMODELSTRHEAD3 = Worksheets("dde2load").Range("B43")
Application.DDEPoke DDE_channel, HEADRHMODELSTR3, RHMODELSTRHEAD3
```

```
Module8 - 5

'SEND VARIABLES OF MODEL ENDRHFEED 3
Set ENDRHMODELSTR3 = Worksheets("dde2load").Range("A44")
Set RHMODELSTREND3 = Worksheets("dde2load").Range("B44")
Application.DDEPoke DDE_channel, ENDRHMODELSTR3, RHMODELSTREND3

'SEND VARIABLES OF MODEL HEADLHFEED 3
Set HEADLHMODELSTR3 = Worksheets("dde2load").Range("A45")
Set LHMODELSTRHEAD3 = Worksheets("dde2load").Range("B45")
Application.DDEPoke DDE_channel, HEADLHMODELSTR3, LHMODELSTRHEAD3

'SEND VARIABLES OF MODEL ENDLHFEED 3
Set ENDLHMODELSTR3 = Worksheets("dde2load").Range("A46")
Set LHMODELSTREND3 = Worksheets("dde2load").Range("B46")
Application.DDEPoke DDE_channel, ENDLHMODELSTR3, LHMODELSTREND3

'SEND VARIABLES OF MODEL HEADRHFEED 4
Set HEADRHMODELSTR4 = Worksheets("dde2load").Range("A47")
Set RHMODELSTRHEAD4 = Worksheets("dde2load").Range("B47")
Application.DDEPoke DDE_channel, HEADRHMODELSTR4, RHMODELSTRHEAD4

'SEND VARIABLES OF MODEL ENDRHFEED 4
Set ENDRHMODELSTR4 = Worksheets("dde2load").Range("A48")
Set RHMODELSTREND4 = Worksheets("dde2load").Range("B48")
Application.DDEPoke DDE_channel, ENDRHMODELSTR4, RHMODELSTREND4

'SEND VARIABLES OF MODEL HEADLHFEED 4
Set HEADLHMODELSTR4 = Worksheets("dde2load").Range("A49")
Set LHMODELSTRHEAD4 = Worksheets("dde2load").Range("B49")
Application.DDEPoke DDE_channel, HEADLHMODELSTR4, LHMODELSTRHEAD4

'SEND VARIABLES OF MODEL ENDLHFEED 4
Set ENDLHMODELSTR4 = Worksheets("dde2load").Range("A50")
Set LHMODELSTREND4 = Worksheets("dde2load").Range("B50")
Application.DDEPoke DDE_channel, ENDLHMODELSTR4, LHMODELSTREND4

'SEND VARIABLES OF MODEL HEADRHFORCE 1
Set HEADRHMODELFORCE1 = Worksheets("dde2load").Range("A51")
Set RHMODELFORCEHEAD1 = Worksheets("dde2load").Range("B51")
Application.DDEPoke DDE_channel, HEADRHMODELFORCE1, RHMODELFORCEHEAD1

'SEND VARIABLES OF MODEL ENDRHFORCE 1
Set ENDRHMODELFORCE1 = Worksheets("dde2load").Range("A52")
Set RHMODELFORCEEND1 = Worksheets("dde2load").Range("B52")
Application.DDEPoke DDE_channel, ENDRHMODELFORCE1, RHMODELFORCEEND1

'SEND VARIABLES OF MODEL HEADLHFORCE 1
Set HEADLHMODELFORCE1 = Worksheets("dde2load").Range("A53")
Set LHMODELFORCEHEAD1 = Worksheets("dde2load").Range("B53")
Application.DDEPoke DDE_channel, HEADLHMODELFORCE1, LHMODELFORCEHEAD1

'SEND VARIABLES OF MODEL ENDLHFORCE 1
Set ENDLHMODELFORCE1 = Worksheets("dde2load").Range("A54")
Set LHMODELFORCEEND1 = Worksheets("dde2load").Range("B54")
Application.DDEPoke DDE_channel, ENDLHMODELFORCE1, LHMODELFORCEEND1

'SEND VARIABLES OF MODEL HEADRHFORCE 2
Set HEADRHMODELFORCE2 = Worksheets("dde2load").Range("A55")
```

