1. Introduction

1.1 Early Engine Development

The idea of harnessing combustion to perform mechanical work is by no means a new one. The internal combustion engine, as we know it today, has its origins in the last century, however the idea for controlling combustion to perform mechanical work dates back to the Renaissance [1]. These early efforts were not to develop a repeating combustion pattern which resulted in power transmission to a shaft like we know today. It was the intention of the early designers to lift large weights by using combustion. The principles of these design efforts are simple to understand:

- Place a large amount of fuel under a piston.
- Attach a cord (or chain etc.) to the large weight.
- Ignite the fuel and let the piston pull the weight upwards.

Looking back at these efforts, it is funny to note that the earliest fuel selected to develop an engine was gunpowder. It should be realized though, that gunpowder was a very logical choice for these efforts. If gunpowder could be made to work, the following advantages would be realized:

- Gunpowder appeared to provide the most power due to the violence of its combustion when compared to other combustibles of the period.
- Gunpowder does not require air to ignite (a definite advantage for engines designed to be submerged underwater).

Most of these efforts were performed before the emergence of steam as a major power source (1670's to 1680's). Once steam emerged as a source of energy, these investigations were abandoned.

Interest in gunpowder engines re-emerged in the first half of the nineteenth century due to the lack of mobility (on a small scale) of steam power and the potential for submarine engine design [1]. The focus of these post-steam gunpowder engine investigations was on mobility and the development of fuels. These efforts, like those of the pre-steam era, did not result in a workable design.

Steam engines, however, did enjoy remarkable success. As reported by Bolles [2], both mobile and stationary steam engines were used in the nineteenth century. Mobile steam engines, in steamboats and locomotives, greatly improved commerce and transportation in this country. Stationary engines were used to power pumps and machinery. One important use for steam was supplying power for pumping and drilling operations in America's oil fields. Steam, however, requires large amounts of water, so drilling could only be done near large bodies of water. In addition, fuel consumption and boiler repair were expensive. It was realized, however, that wellhead gas, a by-product of oil production, was combustible and could be used to power internal combustion engines. These engines can then in turn be used to power oil production equipment. The advantages of using this gas and engine combination in the production of oil was as follows:

- The fuel was a by-product of the oil operations and was readily available.

- Large amounts of water were not required. Therefore, oil drilling operations did not require large bodies of water for steam production and could be placed almost anywhere.

Hence, the desire for expanding oil operations fueled the development of the 2 and 4 cycle engines (pun intended). Therefore, the engines developed in the late 1800's for use in the oil fields are the ancestors of today's internal combustion engine [3].

1.2 Comparison of Installed Power Consumption

As previously discussed, the internal combustion engine was widely used at the turn of the century. It is even more in use today. Even with the advent of alternative sources of power for commerce and personal applications, the internal combustion engine represents a large portion of the power generation available in this country. The following example compares the installed power for the power plants surrounding Raleigh, North Carolina served by Carolina Power and Light (CP&L) to an estimated amount of power installed in automobiles in the same service area. From the CP&L website [4], the following estimates are provided for this service area:

- Estimated total installed power: 9,613 megaWatts
- Estimated total population served: 3.75 million

In addition, Hills [5] estimates that there are approximately 550 automobiles per 1000 inhabitants in the United States. Using these estimates, the approximate number of automobiles in the service area is 2 million. Assuming a conservative engine power of 74.57 KW (100 horsepower) per automobile, this results in a total installed power of approximately 150 GW. As can be seen in Figure 1.1, the total installed power of the automobiles in the area is approximately 15-16 times greater than the power plants. Based upon this estimate, it appears that the internal combustion engine still represents a large power source in the United States.

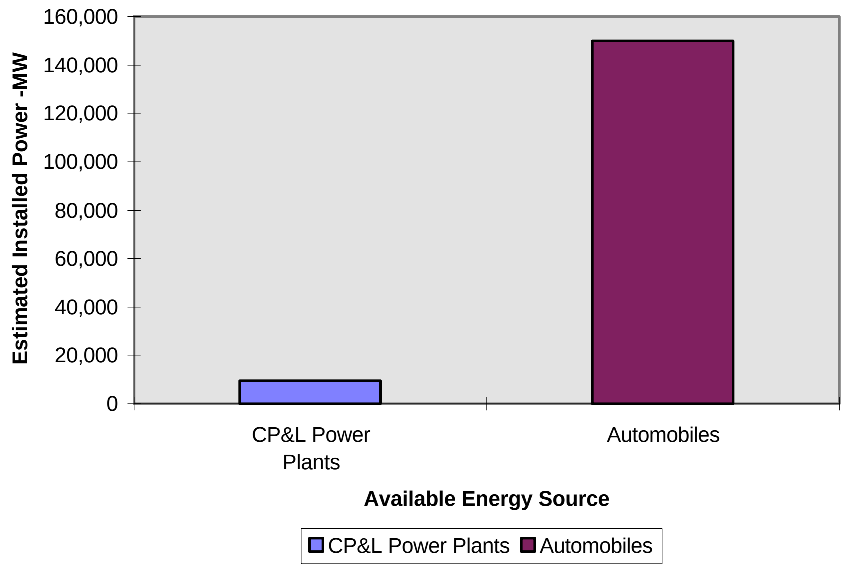

Figure 1.1: Comparison of estimated available power for power plants and automobiles in the Raleigh, NC area served by CP&L

1.3 Brief Description of Valve Train Motion

There are a variety of subsystems on the internal combustion engine. While all of these subsystems are important, this investigation will be focused on the valve train of an internal combustion engine. Basically, the valve train in an internal combustion engine is responsible for controlling the air/fuel mixture into the cylinder during intake and to allow the exhaust gases to exit after combustion. Many valve designs were tried for these engines, but the poppet valve is by far the most popular due to its ease of manufacture and durability. Other valves, such as sliding, rotary and sleeve/piston types, were abandoned from internal combustion engines due to high cost, friction and adverse effect on oil consumption [6].

