Development of Methodologies for Coupled Water-Hammer Analysis of Piping Systems and Supports

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SUMMARY

The paper presents the results of an investigation on the development of methodologies for coupled water-hammer analyses. The study was conducted because the present analytical methods for calculation of loads on piping systems and supports resulting from water-hammer phenomena are overly conservative. This is mainly because the methods do not usually include interaction between the fluid and the piping and thus predict high loads on piping systems and supports.

The objective of the investigation presented in this paper was to develop methodologies for coupled water-hammer analyses, including fluid-structure interaction effects, to be able to obtain realistic loads on piping systems and supports, resulting in production of more economical designs.

The following were the main tasks of the investigation:

- Review of existing coupling techniques for fluid-structure interaction analyses
- Evaluation of available methodologies and computer programs applicable to water-hammer problems
- Review of current experimental data available for computer program verification
- Description of numerical solution techniques applicable to complex piping networks
- Development of methodologies for performing coupled water-hammer analyses of piping systems and supports

As a result of this investigation, specific recommendations were developed for methodologies for coupled water-hammer analyses considering short-term and long-term goals.

1. INTRODUCTION

The present procedures of water-hammer analysis do not include fluid-piping interaction and thus predict high loads on piping systems and supports. The purpose of this investigation was to develop methodologies for water-hammer analysis including fluid-piping interaction effects, to be able to obtain realistic loads on piping systems and supports resulting in more economical designs.

The following are the major considerations, which must be satisfied in the development of a rational and practical methodology for including fluid-piping interaction in water hammer analysis.

- Initiating Events and Sources
- Propagation of Hydraulic Transients in Piping, Accounting for Abrupt Geometric Changes
- Fluid-Structure Interaction Effects, Including the Following:
  - Pipe Expansibility (Radial and Circumferential)
  - Overall Movements of Piping Systems, e.g., at Elbows
- Local Loading Due to Two-Phase Events, e.g., Steam Bubble Collapse
- Nonlinear Piping Deformations

The following tasks of the investigation are covered in this paper:

- Review of existing coupling techniques for fluid-structure interaction analyses
- Evaluation of available methodologies and computer programs applicable to water-hammer problems
- Description of Numerical Solution Techniques Applicable to Complex Piping Networks
- Development of Methodologies for Performing Coupled Water-Hammer Analyses of Piping Systems and Supports

The results of these tasks are summarized in the following text.

2. EXISTING METHODOLOGIES AND COMPUTER CODES

An extensive review was performed of the existing methodologies and computer codes. This included the following:

- Uncoupled Piping Thermal Hydraulic Methodologies and Codes
  - Linear Methodologies and Codes
  - Nonlinear Methodologies and Codes
- Coupled Water-Hammer Methodologies and Codes
- Other Coupled Methodologies and Codes
  - Other Coupled Methodologies and Codes for Light Water Reactor (LWR) Blowdown Analysis
  - Methodologies and Codes for Light Metal Fast Breeder Reactor (LMFBR) Analysis

- Most Recent Methodologies and Codes (with Long Term Application Potential)

A summary of capabilities of codes/methodologies for water-hammer analysis, developed as a result of this review, is presented in Table 1.

3. NUMERICAL METHODS FOR COMPUTATION OF FLUID RESPONSE

This section presents a description of numerical methods for computation of fluid response, applicable to complex piping.

The fluid response in a piping system must satisfy the field equations for the chosen fluid constitutive model, subject to boundary conditions and initial conditions. For one phase flow, the field equation consists of the conservation laws and the fluid constitutive law. For two-phase flow, several formulations of the field equations exist according to the constitutive model used. Boundary conditions on the fluid are given in terms of tractions on the fluid or velocity. Additional boundary conditions are posed by piping components, including area changes, valves, tees, orifices, and pumps. The following three aspects play important roles in the formulation of numerical methods for computing fluid response.

- Frame of Reference
- Spatial Discretization
- Time-Dependent Response

A qualitative assessment of the various fluid models was performed. Models based on three reference frames (Eularian, Lagrangian, Wave Front) were compared with respect to the following features.

- Wave Front Resolution Capability
- Effect of Large Fluid Motion
- Effect of Large Velocity Gradients
- Use and Effect of Numerical Viscosity
- Two Phase Modeling Capabilities

A summary of this assessment is presented in Table 2.

4. COUPLING TECHNIQUES

An evaluation was performed of coupling techniques for treating the problem of mechanical fluid-structure interaction.

