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A REVIEW OF LEAKAGE-FLOW-INDUCED VIBRATIONS OF REACTOR COMPONENTS

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FIGURES

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ABSTRACT

The primary-coolant flow paths of a reactor system are usually subject to close scrutiny in a design review to identify potential flow-induced vibration sources. However, secondary-flow paths through narrow gaps in component supports, which parallel the primary-flow path, occasionally are the excitation source for significant vibrations even though the secondary-flow rates are orders of magnitude smaller than the primary-flow rate. These so-called leakage flow problems are reviewed here to identify design features and excitation sources that should be avoided. Also, design rules of thumb are formulated that can be employed to guide a design, but quantitative prediction of component response is found to require scale-model testing.

1. INTRODUCTION

From startup through steady-state operation, rod, tube, plate, and shell components in nuclear reactors typically are exposed to a wide range of coolant (heat-transfer fluid) cross- or parallel-flow velocities and temperatures. Not uncommonly, the components are a channel for the flow. Thus, the components must be provided sufficient lateral support to maintain acceptable bending vibration levels while allowing axial movement to accommodate thermal expansion, control movements, and/or removal. Invariably the component supports consist of a fixed support at one end and other supports that constrain lateral motion as much as is compatible with allowing axial movement. Typically the lateral support is provided by the wall of a slightly larger hole in a plate, the inside of another tube (Fig. 1a) or shell, or a channel (Figs. 1b and 1c) with similar but slightly larger cross-sectional shape. As a result, finite length annuli with narrow gaps are created between the components and their lateral supports.

If the lateral supports are immersed in a nonflowing liquid, then the dual purpose of limiting lateral motion while allowing axial motion can be readily achieved, especially in liquids. For instance, added mass and fluid viscous damping is created by a liquid being squeezed in finite-length annuli with small gap sizes [1]. The mass and damping can be large enough

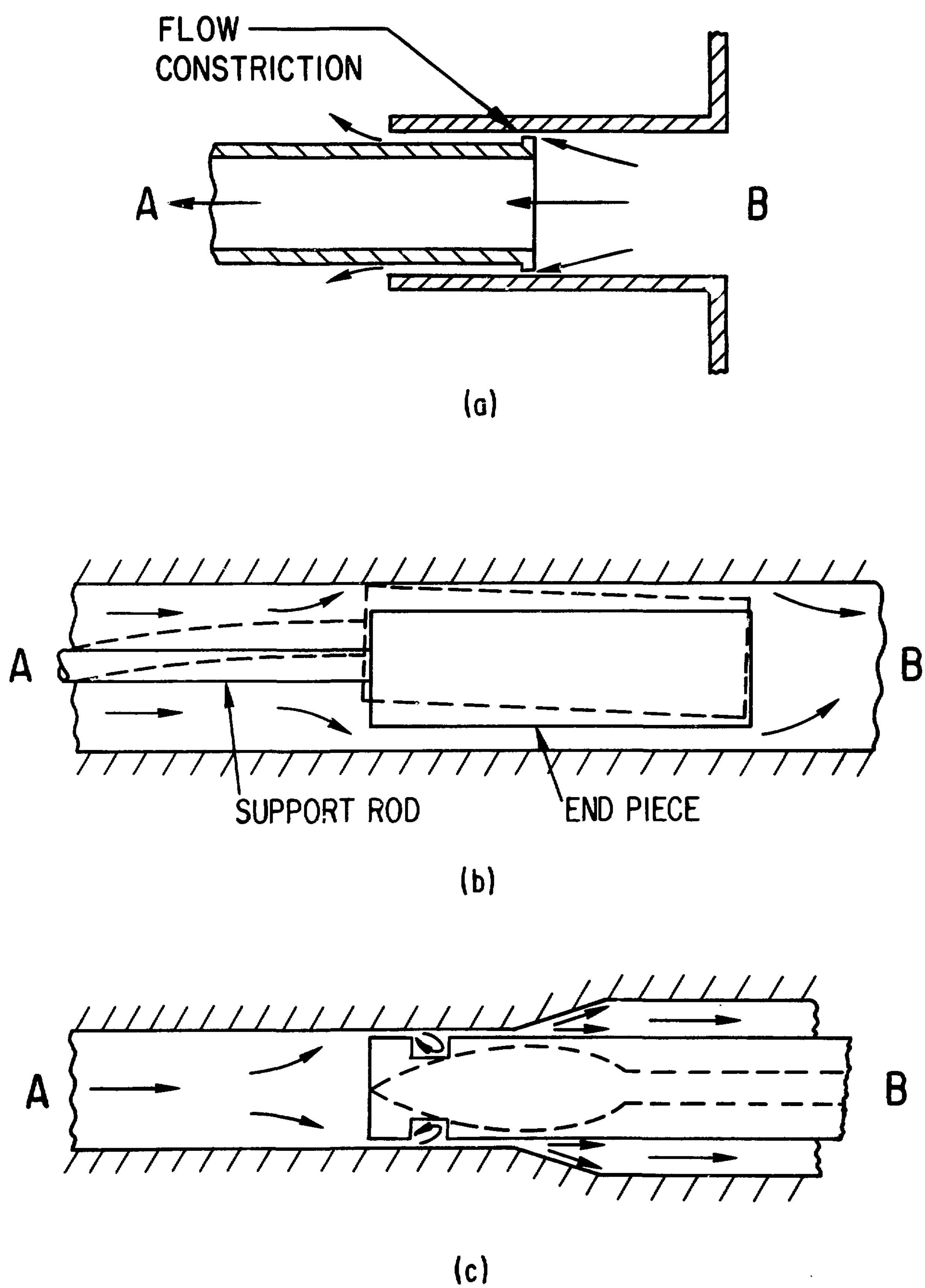

Fig. 1. Typical leakage flow paths

to essentially eliminate lateral motion and cause the support to act like a hinge for short-length annular regions and to approach a fixed support for long annular regions.

However, more likely than not, the main coolant flow establishes a pressure drop across the plate, cylinder, or channel in which the lateral support is located, and fluid flow leaks through the narrow passages created to allow axial motion of the component. As a result, the same narrow passages that form effective dampers in nonflowing fluid may be very effective amplifiers of the pressure variations caused by leakage flow and structural movement. Thus, the support that the designer intended to limit lateral vibration may be the site of a vibration source called, appropriately, "leakage-flow" excitation mechanisms. The term leakage-flow mechanism is meant to focus primary attention on vibrations caused by secondary flows through narrow gaps that form parallel flow paths to the primary coolant flow path. However, the literature of devices that control primary flows [e.g., 2-5] cannot be ignored, because many of the excitation mechanisms are similar and have undergone considerable study.