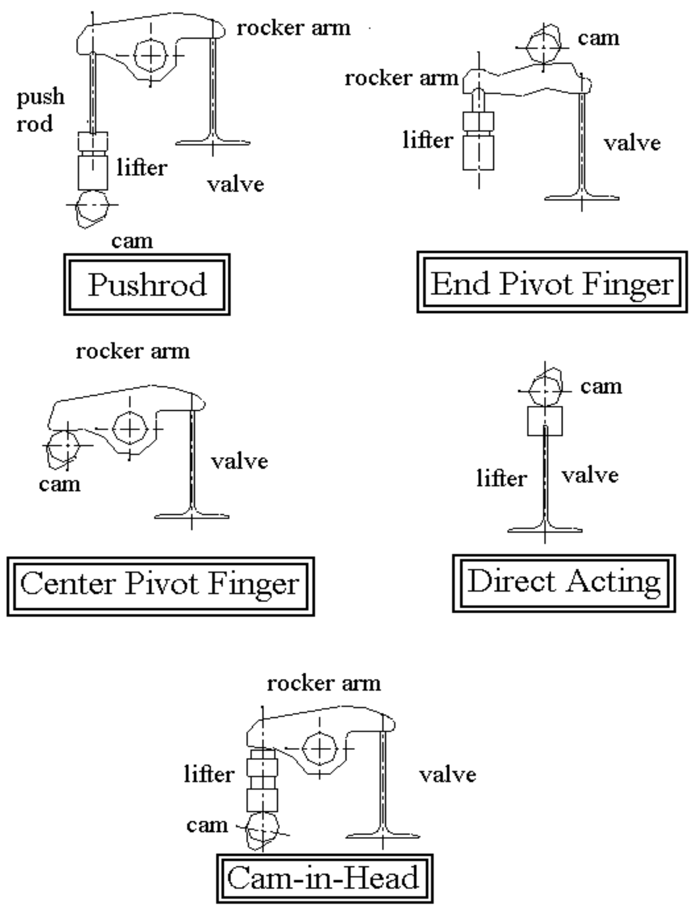

Figure 1.2: Various valve train configurations

Valve trains can have several configurations as shown in Figure 1.2. Even though each of these configurations uses various linkages between the cam and the valve, they all share the fact that a cam actuates the valve motion. Although performance is important in all of the valve train types, the focus of this study will be on pushrod type engines. However, this research will have an impact on all valve train types since each of these configurations perform the same purpose and have similar dynamic characteristics.

A schematic of a single valve for a typical pushrod type engine to be investigated is presented in Figure 1.3. As can be seen in this figure, cam rotation results in a linear motion imparted to the valve. The valve spring is present in the system to provide a restoring force to maintain contact between the components during operation.

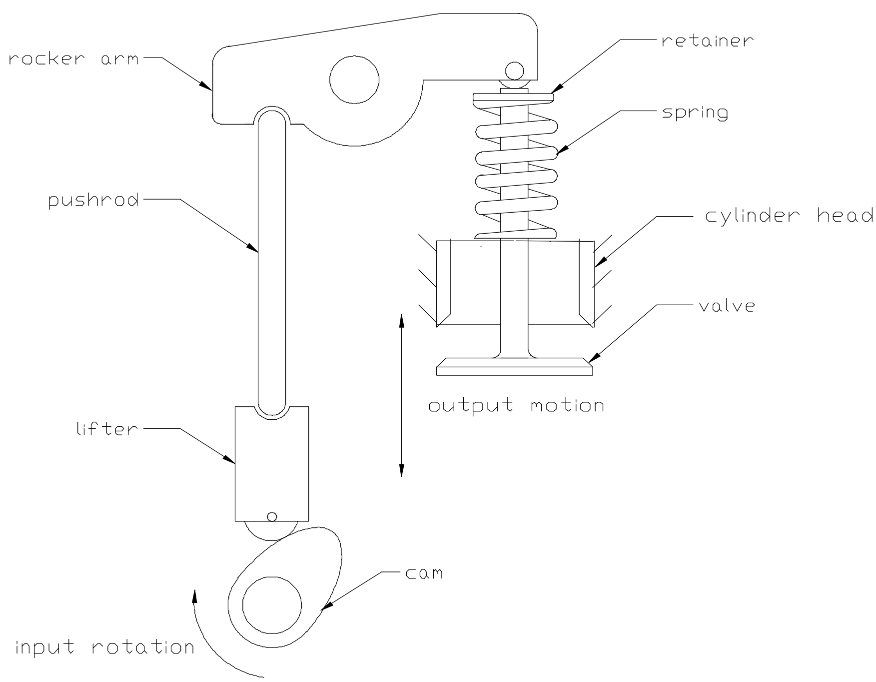

Figure 1.3: Valve train schematic

1.4 Valve Train – Then and Now

In order to better understand the objective of this research, it is helpful to look back at early limit speed investigations. The following question was posed to the members of the American Society of Mechanical Engineers (ASME) in 1885:

"Are there any grave objections to cam motions for moving the valves of high-speed engines? What is a limiting speed for cams?"[7]

Verbal responses to this question were given by Heminway and Babcock[7] and a written response in the form of a technical paper was presented by Porter[8]. The respondents stated that they were currently using cam-actuated valves in steam engines. These engines were turning approximately 75-300 revolutions per minute without difficulty. Even though these engine speeds were low for this time period, what engine speed that was considered high was not stated. In addition, it was unclear what the limit speed of a "cam" might be. The significance of this work is not how high of an speed might be achieved but it is at this point in time that general use of cams to operate valve gear was established.

As shown in the outline of the discussions from 1885, the use of cams to operate valves at high speeds showed great promise. In fact, this technology is still in widespread use as we approach the twenty-first century. However, much has changed with respect to the use of cams to activate valve motion. The following is a brief description of several of these changes:

- The type of engine undergoing investigation has changed from steam engine to internal combustion engine.

- The limit speed of a “cam”(i.e. valve train) is now defined. It is considered to be the engine speed that produces the onset of unstable valve motion.
- Engine speeds have increased greatly. The speeds mentioned by the members of ASME in 1885 were on the order of hundreds of revolutions per minute. Again, these were admittedly low for that time period, however, engine speeds of today can approach thousands and possibly tens of thousands of revolutions per minute.

However, even with these changes, the technology developed in the late 1800’s using cam actuated valve trains is still in use today.

