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LEAKAGE-FLOW-INDUCED VIBRATION OF A TUBE-IN-TUBE SLIP JOINT

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ABSTRACT

The susceptibility of a cantilevered tube conveying water to self-excitation by leakage flow through a slip joint is assessed experimentally. The slin joint is formed by inserting a smaller, rigid tube into the free end of the cantilevered tube. Variations of the slip joint annular gaps and engagement lengths are tested, and several mechanisms for self-excitation are described.

1. INTRODUCTION

Typically rod, tube, plate, and shell components in nuclear reactors are exposed, from startup through steady-state operation, 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, and must be provided sufficient lateral support to maintain acceptable bending vibration levels and allow axial movement to accommodate thermal expansion, control movements, and/or removal. Typically one end of the component is fixed, and lateral support is provided at other axial locations by the wall of a hole in a plate, a channel, or the inside of another tube (see Fig. 1), all of which have similar but slightly larger cross-sectional shapes. Often the support is called a slip joint because it must allow axial motion.

The main coolant flow often establishes a pressure drop across the slip joint, and fluid flow leaks through the narrow passages created to allow axial motion of the component. Thus, the slip joint, which would damp lateral vibrations for no pressure drop [1], may be the site of flow-induced vibration sources called, appropriately, "leakage-flow" excitation mechanisms. For dense fluids (water, sodium), flow-induced vibrations are most likely to be associated with self-excitation mechanisms [2]. Problems arise when the flow paths and structural motion at the joint interact such that more fluid energy is input to the structure than can be dissipated. From the viewpoint of the structural dynamics of a single-degree-of-freedom system, the fluid flow creates negative damping forces that are in phase with the structural velocity. When the critical flow rate is attained, the negative fluid damping equals the positive structural (material and joint) damping and self-excitation occurs.

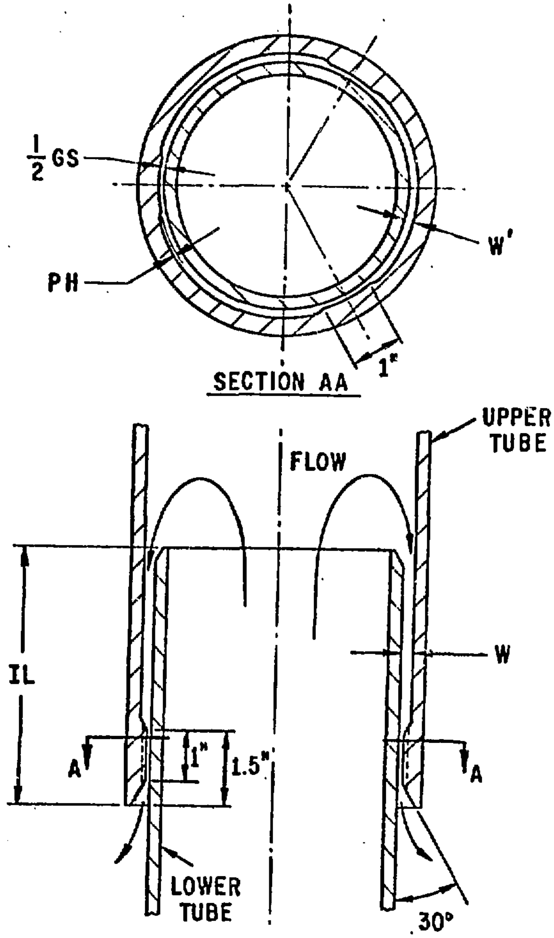

Fig. 1. Slip joint.

Although the basis for self-excitation is simple enough, quantitative analytical predictions of instabilities are not within the state-of-the-art: experimental testing of suspect geometries is required. The main hindrance to analytical solutions is the accurate calculation of the fluid forces associated with the flow along the always narrow and often zigzagged flow paths of slip joints. Sometimes the qualitative prediction of features that lead to self-excitation is possible but it is usually uncertain. Design features that have led to self-excitation have been identified; however, very small changes in the geometry or eccentricity of a previously stable design have been found to result in an unstable design [2].

