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HI-FLOW: Computer Program for Flow-Induced Vibration Analysis of Piping Systems

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Abstract

HI-FLOW is a computer program which enables piping engineers to perform flow-induced vibration analysis of complex piping systems at normal operating conditions. HI-FLOW was developed specifically to minimize problems due to flow-induced vibrations which are otherwise discovered only during the Preoperational Testing Phase in the construction of a nuclear power plant.

This paper describes the complex frequency-domain algorithm and numerical procedures implemented into program HI-FLOW, and its successful application to the flow-induced vibration analysis of a major piping system in a nuclear power plant.

1. Introduction

In the recent past, the Nuclear Power Industry has become increasingly interested in finding a reliable method to minimize, or to avoid the major problems which arise due to excessive flow-induced vibrations of major piping systems during normal operation. Up until now, major manufacturers of nuclear piping systems have relied almost exclusively on preoperational testing to identify problems arising from flow-induced vibration. This has not been a completely satisfactory method for two primary reasons.

First, preoperational testing itself is often on the critical path of the construction schedule leading to startup and licensing of each nuclear power plant. Discovery of excessive vibration problems in that phase of the schedule can lead to severe logistical problems, including diagnosis, development of a feasible solution, procurement of necessary hardware, and implementation of the required repair or retrofit.

Second, the problems arising from flow-induced vibration are unique to each piping system, and are quite sensitive to such parameters as pipe configuration, type and location of supports, and the flow regime. Although successful completion of preoperational testing undoubtedly reduces the likelihood of potential problems of vibration due to loads to which the piping system may be exposed to during its lifetime, no preoperational testing program can provide a truly comprehensive test of those loads and load combinations. As a result, although trial-and-error field modifications may solve the vibration problems in one flow regime, they may inadvertently aggravate the problem in another flow regime, or when combined with other loads.

Flow-induced vibrations under normal operating conditions are initiated by the cyclic pulsations caused by mechanical sources such as valves and pumps and, on occasion, by cavitation and turbulent flow in elbows, tees, reducers and orifices. Due to the relatively low damping in piping systems, when the dominant frequencies of cyclic pulsations approach, or coincide with, the natural structural frequencies of the piping system, unacceptable levels of resonance are induced. The resulting vibrations, when excessive, can severely shorten the life of the piping, pipe supports, and all other appurtenant equipment, including instrumentation and gauges.

2. Theoretical Background

During normal operating conditions in a nuclear power plant, the fluid in the piping system usually undergoes a period flow behavior in time. Such a behavior is commonly referred to as "steady-oscillatory". This behavior is in contrast to the "transient" flow in which a sudden change in flow occurs due to some abrupt change of a source (e.g., valve opening).

Basically, there are three methods by which steady-oscillatory flow in a piping system can be analyzed. They are (1) the Method of Characteristics (time domain solution), (2) the Impedance Method (frequency-domain solution), and (3) the Extended Transfer Matrix Method (frequency-domain solution). The Extended Transfer Matrix Method was implemented into HI-FLOW because frequency domain analysis is much more suitable and cost-effective for the analysis of steady oscillatory flow, and is much simpler and more systematic to implement than the Impedance Method.

The variables of interest in the flow in piping are h (head) or p (pressure), and q (discharge or volume velocity) or v (velocity). In steady-oscillatory flow of a piping system, the volume velocity, Q, and the pressure head, H, at any instant are described as:

$$Q = Q_o + q \qquad \text{eq. (1)}$$

$$H = H_o + h \qquad \text{eq. (2)}$$

where
- Q_o = mean velocity
- q = velocity variation about the mean value
- H_o = mean head
- h = head variation about the mean value

It should be noted that q and h are functions of both time and geometry of the piping system. In steady-oscillatory flow, it is assumed that the magnitude of q and h are relatively small in comparison to Q_o and H_o, respectively. Furthermore, q and h are periodic in time due to periodic excitation of the source.