1.5 Discussion of Cam Motion, Profile Errors and Tolerances

In 1889, Smith [9] recommended the use of a graphic analysis to evaluate reciprocating motion. During the discussion of this paper by ASME, it appears that there was a question as to how cam information should be plotted. It was suggested that both the rectangular coordinates of a cam be plotted to look at the displacement as a function of cam angle as well as a polar coordinate plot to aid in the physical construction of the cam. In 1923, Low [10] presented a numerical analysis of cam displacement, velocity and acceleration using cams constructed of circular arcs for various followers. These cams were typical of the cams in use in the automotive industry at that point in time. In 1945, a method of calculating cutter position for various cutter and follower configurations was published [11]. Each of these developments are important to this work since without an appropriate method of determining cam lift curves and their relationship to the physical cam profile, it would not be possible to determine how the manufacturing errors relate back to the cam lift curves.

In the 1950's, Cousins [12] and Johnson [13] introduced the use of numerical differentiation in the analysis of the velocity and acceleration of cams. Johnson also used finite difference methods for several investigations [14][15]. These investigations used finite differences to estimate the angular and radial error of a cam profile and to predict the effects of these errors on the dynamic performance of the cam follower system. Nourse [16] also discussed several important points in cam evaluation. He suggested that data sets require smoothing for evaluation since it is known that cam motions do not follow the jagged motion as suggested by the finite difference method. In addition, he states that cam profiles can be evaluated according to two separate criteria. Cams can be measured and compared to a theoretical cam profile and it can then be decided if it falls within a given tolerance. For example, when measuring a shaft, the tolerance is given as plus or minus a specific range. If it is outside of a given range it is then it is rejected even though it may or may not perform its intended purpose. The second criteria is to see how closely the dynamic characteristics, particularly the acceleration curve, change the performance of a system. This is to say that a cam may be off by a certain tolerance and still may perform its intended task in an acceptable manner.

In 1967, Brittain and Horsnell [17] investigated the effect of manufacturing errors due to grinding wheel size on cams manufactured on cam copying machinery. In addition, the changes in lift properties were used to analytically investigate the effect on pushrod force on a valve train. In 1979, Bialkowicz, Klimowicz and Swietlik [18] investigated cam wear due to random manufacturing errors and their effects on cam system dynamics. Kim and Newcombe [19] performed a stochastic error analysis to obtain variances in not only the lift curve but also the velocity and acceleration curves. This investigation used the principle of maximum likelihood with the finite difference method to theoretically determine the variances. Kim and Newcombe [20] extended their previous work [19] to investigate the effect of cam profile errors and system flexibility on cam mechanism output. This investigation was performed analytically on lower speed systems using finite element analyses. Rao [21] presented a probabilistic approach for error analysis to determine which tolerances are more or less important to hold during the manufacturing process. Gal-Tzur, Shpitalni and Malkin investigated the interconnection of cam design and manufacturing techniques on the profile of a given cam [22]. Norton et al. [23] [24] [25] investigated the effect of various manufacturing techniques the dynamics of cam systems using simple lift profiles. The noise level resulting from the various surface finishes/hardening techniques was measured.

This brings us to the point of determining an acceptable cam manufacturing tolerance and geometric change in the cam profile. In their investigation of cam tolerancing and the effect of error on dynamic performance, Grewal and Newcombe [26] stated that cam tolerancing may be thought of as having two parts:

- size tolerance (maximum allowable deviation)
- waviness specification

For automotive cams these values are +/-0.0254 mm (0.001 inch) and 0.00254 mm/degree (0.0001in/degree) for the above mentioned quantities. However, based upon dynamic simulation, they added that high frequencies are filtered out by flexibility of the cam follower and that system dynamics may not be adversely affected by size errors on the order of 0.0127 mm (0.005 inches). These results were generated by a dynamic simulation at a low cam speed (1,500 rpm) and were not verified experimentally to this author’s knowledge. Moreover, an analysis of the manufacturing techniques used to fabricate the cam were not investigated in the aforementioned work.

This brings us to a quandary: The simulation work of Grewal and Newcombe indicates that cam actuated systems can withstand a larger tolerance than current specifications. However, automotive cam grinders are designed to provide tolerances on the order of 0.0001 inches [27]. If this is the case, automotive cams may be currently produced to tolerances that are much too stringent. Producing cams (or any other item) to too stringent a tolerance is the equivalent of building a house using laser measurements, it just isn’t required. It is well known that manufacturing tolerances which are too stringent are a waste of time and money. This is by no means a small problem. For example, if one or two cams a year were produced, there wouldn’t be much interest. However, General Motors alone produced 8.3 million vehicles world wide last year [28]. This is a minimum of 8.3 million cams (not accounting for dual cam vehicles and replacement parts). In addition there are numerous other manufacturers of vehicles and aftermarket parts. If too stringent tolerances are applied, there may be much wasted manufacturing effort by all of these manufacturers.

1.6 Objective

As discussed above, there are a lot of automotive cams produced worldwide. Each one of these valve trains may be subject to dynamic malfunctions since this is dependent on the shape of the cam. The current thought process on the manufacture of cams, however, is to use higher tolerances in order to produce “more uniform cams”[29]. What was meant by "more uniform cams" was not better defined in the paper. If this is meant with respect to valve dynamics, tight tolerances may not be justified.

At this point, the overlooked question appears to be ”What is the importance of maintaining or raising the limit speed of an engine? Today’s engines appear to be successful at operating high speeds, so what more can be gained?” The answer to these questions lies in the fact that maintaining or increasing the limit speed of an engine will allow it to turn faster and produce more power. In addition, it will allow smaller, lighter, engines to operate at higher engine speeds and produce the same power as larger, lower revving engines. Moreover, improvements and better understanding of camshaft considerations will allow for more work to be done in the area of low friction valve trains. For these reasons, advances in limit speed technology are of the utmost importance in both passenger and racing automobiles.

Cams that are consistent with design considerations are required to maintain limit speed. Consistency in performance must also be present not only lobe to lobe on a particular camshaft but must be consistent camshaft to camshaft to maintain desired performance. By determining acceptable camshaft variation and by manufacturing to these standards, engine builders can expect similar performance from an engine when replacing one camshaft with another of the same make and model. If the range of consistent performance is identified, it may be possible to increase the limit speed of a particular engine through redesigning the other components such as the spring, push rod, rocker arm, valve or various combinations there of. Therefore, finding an appropriate balance between consistent performance and manufacturing considerations is important not only for engine builders but for cam manufacturers as well.