Although leakage flow self-excitation sources (geometries) are not prevalent throughout reactor systems, a sufficient number of problems, associated damage, and expense have been incurred to require the assessment of the potential of each slip joint in a design. Not uncommonly, two tubes conveying the same flow are required to overlap (telescope) at their free ends (see Fig. 1). Although the operations engineer and thermal stress analyst desire an annular gap at the overlap to allow easy engagement and axial movement, the thermal/hydraulist and structural dynamist want to close the gap to avoid thermal striping and flow-induced vibrations. As a result, some rather unique geometric configurations are generated in the design of reactor components. The geometry and experimental instability conditions for the slip joint shown in Fig. 1 are reported here.

2. COMPONENT DESCRIPTION

The upper tube of the slip joint is approximately 200 in. long with a 6.0-in. OD and 5.5 in. ID. It is cantilevered from a top support (see Fig. 2) and the only other potential support is where it slips over the top of the lower tube (see Fig. 1). The stainless steel lower tube is approximately 124 in. long with a 5.0-in. OD and a 4.5-in. ID; two hinged supports are located ~24 and 98 in. below the slip joint. Using the computer code ANSYS, several vibration modes and frequencies were predicted

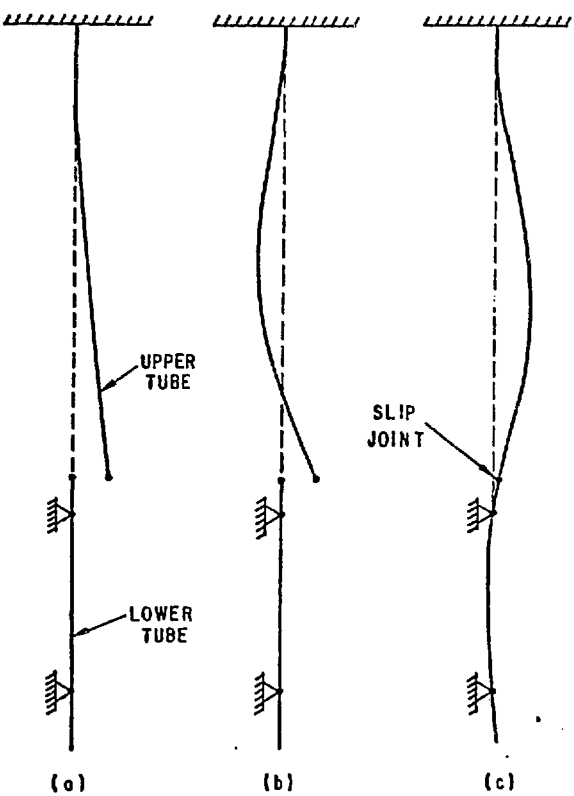

Fig. 2. Possible vibration modes: (a) unhinged first mode (3.4 Hz), (b) unhinged second mode (23 Hz), and (c) hinged first mode (13 Hz).

that included the effects of contained mass and the added fluid mass due to the presence of a surrounding vessel. The vessel provided both the support for and the flow through the tubes. The results are shown in Fig. 2, which represents the two extremes of the expected motion: (1) unhinged--the upper tube moves freely in the slip joint as the free end of a cantilevered tube and (2) hinged--the lateral displacement of the bottom of the upper tube and the top of the lower tube are the same. The isolated lower tube has a higher fundamental frequency (>50 Hz) and is essentially rigid for the modes identified in Fig. 2. The unhinged modes were expected to represent small motions of the upper tube in a relatively large gap, while the hinged mode was expected to occur for relatively small gaps where lateral motion was not possible. For intermediate and larger gaps at relatively large motions, the slip joint was expected to produce a nonlinear support and vibration. Because the existence (initiation) of an instability is of most interest, the assumption of small motions is justifiable.