Structural vibrations associated with flow through the narrow gaps formed by a nearly closed gate on a hydraulic channel could occur every time the gate is opened and shut, if an excitation mechanism exists. Therefore, much effort has been put into study of the problems, and over many years, many geometries have been associated with flow-induced vibration (FIV) problems [2]. Although the mechanisms may not be fully understood, rules of thumb have been developed that are useful for design. Current efforts focus on developing general and systematic analysis methods for the identification of problem geometries [3,4].

Valves operating at small openings also are subject to excitation mechanisms: valve chatter, valves slamming shut, and water hammers are all familiar examples. Plug valves and check valves have been researched in detail [3,5]. However, most valve FIV problems appear to have been circumvented by trial and error during design or avoided in use by carefully selecting operating procedures.

The literature for channel gates and valves makes clear that the existence of excitation mechanisms are very dependent upon local geometry, and the development of a general understanding and predictive methods are still in progress. Thus the identifiation and compilation of the problem geometries in each new technology, such as the nuclear industry, is a necessary first step toward achieving problem-free designs. Already, many damaging and expensive leakage-flow vibration problems have been experienced in the nuclear reactor industry and some excitation mechanisms have been identified.

One purpose of this review is to identify and compile the known leakage flow mechanisms and problem geometries and thus provide a basis to avoid leakage-flow-induced vibrations in the design stage. Since the analytical procedures in the literature generally lack a quantitative predictive capability, another purpose of the review is to generate design rules of thumb (DRT) that can be used as guides in a new design. Of course, as in any developing area, the DRTs only represent trends in existing knowledge, and as new information is obtained the DRTs may require modification. Certainly, the state-of-the-art has not progressed such that design acceptance testing can be eliminated. However, before the problems, mechanisms, and DRTs are enumerated component by component, a general characterization of the fluid forces and vibration excitation mechanisms will be given for perspective.

2. FLUID FORCES

As for other geometries (if not more so), FIV mechanisms formed by narrow leakage flow passages are very complex. To discuss the mechanisms, one needs simplifications and definitions, but these are not unique. In the past, excitation mechanisms have been categorized [6] by associating them with two extreme types of fluid forces: fluid-excitation forces, which would exist independent of structural motion, and fluid-structure coupling forces, which cannot occur without structural motion. Structural vibrations caused solely by fluid-excitation forces are often called forced vibrations, while vibrations associated with fluid-structure coupling forces are often called self-excited vibrations. Example sources of fluid-excitation forces are random turbulence and discrete pump pulsations in the flow incident upon a flexible structure. An example of the creation of fluid-structure coupling forces is movement of one tube in a bundle of tubes that causes changes in the flow field around an adjacent tube, and vice versa. Such forces are the basic source of the self-excited whirling motion of tube bundles (heat exchangers) in cross-flow [7]. Depending on flow and structural conditions, other fluid-flow phenomena may result in either a fluid-excitation force, a fluid-structure coupling force, or a combination of both types of forces.

The fluid dynamic instability of flow separation is a phenomenon that may or may not couple with the motion of the structure from which it separates. The periodic vortices shed in the wake of a tube in cross-flow clearly lead to a fluid-excitation force and forced vibration when the frequency of vortex shedding and the structural natural frequencies are widely separated; when the frequencies are coincident and the structural damping is small, vortex shedding leads to a fluid-structure coupling force and self-excitation. For other combinations of frequencies and damping, which include the majority of situations, the fluid forces are difficult to categorize. In one attempt at further understanding, this situation has been classified [4] as a forced structural vibration due to fluid-excitation forces (flow oscillator forces) associated with a fluid dynamic instability controlled by structural (body resonator) movement. Also, the point is made, and well taken, that fluid dynamic instability could be controlled by fluid resonators in the system (e.g., periodic motion of a fluid reservoir, edge tones, or acoustic resonances of plenums and cavities). One of the most devastating excitation mechanisms occurs when a tube in a plenum is subject to vortex shedding at a frequency coinciding with both a structural natural frequency and an acoustic frequency of the plenum.

Although vortex shedding from tubes is the most widely studied and understood flow separation FIV excitation source, the potential for qualitatively similar behavior exists for any body from which the flow separates. Any bluff body has the potential to shed distinct (narrow frequency band) vortices. Alternatively, instead of vortices, the separated flow may reattach to the surface of the same or an adjacent body and periodically detach and reattach. Fluid-excitation forces are created when the periodic separation occurs without body motion, while fluid-structure coupling forces are created when periodic separation only occurs with structural motion [4,8].

3. FORCED EXCITATION

At first consideration of the flow in a narrow passage, the existence of vibration excitation mechanisms due to fluid-excitation forces might be deemed unlikely. After all, excitation of rods, plates, and shells due to the pressure fluctuations of an attached turbulent boundary leads to relatively small motion for isolated bodies [9]. Essentially, increases in the flow velocity parallel to a boundary increase the fluid damping as well as the excitation forces. The extreme confinement of narrow passages can be expected to produce even greater fluid damping for dense fluids and, therefore, smaller vibrations. Thus, significant fluid-excitation forces are not expected due to an attached boundary layer flow.

Excitation forces for separated flows are much stronger, partly because energy is concentrated in narrow frequency bands. In practice, the narrow passages are of finite length and geometric discontinuities usually occur at the entrance, exit, or intermediate cavities. The bluff leading and trailing edges of the bodies forming entrances and exits in Figs. 1b and 1c, the diffuser exit in Fig. 1c, and the cavities in Fig. 1c are places where flow separation may occur. Moreover, there are examples [8,10-12], of significant fluid-excitation forces created by detached boundary layer flows. Also, amplification by structural resonances or fluid resonances associated with the inlet plenums, outlet plenums, or intermediate cavities cannot be overlooked [4,13]. Vortex shedding from the trailing edge of finite-length plate and rods in parallel flow can be a strong mechanism for isolated bodies [14], but the effects of wall confinement [15] in very narrow channels has not been investigated. Periodic separation and reattachment of boundary layer flows are significant excitation sources for control gates in flow channels [2,8]; every attempt is made during design to avoid the creation of periodic reattachment phenomena, which are dependent upon local (seal) geometry.

Apparently, fluid flow behavior, potential for an excitation mechanism, and strength of fluid-excitation forces are highly dependent upon entrance geometry, exit geometry, and passage parameters such as the width-to-length ratio. This has been the experience with flow control gates. Thus, further characterization of a forced-excitation mechanism is difficult without reference to a specific problem geometry. In fact, analysis of forced-excitation problems usually includes scale-model tests to determine by direct measurement whether the excitation forces are sufficient to overcome the fluid damping forces.

Acoustic energy or pump pulsations are other sources of significant energy concentrated at discrete frequencies that usually are known or readily determined. If their strength and distribution also are known, vibrations can be predicted. Most often, resonant vibrations are avoided by making sure the source and structural natural frequencies are not near coincidence.