With this in mind, there are several objectives in this investigation. These are as follows:

- Predict the kinematic error due to mechanical loop changes in the rocker type cam grinding equipment used to produce cams.
- Experimentally determine the effects of these errors on the dynamic response of high speed valve trains.
- Use an existing valve train dynamics model to predict errors and determine correlation with experimental data.
- Determine the effects of cnc type grinding machine errors on valve train dynamics using actual error traces.

In order to start this investigation, the remainder of this chapter will discuss valve train dynamics, cam manufacturing techniques and the scope of work undertaken in this investigation.

1.7 Valve Train Dynamics

The current maximum speed of pushrod engines manufactured in the United States is approximately 9,000 to 10,000 revolutions per minute. According to Kim [30], operating these engines at too high of an engine speed usually causes dynamic malfunctions such as spring surge, lifter/cam pair separation, valve bounce, etc. Although the interaction of each of the components contributes to the limit speed, the shape of the cam plays a critical role. Therefore, this investigation will look at how small changes in the cam profile due to manufacturing errors change the limit speed of a valve train.

In order to observe changes in limit speed, the valve bounce amplitude can be monitored for various engine speeds. Simply put, when the valve bounce amplitude has reached a certain value, unstable valve motion is occurring at that engine speed. Experimentally, this can be determined by running the valve train and using a short range proximeter to monitor the results. By monitoring the valve motion over the engine speed range, differences in valve bounce can be observed. Figure 1.4 shows the difference between stable and unstable valve motion using the results from a test using a short range proximeter. The flats on the bottom of the graph are the lift regions that exceed the measurement range of the proximeter. These values may be truncated due to the limited sensing range of the proximeter used. A short range sensor has a range of approximately 1 mm (0.040 inches). Therefore, the entire valve motion is not recorded; only the motion in the proximity of the valve/valve seat contact is recorded. This does not limit the validity of the results as the dynamics of interest in this system occur when the valve closes and strikes the seat.

Test results can be obtained for the entire operating range. Figure 1.5 shows the bounce amplitude for the entire operating range. The valve bounce amplitude is defined as the sum of the absolute value of the penetration of the valve into the seat and the absolute value of the bounce of the valve after initial contact.

In an ideal valve train there would be no bounce when the valve contacts the seat. However, the system is not ideal and upon closure at an acceptable engine speed, and as can be seen in the figures, the valve bounces slightly after contacting the seat and closes. When limit speed is reached however, it is obvious that the valve behaves in an unstable manner. Here, it can be seen in Figure 1.4 that after its initial contact with the valve seat on the closing event, the valve bounces out of the range of the proximeter. This motion is a dynamic malfunction and is unacceptable for valve train motion. A valve train dynamic model developed by Kim [30] and modified by Cheng [31] and Etheridge [32] will also be used to predict changes in the limit speed.

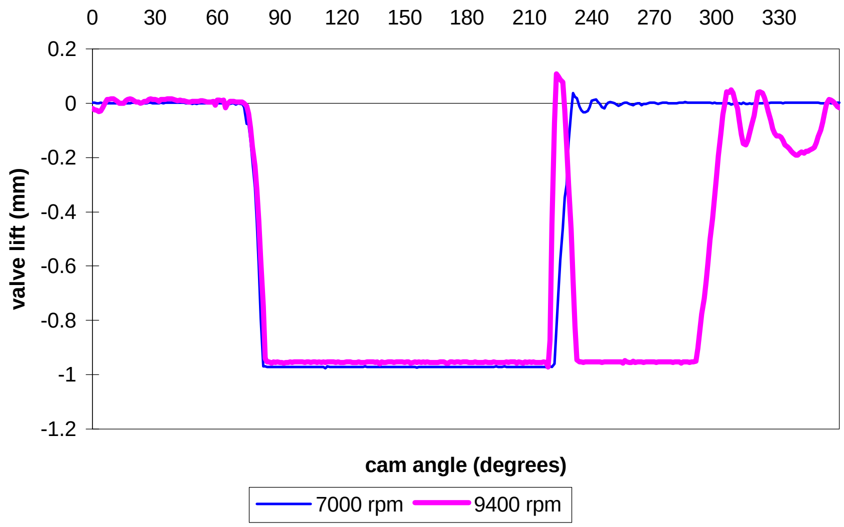

Figure 1.4: Short range experimental valve bounce comparison

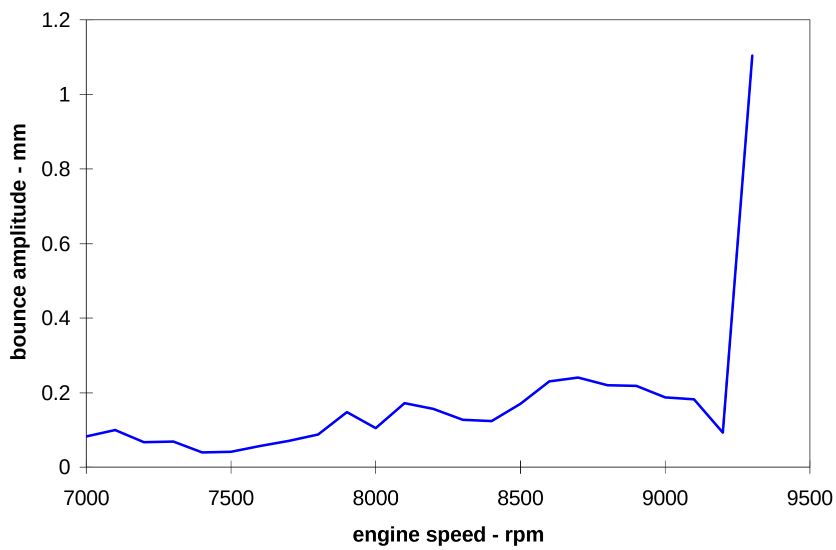

Figure 1.5: Amplitude of valve bounce for entire engine operating range

1.8 Cam Manufacturing Options

In order to investigate cam manufacturing errors, the methodology used to produce a cam must be investigated. It should be noted that the discussion contained herein applies to plate cams only since this is the type used in automotive valve trains. As can be seen in Figure 1.6, a camshaft is merely a collection of plate cams that are offset by a particular design angle and are connected by a shaft. Some of manufacturing techniques may be shared with the production of barrel, camoid, face and other cam types but these items will not be specifically discussed herein.