The design of the structural geometry described above was fixed, but some of the slip joint dimensions could be varied. The slip joint was formed by inserting the top of the lower tube into the bottom of the upper tube, which was modified with an ~1-in.-long raised internal diameter (see Fig. 1). The leading and trailing edges of the raised diameter were beveled (30°), and three 1 in. x 1 in. raised pads, spaced at 120° intervals around the circumference of the ID, were included in an attempt to isolate the flow into three separate channels. The primary purpose of this design was to allow easy engagement and relative motion of the upper and lower tube while still constraining lateral motion. The slip joint design variables were the engagement length IL, which could be changed by modifying the length of the lower tube, and the lateral motion constraint provided by the gap 1/2 GS, which could be changed by modifying the external diameter of the lower tube or the pad height PH on the upper tube. Choosing 1/2 GS and PH defines the other slip joint gaps W and W', and the 1 in. x 1 in. pads could be eliminated (PH $\approx$= 0).

3. POTENTIAL SELF-EXCITATION MECHANISMS

Three self-excitation mechanisms were considered possible for the structural and slip-joint geometry; they were (1) a local valving mechanism created by translational motion, (2) a similar mechanism but with rotational motion, and (3) a mechanism associated with a downstream annular diffuser.

The local valving mechanism was identified for plates with hydraulic dams [3,4] (see Fig. 3), and recently the same mechanism has been shown to exist for concentric tubes. The mechanism can exist when the dams (flow constrictions) are at the upstream end of the blade (leakage flow path) and a constant pressure drop exists along the blade. If the blade is given a pure translational velocity upward, as in Fig. 3, then the flow rate will

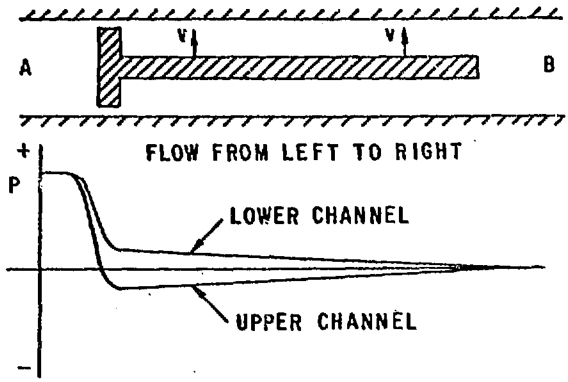

Fig. 3. Local valving mechanism.

decrease instantaneously (decelerate) in the upper channel and increase instantaneously (accelerate) in the lower channel. Since the pressure at the downstream end B remains constant, the pressure in the upper channel must be less than at B to decelerate fluid, while the pressure in the lower channel must be greater to accelerate the fluid. As a result, a net fluid force in the direction of the velocity (negative damping) exists, which is destabilizing. For pure translation, the constriction flow area must be much smaller than the channel areas so that a small motion creates considerable local valving and fluid inertia changes. If the flow direction is reversed, then positive damping is created by the fluid flow, which stabilizes blade motion This mechanism could be active in the first unhinged mode of vibration (see Fig. 2a).

The second mechanism is the same as the first except that rotational motion of the plate is postulated, and upstream dams may not be necessary. Essentially, rotation of the upstream end of the blade may create enough local valving and fluid inertia changes to destabilize the motion. Because considerable rotation of the bottom of the upper tube is required, this mechanism can be active only for the higher-frequency modes such as the second unhinged mode (see Fig. 2b) or the first hinged mode (see Fig. 2c).

The third possible mechanism is identified with a downstream annular diffuser (30° expansion) section of the slip joint (e.g., Fig. 3). If the efficiency of the diffuser section increases with a pure translational opening of the gap, then an instability mechanism is possible [5]. An example of such a mechanism has been observed [6] and related to flow separation. For a similar geometry, flow separation was observed to occur in the diffuser section just as the central body contacted the outer body and the fluid velocity went to zero. However, because a finite fluid velocity is required, flow reattachment did not occur immediately upon reopening of the gap, and the fluid forces developed were slightly out of phase with the displacement and slightly in phase with the velocity. As a result, negative fluid damping was produced, with a potential for self-excitation. Because the diffuser angle is large in this case (30°), flow separation can be expected to occur all the time, and any excitation mechanism would have to be associated with the change in the character of the flow separation as a function of the movement of the central body. If a mechanism exists, it could be associated with any vibration mode.