```
Set RHMODELFORCEHEAD2 = Worksheets("dde2load").Range("B55")
Application.DDEPoke DDE_channel, HEADRHMODELFORCE2, RHMODELFORCEHEAD2

'SEND VARIABLES OF MODEL ENDRHFORCE 2
Set ENDRHMODELFORCE2 = Worksheets("dde2load").Range("A56")
Set RHMODELFORCEEND2 = Worksheets("dde2load").Range("B56")
Application.DDEPoke DDE_channel, ENDRHMODELFORCE2, RHMODELFORCEEND2

'SEND VARIABLES OF MODEL HEADLHFORCE 2
Set HEADLHMODELFORCE2 = Worksheets("dde2load").Range("A57")
Set LHMODELFORCEHEAD2 = Worksheets("dde2load").Range("B57")
Application.DDEPoke DDE_channel, HEADLHMODELFORCE2, LHMODELFORCEHEAD2

'SEND VARIABLES OF MODEL ENDLHFORCE 2
Set ENDLHMODELFORCE2 = Worksheets("dde2load").Range("A58")
Set LHMODELFORCEEND2 = Worksheets("dde2load").Range("B58")
Application.DDEPoke DDE_channel, ENDLHMODELFORCE2, LHMODELFORCEEND2

'SEND VARIABLES OF MODEL HEADRHFORCE 3
Set HEADRHMODELFORCE3 = Worksheets("dde2load").Range("A59")
Set RHMODELFORCEHEAD3 = Worksheets("dde2load").Range("B59")
Application.DDEPoke DDE_channel, HEADRHMODELFORCE3, RHMODELFORCEHEAD3

'SEND VARIABLES OF MODEL ENDRHFORCE 3
Set ENDRHMODELFORCE3 = Worksheets("dde2load").Range("A60")
Set RHMODELFORCEEND3 = Worksheets("dde2load").Range("B60")
Application.DDEPoke DDE_channel, ENDRHMODELFORCE3, RHMODELFORCEEND3

'SEND VARIABLES OF MODEL HEADLHFORCE 3
Set HEADLHMODELFORCE3 = Worksheets("dde2load").Range("A61")
Set LHMODELFORCEHEAD3 = Worksheets("dde2load").Range("B61")
Application.DDEPoke DDE_channel, HEADLHMODELFORCE3, LHMODELFORCEHEAD3

'SEND VARIABLES OF MODEL ENDLHFORCE 3
Set ENDLHMODELFORCE3 = Worksheets("dde2load").Range("A62")
Set LHMODELFORCEEND3 = Worksheets("dde2load").Range("B62")
Application.DDEPoke DDE_channel, ENDLHMODELFORCE3, LHMODELFORCEEND3

'SEND VARIABLES OF MODEL HEADRHFORCE 4
Set HEADRHMODELFORCE4 = Worksheets("dde2load").Range("A63")
Set RHMODELFORCEHEAD4 = Worksheets("dde2load").Range("B63")
Application.DDEPoke DDE_channel, HEADRHMODELFORCE4, RHMODELFORCEHEAD4

'SEND VARIABLES OF MODEL ENDRHFORCE 4
Set ENDRHMODELFORCE4 = Worksheets("dde2load").Range("A64")
Set RHMODELFORCEEND4 = Worksheets("dde2load").Range("B64")
Application.DDEPoke DDE_channel, ENDRHMODELFORCE4, RHMODELFORCEEND4

'SEND VARIABLES OF MODEL HEADLHFORCE 4
Set HEADLHMODELFORCE4 = Worksheets("dde2load").Range("A65")
Set LHMODELFORCEHEAD4 = Worksheets("dde2load").Range("B65")
Application.DDEPoke DDE_channel, HEADLHMODELFORCE4, LHMODELFORCEHEAD4