4. SELF-EXCITATION MECHANISMS

Self-excitation mechanisms appear to be more prevalent than fluid-excitation mechanisms in narrow passages, at least for dense fluids. Apparently any squeeze film damping, which can be an effective attenuator of forced excitation, is modified in a self-excitation mechanism. In fact, in many situations, self-excitation can be interpreted to occur when the negative fluid damping created exceeds the positive structural damping. The major design problem is to identify what conditions produce self-excitation.

Fluid-structure coupling forces and self-excitation mechanisms are even more system-dependent than fluid-excitation forces and forced vibrations. Not only must a particular type of flow geometry exist, but it must occur in combination with particular structural motions. As an example, one flutter instability of an airplane wing exists only when lateral and torsional (coupled) vibration motions occur at similar frequencies and slightly out of phase with each other. Thus, quantitative generalizations about self-excited vibrations cannot be expected, but there are some generalizable qualitative features that are worth identifying.

Self-excitation occurs when, during a complete cycle of vibration, the energy input to the structure by the fluid exceeds that which can be dissipated. This is a conceptually simple statement of the conditions necessary for instability, but one that is difficult to verify in general because the motion of the structure and the fluid forces are nonlinear functions of each other and the flow velocity field. Fortunately, the existence of an instability usually is of interest and not the actual motions. In such cases, infinitesimal, periodic motions can be assumed to occur, which greatly simplifies the analysis.

Often the structure can be approximated as a finite-degree-of-freedom system that can be combined [9] with the fluid equations of motion into a single matrix equation:

$$[M_s + M_f]\{\ddot{q}\} + [C_s + C_f]\{\dot{q}\} + [K_s + K_f]\{q\} = \{Q\} , \tag{1}$$

where $\{q\}$, $\{\dot{q}\}$, and $\{\ddot{q}\}$ are, respectively, the generalized displacements, velocities, and acceleration vectors of the structure. The mass, equivalent viscous damping, and stiffness matrices are composed of the usual structural components M_s, C_s, and K_s, respectively, plus the additional fluid components M_f, C_f, and K_f, respectively, which characterize the generalized fluid-structure coupling forces. For small motions, the M_f are assumed to be represented by added mass coefficients [6,9] determined at a zero flow velocity. The fluid damping C_f and fluid stiffness K_f include any flow velocity-dependent terms, and the fluid-excitation forces are represented by the force vector $\{Q\}$ on the left hand side of Eq. 1. The existence of a self-excited vibration is determined by seeking the flow conditions for which homogeneous solutions to the differential equation (Eq. 1) exist [e.g., 7].

If Eq. 1 represents a single-degree-of-freedom system, then $|q|$ can monotonically increase at zero frequency (statically) when flow conditions exist for which the total stiffness goes to zero, $K_s + K_f = 0$. This static instability, called divergence, may occur for multiple-degree-of-freedom systems if solutions to

$$[K_s + K_f]\{q\} = 0 \tag{2}$$

exist. A dynamic instability for a single-degree-of-freedom system, where the oscillations of the structure become unbounded with time, is possible for flow conditions which cause negative damping:

$$C_s + C_f < 0 \ . \tag{3}$$

For a multiple-degree-of-freedom system that possesses diagonal matrices in Eq. 1 and, therefore, uncoupled vibration modes, dynamic instability can occur in any vibration mode for which Eq. 3 is satisfied. Essentially, the instability depends upon dissipation or creation of energy through the structural velocity. In general, the matrices of Eq. 1 are unsymmetric, and the associated vibration modes are said to be coupled. For instance, translational and torsional motion of an airplane wing may occur at the same frequency but out of phase such that a zero value of translation and torsion do not occur simultaneously. For such coupled motion, fluid-structure coupling forces dependent solely upon structural displacements, not velocities, can dissipate or create energy which, in the latter case, can lead to a dynamic instability at a sufficiently high flow velocity. In most situations, the dynamic instabilities of multiple-degree-of-freedom systems are created by fluid-structure coupling forces associated with both structural displacements and velocities.

The qualitative characteristics given above for self-excited, unstable structural motions are valid for any structure, but there is a difference between the flow conditions of an isolated structure and a structure in channel flow. The distinction is certainly important for flow-control devices and may be for leakage flows.

For an isolated structure, only the changes in the flow-velocity field in the immediate vicinity of the structure are important in an analysis for self-excitation, since constant flow velocity upstream and downstream usually is a valid assumption. However, in pipe or channel flow, the pressure drop is more likely maintained constant, and motion of a structure in the channel may cause unsteady flow for all upstream and downstream fluid. This is the case, by definition, for a flow-control device operating normally, and upstream and downstream fluid inertia effects have been found to be significant in determining the instability of valves and gates [2,3,5]. Also, perturbations in the far field flow of a reed valve had to be postulated to predict both the initiation and the nonlinear limit cycle motion of unstable vibration [16]. For structures that are not flow-control devices (where flow is diverted from one side of the channel to another by structural motion, such as in leakage flow passages), the importance of upstream and downstream flow inertia effects is not as clear. If not important at small oscillations, these inertia effects may become important at large oscillations when flow is cut off periodically on different sides of the channel. None of the leakage flow analyses that were reviewed accounted for upstream or downstream acceleration effects.

The importance of fluid inertia can be demonstrated qualitatively by consideration of the often-employed [2,5] example of a plug valve (bathtub stopper) vibrating about a partially open position. Figure 2 shows an idealized single-degree-of-freedom model of the valve with significant upstream and downstream fluid mass. Assuming the valve oscillates at a very high frequency, the rate of flow through the valve opening will remain steady because not enough time occurs during a vibration cycle to accelerate and decelerate the upstream and downstream flows. For a steady flow rate and an opening valve ($y > 0$), the flow velocity in the gap will decrease in proportion to the displacement, and thus create an increase in fluid pressure below the valve in phase with the displacement. However, forces in phase with the displacement cannot do net work in a cycle of harmonic motion; therefore, a dynamic instability will not occur. Static divergence may occur, but displacements would be minimal for a stiff valve.

At a substantially lower frequency of valve oscillation, enough time will be available during a cycle for accelerating and decelerating the upstream and downstream fluid, and unsteady flow will occur. For a positive valve velocity ($\dot{y} > 0$), the rate of flow through the valve will increase instantaneously and the downstream fluid will accelerate. This requires an increase in the downstream pressure gradient and, because P_1 is constant, an increase in pressure below the valve. Because this fluid force is in phase with the valve velocity, positive work is done and the potential for a dynamic instability exists. For valves having a very low frequency of oscillation, changes in flow rate may occur in a relatively short time with respect to the period of oscillation, and the flow is essentially steady. Because the flow velocity and pressure again are in phase with the valve displacement, a dynamic instability is not possible but static divergence with large displacements may occur for very flexible structures.