As illustrated above, several self-excitation mechanisms could be qualitatively postulated for the slip joint geometry of Fig. 1. However, the existence of any of the mechanisms would remain in question unless verified by experiment, and critical flow velocities or pressure drops can be determined only by experiment. Accordingly, a series of tests was performed.

4. TESTING

A test facility (see Fig. 4) was constructed that supported the upper and lower tubes and provided a pressure boundary for the flow. The pressure drop (ΔP) across the slip joint could be controlled (pump P and valve V1) and the flow rate measured (turbine meter FM). Also, the system was pressurized (nitrogen supply N through valve V7) and insulated so that the

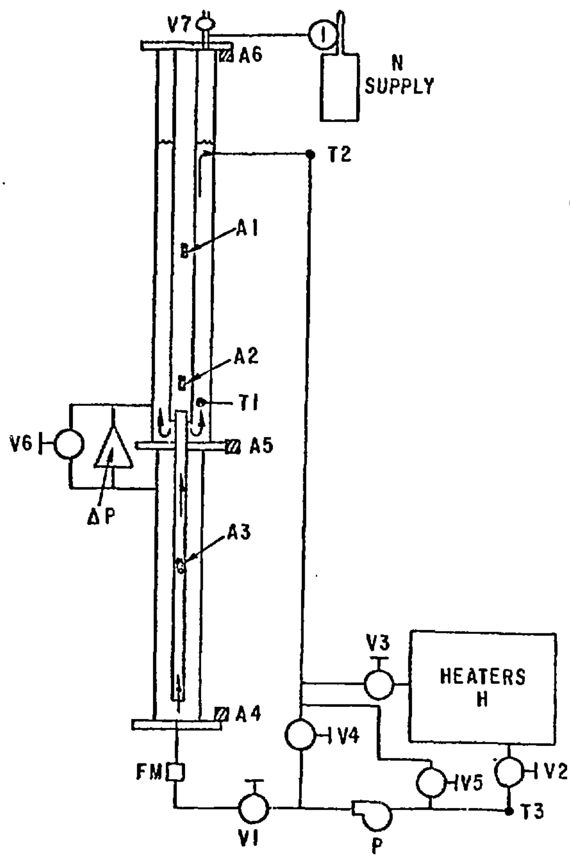

Fig. 4. Slip-joint test facility.

water temperature (Reynolds number) could be raised to 250°F. Electric heaters (H) were provided to raise the water temperature before flow testing by appropriate diversion (bypass) of the test fluid (valves V2-V5). The fluid temperature was monitored by two thermocouples (T1-T2). Three biaxial piezoresistive (DC) accelerometers (A1-A3) were attached to the components to monitor motion at the slip joint and determine vibration modes and frequencies. Three triaxial accelerometers (A4-A6) were employed to verify that the motion of the pressure vessel was uncoupled from that of the tubes. When testing with room-temperature water, a large plexiglas port could be used to observe the motion of the upper tube at the slip joint.

Before each flow test of a different slip joint geometry (see Table 1), the upper tube was impacted in an otherwise still fluid, and attempts were made to determine average values of the modal frequencies and damping from the recorded transient responses. These slip joint results can be compared with results obtained in water (Test SW) and in air (Test A) without the lower tube. As shown in Table 1, the first two frequencies in water were 3.1 and 20.3 Hz, and the percents of critical damping associated with the two modes were 0.4 and 0.1%, respectively. The second modal frequency for the unhinged case was slightly less than predicted, probably due to a less-than-perfect fixed support at the top of the pressure vessel (see Fig. 4). In air, the expected structural frequencies were observed and very low damping was measured.