'SEND VARIABLES OF MODEL ENDLHFORCE 4
Set ENDLHMODELFORCE4 = Worksheets("dde2load").Range("A66")
Set LHMODELFORCEEND4 = Worksheets("dde2load").Range("B66")
Application.DDEPoke DDE_channel, ENDLHMODELFORCE4, LHMODELFORCEEND4
```

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```
'SEND VARIABLES OF SIMULATED END LH FORCE
Set ENDSIMLHFORCE = Worksheets("dde2load").Range("A76")
Set ELHSIMFORCE = Worksheets("dde2load").Range("B76")
Application.DDEPoke DDE_channel, ENDSIMLHFORCE, ELHSIMFORCE

'SEND VARIABLES OF SIMULATED END RH FORCE
Set ENDSIMRHFORCE = Worksheets("dde2load").Range("A77")
Set ERHSIMFORCE = Worksheets("dde2load").Range("B77")
Application.DDEPoke DDE_channel, ENDSIMRHFORCE, ERHSIMFORCE

'SEND VARIABLES OF SIMULATED HEAD LH FORCE
Set HEADSIMLHFORCE = Worksheets("dde2load").Range("A78")
Set HLHSIMFORCE = Worksheets("dde2load").Range("B78")
Application.DDEPoke DDE_channel, HEADSIMLHFORCE, HLHSIMFORCE

'SEND VARIABLES OF SIMULATED HEAD RH FORCE
Set HEADSIMRHFORCE = Worksheets("dde2load").Range("A79")
Set HRHSIMFORCE = Worksheets("dde2load").Range("B79")
Application.DDEPoke DDE_channel, HEADSIMRHFORCE, HRHSIMFORCE


UpdateData

End Sub

Sub UpdateData()
'This is the rule that will re-run the Macro beginning with 'SendData' subroutin
e
'when any change occurs to 'DesiredRuntime'

ActiveWorkbook.SetLinkOnData "tnd2dde|data!DesiredRuntime", "SendData"

End Sub
```

APPENDIX C: REAL-TIME STROKE CONTROLLER

APP C.1 MATLAB CODE FOR PLANT MODEL AND CONTROLLER

```
%%This is the data that is supplied from the cylinder and valve and other
%%properties required
%%-----------------------------------------------------------------
% Using parameters for the Press- SI UNITS
% CYLINDER PARAMETERS
m=20; % kg--mass of piston
A=7.619*10^3;  % mm^2-- EFFECTIVE push area (11.81.in^3)
V=2.286*10^5;  % mm^3-- Volume of oil in push stroke
C=2*10^3; % (mm^5/N.s)cylinder leakage coeff

% OTHER DATA
Cd=0.61; % discharge coefficient
Av=27.74; % mm^2--valve orifice area
rho=8.6*10^-7; % kg/mm^3-- density of hydraulic fluid
Ps= 68.95;% MPa==N/mm, supply pressure
Kq=(Cd*Av)/((2*rho*0.01*Ps)^0.5);

Beta= 1.72*10^3; % N/mm --bulk modulus (MPa)
Ck=1*10^4; %(mm^5/N.s)--Pump leakage coeff
D=6.814*10^2; % (mm^3/s rad)--Pump displacement
Ke1=11006; % Environment Stiffness time 0-4mm Double T-ShapeTHF
Ke2=-3786.1; % Environment Stiffness time 4-6.5mm Double T-ShapeTHF
Ke3=3135; % Environment Stiffness time 6.5mm-13mm Double T-ShapeTHF
Ke4=10200; % Environment Stiffness time 13mm-40mm Double T-ShapeTHF
npm=0.85; % Pump volumetric efficiency
K1=(2*Beta*A^2)/V; % MPa/mm Cylinder Stiffness

% Plant numerator
GGnum=2*D*A*Kq*Beta*(1-npm);

% Plant denominator1
GGden1=[Ck*m*V  2*Beta*Ck*C*m Ck*((V*(K1+Ke1))+(2*Beta*A^2)) 2*Beta*Ck*C*(K1+Ke1)];

% Plant denominator2
GGden2=[Ck*m*V  2*Beta*Ck*C*m Ck*((V*(K1+Ke2))+(2*Beta*A^2)) 2*Beta*Ck*C*(K1+Ke2)];

% Plant denominator3
GGden3=[Ck*m*V  2*Beta*Ck*C*m Ck*((V*(K1+Ke3))+(2*Beta*A^2)) 2*Beta*Ck*C*(K1+Ke3)];

%Plant denominator4
GGden4=[Ck*m*V  2*Beta*Ck*C*m Ck*((V*(K1+Ke4))+(2*Beta*A^2)) 2*Beta*Ck*C*(K1+Ke4)];
```

