MODELING OF FLUID TRANSIENTS IN MACHINES
Part II: Advanced Considerations

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Abstract - This paper is Part II of a state-of-the-art literature review; emphasis is on advanced mathematical modeling considerations. The following topics are discussed: modeling of turbomachinery and positive displacement machinery, dynamic coupling of machines, transient behavior of machinery systems and installations, multi-dimensional transients, two-phase flow, interaction between wave propagation and fluid flow modes, and experimental modeling methods.

Part I[2] of this paper dealt with basic equations, assumptions, and other factors involved in the mathematical modeling of fluid transients in machines [71]. Typical boundary conditions, source descriptions, and solution methods were given. Part II emphasizes advanced topics.

MODELING OF TURBOMACHINES

For the analysis of transient flows in turbomachines, it is assumed that the steady-state operational characteristic curves are also applicable to the perturbations. It is also assumed that the dimensionless-homologous characteristics are also valid for the pulsating or transient flows [11, 12, 65, 72-78].[3]

The relationship between pulsating variables[4] across a turbomachine running at a constant speed can be given as

$$\begin{Bmatrix} p_d - p_i \\ \rho_d Q_d - \rho_i Q_i \end{Bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{Bmatrix} p_i \\ \rho_i Q_i \end{Bmatrix}$$

Subscript i is for inlet quantities; d is for discharge quantities. The impedance matrix terms Z_{11} and Z_{12} can be obtained from the steady-state characteristics; Z_{11} is the pressure gain and Z_{12} is the slope of the head vs. flow rate curve [11, 12, 65, 72, 73]. For an incompressible fluid, in the absence of cavitation and any structural compliance, Z_{21} and Z_{22} are negligible. When the cavitation phenomenon is important, Z_{21} and Z_{21} must be incorporated [65, 74, 78].

Running speed variations can also be incorporated in the above matrix in order to study various dynamic problems dealing with load and speed changes. The impedance term relating flow variables to the speed change variable can be deduced in a quasi-steady state manner from the characteristic curves [65].

Impedance matrix terms can either be computed theoretically or determined experimentally. Analytical predictions are usually based on the two dimensional free stream-line cascade theory. The frequency response is calculated for the oscillating inlet conditions [73]. Experiments are designed to determine an individual impedance matrix term or its equivalent under controlled perturbations of the inlet flow [72]. However, much more work needs to be done before a complete understanding of the turbomachine transfer function is achieved. This is especially true for cavitation conditions at the inlet of a turbopump or at the discharge of a turbine.

Lumped parameter models have been used to describe the dynamic behavior of turbomachines [59, 65, 73]. Impedance matrix terms can be modeled as discrete dynamic elements; e.g., Z_{11} as a gain amplifier, Z_{12} as a resistance, Z_{21} as a compliance element, Z_{22} as a gain amplifier. Discharge and inlet lines can also be modeled as discrete elements.

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[3] *References 1-70 are given in Part I*

[4] *For definition of variables, see Part I*

MODELING OF POSITIVE DISPLACEMENT MACHINES

Periodic flow variations are inherent in a positive displacement machine because of its kinematics. Consider a single cylinder machine with suction and discharge pipes. Unsteady flows in suction and discharge pipes, generated by the reciprocating action of the piston, are aided and modulated by the rapid opening and closing of valves. Pulsating flows are excited at the fundamental running speed and its higher harmonics [6-9, 23, 56-64, 79-91].

The basic processes of a positive displacement machine are interactive; for example, the fluid pulsations affect cylinder pressure, instantaneous mass flow rates, and valve displacements. Because of these dynamic interactions a simultaneous solution of mathematical models describing all basic processes has gained acceptance as a recommended procedure [60-64, 81-91]. For example, the following models are required to describe the source and fluid transient system for a compressor: cylinder thermodynamics, fluid flow through valves, valve structural dynamics, kinematics, suction and discharge manifolds, mufflers, and piping boundary conditions [61, 63, 82, 85, 87-89, 91].

Fluid oscillations are further complicated in a multicylinder machine because of the dynamic interactions between cylinders; such interactions can be identified and modeled as kinematic and geometric types of coupling [61, 63, 88-91]. The kinematic coupling effect is usually incorporated in the mass flow rate variables; the geometric coupling terms are included in an impedance matrix [61]. An alternate method of modeling multi-cylinder machinery manifolds involves a lumped parameter Helmholtz resonator approach [23, 60, 69, 91].

It is important to be able to calculate the effect of fluid transients on the thermodynamic efficiency and mass flow rate capacity. Various investigators have shown that adverse pulsations can drastically reduce thermodynamic efficiencies [6, 82, 92-94]. On the other hand, favorable pulsations, usually achieved through tuning, can improve mass flow rates and thus dramatically influence energy consumption or production efficiency [62, 82, 92-94]. Much work remains to be done in this area, especially for multicylinder machines [61]. Such similar studies as the analysis of a variable displacement pump are underway [30].