Results obtained for different slip joint designs were very dependent upon the size of the gaps, as might be expected. In all cases, the center tube was aligned concentrically in the outer tube within ~10% before testing. Heating of the tube and flow was found to significantly change the initial alignment. When the 1/2 GS was 0.010 in. or less, the measurement of frequencies f and percent of critical damping ζ was very difficult because of immediate impacting with the lower tube; the results in Table 1 are only estimates. As expected, for very small gaps the upper tube responded as if hinged to the bottom tube (Tests F-1 and B-3 in Table 1). For 1/2 GS approximately 0.010 in., intermittent behavior between a hinged and unhinged condition occurred (Tests F-2, F-4, and B-4). For 1/2 GS > 0.10, unhinged first-and second-mode frequencies and damping could be obtained by gentle impacting. The frequencies were as expected, based on the infinite gap Test SW, and various amounts of damping were obtained, depending on the gap size. Although the trend is not clear, the amount of first unhinged mode damping appeared to depend most on the gap size W'. It was equal to or larger than 1/2 GS, depending upon the pad height PH, but the circumferential length of the annulus associated with W' was much larger (~13 in.) than three pad widths (~3 in.). More accurate estimates of the modal damping would have been important, if the critical flow rates had shown a strong dependence on damping, which they did not.

Two separate sets of flow tests were performed that could be distinguished by the direction of the flow. Flow tests in the forward

Table 1. Flow Test Parameters and Results

Test	IL (in.)	1/2 GS (in.)	PH (in.)	Stable	W' (in.)	W (in.)	f_o (Hz)	ζ_o (%)	f_1 (Hz)	ζ_1 (%)	°F	ΔP (PSI)	GPM	Comments
F-1	5	0.003	0.028	Yes	0.031	0.271	14	1	45	0.3	235	6.8	28.5	Hinged
F-2	5	0.010	0.028	Yes	0.038	0.278	19	-	24-28	~1	235	5.1	33.5	Tube contact
F-3	5	0.020	0.028	Yes	0.048	0.288	3.1	7	20.3	0.2	235	3.5	38.0	-
F-4	3.5	0.010	0.028	Yes	0.038	0.278	14	-	19-30	-	237	5.3	34.0	Tube contact
F-5	3.5	0.020	0.018	Yes	0.038	0.278	3.1	10	20	1	239	4.7	36.0	-
F-6	3.5	0.038	0.00	Yes	0.038	0.278	3.1	7	20	0.2	238	3.9	36.5	-
SW	0	∞	0.028	-	∞	∞	3.1	0.4	20.3	0.1	70	0	0	Water
A	0	∞	0.028	-	∞	∞	4.85	<.05	31	<1	70	0	0	Air
B-1	5	0.009	0.022	No Yes	0.031	0.271	3.0	3.4	20	0.3	46	~0.25 1.83	<3 >14	Instability intermittent
B-2	5	0.031	0.0	No	0.031	0.271	3.1	1.8	20.3	0.6	46	~0.05	<1	-
B-3	3.5	0.004	0.022	Yes	0.026	0.245	-	-	-	-	-	-	-	Hinged
B-4	3.5	0.010	0.00	Yes	0.009	0.248	-	-	20	2.2	50	3.8	8	-
B-5	3.5	0.016	0.022	No	0.048	0.278	3.0	1.1	20.2	0.4	51	~0.25	<1.3	-
B-6	3.5	0.019	0.00	No	0.019	0.260	3.0	2.5	20	0.5	50	~0.10	~0	-
B-7	3.5	0.038	0.00	No	0.038	0.278	-	-	-	-	50	~0.03	<1	-
B-8	1.5	0.019	0.00	Yes	0.019	∞	3.0	1.7	20.5	0.4	52	8.0	22	-
B-9	1.5	0.038	0.00	Yes No	0.038	∞	3.1	0.7	20	0.4	50	6.2 7.8	45 51	f_o stable f_1 unstable

direction, as defined in Fig. 1, were performed first and are identified in Table 1 by F-1, ... The pump was then reversed and the backward flow tests were performed with the flow in a direction opposite to that shown in Fig. 1. Results of the flow tests are given in Table 1. The maximum flow rate (GPM) and pressure drop ΔP (psi) are given when the motion was stable, and the critical flow rate and pressure drop are given when self-excitation occurred. Self-excitation was defined to occur as soon as the very small background random motion (in direction and amplitude) changed to periodic motion. Because the instabilities were initiated at very low flow rates, the backward flow tests were performed at room temperature.