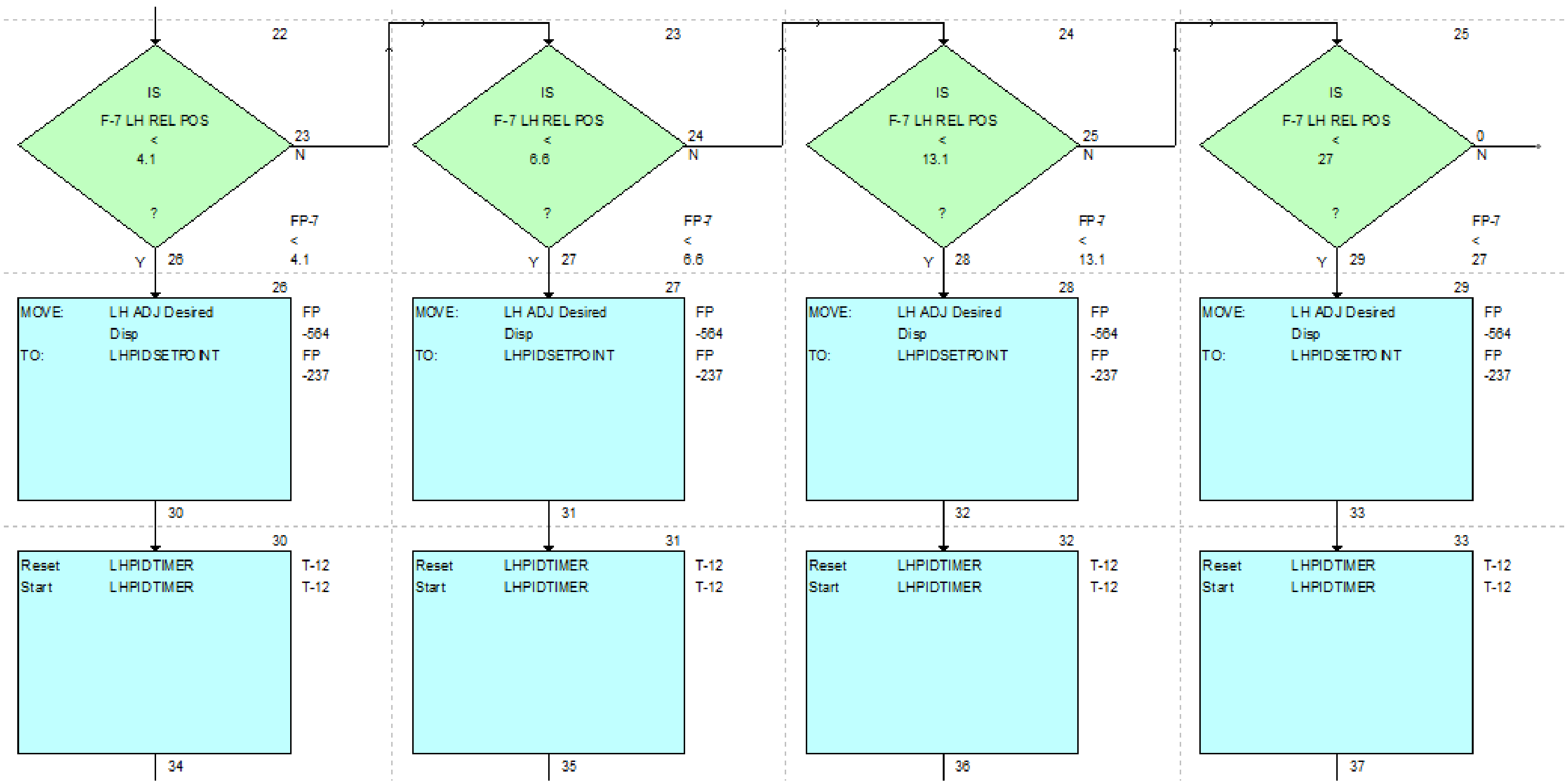
```
%==========================================================================
% Transfer function 1
sysGP1=tf(GGnum,GGden1);
sysGPmin1=minreal(tf(GGnum,GGden1));
Ts = 1/80;

% Discrete transfer function 1
sysGPdis1=c2d(sysGPmin1,Ts,'tustin');

% Transfer function 2
sysGP2=tf(GGnum,GGden2);
sysGPmin2=minreal(tf(GGnum,GGden2));
Ts = 1/80;

% Discrete transfer function 2
sysGPdis2=c2d(sysGPmin2,Ts,'tustin');

% Transfer function 3
sysGP3=tf(GGnum,GGden3);
sysGPmin3=minreal(tf(GGnum,GGden3));
Ts = 1/60;

% Discrete transfer function 3
sysGPdis3=c2d(sysGPmin3,Ts,'tustin');

% Transfer function 4
sysGP4=tf(GGnum,GGden4);
sysGPmin4=minreal(tf(GGnum,GGden4));
Ts = 1/60;

% Discrete transfer function 4
sysGPdis4=c2d(sysGPmin4,Ts,'tustin');