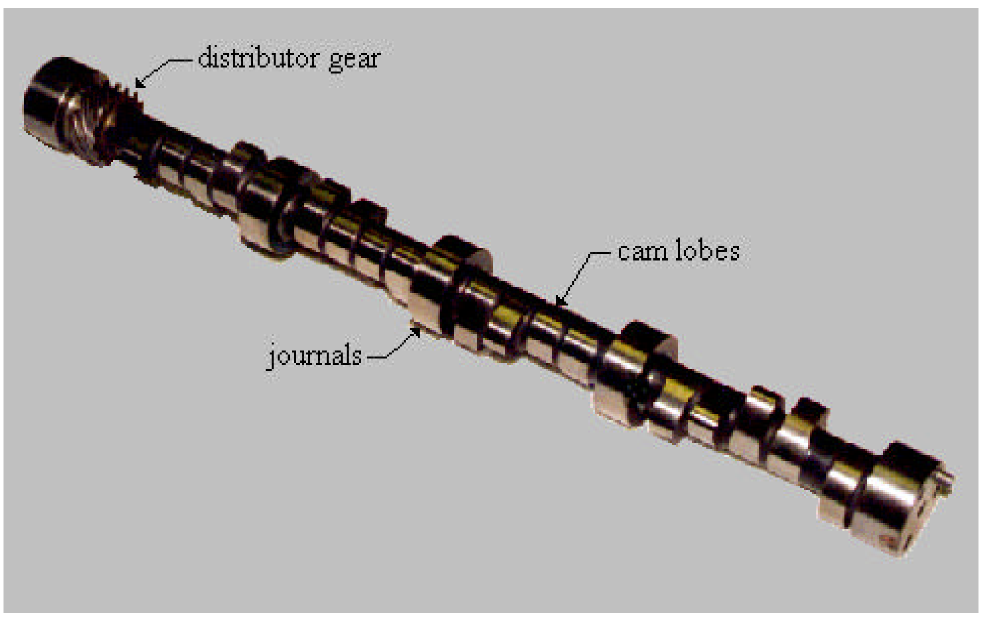

Figure 1.6: Typical multi-lobe internal combustion engine camshaft

In 1979, cam manufacturing techniques were surveyed by Grant and Soni [33]. The two methods that were identified for manufacturing cams are as follows:

- Original (Master) Cam Production Methods
- Copied Cam Production Methods

The next two sections will further expand on these manufacturing techniques. However, it should be noted here that both methods are used to produce automotive camshafts and again, since a camshaft is simply a collection of plate cams both methods are justified. Originally, most automotive cams were manufactured by copying the required profile onto the multiple lobes of the camshaft. However, due to the advances in machine tools, especially numerically controlled equipment, it may be cost effective to produce camshafts as original cams.

1.9 Original Plate Cam Manufacture

As the title of this section indicates, original plate cam manufacturing techniques are used to fabricate a cam from drawings or some other descriptive information when no physical master is available to duplicate it by mechanical methods. These cams may be used directly in the mechanism requiring the cam or used as a master to produce other cams in a copying mechanism. In 1892,Gabriel [34] introduced a copying device for pocket watch cam manufacture. In simple terms, the contour of a master cam was traced and this action positioned a cutter with respect to a cam blank. The mechanism is similar in purpose to a key copying machine that is still used in hardware stores today. This method is much easier to produce multiple cams of the same size than producing cams ‘from scratch’. However, in order to use this mechanism a master cam must first be produced - hence the 'original' cam. Therefore, to manufacture the master cam, its profile was laid out on a piece of sheet brass and was produced by band sawing and filing the blank to the final desired shape.

Also in the late 1800's, Smith [9] suggests the use of graphical analysis methods to display lift characteristics as well as determining velocity and acceleration information of a particular cam layout, since this would be useful in cam design. Both Polar and Cartesian coordinates were now used to more accurately design and manufacture cams. By the turn of the century, these methods were used to more accurately calculate the profile of more complex cam profiles. With these more accurate layouts, skilled craftsmen were then able to turn to various machine tools that were available to them to produce plate cams. Typical machine tools used in the production are as follows:

- Lathe[35]
- Gear Shaper [36] [37]
- Milling Machine [38][39][40]
- Screw Machine [41]
- Boring machine[42]

Although the availability of machinery varied from machine shop to machine shop, the methodology used to produce a cam came down to the following three methods:

- Layout
- Increment
- Continuous path

The layout method is the same as the production of the master cam described for the aforementioned watch cam copier. Typically, this method requires transferring the cam outline to a cam blank and cutting around this pattern. This could be obtained by using a band saw and file as was used by the watch cam manufacturer described above or using a milling machine and power fed rotary table [43]. By this method, the cam blank is rotated automatically and the machine operator moves the longitudinal feed of the milling machine to follow the contour of the cam outline.

The next method used was the increment method. Increment methods involve the accurate calculation of the follower position with respect to the cam center. The cam blank is placed on a rotary table (with or without a dividing head) and the center of the mill cutter is positioned at the calculated center of the roller follower. The cutter is then plunged through the work piece. After the entire cam profile is cut in this manner it is lightly filed to remove the asperities from the cam.

Continuous path methods would involve the use of a mechanism that would allow the cutter to traverse along the same path as the follower. The advantage of this method is that asperities are reduced (if not totally eliminated) since the cutter moves from position to position and is not plunged. Typical methods included the use of power feed to produce constant rise and circular arc cams.

Fromelt [44][45][46][47][48][49] summed up the available technology for cam manufacture up to and including World War Two. In addition to the machine tools themselves, attachments such as rotary tables, dividing heads and custom jigs were used to accurately position the cam blank as described above instead of control technology. The combination of this equipment was used to manufacture various cams on existing machine tools without much specialized equipment since it was necessary to produce cams on any available machinery [50]. During this period, the use of jigs on existing machinery to cut cams was accelerated. In addition, the importance of creating more accurate cams for computing and control equipment after the war had emerged [51]. Jigs for cutting cams on milling machines were developed to produce more accurate cams for use in harmonic motion, oscillating follower, and other special applications [52][53][54].