5. DISCUSSION

The most obvious result of the testing program was that motion in the first unhinged (cantilevered) vibration mode (see Fig. 2a) was stable for forward flow (see Fig. 1), where the constriction is at the downstream end of the leakage flow path, while the motion could be unstable for very small flow rates in backward flow direction--opposite that shown in Fig. 1. The only circumstances for which a first unhinged mode instability would not occur is when the gap 1/2 GS was so small (Test B-3 in Table 1) that lateral motion was not possible at the slip joint, or when no channel existed downstream from the constriction: IL = 1.5 in. (Tests B-7 and B-8). Test B-1 gap size evidently represented an intermediate constraint, because slightly larger flows were required to initiate unstable motion and at the higher flow rates static divergence occurred, forcing steady contact of the raised pads of the upper tube with the lower tube and elimination of instability. In the forward flow direction, static divergence always occurred and, as a result, the very small random motion decreased with increased flow rate and was essentially zero after the two tubes contacted.

The behavior of the upper tube in its first unhinged mode was completely compatible with the first (pure translation) mechanism postulated in section 3, Potential Self-Excitation Mechanisms. The second mechanism was thought to occur after the flow rate was raised sufficiently to excite the second unhinged mode for which the required rotation at the slip joint occurred. A composite picture of the lateral motion of the end of the upper tube at different flow rates during test B-6 is shown in Fig. 5, which reveals several interesting nuances of the unstable motion and identifies the transition to a predominantly second unhinged vibration-mode instability. The trends of the motion were similar in the other backward flow tests, but they were not as distinct as for test B-6 which had a relatively large GS and no raised pads.

As shown in Fig. 5, the initiation of the unstable motion of the end of the upper tube occurs at almost zero flow in a nearly one-dimensional translation, which is the preferred free-vibration response of the

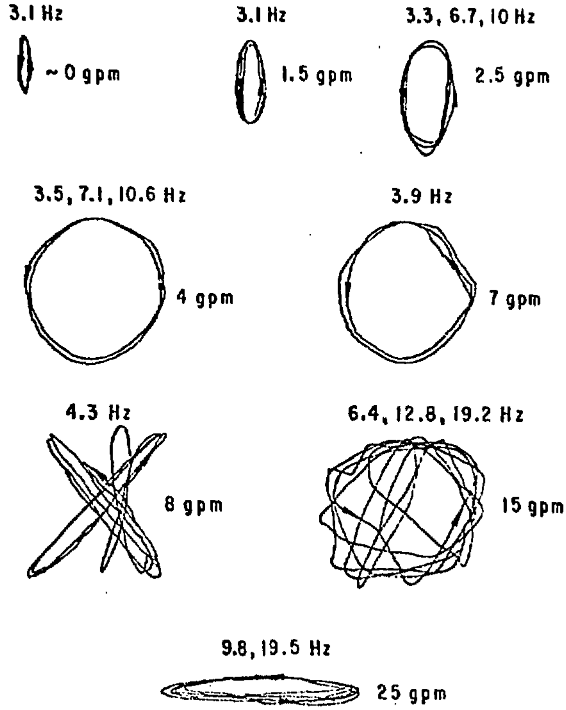

Fig. 5. Unstable motion (test B-1).