% ====================================================================
%
```

```
% ===============================================================
%
% PID CONTROLLER

Kp1=0.1;
Kp2=0.1;
Kp3=0.1;
Kp4=10;
Kd1=0;
Kd2=0;
Kd3=0;
Kd4=0;
Ki1=7270;
Ki2=7115;
Ki3=7190;
Ki4=20000;


Ti1=Kp1/(60*Ki1)
Ti2=Kp2/(60*Ki2)
Ti3=Kp3/(60*Ki3)
Ti4=Kp4/(60*Ki4)
%
%
% %PID 1 control
Gc_PID1=tf([Kd1 Kp1 Ki1],[1 0]);
Gc_PIDz1=c2d(Gc_PID1,Ts,'tustin');

sys_cl1=feedback(Gc_PID1*sysGP1,1);
sys_clmin1=feedback(Gc_PID1*sysGPmin1,1);
t=0:0.01:1;
figure(1)
step(sys_cl1,t)
%ltiview(sys_cl)
title('Step response with PID Control')
%
%PID 2 control
Gc_PID2=tf([Kd2 Kp2 Ki2],[1 0]);
sys_cl2=feedback(Gc_PID2*sysGP2,1);
sys_clmin2=feedback(Gc_PID2*sysGPmin2,1);
t=0:0.01:1;
figure(2)
step(sys_cl2,t)
%ltiview(sys_cl)
title('Step response with PID Control')
%
```