For the increment and continuous path methods described above, it should be noted that the diameter of the cutter must be the same as the roller follower used with the cam [44] [54]. If the tool diameter is not the same as the follower for these methods, the kinematics of the cam follower system will not be as designed. If it is desired to use a different sized cutter, then the cam follower contour with respect to the new cutter size must be calculated and used to produce the cam.

Other ideas of note in reducing the effort in manufacturing a master cam were developed. Newman [56] describes a method to 'reproduce the same mechanical conditions that exist when a cam is in operation'. By reversing the mechanism, the cam can be manufactured 'under the same conditions as exist when it is in operation, and therefore no doubt can arise as to its accuracy.' Basically, an existing cam with the desired profile and the master cam blank are switched in the cam grinding machine. The master cam follower was replaced with a (powered) grinding wheel and the grinding wheel was replaced with a roller follower. An existing camshaft was then placed in the machine and used as a master to produce several plate cams. These plate cams then became the master cams for additional cam copying machinery [57].

Another method of reducing the labor and hence cost of master cams was to replace the cam material. Honegger [58] describes an inexpensive way to make temporary master cams for use in small production runs. The following is an outline of the procedure:

- A steel core (i.e. arbor) has a softer alloy cast around it.

- The softer alloy (which machines much quicker than steel) is machined to the desired profile.
- A thin layer of plating is applied to the master cam to increase the wear resistance.

The chief advantage in fabricating a short run master cam in this fashion is the reduction of machining time required to cut a material that is much softer than steel. This shows how labor intensive it was to produce a cam at that point in time.

As it was desired to more accurately produce cams in the 1950's, Wright [59] described the following procedure to make an original cam for a cam grinder:

- A soft model was hand planed on a machine using a highly accurate optical indexing head. A microscope was used to permit indexing to seconds of an angle.
- The soft model was used to grind a master cam. The master cam was then used to grind a workpiece. This workpiece was then checked and any errors that were found were corrected by hand on the soft model.
- After the errors were corrected, the soft model was then used to grind a hard tool room cam. This tool room cam was used to produce several master cams for several cam (copier) grinders.

It should be noted that the tool room cam was twice as large as the soft model and four times as large as the final workpiece (i.e. camshafts.) This ratio reduces an approximate error of 0.001 inch on the model cam to 0.0005 inch on the tool room cam. This in turn reduces to an error of 0.00012 on the finished product.

Up to this point automotive camshafts were not cut as originals. The plate cams produced up to this point in time were used in cam copier grinders (discussed in the next section and as described above) to produce camshafts. However, during the 1950's, a greater emphasis was placed on the use of electronic controls in cam manufacture. In addition, with the advent of numerically controlled equipment, camshafts could then be treated as originals as the required cam outline would not be physically manufactured (i.e. master cam) but would be a series of data points stored on various media.

The initial work with electronically controlled equipment was used to produce master cams. Hale [60] details the use of a machine using an electronic cam template to trace a path around an electrically conductive line drawing. The traced path positions the machine bed with respect to a cutter to produce a cam. The master cam in this case is the electrically conducting drawing. This master is drawn much larger than the desired cam. The machine is then capable of compensating for a master that is drawn to a larger scale than the required part. The path of the cutter was continuous instead of plunged. Therefore the cam surface was much smoother than those produced by increment methods.

A similar machine to that described by Hale was constructed using a 325 foot paper scroll to lay out cam information [61]. The scroll would be suspended in a machine that would advance the paper (similar to the operation of a player piano). As the scroll would pass, a human operator was required to center a pointer over the passing line. This in turn would control the position of a cutter in a cam mill that would produce the cam.

During the 1950's however, one of the largest innovations in machine tool technology this century was developed - Numerical Control. Sims [62] and Morgan [63] detail the use of punch tape technology to produce cams. Punch cards were not only used to aid in the design of the cam profile on a computer but were also used to prepare punch tape to control the machine to fabricate it. Using a cam mill that is operated by a punched paper tape controller, more accurate cams were produced since this offered less error than human control. In Morgan's example, the punch tape would provide signals to activate a servo-motor that would control the lead screw of a sliding table. The cam blank was mounted in a rotary table that was mounted on the sliding table. This rotary table was not numerically controlled but was actuated to rotate at a constant angular velocity. (This velocity can be set at the beginning of the process based upon the size of the cam to be produced.) As the cam was rotated, the sliding table is electronically positioned and the cam is cut. The main contribution of numerical control is the elimination of many of the time consuming steps in cam manufacture. Accurate layout of the cam on the blank is not required and the repetitive work of indexing and cutting was eliminated. In addition, since the tape can position the cutter at large number of close spaced increments there is no need for finish filing. These early models were excellent for machining master cams but were still more time consuming than cutting cams on a copier type grinder [33].

Improvements to numerical control machines in the 1960's were to increase the number of steps that can be programmed and hence the accuracy [33]. In addition, numerical control was used to enhance other processes such as electrochemical machining and conventional machining [64]. An example of this was the use of electrochemical machining to rough out a cam profiles to 0.005 inches on a multi-cam blank. The blank was then hardened and ultimately ground on a numerically controlled grinder. This shows the increasing role of numerical control not only in manufacturing prototype parts but of being integrated in production lines as well.

Other applications of paper tape controlled machines arose in the automotive industry. Automotive cams were being produced in small quantities for prototype work on a modified cylindrical grinder [65]. This machine was not only used to produce prototype but also produced master cams for cam copying machines. It should be noted that wheel diameter compensation was not available on this machine. Therefore, when wheel wear was unacceptable, either a new tape was punched to control motion or the wheel was changed. Advantages of the machine were increased accuracy of the prototype and master cams produced as well as a large reduction in the lead time of these items.

The role of the computer was also increased during the 1970's [66][67][68]. Cams were designed on the computer using their characteristics and lift requirements instead of physical coordinates. This design information was used to calculate the cam profile and the output was coded on punched paper tape for the machine tool. Using this method, it was no longer necessary to use the same size cutter as the cam follower diameter. The cutter, in fact, could be much larger than the diameter of the follower (for a roller follower) provided that the cam surface is not inverted. In the late 1970's computer numerical control (CNC) machines were developed that accepted keyed-in instructions from an operator responding to written text [69].