Conventional methods of uncoupled analysis usually require two steps: (1) The structure is considered to be fixed (rigid) to calculate the time histories of fluid loadings over the entire duration of the event; (2) The time histories of fluid loadings so obtained are then applied to the structure (now allowed to be flexible) to obtain the uncoupled structural response history. Coupled techniques of analysis, on the other hand, consider the fluid-structure interaction effects to obtain the coupled fluid-structure response.

The following three approaches appear in the literature for the solution to the problem described above.

- Simultaneous direct solution of coupled equations, using 1D fluid model and 1D/2D/3D structural model, applicable to piping problems only

  This approach has so far been applied to piping, where the fluid region is reasonably represented in 1D, and the pipe structure is represented at various levels of dimensionality (1D, 2D, 3D), and includes the following methods

  - Lumped Parameter Methods, e.g., the SPAR fluid element and modal recovery methods (Refs. 7, 8), transfer matrix approach (Ref. 9), and modal synthesis method (Ref. 10)

  - Methods of Characteristics, e.g., PTA Code (Ref. 11)

  - Other Methods, e.g., Elbow Model (Ref. 12)

- Sequential solution, using unified 2D discretized model for fluid and structure, with built-in coupling condition, applicable to containment or piping problems

  In this method, the fluid and structural regions are both modeled with using finite elements. Thus the interface conditions on forces and velocities are built into the unified treatment. The fluid and structural equations are all integrated explicitly in time. Consequently, the solution obtained is not simultaneous. This approach has been used in the STRAW code (Ref. 13).

- Staggered solution, using separate 2D/3D discretized models for fluid and structure, with auxiliary coupling conditions, applicable to containment or piping problems.

  In this method, the fluid and structural regions are modeled separately, usually with a 2D/3D finite difference model for the fluid and a (2D/3D) finite element model for the structure. The two discretized regions are then coupled at the fluid-structure interface with coupling conditions, using the following staggered procedures.

  - Structural response is calculated from applied fluid pressures at interface and any other kinematic and loading conditions on the structure.

  - Fluid pressure and flow field are then calculated to satisfy fluid field equations and to match fluid and structural motions in a direction normal to the interface. Two variations then arise.

    - --- Strong coupling , where the interface conditions are strongly enforced by iterating on the fluid pressure and flow field until both the fluid field equations are satisfied and the fluid-structure normal velocities are matched. This technique is used in the codes ICEPEL, SHAPS (Ref. 14).

    - --- Weak coupling, where the interface conditions are weakly applied, in the sense that fluid velocity normal to interface is set equal to normal structural velocity. Fluid pressure and flow field are not adjusted to conform with new interface conditions due to structural motion. This technique is used in the codes STEALTH, K-FIX/FLX (Ref. 15).

Table 3 shows a qualitative evaluation of fluid-structure interaction models for piping analysis problems. Six coupled formulations are compared. All fluid models are coupled to a finite element structural model, except PTA and PIPVIB2. These fluid-structure interaction models have been evaluated with respect to the following criteria:

- Performance in Comparison with SRI International Piping Experiments (Ref. 16)

- Applicability to Complex Piping and Cost Effectiveness

5. RECOMMENDATIONS

The recommendations were divided into two phases. Phase I would concentrate on the development of a methodology and computer code for linear water-hammer analysis of piping systems. Phase II would be an extension to nonlinear water-hammer analysis of piping systems including complex thermal hydraulics and nonlinear behavior (material and geometric) of piping system.

There would be two major considerations in the development of the methodology proposed herein. First, there would be options available for upward compatibility. This means that the basic computer codes and tools used for achieving the goals of Phase I would also be used for achieving the goals of Phase II, so that future modifications can be made by expending least efforts and costs (without repetition of efforts). Secondly, division of labor between thermal hydraulics and structural/ piping analysis groups would be clearly recognized and taken into consideration in the development of the proposed coupled methodology. Thus, the thermal hydraulics group engineers would be responsible only for performing the thermal hydraulics portion of the analysis and development of loads for input to the piping analysis. The structural/ piping analysis engineers can then perform the dynamic analysis of piping systems and supports using the loads provided to them. The details of the recommendations are not presented here becasue of the confidential nature of the work. They will be presented in a separate paper after the completion of their implementation.