In short, the significance of the upstream and downstream fluid on a leakage flow excitation mechanism should be assessed on a case-by-case basis. In an analysis of leakage flow instabilities, a constant upstream flow rate should not be assumed automatically. In scale-model testing, upstream and downstream hydraulics require simulation unless their distortion can be justified. If fluctuations in the upstream and downstream flows are prototypic and significant, then care must be exercised in the selection of the model's flow source, flow-control device, and fluid reservoirs. For instance, flowstream fluctuations at the proper frequency could interact with the pressure head of a pump along its pump curve, with the servo mechanism on an automatic valve, or with the sloshing frequencies of a reservoir and thus distort the scale modeling.

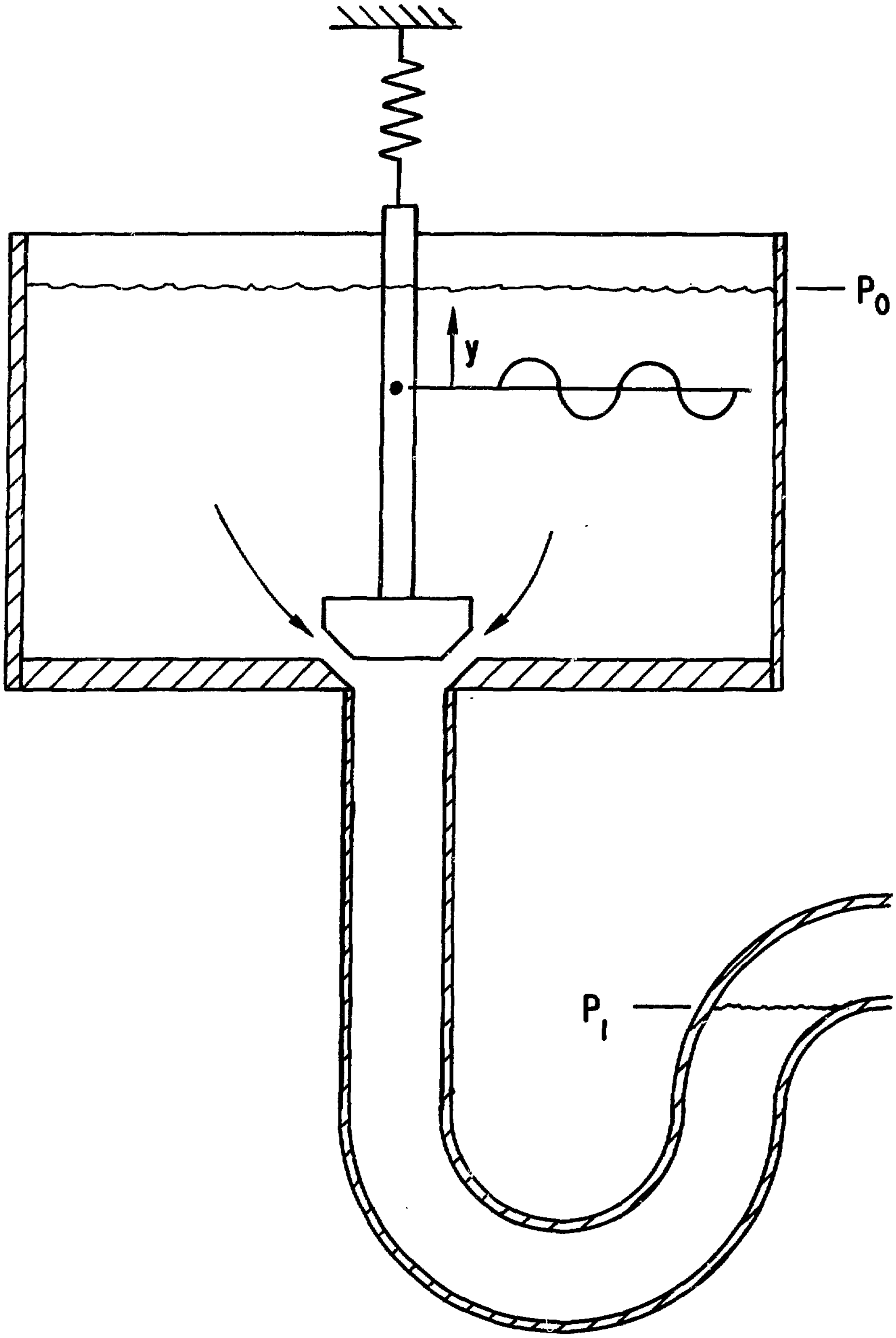

Fig. 2. Plug valve

5. PLATES AND BLADES

Forced excitation of plates and blades in narrow channels (e.g., Figs. 1 and 3) does not appear to be a strong excitation mechanism; no specific problems were found reported in the literature. Only general guidance, such as given in 3. Forced Excitation, is available for the FIV review of a specific design.

Early interest in the self-excitation of rods and blades in nuclear reactors was stimulated by the concern for vibration of control rods. A typical control-rod geometry is well represented by Fig. 1(b), if it is rotated into a vertical position with the end piece down. In the case of the control rod, the end piece is massive and rigid in comparison to the very flexible support rod. To determine geometries that would produce static divergence (negative fluid-stiffness forces), a steady, two-dimensional (assuming a wide blade), viscous flow analysis was performed [17]. The inlet and outlet pressures for both leakage flow channels along the side of the end piece were assumed to be the same, and no entrance or exit losses were included. When the sides of the blade were parallel to the sides of the flow channel, the resultant fluid force due to both leakage flow channels was zero for any location in the channel. However, if the end piece rotated (see dashed lines in Fig. 1b), the expanding leakage flow channel on one side of the blade was found to produce a negative fluid stiffness force larger than the positive stiffness force produced in the converging leakage flow channel on the other side of the blade. This imbalance resulted in a static divergence. As a result of this study, a useful design rule of thumb (DRT) was developed:

> DRT1 - Building a convergence or, alternatively, a divergence into the leakage flow channel geometry on each side of a blade can result in a self-centering or, alternatively, a divergence of the blade.

Because the upstream end seals (hydraulic dams) of Fig. 1a represent the severest example of a diverging leakage flow channel geometry, then Fig. 1a may result in a divergence of the central body. If the leakage flow were reversed or the flow constriction moved to the upstream end of the leakage flow channel, then self-centering of the central body would be possible.

To anticipate the potential existence of dynamic instabilities for the geometry of Fig. 1a, a design rule developed in the flow-channel control-gate technology [2] is applicable here. As illustrated in the plug valve example in 4. Self-Excitation Mechanisms:

> DRT2 - A static divergence for a low-frequency (stiffness) structure often is an indicator that a dynamic instability will occur for the same structure with a higher frequency (stiffness).