In the 1980's cam grinders were constructed to coordinate wheelhead reciprocating motion with spindle rotation to cut accurate lobes [69]. These machines were no longer controlled by punch tape but by computers or microprocessors. By using a computer, in-process geometry adjustments can be made. An example of this is the control of rotational velocity of a cam blank during machining. When a cam is manufactured, it is rotated between centers (like a lathe). If the cam blank is rotated at constant angular velocity and the grinding wheel is spinning at a constant velocity, the velocity at the point of contact on the rise/return portion of the cam will be greater than that for the base circle. The higher grinding velocities will cause imperfections on the cam surface. Therefore, if it is not possible to control the speed and feed of the cutting process, the rotational velocity of the cam blank is set to that required for the position of highest tangential velocity of the cam. This results in setting the machine for the slowest rotational velocity. Although this is not damaging to the cam, the manufacturing process is unnecessarily extended for a majority of the cam surface. In high production work, the extra time spent cutting the base circle and lower portion of the rise/return portion of the cam could slow down production greatly. With computer numerical control, the rotation of the cam blank is controlled by a microprocessor. The microprocessor is able to control the rotational velocity so that the surface velocity is constant during the cutting process.

Processor controls were also upgraded in the 1980’s to include liquid crystal diode or cathode ray tube displays. Programming a grinder was now typically accomplished at a workstation attached to the grinder rather than using an off-line computer. In addition, many of the processes were contained in canned subroutines rather than writing the routine from scratch. This allowed more interaction from the machine operator as menu driven displays were combined with the canned subroutines. This allowed for quicker and easier programming of the machine. The operator just needed to scroll through different screens provided on the display and select various options and parameters. In addition, creep feed grinding (which is analogous to plunge cutting of a work piece) was not very common up to this point [70]. With the advent of more sophisticated controls (and cubic boron nitride grinding wheels) creep feed grinding was employed more often [69].

As the speed and ease of use of numerical control machines were advancing, camshaft production was switching from the master type grinders to the direct cutting of the profile. Early machines used a single grinding wheel to cut single cam lobes. The grinding wheel was then moved from lobe to lobe to finish the camshaft [71][72]. The advantages of these machines are as follows:

- Grinding wheel compensation became available to automatically recalculate curve points which are dependent on wheel size.
- Inverted flank cutting of the cam lobes was easier [71][72][73].
- Continuous dressing of the grinding wheel. This allows a fresh and true surface to always be present during the grinding operation.
- Workholding went from between centers to supporting the cam on its journals. This allowed for a more accurate cam surface to be generated with respect to the cam journals.
- Wheel life is increased by wheel compensation. Copy type grinders typically have a limited wheel range before the copied cam characteristics are out of tolerance. This is typically on the order of two inches of grinding wheel diameter. Even with a second set of masters, the acceptable wheel range could be increased to four inches of grinding wheel diameter [74]. Wheel compensation allows for wheel use up to a change in six to eight inches in diameter [75].
- Complex contour generation was now more available.

It should be noted that with continuous wheel dressing, cam blanks were switched from nodular cast iron to steel. Steel camshafts are preferred since they hold up better to increased surface forces from higher revving engines. The disadvantage however is the additional production time associated with steel camshafts. By using continuous dressing though, production time is reduced for steel cam manufacture and in addition, surface burning and cracking are better controlled, if not eliminated. If it is still desired to use cast iron, the accuracy and surface finish of a cast iron blank processed on this type of machine allows for post process hardening [75] instead of finish grinding the cam after it has hardened.

In the 1990's, the focus on cam grinding machinery was as follows [29][76][77][78][79]:

- Grinding wheels were replaced with a long grinding belt (approximately 12 feet in length). A grinding belt provides much more wearing surface than a wheel. In addition, belt changeover is only eight to ten minutes as compared to wheel changeover, which is approximately two hours.
- Increase the number of grinding operations at one time. Up to this point a single wheel would move to each lobe. In the new design, several belts or grinding wheels would grind several lobes simultaneously.
- Cubic spline interpolation was used to produce smooth cam contours.
- Camshafts are placed in the grinder pre-assembled with a sprocket for the timing belt/chain. The timing tooth is located and the cam is ground with respect to this tooth.

1.10 Copied Plate Cam Manufacture

As discussed above, it is difficult and time consuming to produce accurate cams using conventional (i.e. non-numerical control) machine tools. However, once an acceptable master is developed, a copying mechanism can be employed to produce additional cams with the same profile (within an acceptable tolerance.) The watch cam copying device introduced by Gabriel [34] allowed for a master cam to be constructed in proportion to copied cams. Since watch cams are small, a larger master was first produced and by applying the correct ratios to the copying machine linkages, smaller cams were produced. The idea of using a master cam to produce copied cams was adapted to a wide variety of machine tools. The following are examples of the machine tools that cam copiers were employed on:

- Drill press [80]
- Lathe[81][82]
- Cylindrical grinder [50][83]
- Boring machine[84]
- Milling machine [44][85][86]

Cam copying had no greater importance than in the production of automotive camshafts. Therefore, copy grinders were well in place by the turn of the century [87][88][89]. In order to copy grind these camshafts two types of cam copying mechanisms were developed. The first type is the rocker type grinder. As can be seen in Figure 1.7, the master cam and camshaft are rigidly attached. The master cam is in contact with a roller follower and the camshaft is in contact with a grinding wheel. As the master cam is rotated, the rocker oscillates and provides positional control of the copied cam. Based upon this positioning scheme, a cam lobe is ground on the camshaft. Contact between the master cam and follower is achieved by using a spring, air cylinder, counterweights or other force mechanisms. Typically, only one cam lobe was ground at a time [87][90].