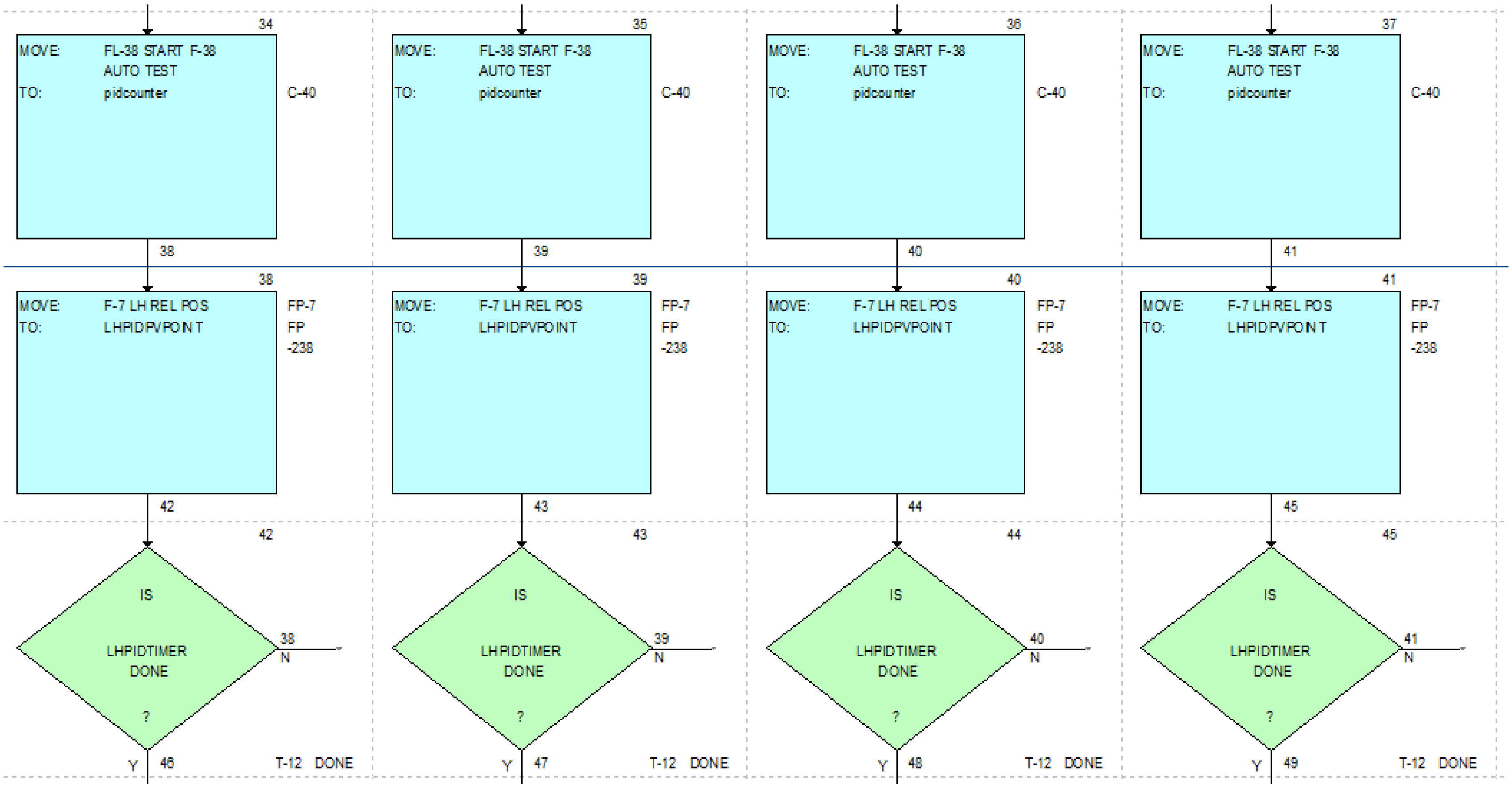
```
%PID 3 control
Gc_PID3=tf([Kd3 Kp3 Ki3],[1 0]);
sys_cl3=feedback(Gc_PID3*sysGP3,1);
sys_clmin3=feedback(Gc_PID3*sysGPmin3,1);
t=0:0.01:1;
figure(3)
step(sys_cl3,t)
%ltiview(sys_cl)
title('Step response with PID Control')
%
%PID 4 control
Gc_PID4=tf([Kd4 Kp4 Ki4],[1 0]);
sys_cl4=feedback(Gc_PID4*sysGP4,1);
sys_clmin4=feedback(Gc_PID4*sysGPmin4,1);
t=0:0.01:1;
figure(4)
step(sys_cl4,t)
%ltiview(sys_cl)
title('Step response with PID Control')
%
```