MODELING OF MACHINERY SYSTEMS

Machines are often an integral part of systems and installations; their fluid transient behavior is therefore strongly dependent on dynamic interrelationships with other components. An installation generally consists of several machines and such components as associated piping, valves, speed control mechanisms, and safety devices. Fluid transients are often caused by the following situations: sudden power failure, sudden start-up and stoppage of machines, abrupt changes in valve adjustment, load variations, and unstable operation [95-105]. Depending upon the situation and the installation network, the problem can either be truly transient or of the steady-state oscillation type. Both the method of characteristics approach and the linear impedance/transfer matrix approach have been successfully used to model and diagnose these problems [8-12, 95-105].

An additional complication can arise due to the cascading of machines -- that is, combining machines in series or in parallel. Such combinations form a dynamically coupled system; consequently, fluid pulsations are complicated [6, 12]. Pressure oscillations in a pipe between the interstaged machines are often pronounced [6].

MULTIDIMENSIONAL FLUID TRANSIENTS

Because the transverse dimensions of fluid-containing devices are generally smaller than the wavelength of interest -- which is dictated by the highest analysis frequency -- a one-dimensional model is sufficient. However, a two- or three-dimensional model may be required if the tranverse dimensions are large or a higher frequency range of analysis is desired [106-111].

Multidimensional models are complicated and costly. Unlike the one-dimensional model, the characteristics of multidimensional models can no longer be described by lines on a t-x plane; rather, a spatial description is required [107, 108]. An alternate simple approach is to represent flow by a latticework of one-dimensional flow elements, provided an account for the element overlapping is made [109]. This method is applicable only at low Mach numbers. As with some one-dimensional models, the finite-difference technique is used with multidimensional models [107, 109].

The finite element modeling technique has also been used in some cases [110, 111]. The NASTRAN program has only an axisymmetric finite element model; this model not suitable for some multidimensional problems [110]. Work in this area is currently in progress.

TWO-PHASE FLOW TRANSIENTS

Two-phase flow transients occur in the following cases: gas trapped in liquid systems, formation of gas or vapor bubbles by lowering pressures or increasing temperatures, and mixing of liquid and gas stream [112-128]. For modeling purposes, the dynamics of gas or vapor bubbles -- which depend on the amount, distribution, and size of the bubbles -- should be accounted for. These characteristics vary with time and thus are very difficult to assess. One technique relies on correlating the concentration of bubbles with the speed of wave propagation -- but the speed of propagation is no longer a constant [123-125]. Because of the complexity of the situation, therefore, very few modeling efforts have been successful [126-128].

The separated-flow model assumes that gas and liquid flow in separate regions [126]. A two-phase interface node description has been used to predict transients and steady state behavior of an engine carburetor reasonably well [128]. An implicit finite-difference technique was used for computations.

There is a strong need for basic mathematical and experimental models in the general area of two-phase flow. In particular, prediction and avoidance of cavitation phenomenon is important for the design and operation of machines and power-generating units [74-78, 111-113, 119-121]. Research in this area is currently in progress.

WAVE PROPAGATION AND FLUID FLOW INTERACTION

The development of wave propagation equations generally assumes that fluid flow and wave propagation modes are not coupled. However, many interesting physical phenomena exist due to the higher order coupling of these two modes; these phenomena are generally nonlinear [129-133].

Fluid-wave interaction effects can be categorized as a connective effect due to fluid flow, fluid-induced damping of the wave propagation, and fluid-induced oscillation and wave amplification. Some of these effects have already been covered in Part I of this review. Interactions between fluid and wave modes are more pronounced when the flow velocities (u_0) are higher and/or wave perturbation velocity (u) is finite [129-132].

Self-sustaining oscillations of flow cavities can be attributed to the instability of cavity shear layer and a feedback mechanism or to the excitation of fluid resonances by fluid flow or a solid boundary [133-136]. Wave propagation pressure amplitudes can also be amplified if a mechanism exists for continuous feed of energy from the fluid mode [131, 132]. Such effects have not yet been incorporated in mathematical models.

EXPERIMENTAL MODELING

Experimental methods are used to study physical phenomena and to verify results predicted by mathematical models. For complicated fluid transient systems and phenomena, it is not always possible to develop a model from theory. Consequently, experimental modeling methods are used [137-139].

A need for efficient and reliable experimental methods exists so that the inherent characteristics of fluid elements can be determined effectively without any influence from the machinery sources and terminations. The model experimentally obtained should possess both magnitude and phase information in order to describe fluid elements completely. This makes the concept of a building-block approach feasible when experimentally and analytically obtained transfer functions can be combined to build an overall mathematical model [139-140].

CONCLUDING REMARKS

This paper has been a state-of-the-art literature review of mathematical models applied to the study of transient and steady state flows in machinery. Because space limitations prevent lengthy discussions of many pertinent topics, the interested reader is referred to the references.

One question that has not been adequately explored is whether these mathematical models are only research tools or can be applied to conventional machine design and development. The answer lies somewhere in between. The state of the art is such that a designer can effectively incorporate some basic models into his analysis and obtain his decisions accordingly. However, sophisticated models are such that additional fundamental work must be done before technology transfer can take place. In this context, the use of finite-element programs for fluid transient problems should bring designers and non-experts closer to mathematical models. General purpose computer programs are not presently available; therefore, the fluid transients research should be concentrated in this area.

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