REFERENCES

1. "Water-Hammer in Nuclear Power Plants," U.S. NRC Report NUREG-0582, July 1979.
2. Moore, K. V., Rettig, W. H., "RELAP 4 - A Computer Program for Transient Thermal-Hydraulic Analysis," ANCR-1127, Rev. 1, March 1975.
3. Liles, D. R., et al., "TRAC-PF1: An Advanced Best-Estimate Computer Program for PWR Analysis," LASL Draft Report, 1981.
4. Hirt, C. W., et al., "SOLA-LOOP: A Nonequilibrium, Drift-Flux Code for Two-Phase Flow in Networks," LA-7659, NUREG/CR-0626, June 1979.
5. "EDAC/PIPE User's Manual," Nov. 1979.
6. "EDAC/PWAP User's Manual," 1981.
7. Belytschko, Ted, "Modal Recovery Methods for Solution of Fluid- Structure Problems with Rigid Wall Loads," to be published.
8. Schwirian, R. E., Karabin, M. E., "Use of SPAR Elements to Simulate Fluid-Solid Interaction in the Finite Element Analysis of Piping System Dynamics," Fluid Transients and Structural Interactions in Piping Systems, ASME Fluids Engineering Conf., June 1981, p. 1.
9. Keskinen, R. P., "Hydroelastic Piping Vibration Analysis by Transfer Matrices," Int. J. Pres. Ves. Piping, Vol. 9, 1981, p. 263.
10. Hatfield, F. J., and D. C. Wiggert, "Fluid-Structure Interaction in Piping by Component Synthesis," Fluid Transients and Structural Interactions in Piping Systems, ASME Fluids Engineering Conference, June 1981, p. 13.
11. Youndahl, C. K., Kot, C. A., Valentin, R. A., "Pressure Transient Analysis of Elbow-Pipe Experiments Using the PTA-2 Code," J. Press. Vess. Technology, v. 103, Feb. 1981, p. 33.

12. Valentin, R. A., J. W. Phillips, and J. S. Walker, "Reflection and Transmission of Fluid Transients at an Elbow," SMiRT5, Paper B2/6, Aug. 1979.

13. Belytschko, T. B., and J. M. Kennedy, "Computer Models for Subassembly Simulation," Nucl. Engg. & Des., Vol. 49, 1978, p. 17-38.

14. A - Moneim, M. T., "Coupling of a Three-Dimensional Structural Pipe Element to Two-Dimensional Implicit Dynamics," ASME Pressure Vessels and Piping Technology Conference, San Francisco, CA (1980).

15. Rivard, W. C., et al., "K-FIX: A Computer Program for Transient, Two-Dimensional, Two-Fluid Flow, THREED: Extension of the K-FIX Code for Three-Dimensional Calculations," LA-NUREG-6623, Supp. 2, Jan. 1979.

16. Romander, C. M., D. J. Cagliostro, "Experiments on the Response of Flexible Piping Systems to Internal Pressure Pulses," S. R. I. Fourth Interim Report, April 1976.

17. Gelinas, R. J., Doss, S. K., Miller, K., "The Moving Finite Element Method: Applications to General Partial Differential Equations with Multiple Large Gradients," J. Comp. Physics, v. 40, No. 1, Mar. 1981, p. 202.

18. Chorin, A. J., "Random Choice Solution of Hyperbolic Systems," J. Comp. Physics, v. 22, 1976, p. 517.

19. Engineering Decision Analysis Company, Inc. (EDAC), "Initial Investigations for Development of a Methodology for Coupled Water-Hammer Analysis," EDAC Report No. 330-010.01, prepared for Ontario Hydro, Canada, January 1982.

TABLE 1 SUMMARY OF CAPABILITIES OF CODES/METHODOLOGIES FOR WATER-HAMMER ANALYSIS

I. PHYSICS		
1. COMPRESSIBLE FLOW		MFE, RCM, MOC, LAGRANGIAN, EULERIAN, ALE
2. INITIATING MECHANISMS & TWO-PHASE EFFECTS		
• VALVE ACTION		SOLA-LOOP, TRAC, RELAP, STEALTH-1DP, ICEPEL, SHAPS
• FLASHING		
NON-EQUILIBRIUM		SOLA-LOOP, TRAC, RELAP 4 (MOD7)
EQUILIBRIUM		STEALTH-1DP, PTA, DAPSY
• BUBBLE COLLAPSE		SOLA-LOOP
• SLUG IMPACT		
LIQUIO-STRUCTURE		ICECO, SOLA-LOOP - FOR RIGID STRUCT.
LIQUID-LIQUID		POTENTIALLY WITH SOLA-LOOP
• INJECTION INTO VOIDED LINES		SOLA-LOOP, TRAC, RELAP
3. FSI COUPLING		
• PIPE RADIAL EXPANSION	DYNAMIC:	SHAPS (3D), ICEPEL (2D), STEALTH - 1DP
	STATIC:	DAPSY, PTA
• PIPE MOTION		SHAPS (3D), ICEPEL (2D), WECAN-SPAR (3D), TM(3D), MS(2D)
• PIPE FRICTION		(MOST THERMAL-HYDRAULICS CODES)
4. COMPLEX PIPING COMPONENTS & NETWORK		
• THERMAL HYDRAULICS		TRAC, RELAP, PTA, SHAPS, ICEPEL, DAPSY, STEALTH-1DP, SOLA-LOOP, TM
• STRUCTURES		SHAPS, EDAC/PIPE, WECAN-SPAR, ICEPEL, DAPSY, TM, MS
II. USER ORIENTATION & CODE DEVELOPMENT		
1. DIVISION OF LABOR		MRM (requires linearity)
2. UPWARD COMPATIBILITY		SOLA-LOOP, TRAC, ICEPEL, SHAPS