fundamental mode. As the flow rate is increased to 1.5 and 2.5 GPM, the confining effects of the inner tube cause the end of the tube to orbit in wider and wider elliptic paths. At 4 GPM, just before contact is made with the inner tube, the orbit is nearly circular. Surprisingly, at 7 GPM a single point of contact is quite repeatable during each cycle, but at 8 GPM another point of contact occurs and the motion consists of precisions between the two distinct points of contact. For higher flow rates (e.g., 15 GPM) more points of contact occur during a cycle and the motion becomes chaotic. At all but the lowest (< 1.5 GPM) flow rates cited above, the fluid flow can be seen to add (fluid) stiffness to the structure because the fundamental frequency increases with flow rate. Increases in the negative damping forces also occur because the motion becomes larger with increased flow rate. The nonlinear nature of the instability is indicated by two features: (1) at each flow rate, a limit cycle is attained that often is quite repeatable, and (2) superharmonics of the fundamental frequency are created by squeeze film effects before impacting and by a combination of both after impacting. Superharmonics often are associated with the presence of nonlinear hardening or softening springs in a structural system.

Most interestingly, when the flow rate was increased (15 to 25 GPM) to the point where the second unhinged mode frequency (see Fig. 2b) became a superharmonic of the fundamental frequency, the upper tube motion would intermittently switch between a first-and second-mode shape response. At 25 GPM, when the second-mode frequency was the first superharmonic of the fundamental, the switch to second mode was permanent and very periodic in the preferred free-vibration response of the second mode. The switch to the second mode implied that a leakage-flow mechanism based on rotation in the slip joint could be activated at sufficiently high flow rates.

To verify the existence of a rotation-based leakage-flow mechanism, two tests were performed (B-8 and B-9 in Table 1) in backwards flow, where the engagement length IL was chosen to eliminate the larger downstream leakage flow channel (of width W) and thus the possibility of the first (pure translation) leakage mechanism. When the existing pumping capacity was used, no instability was observed to a flow rate of 33 GPM and a pressure drop of 3.5 psi (Test B-9). A larger pump was installed and no instability was encountered up to 45 GPM and a $\Delta P = 6.2$ psi; however, increases in the fundamental frequency of the small random motions with flow rate increases implied that fluid stiffness effects were still occurring. Above 45 GPM the random motion continued to build in amplitude and at approximately 51 GPM and a pressure drop of 7.8 psi, impacting occurred, the motion became very organized, and a fundamental frequency of 8.8 Hz and superharmonics of 17.6 and 24.4 Hz appeared along with significant second-mode type of motion. This was taken as a confirmation of a leakage-flow mechanism dependent upon rotation at the slip joint.

6. CONCLUSIONS

The test series performed for a cantilevered tube excited by leakage flow through a particular slip joint (see Fig. 1) at its free end confirmed that self-excitation in the fundamental mode (Fig. 2a) is very likely to occur (at almost zero flow rates) when flow constrictions (hydraulic dams) are at the upstream end of the leakage flow channel (so-called backward flow). When the constrictions are at the downstream end of the channel (so-called forward flow), the tube statically diverges to contact the inner (lower tube) but no dynamic instability occurs in the fundamental mode. This behavior was entirely consistent with postulated leakage flow-induced vibration mechanisms [3-5].

The unstable motion in the fundamental mode was very nonlinear in that an amplitude limit cycle of motion occurred at a constant flow, even before tube-to-tube impact. The fundamental frequency (fluid stiffness effects) increased with flow rate and exhibited superharmonic frequency content typical of systems made from materials whose stiffnesses harden or soften with increases in amplitude of motion, and tube to tube impact occurred at sufficiently large flow velocities. Most interesting, when the flow rate was large enough that the fundamental frequency's lowest superharmonic coincided with the second-mode frequency (Fig. 2b), the unstable motion switched to predominantly second-mode motion, where primarily rotation occurred at the slip joint.

The switch to second-mode motion prompted an investigation that showed that at high enough flow rates, a rotation-based leakage-flow self-excitation mechanism would occur even when an instability mechanism associated with the fundamental mode was not possible. Although tested only in the backward flow direction, the mechanism associated with the second mode should occur in the forward flow direction, also.

The confirmed existence of these leakage-flow mechanisms serves as an incentive for careful design of the slip joint between telescoping tubes, and a strong argument for the use of only one or two joints whose behavior has been completely researched.

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