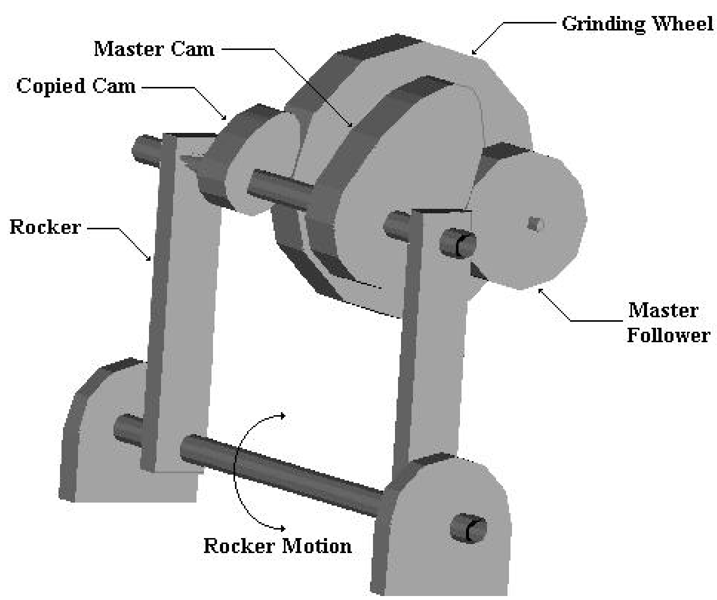

Figure 1.7: Rocker type cam grinder schematic

The second design was the use of cam operated mechanical slides [91][92]. The slides were used instead of a rocker mechanism to position a grinding wheel with respect to a rotating cam. In addition, other designs used a master cam to reciprocate a knife edge which in turn cuts a profile on a cam blank. The tool is traversed along the cam surface similar to straight turning on a conventional lathe. The only operations remaining were surface hardening and finish grinding.

Landis introduced a cam grinder that would grind multiple lobes at one time [93] Machining lobes concurrently allows for more accurate production of lobe timing as well as decreased production time. Norton introduced a totally automatic, hydraulically controlled cam grinder in 1949. The operator would only need to place a rough casting between centers and activate the process. The cam grinder would rough and finish grind all lobes and also automatically dress the wheel between lobes [94].

It should be noted at this point, that many camshaft manufacturers still use the rocker type cam copier. However, one of the critical problems of the rocker type cam copier is the change in wheel diameter. The kinematics (to be further discussed in this investigation) dictate that only one grinding wheel size is correct for a master cam. As previously mentioned, small changes in wheel size may be acceptable but efforts have been made to increase wheel life by adding new masters for different wheel sizes [74]. This extends the life of the wheel for a while but must still be replaced sooner (relative to diameter) than numerically controlled machines. This may be acceptable for some manufacturers in this day but some manufacturers (i.e. Original Equipment Manufacturers) are using computer numerical control as described above.

1.11 Overview of the Thesis

As shown in Figure 1.8, some work has been done in the field of predicting the effect of errors on cam actuated mechanisms, however, this work has not been performed on high speed valve trains either theoretically or experimentally. Therefore, it is a natural progression that the objective of this investigation is to determine how manufacturing errors will impact the dynamics of a high speed valve train. This investigation will be carried out using pushrod type engines. In this analysis, both predicted and actual errors are used. These errors are added to the theoretical lift curve of a cam. Some of the resulting lift curves are used to fabricate physical cams that are placed in a valve train and tested. All of the curves are used in a high speed valve train model and their effects are the dynamics of the system are determined.

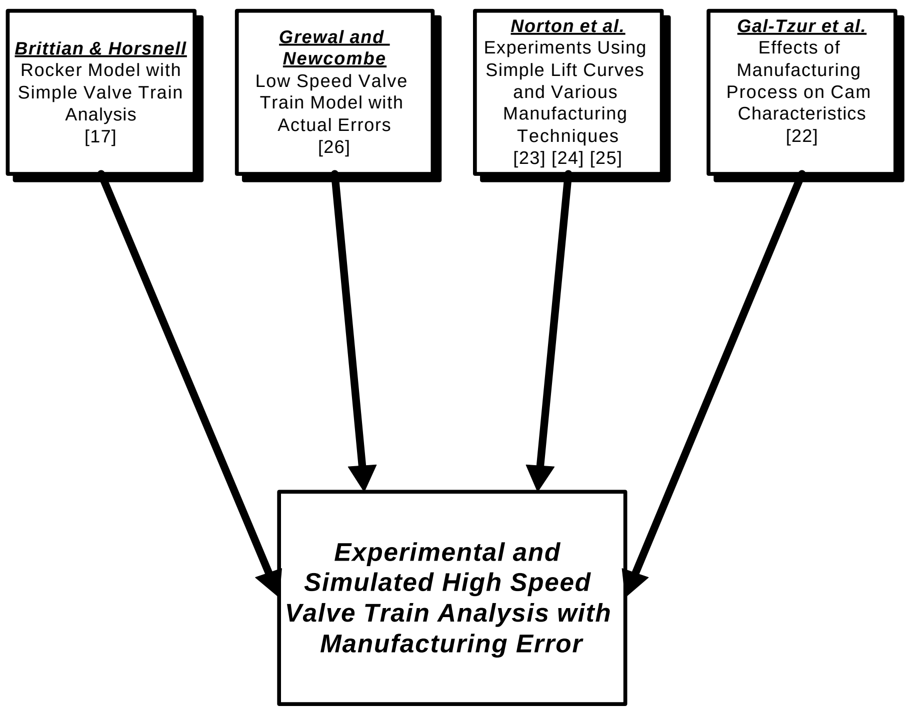

Figure 1.8: Flowchart of cam error research

Chapter 2 details the determination of a cam profile from a given lift curve and how it will be changed due to changes in the rocker mechanism used to manufacture it.

Chapter 3 is a summary of the results for the model presented in Chapter 2. The manufacturing “defects” that are observed in the cam profile by varying machine set-up in the models are used to determine changes in the lift, velocity and acceleration curves of the cam. These curves provide some of the error cam profiles used in the next chapters.

Chapter 4 is a discussion of the experimental results of several cam systems. These results are as follows:

- Comparison of valve train dynamics for two cams on the same camshaft for the same test.
- Successive testing for the same cam and valve train set up.
- Experimental valve train testing using cams that were produced with a prescribed amount of error (changes in grinding wheel size).

Chapter 5 presents a summary of the numerical model used in this analysis. These results are correlated with experimental results for cams produced with changes in grinding wheel size. In addition, other predictions of the effects of the rocker mechanism errors are presented. Moreover, changes in valve train dynamics due to cnc errors are investigated using actual error traces.

Finally, Chapter 6 draws some conclusions from this investigation and makes some suggestions for future work.