KEY:
RCM (RANDOM CHOICE METHOD) (Ref. 17
MFE (MOVING FINITE ELEMENT) (Ref. 16)
MOC (METHOD OF CHARACTERISTICS)
TM (TRANSFER MATRIX METHOD used in PIPVIB2 code) (Ref. 9)
MS (MODAL SYNTHESIS) (Ref. 10)
MRM (MODAL RECOVERY METHOD) (Refs. 7, 8)

TABLE 2 EVALUATION OF FLUID MODELS

(Frame of Reference)

FEATURE	EULERIAN (FDM)	LAGRANGIAN (FDM)	WAVE FRONT (MOC, MFE)
Wavefront Resolution	Smoothed by Built-In Viscosity	May be smoothed by viscosity required for damping noise	MFE gives sharpest resolution
Fluid Motion Magnitude	No restriction implied by mesh	Must be small to avoid mesh tangling, requiring short duration event or frequent rezoning	MOC is limited to small fluid motions
Velocity Gradient	Large gradients cause numerical diffusion	Large gradients require rezoning, causing diffusion	MFE best handles large gradients
Numerical Viscosity	Built-in (out of user's control)	Within user's control	Not used in MOC; used in MFE for node positions (not for production use)
Two-Phase Flow	Multi-fluid model possible for non-equilibrium processes within single zone	Homogeneous equilibrium model only, in single zone; zones with different phases require further modeling	With MOC, it is difficult to model two-phase flow because sound speed changes abruptly at phase interface MOC allows cavitation anywhere in piping

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Key:

FDM: Finite Difference Method
MOC: Method of Characteristics
MFE: Moving Finite Element Method

Table 3 EVALUATION OF FLUID-STRUCTURE INTERACTION MODELS FOR PIPING PROBLEMS

Description	STEALTH-1DP	SHAPS	STRAW	PTA-2	WECAN-SPAR	PIPVIB2
Fluid Model	Finite Diff. Lagrangian	Finite Diff. Eulerian	Finite El. Quasi-Eulerian	Meth. of Ch.	Acoustic	Acoustic
Structural Model	1D-Hoop (Elast.-Plast.)	Finite El. (3D-Pipe with 8 DOF)	Finite El. (2D-Axisym. beam)	1D-Hoop (Elast.-Plast.)	Finite El. (3D-Piping)	Lumped Param. (3D-Piping)
Coupling	Auxil. Weak	Auxil. Strong	Built In	Direct (Static Rad. Expansion)	1D Quasi-Euler. + Elbow Forces	Direct Analytic (Several Features; See Text)
Evaluation						
Performance on SRI Pipe Expts.	Excellent in Rigid Sect.; Overestimate Press. in Flex. Sect.	Good in Flex. Sect. Underestimate Press in Rigid Sect.	Good in Flex. Sect.; No Data for Rigid Sect.	Overestimate in Flex. Sect.; Underestimate in Rigid Sect.	(Not Appl.)	(Not Appl.)
Applicability to Complex Piping Syst. with FSI Cplg.	Several hydraulic Components; No Flexible Elbow; Straight Pipe Expansion	Several Components with FSI, including Flex. Elbow (2D Fluid-3D Pipe)	(Not for Complex Piping)	Several hydraulic components; No Flexible Elbow Straight Pipe Expansion	Few Hydraulic Components; Simple Flex. Elbow Model; Good for Transient Response of Complex Piping with Simple Hydraulics	Simple Hydraulic Components; Good for Vibration Anal. of Pipe-Fluid Interaction
Relative Cost of Complex Piping Analysis	Low	High	(Not Appl.)	Low	Low	Low