Flow through a pipe is governed by the continuity equation (see Wylie[1])

$$\frac{dQ}{dx} + \frac{gA}{a^2}\frac{dH}{dt} = 0 \qquad \text{eq. (3)}$$

and the dynamic equation of motion

$$\frac{dH}{dx} + \frac{1}{gA}\frac{dQ}{dt} + \frac{fQ^n}{2gDA^n} = 0 \qquad \text{eq. (4)}$$

where g = gravitational constant
A = cross-sectional area of the pipe section
a = wave acoustical velocity along the pipe
f = Darcy-Weisbach frictional factor
D = wet or inside diameter of the pipe
n = exponential term of velocity in friction loss along the pipe

The solution of the equations of continuity and motions in terms of q and h as a function of space, x, is described in Wylie [1], and is given by

$$q(x) = c_1 \sinh(mx) + c_2 \cosh(mx) \qquad \text{eq. (5)}$$

$$h(x) = -\frac{a^2 m}{jgA\omega}(c_1 \cosh(mx) + c_2 \sinh(mx)) \qquad \text{eq. (6)}$$

where

$$m = -\frac{\omega^2}{a^2} + \frac{jgA\omega R}{a^2}$$

R = linearized resistance factor to account for the characteristics of the flow (turbulent or laminar)
c_1, c_2 = arbitrary constants to be determined
j = $\sqrt{-1}$
ω = harmonic frequency (rad/sec)

Eqs. (5) and (6) describe the state variables, q and h, at any section of pipe. The equations relating the variables at both ends of a pipe element of length L and flow from node i to node j are given by

$$q_j = \cosh(mL)\, q_i - \frac{j\omega gA}{ma^2} h_i \qquad \text{eq. (7)}$$

$$h_j = -\frac{ma^2}{j\omega gA} \sinh(ml)\, q_i + \cosh(mL)\, h_i \qquad \text{eq. (8)}$$

or, in matrix notation

$$\begin{Bmatrix} q \\ h \\ 1 \end{Bmatrix}_j = \begin{bmatrix} \cosh(mL) & -\frac{1}{Z_c}\sinh(mL) & 0 \\ -Z_c \sinh(mL) & \cosh(mL) & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} q \\ h \\ 1 \end{Bmatrix}_i \qquad \text{eq. (9)}$$

$$\text{where} \quad Z_c = \frac{ma^2}{j\omega gA} \qquad \text{eq. (10)}$$

is called the characteristic impedance of the element. The matrix in eq. (9)

which relates the state variables from node i to node j is called the extended field transfer matrix, [F], such that

$$\{f\}_j = [F] \{f\}_i \qquad \text{eq. (11)}$$

This matrix ix computed for each element and for every frequency throughout the execution of HI-FLOW.

Going from element to element, it is necessary to relate the state variables on the upstream side of the connecting node to the state variables on the downstream side of the connecting node. In order to do so, we need to define an extended point transfer matrix, [P]. This matrix is necessary to model changes in flow at a point due to changes in the boundary condition due to the existence of special devices (e.g., pump, valve, orifice, etc.). Examples of extended point transfer matrices for various boundary conditions and devices is given in Wylie [1].

3. Computational Procedure

The basic steps in the computational procedure is given in the flowchart in Figure 1. Briefly, the computational procedure can be described in the following way:

(a) In the data generation phase, the nodal coordinates and piping data are defined. Each run or section is defined in terms of run type (parallel, branch) and the pipe elements within each run. The flow vector define the connectivity of all runs from the upstream to downstream are identified. This flow vector is used to assemble all of the field and point transfer matrices for each run to the overall transfer matrix. Tee nodes and loop runs are also identified for subsequent computations. All boundary conditions for any nodes with either prescribed pressure or velocity are identified. Nodes with specific devices, including oscillating valves or pumps, are also identified. The range of frequencies over which the analysis will be performed is also required.

(b) In the excitation decomposition phase, a Fast Fourier Transform is performed for each prescribed source of excitation in order to define the number of required harmonics at which the flow-induced vibration analysis will be performed.

(c) In the run computation phase of HI-FLOW, the point transfer matrix, [P], for each node, and the field transfer matrix, [F], for each element of each run is computed. Nodes with special devices attached are updated in the corresponding point matrix. The transfer matrix for each run, $[U_r]$, is calculated by alternately premultiplying the point and field transfer matrices of each node and each element added, respectively, in going along the assumed flow direction. For example, in going from node 1 to node j, the transfer matrix for run r would be calculated as

$$[U_r] = [F_j][P_j][F_{j-1}][P_{j-1}] \ldots [P_2][F_2][P_1][F_1] \quad \text{eq. (12)}$$

(d) In the system transfer matrix assembly phase, the relative configuration of each run is identified as being either series, branch, or loop. Loop runs are first assembled to overall transfer matrix. The branch runs are then assembled, incorporating the boundary conditions at the ends of the runs. Series runs are then assembled and added to the overall transfer matrix. The overall transfer matrix, $[U_t]$, for the entire system is finally calculated.