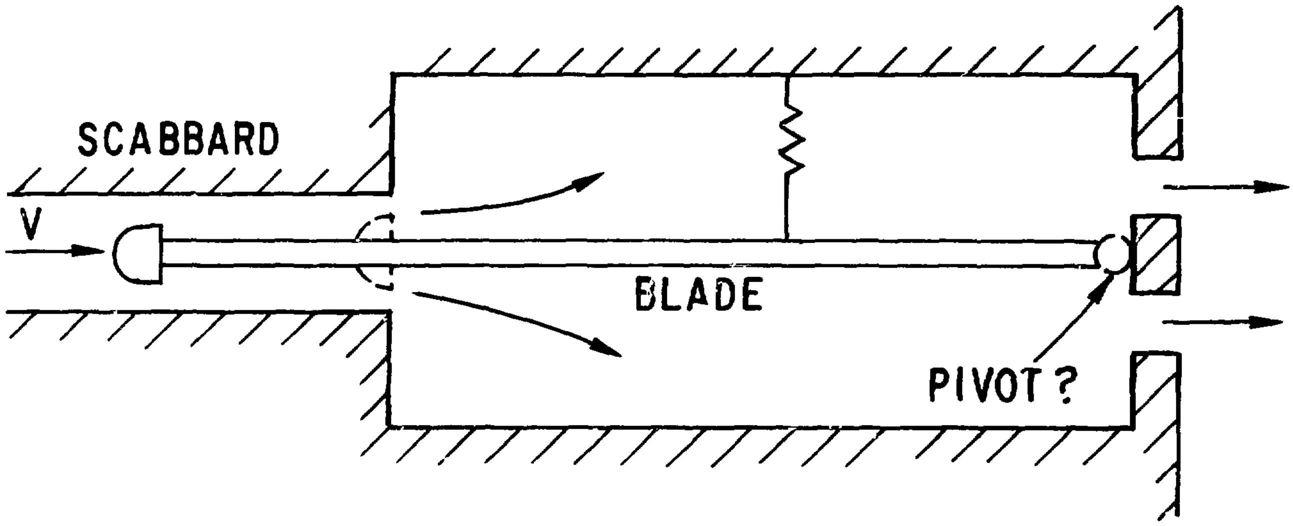

Fig. 3. Blade in channel flow

Indeed, without the benefit of this hindsight, a dynamic instability was postulated and demonstrated [18] for the diverging leakage flow geometry of Fig. 1a. However, the initiation of the instability was not based on static fluid forces and angular motion alterations produced by impacting with the flow channel walls, as hypothesized in [17], but the mechanism was based on local fluid acceleration effects similar to those at the root of the plug valve instability (Fig. 2).

Consider giving the center body of Fig. 1a an upward transitional velocity that results in a flow rate decrease in the upper channel and a flow rate increase in the lower channel. As a result of these localized valving effects, fluid in the upper channel must decelerate while the fluid in the lower channel must accelerate. Therefore, the pressure in the upper channel must instantaneously become smaller than at A, while the pressure in the lower channel must become greater. The resultant force on the central body is in phase with its velocity (negative damping), and the single-degree-of-freedom system may become unstable. However, if the end seals were switched to the end of the outer body (the upstream end of the leakage flow channel), then positive damping would be produced and the potential for dynamic instability would not exist. The design rule of thumb is:

> DRT3 - A strong potential exists for a dynamic instability when hydraulic dams or partially open seals occur on the upstream end of a leakage flow channel.

Of course, only a test or analysis will determine whether the structural frequency or fluid inertia are such that static divergence or a dynamic instability will occur.

Several quantitative analysis methods have been offered to identify when static divergence, dynamic instability, or stability would occur for more complicated examples. The failure of a fuel plate in a nuclear rocket led to two analyses and one experimental study [19,20] of a very thin plate, with a rounded leading and streamlined trailing edge, in a channel whose width, and therefore the leakage flow gap, could be varied. The plate was supported at its leading edge such that it could translate and rotate like the end piece in Fig. 1b. In one flutter analysis [19], the fluid forces were obtained with a two-dimensional, inviscid potential flow theory developed specifically for model aircraft wings where wind tunnel wall interference effects are significant. In a subsequent analysis [20], the fluid forces were obtained by one-dimensional channel flow analysis to determine whether the inclusion of first-order viscous effects could explain the poor correlation of the potential flow based theory with the experimental results.

Although both analysis methods [19,20] are able to correlate reasonably well with the experimental data at large leakage flow channel gap sizes, neither predicted, even qualitatively, a rise in critical velocity with a decreasing gap size. Even though inertia effects were shown to be dominant, the poor correlation was thought due to the neglect of second-order viscous effects brought about by the linearization of the equations of motion. Based on the possible importance of fluid inertia, discussed previously, an alternative explanation of the discrepancy can be formulated. Although both analyses accounted for local fluid-inertia effects in the vicinity of the blade, both assumed the upstream and downstream flow rates were constant. One analysis procedure [20] accounted for the possibility of upstream and downstream variations in the flow rate but assumed them zero to simplify the numerical evaluations. If accelerations of the upstream and downstream fluid became significant at narrow gap sizes, they could have a relatively larger effect than fluid accelerations around the blade and change the qualitative trends of the variation of critical velocity with gap size.

Despite the poor correlation of theory with experiments at small gap sizes, the streamlined plate studies showed that:

> DRT4 - Even without an upstream constriction, a dynamic instability is possible if simultaneous rotations and translations of the plate element are possible.

The results of the constricted and streamlined plate studies point out a need for information that would be useful in design. In particular, under what conditions will a downstream constriction stabilize the motion of a plate element which can simultaneously translate and rotate?

A one-dimensional, viscous flow analysis was employed in a linearized stability analysis of a blade in a scabbard geometry (see Fig. 3) [21], which has features very similar to the geometry of Fig. 1a. Instabilities were determined to exist for either a rigid body translation mode or a rotation mode (about the pivot shown hidden in Fig. 3). Also, many qualitative trends predicted by analyses [21,22] were experimentally observed. At low flow rates, stable oscillations of the blade were followed by dynamic instabilities at intermediate flow rates. A further increase in flow rate was shown to result in a sudden drop in vibration frequency and static divergence. Holding other parameters constant, either an increase in the channel (Darcy) friction factor or an increase in the length of insertion of the blade in the scabbard (overlap in Fig. 1a) decreased the range of flow rates and the minimum flow rates for which dynamic instabilities occurred. The strongest effects are worthy as a design rule of thumb:

> DRT5 - A decrease in the flow area at the upstream constriction (hydraulic dam) of a translating blade will lower the critical velocity, while including additional pressure losses at the downstream end of the scabbard (dashed hydraulic dam in Fig. 3) will increase the critical velocity.

Although the qualitative behavior was predictable, the quantitative predictions of critical flow velocities and vibration frequencies were off by at least an order of magnitude. The discrepancies were attributed to the experimental difficulty of eliminating cross-flow between the upper and lower channels at the sides of the blade. The cross-flow was assumed zero in the analysis. However, again, the analysis does not account for any upstream or downstream flow acceleration effects.