APP C.2 FLOWCHART FOR PID AND PLANT MODEL

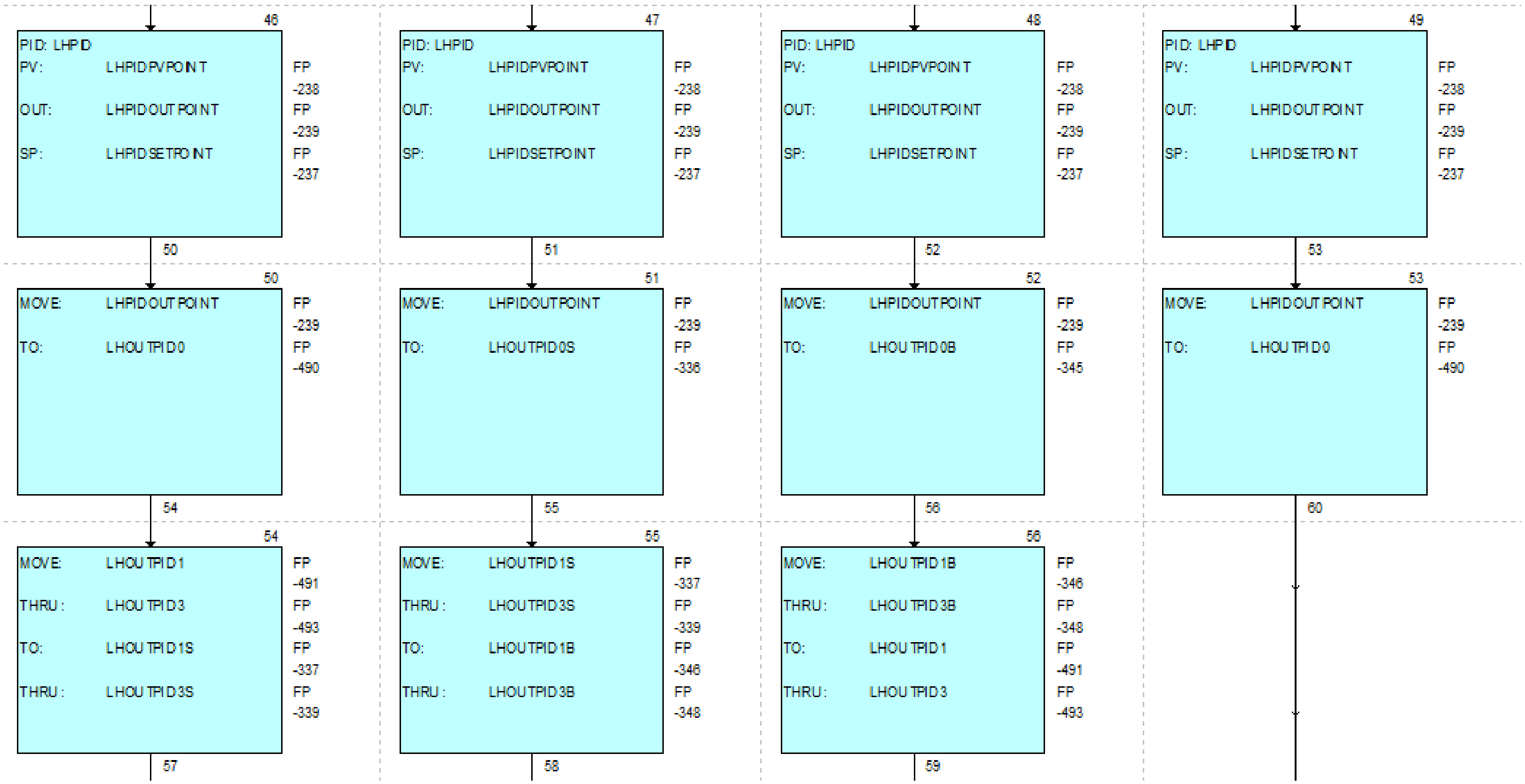
The flowcharts in this section are the blocks for the PID and plant model that are added to the Database Back-Step (DBS) method shown in Figure A-2 to A-4. Blocks 22-25 capture the position of the cylinder based on the 4 segments of stroke where Block 26 is for the first segment and Block 29 for the fourth segment.