(e) In the response calculation phase, with $[U_t]$ known between the two end points of the system at which at least two flow variables are known, the other two unknown flow variables (pressure and/or velocity) can be calculated. Once the pressure and velocities are known at these two end points, the pressures and velocities at all other nodes in the entire piping system can be calculated by constructing the appropriate transfer matrix linking the nodes with known variables to the node with unknown variables.

(f) In the total response time history calculation phase, steps (c) through (e) are repeated for each source of excitation. The responses at each harmonic for each source of excitation (in the frequency domain) are superposed. A Backward Fast Fourier Transform is then performed to obtain the pressure and velocity time history at each node. These time histories are saved for used in subsequent structural response analysis using standard finite element computer programs.

4. Applications

HI-FLOW was used to analytically predict the flow-induced vibration response of a major large-bore piping system in the Turbine Building of a nuclear power plant. The primary objective of that study was to demonstrate that the response of that piping system under normal operating conditions could be reasonably predicted using the analytical methods implemented into program HI-FLOW. The flow-induced vibration response of that piping system had been previously measured at selected locations along the pipe.

The pipe system consisted of pipes ranging in diameter from approximately 0.35 m to 0.75 m, and is approximately 80 m in length. The entire system was supported by several rigid hangers, spring hangers and snubbers. Flow under the normal operating conditions test ran through a series of valves, reducers, and tees to one of two pumps.

HI-FLOW was used to calculate the hydrodynamic force time histories at various points along the pipe. The FIV displacement responses to these hydrodynamic force time histories were then calculated using standard finite element structural analysis programs. The overall correlation between measured and predicted displacements was quite good, in light of the uncertainties in the material properties, particularly damping, and the support boundary conditions (effective stiffnesses of the snubbers) during the test.

5. References

/1/ Wylie, E. B., and Streeter, V. L., FLUID TRANSIENTS, McGraw-Hill, New York, 1978

/2/ ASD International, Inc., HI-FLOW: COMPUTER PROGRAM FOR FLOW-INDUCED VIBRATION AND STRESS ANALYSIS OF PIPING SYSTEMS, User's Manual, Version 1.0, June, 1984

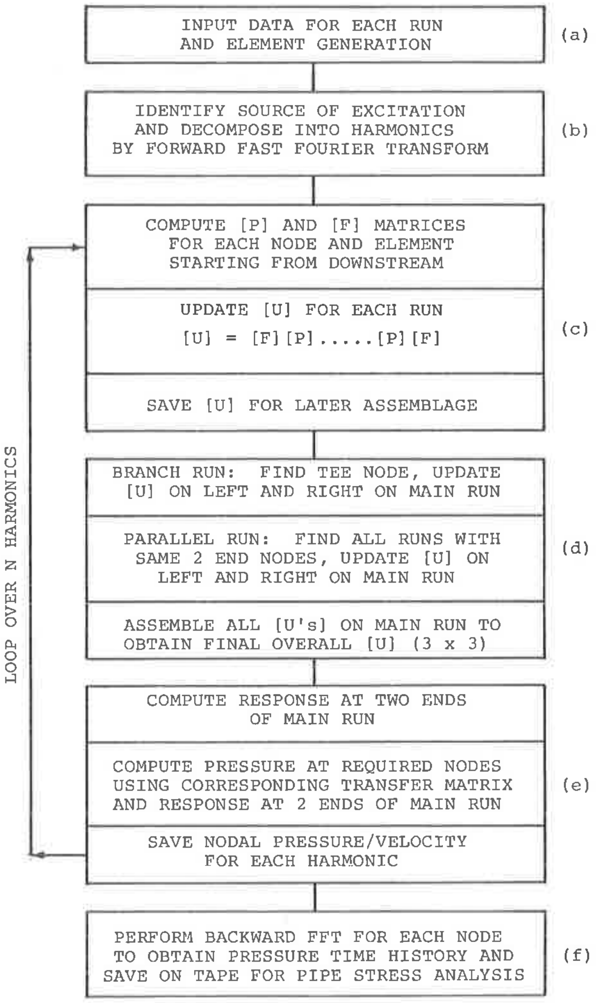

FIGURE 1

FLOWCHART FOR HI-FLOW COMPUTATION PROCEDURE