6. RODS AND TUBES

Many forced-excitation mechanisms have been identified for a rod or a tube in a slightly larger circular channel because this geometry is prevalent in the fuel channels of the UK Advanced Gas Cooled Reactors (AGR) where long, slender, often articulated fuel stringers are loaded into fuel channels while the reactors are generating power. As the stringer is lowered into the channel, many different entrance and exit conditions are created that cause the gas flows to separate. Several have been found to excite the fuel stringer into vibration. It may be significant that all these forced-excitation mechanisms occur in gas flow. Similar and larger fluid-excitation forces can be expected for dense fluids, such as water or sodium, but the squeeze film damping also will be significant and, perhaps, dominant.

Because refueling during operation is a major advantage of the AGR reactor, a considerable amount of research has been done and reviewed several times [10-12]. The reader is referred to these reviews for details of fluid-excitation mechanisms whose sources are:

a. Flow separating off the front end of a centered cylinder that triggers two periodic flow separations in a downstream, annular diffuser section (e.g., Fig. 1c),
b. A periodic flow separation from the side walls of an annular diffuser that is not axisymmetric because of the eccentricity of the central rod (e.g., Fig. 1c with the central rod moved off center),
c. Vortex shedding across the ligaments between the holes in the outside wall of an annular region perforated to allow outward radial flow, and
d. Impinging jet instabilities created by the radial outflow through a circumferential slot forming the common exit in the outside wall for two opposing annular flows (as the third leg of a pipe tee is the exit for flow feeding into the other two legs).

Although structural motion was observed to amplify the strength of some of the fluid-excitation mechanisms listed above, fluid-excitation forces always were present and said to be sufficient alone to create undesirable vibrations. On this basis, hydraulic (structurally rigid) models were employed to identify and understand the fluid instability mechanisms, but further characterization of the structural dynamic problem was minimal. Usually the problems were eliminated by redesign.

However, structural motion was found to be important in the self-excitation of an AGR flow-control device: a gag bomb. Details of the fluid flow and structural response were determined in an extensive research effort [23]. Because fluid stiffness, fluid inertia, fluid damping, and flow separation were all found to be important in determining the fluid-structure coupling forces, the problem will be discussed in some detail here, even though the device was not a true rod or tube.

The diffuser section geometry of Fig. 1c represents well the local flow geometry near two of the four equally spaced, narrow guide fins that protrude only slightly at the major diameter of the axisymmetric main body (dashed lines) of the flow control gag bomb. Nearly pure translatory motion prevailed for the gag bomb which was hung vertically, much like a pendulum, and the fluid flow provided the only stiffness that was substantial at the normal operating gas flow rates (<200 ft/sec). At least two self-excitation mechanisms were associated with secondary flow in and around the smallest gaps between the narrow fins and the flow channel walls: the throat at the upstream end of the diffuser section. These mechanisms may have been active in the much larger primary flow channel between the main gag body and the flow channel wall, but the secondary flow, which is loosely interpreted as leakage flow, was identified as the source of self-excitation.

One mechanism was the flow acceleration and deceleration (local valving) mechanism [17] discussed in 5. Plates and Blades. Not only was the same rationale given for its existence, but the theoretical considerations reaffirmed DRT5 and identified another rule of thumb:

> DRT6 - A dynamic instability is more likely and/or will occur at a lower flow rate when a greater change of flow velocity occurs for the same change in constriction (throat) size due to structural movement.

Already, this design rule of thumb has been employed to eliminate valve excitation mechanisms [3].

The other self-excitation mechanism identified for the gag bomb was associated with localized choking of the flow that could occur on the fins but not on the main body of the gag bomb. At the instant one fin touched the side of the flow channel, the flow velocity would go to zero and flow separation would occur. However, upon reopening, a finite time was required to reaccelerate the fluid to the velocity necessary for reattachment. Thus, the fluid forces have a component in phase with the fluid velocity. Although the width of the fins was narrow in comparison to the circumference of the main body of the gag bomb at the diffuser section throat, the hysteresis mechanism developed at the fins evidently prevailed over a larger area of the diffuser throat. As a result, the associated negative damping was large enough to produce a dynamic instability. The rule of thumb to be learned here is:

DRT7 - Avoid designs where velocity gradients created by structural movements cause boundary layer separations.

Although this design goal is difficult to attain completely, the severity of the separation (in space and time) can be minimized [2].

Since a complete redesign of the diffuser and gag bomb geometry could not be accomplished to eliminate the features causing the dynamic instabilities, simpler design modifications were made to pin the gag bomb against the side of the channel: intentionally cause static divergence. One side of the throat of the diffuser was vented (holes were drilled), which locally spoiled the flow, slowed the fluid velocity, and raised the static pressure, creating a negative fluid stiffness sufficient to hold the gag bomb against the side opposite the vent holes most of the time. Also, when momentary excursions away from the wall did occur, the energy that could be input to the gag bomb was greatly reduced because of the substantial reduction in fluid stiffness and much lower frequency of motion. This is an alternative rule of thumb:

DRT8 - Intentional static divergences can be created to eliminate a dynamic instability.

However, DRT8 must be used with care. The negative stiffness created must be large enough to pin the center body against the side wall for all expected flow velocities and structural motions. In the case of the gag bomb, trial holes in the lower velocity downstream section of the diffuser were not able to create negative fluid stiffness forces sufficient to dominate the negative damping forces created in the higher velocity diffuser throat section, and a severe instability persisted.

Although the gag bomb is not a true rod in an annular region, it hints that many of the mechanisms and design rules identified for plates in channel flow may be applicable for annulus flows. Indeed, this trend was shown to be the case in a very recent study [24]. Linearized, two-dimensional equations governing the axial and circumferential motion of an incompressible, inviscid fluid in a very narrow annulus formed by a finite-length rod located concentrically in a slightly larger, rigid channel were solved for infinitesimal translational motion of the rod. The mean axial flow velocity in the annulus was assumed much larger than the periodic velocity fluctuations produced in the flow by the rod movement, and the flow immediately upstream and downstream of the rod was assumed to be quasi-steady: acceleration effects were not postulated to occur in the upstream and downstream flow, only in the fluid annulus. As might be expected by now, the existence of a fluid force in phase with the rod velocity, a necessary condition for self-excitation, was found to be very dependent on the upstream and downstream fluid boundary conditions.

For a finite-length rod with a front end streamlined to provide a no-loss entrance to the annular region (e.g., a bullet) and a free discharge at the annulus exit (see Fig. 4 exit) into a constant pressure plenum, no instability existed because the fluid damping and stiffness were positive and increased with flow. As for the blade and gag bomb examples, negative damping and dynamic instabilities were possible for a rod of radius r with a constriction at the entrance to the annular region and free discharge at the exit to the annulus (Fig. 1a). Not only was DRT5 identified with an annulus, but the analysis enabled more definitive information: self-excitation at a frequency ω was not predicted unless the constriction blocked more than one-half the annular channel; the reduced velocity $U/(\omega r)$ was identified as the dimensionless parameter that had to exceed a critical value for self-excitation; and increases in the length of the annular region up to three rod diameters significantly increased the fluid damping (whether positive or negative), but further increases had little effect.