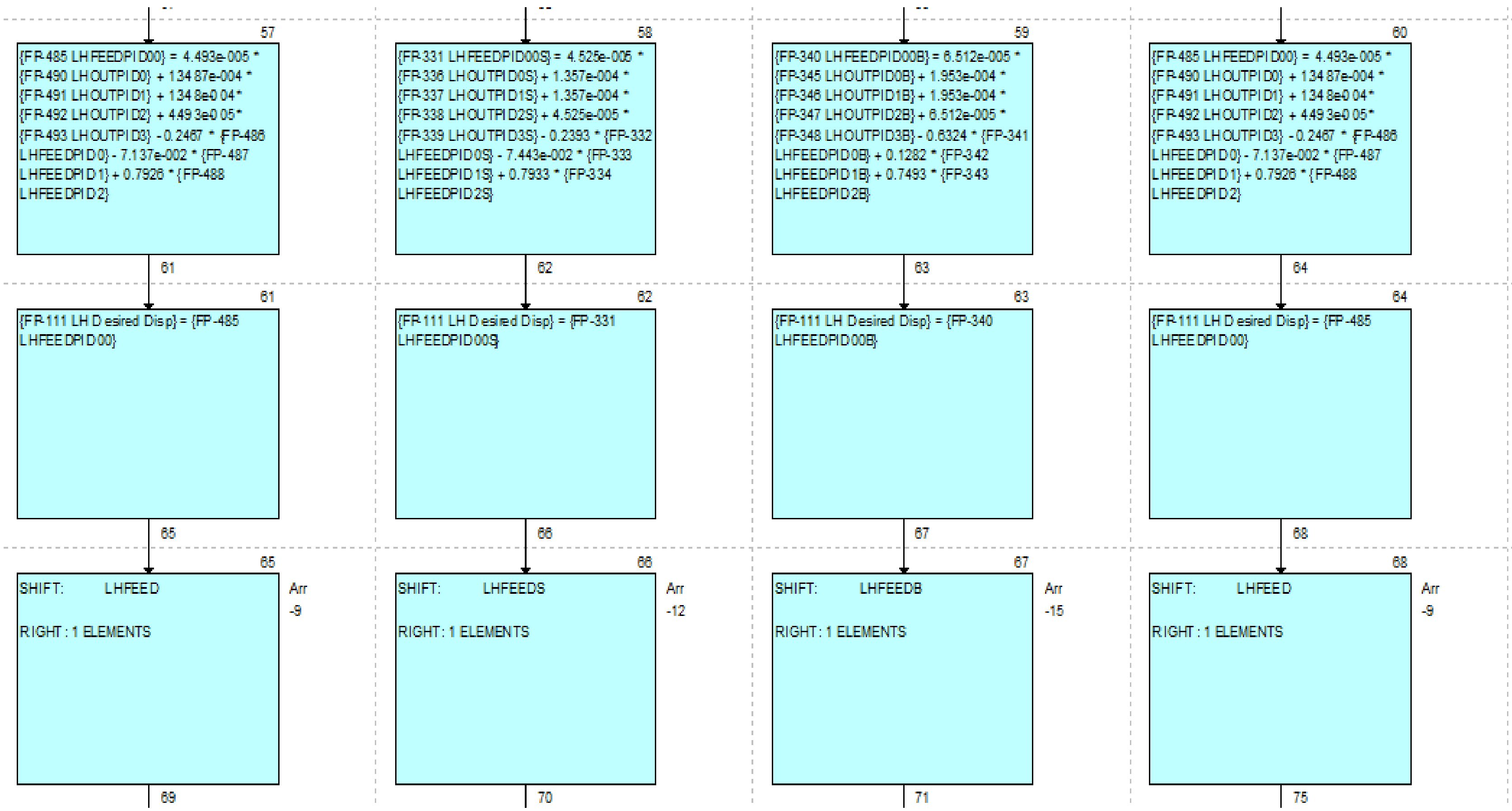
Blocks 30-31 obtain the reference points from the Database Back-Step method for the 4 segments of stroke. Blocks 34-37 show the PID timers. Blocks 38-41 ensure the PID is operating on Automatic mode hence using the PID gains provided in the PID blocks. Blocks 42-45 are the process variables for the 4 segments.



Blocks 46-49 represent the PID blocks for the 4 segments. Blocks 54-60 move the outputs of the controller to an array to be used in the plant model. Blocks 57-59 capture the outputs of the controller for purposes of carrying forth the previous output from one segment to the other.



Blocks 57-60 represent the plant models for the 4 segments. Blocks 61-64 define the plant output to be sent to the press. The arrays undergo shifting in Blocks 65-68 hence capturing the previous positions.



Blocks 72-74 capture the plant outputs for purposes of carrying forth the previous position from one segment to the other. Blocks 72-75 perform the shift for the controller outputs hence capturing the previous outputs for the plant model in the next scan. The Exit block ends the sub-flowchart routine and the position obtained from Blocks 61-64 is moved to another flowchart and sent to the press to move the cylinder.