For a rod with a streamlined (no-loss) inlet and a constriction at the exit to the annular region, positive damping was always predicted. This reinforces the research results for blades and makes clear that:

> DRT9 - To avoid self-excitation, any necessary constrictions (blockage) should be placed at the downstream end of a leakage flow path.

For a rod with a streamlined entrance and annular diffuser exit to the annulus, negative damping was not predicted unless the efficiency of the diffuser was assumed to increase as the throat size enlarged due to structural motion. Since the separation that occurred for the diffuser section of the gag bomb is an example of such efficiency changes, then the validity of design rule DRT7 is extended to true annular regions.

The analysis results recited above for the annular region reinforce the applicability of all the qualitative trends and rules of thumb observed for blades and the gag bomb, and give some hope that more quantitative information can be determined. However, experimental results and additional numerical results for more complicated geometries from the same study [24] make clear that:

> DRT10 - The available information on self-excitation due to leakage flow have a limited range of application.

In particular, the inability to correlate theory with experimental results was traced to the inability to concentrically align the rod in the channel. Some lateral and rotational eccentricities are inevitable for such small gap sizes, and they were found to significantly influence the results. For example, experiments showed the rod with a streamlined entrance and free discharge exit to the annulus was unstable for some conditions of eccentricity. In addition, the effects of wall friction losses were included in a numerical study that showed an increase in the fluid damping in many cases but a decrease in other cases. Further, numerical studies of a rod that could rotate, as well as translate, or deform as a cantilever beam, showed that axial mode shapes were an important parameter. The same geometric configuration could be stable in one mode but unstable in another. For example, a rod with a streamlined upstream entrance and constricted exit to the annulus is stable for rigid-body lateral translations but could become unstable if a displacement node lies close to the constriction.

Other examples exist that indicate the need for a detailed knowledge of the fluid-structure interaction and a cautious application of past experience to a new design. The self-excited vibrations of a feedwater sparger [25] were attributed to leakage flow in a true annulus having features similar to Fig. 1a. In this case, the center tube represents the third leg (thermal sleeve) of a tee forming the inlet to the feedwater sparger: a semicircular, perforated pipe with the tee located at midlength and supports located at the two closed ends. The outside tube in Fig. 1a represents a penetration nozzle in the side of the reactor vessel. Unstable lateral (out of plane) vibrations of the semicircular sparger were found to occur. The structural motion did not occur at the measured fundamental structural frequency, but at sub and superharmonics of a lower key frequency that varied with flow velocity. Such motion is characteristic of a nonlinear system. Another nonlinearity indicator was that slight perturbations in motion could cause the sparger to become unstable at flow rates for which the motion would have otherwise remained stable. All these features suggested that the previously discussed local flow valving mechanisms [17,23], associated with lateral translations of the thermal sleeve, could have been responsible for the self-excitation. However, the existence of valving was refuted by dynamic pressure transducer measurements made on the wall of the overlap region. The measurements showed no correlation with any of the periodic structural motion. Also, self-excitation occurred even when the overlap region was eliminated: only the very short annular region of the constriction was left.

In subsequent shaker tests of the sparger, a further understanding of the structural motion was obtained. Because of the complex support system, small axial movements of the thermal sleeve could be responsible for large lateral motion of the main sparger. As a result, an excitation mechanism based on axial movement of the thermal sleeve was theoretically postulated and found to exist in a model experiment [26]. Although this may not have been the sparger's excitation mechanism, it is another mechanism to be aware of in a design review.

The geometry of the model experiment is essentially that of a piston (see Fig. 4) that can oscillate only in the axial direction and is subject to a constant rate of flow. The key assumption in the analysis identifying the excitation mechanism was that the leakage flow exits from the annular region and separates from the trailing edge into a constant pressure plenum. A free discharge existed for the plant unit sparger. The acceleration of the fluid as it entered the narrow annular region around the upstream corner of the piston was explained to result in a pressure depression which was modulated by the relative velocity of the piston with respect to the fluid. Upstream pressure fluctuations in phase with the piston velocity and a constant downstream pressure produced a negative damping force. When this exceeded the positive damping force produced by shear stresses in the annular leakage flow path of length L and width δ, unstable motion was predicted to occur at velocities dependent mainly on fluid viscosity and L, but not on δ. Of course, a larger L produced more positive damping. This qualitative feature was verified in experiments, but the actual critical velocities were again greatly underestimated (factor of 4).

7. OTHER CONFIGURATIONS

One of the earliest reactor industry identifications of leakage flow as vibration excitation mechanism was made in an investigation of the loosening (broken retainer bolts) at the supports of a cylindrical shell serving as a thermal shield between a reactor core and pressure vessel wall [27]. Although the annulus between the thermal shield and the pressure vessel was subject to the constant pressure drop developed by flow through the reactor core, a seal ring at the bottom of the shield was supposed to prevent water from bypassing the core through the annulus. However, leakage did occur after a threshold core pressure drop was exceeded, and it was characterized as a very nonlinear function of core pressure drop and movement of the shield. The geometric and flow configurations were very similar to Fig. 1a, where the inside tube represents the thermal shield, the outside tube represents the vessel wall, and the constriction at the entrance to the annular region represents the seal. The vibration motion was characterized as a rigid-body, transverse (vertical in Fig. 1a) translation of the thermal shield such that its center motion described an elongated ellipse. Analytical estimates of the fluid forces were made in the same manner as they were made for the rod in circular channel having an entrance constriction and free discharge to the annular region [25]. Not surprisingly, the qualitative results were the same. For a sufficiently large leakage flow

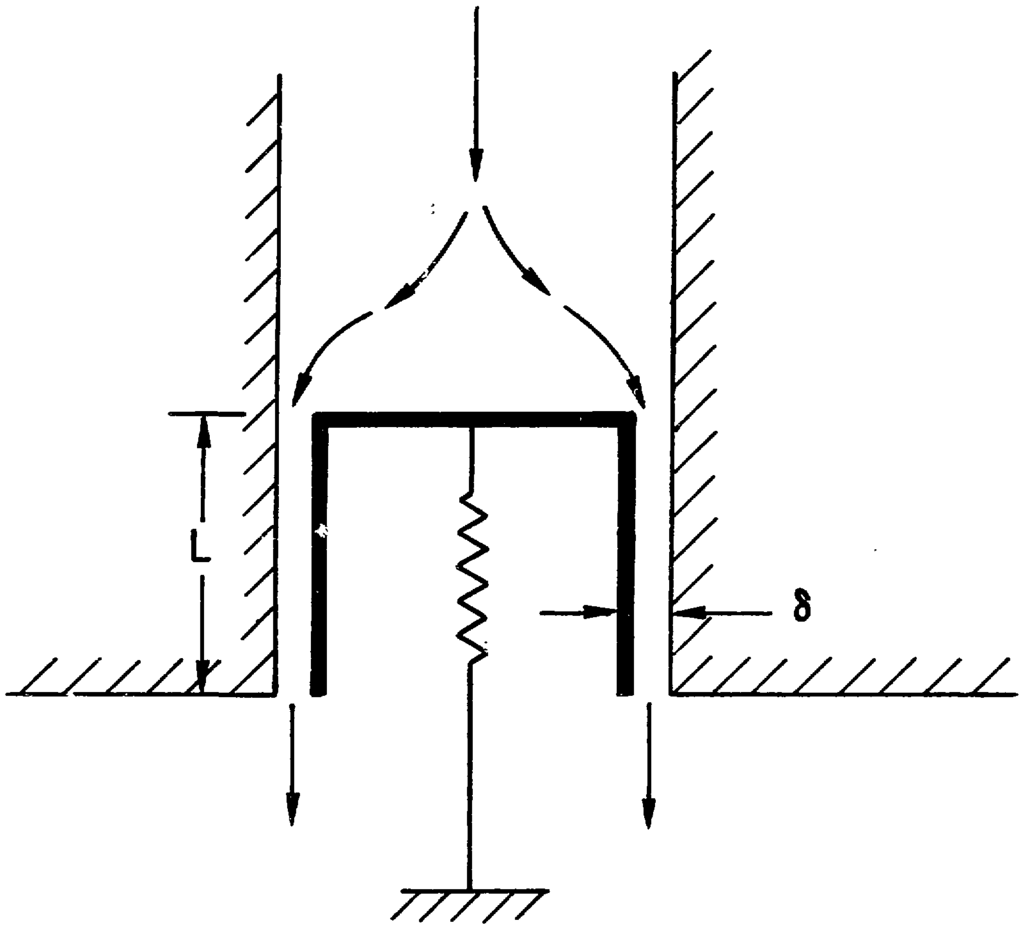

Fig. 4. Piston in axial motion

(pressure drop), an instability was possible for an entrance constriction, but an exit constriction would not create an instability because it always produces positive fluid damping. The instability was eliminated in the reactor by modifying the bottom seal to reduce the rate of leakage flow and by adding a top seal to add positive fluid damping.

In the mid-1970s, flow-induced vibrations were found to cause unacceptable wear damage in a jet pump of a boiling water reactor. The problem was corrected by a substantial research effort [e.g., 28-30] that consisted primarily of full-scale component tests outside of the reactor. The excitation mechanism was identified with the leakage flow through a slip joint required to avoid large thermal stresses. Because the jet pump had to be fixed to a support structure at both the upstream (mixer) and downstream (diffuser) ends, it was made from two separate pipes that overlapped each other and formed a slip joint that allowed relative thermal expansion. The slip joint was near the center of the jet pump and had a geometry similar to Fig. 1a, except the overlap region was very short (not much larger than the 1-in. length of the constriction) and the width of the overlap annulus expanded in the downstream direction like an annular diffuser. The radial gaps at the constriction were typically between 0.003 and 0.012 in. and were formed by a 1-in.-long raised diameter on the approximately 9-in. diameter center pipe. Although the gaps were made small to minimize leakage flow, the high-velocity internal flow could create substantial pressure drops across the slip joint (0 to 40 psi). As might be expected, the vibration modes of the jet pump were complex, and both translation and rotation of the pipes at the slip joint were possible.

Any of the mechanisms discussed previously for Fig. 1a geometry could have been active at the slip joint of the jet pump, but a specific mechanism could not be expected to be identified in the test of such a complex system. However, several important observations were made: (1) the vibrations were driven by pressure fluctuations in the annular region formed by the constriction of the slip joint; (2) the initiation of unstable motion was temperature (Reynolds number) sensitive; (3) the vibration response was nonlinear (hysteretic with flow) and did not occur at natural frequencies of the structure but at harmonics of a key frequency which varied with flow rate, (4) sufficient preload of the two pipes at the slip joint could eliminate the unstable motion; and (5) the inclusion of a labyrinth seal, five circumferential grooves (~ 0.1 x 0.1 in. cross-section) spaced ~ 0.1 in. along the length of the 1-in.-long raised diameter, eliminated the unstable motion. The identification of the dependence of the critical pressure on temperature is most important. Apparently the hydraulic resistance (fluid viscosity) in the slip joint is lowered at higher temperatures and the leakage flow kinetic energy necessary for an instability can be attained at a smaller pressure drop. Using the same reasoning, the labyrinth seal was added to the original design to increase the hydraulic resistance, decrease the leakage flow kinetic energy, and, therefore, increase the critical pressure. The preloading at the slip joint was thought to increase the structural damping.

The temptation to extrapolate several design rules of thumb and design fixes from the jet pump research is mitigated by previous research showing the extreme sensitivity of the mechanisms to flow and structural detail. The conservative approach is:

> DRT11 - Scale model testing should be performed to establish quantitative instability conditions and verify the worthiness of design fixes. Also, both structural dynamic reduced velocities and Reynolds number must be considered in establishing test model similitude requirements.

In one jet pump test operating at normal flow rates, the excitation mechanism was not active until the temperature (Reynolds number) was raised to near prototypic values.

8. SUMMARY

The strong dependence of leakage-flow-path excitation mechanisms on the details of the flow paths and structural motion should now, if not already, be quite apparent to the reader. Qualitative trends and rules of thumb for design can be defined (see text); however the generalization of knowledge gained for one design to another design must be done with care. Even when the flow geometry looks identical, the structural motion also must be similar.

The mechanisms identified and researched to date have been for relatively simple structural motions: the vibration (translation or rotation) of a single-degree-of-freedom rigid body ideally positioned in a rigid, stationary flow channel. All the analytical and experimental evidence that is available, which is not a lot, indicates that more complicated vibration modes and geometric eccentricities may greatly influence the existence of known instability mechanisms and/or create new ones. These may be the reasons why the ability to analytically predict experiment results has been so poor.

There is little doubt that scale-model testing will have to be performed if we are to understand any suspected leakage-flow mechanism or problems experienced during reactor operation. If more than qualitative identification of a mechanism by scale-model testing is desired, the conflicting requirements of simulating both reduced velocities and Reynolds number requires [31] testing of prototypic structures including full geometric scale with flows at operating temperatures. Sometimes these modeling requirements, which lead to very expensive tests, can be relaxed in design verification testing by justifying that a distorted model is more likely to experience flow-induced vibrations than the prototype.

The strong dependence of leakage flow mechanisms on the details of flow geometry and structural motion, the difficulty of identifying excitation mechanisms with particular geometries and conditions, and the expense of model testing and of repairing operating reactors make clear that reactor component supports that create leakage flow paths should be limited to a few designs shown by comprehensive experimental and analytical research to be free of FIV excitation mechanisms.

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