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LEAKAGE FLOW-INDUCED VIBRATION OF AN
ECCENTRIC TUBE-IN-TUBE SLIP JOINT

by

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NOMENCLATURE

D	Inside diameter of slip joint annular constriction
BL	Length of bevel
EC	Eccentricity of tubes
f	Modal frequency
IL	Engagement length of tubes
L	Length of annular part of constriction
LD	Length of annulus downstream of the constriction
W	Radial width between concentric tubes
W'	Radial width of annular constriction for concentric tubes
ζ	Modal damping (% of critical damping)
ΔP	Pressure drop across the slip joint

LEAKAGE FLOW-INDUCED VIBRATION OF AN ECCENTRIC TUBE-IN-TUBE SLIP JOINT

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ABSTRACT

Eccentricity of a specific slip-joint design separating two cantilevered, telescoping tubes did not create any self-excited lateral vibrations that had not been observed previously for a concentric slip joint. In fact, the eccentricity made instabilities less likely to occur, but only marginally. Most important, design rules previously established to avoid instabilities for the concentric slip joint remain valid for the eccentric slip joint.

I. INTRODUCTION

Main coolant flow paths through the components of a reactor system often parallel each other from one relatively stagnant plenum region to another. However, the flow paths and plenum regions are rarely completely sealed from each other because of design requirements to allow for thermal expansion of components of their removal. Thus, leakage flow across pressure boundaries is not uncommon. When component vibration can interact and alter the leakage flow, the conditions for self-excited vibrations are present. Many reactor component designs have suffered from leakage flow-induced vibrations [1-3].

The avoidance of leakage flow-induced vibrations is difficult. Research to date shows that many excitation mechanisms can exist, depending on the local geometry of the leakage flow path, structural dynamics, and misalignment of components in the field. Rules-of-thumb for design exist [2], and unstable configurations often can be identified by analytical predictions. But the ability to quantitatively predict critical flowrates is very poor, and most commonly suspect geometries must be subject to extensive full-scale model testing.

Recently an experimental study was initiated [4] to gain a comprehensive understanding of the leakage flow excitation mechanisms associated with a specific tube-in-tube slip joint formed where two cantilevered tubes conveying fluid overlap. The purpose of the continuing study is to understand the conditions for self-excitation so that at least one instability-free slip joint design can be defined for this common reactor structural configuration. The most recent testing [6] concentrated on determining critical flowrates, flow damping, and pressure drops for the slip joint when the

telescoping tubes were initially concentric. Here, the same quantities are reported for different degrees of initially eccentric tubes. This work was deemed necessary because the literature is replete with claims that slight eccentricities or misalignment greatly effect the existence of excitation mechanisms. Quite often the inability to avoid misalignment in a test is given as the reason for the usual poor quantitative correlation between experiment and theory.

II. THE CONCENTRIC SLIP JOINT

The slip joint chosen for testing, shown in Fig. 1, is an outgrowth of a design used in the Clinch River Breeder Reactor. Essentially, two annular regions are formed where the two tubes overlap: one narrow (W') annular region is formed by a raised diameter on one of the tubes and another wider annular region (W) is formed by the inside diameter of the larger tube and the outside diameter of the smaller tube. The constriction formed by the raised diameter serves to limit leakage flow from the inside to the outside of the tubes as well as relative motion of the tubes. The beveled approaches to the constriction were provided to guide the engagement of the tubes, for which periodical disassembly was planned.

Fig. 1. Slip Joint with Leakage Flow

The slip joint in the test facility was formed, as shown in Fig. 2, at the overlap of the free ends of a relatively short, rigid tube cantilevered from the top flange of a main vessel and a long, flexible tube cantilevered from the bottom flange. The pertinent dimensions of the slip joint are given in Table 1.

For the initially concentric slip joint defined in Fig. 1 and Table 1, the reduced velocity for unstable motion was shown to be a function of the engagement length IL and initial modal damping ζ_1 for the upstream constriction of Fig. 1. No instabilities were observed in either the first or second vibration mode for a downstream constriction, a condition realized by reversing the flow direction of Fig. 1.

Fig. 2. Test Facility

Table 1. Slip Joint Geometry

$D = 5.0 \text{ in. (127 mm)}$	$L = 0.20 D$
$W = 0.0562 D$	$IL = 0.30 \text{ to } 1.0 D$
$W' = 0.008 D$	$BL = 0.5 L$

With the annular constriction upstream, sufficient flow rate caused unstable, primarily translational, motion of the flexible tube in its fundamental mode for some IL and ζ_1 , as shown by the open symbols in the instability map of Fig. 3. Note that critical flowrates are given in Fig. 3 instead of reduced velocities. They are equivalent since the modal frequency prior to an instability and constriction dimensions remained constant for all testing.

Suspected second-mode ($f_2 \sim 21$ Hz) instabilities were observed for an upstream constriction at higher flowrates, as shown by the solid symbols in Fig. 3. Second-mode motion of the flexible tube at the slip joint was primarily rotational. The initial damping in the second mode was not controllable and was $\sim 0.2\%$ for all testing. The slash through a symbol in Fig. 3 indicates unstable motion ceased. Cessation of second-mode motion occurred in several instances and once ($IL = 0.6 D$) restarted at even higher flowrates.

As can be seen in the instability map of Fig. 3 for upstream constrictions, once an engagement length of $IL = 2.25$ in. (64.52 mm) was exceeded, the critical flowrate for a first-mode instability was relatively insensitive to the amount of initial modal damping ζ_1 in the range 0-3%. The solid lines in Fig. 3 bound stable regions for each ζ_1 . However in the range $\zeta_1 > 3\%$, an increase in modal damping increased the critical flowrate and eliminated the

Fig. 3. Instability Map for Concentric Tubes with an Upstream Constriction. Fundamental mode nominal ζ_1 (%) = 0.5, $\square$; 2.2, ∇ ; 3.3, Δ ; 6.6, $\circ$.

instability for some IL. Thus, first-mode instabilities for concentric tubes could be avoided by maintaining

- a downstream flow constriction,
- a downstream annulus length LD less than $1.25 L$, and
- sufficient initial modal damping ζ_1 , according to Fig. 3.

The first two methods of avoiding first-mode instabilities are relatively easy to realize, if design constraints allow. The third method, providing external damping $>3\%$, is much more difficult and probably not realizable, with one exception.

The constriction of the slip joint can be an effective squeeze film damper and can provide high initial (no flow) damping if design constraints allow reductions in W' . For purposes of design, the squeeze film damping is predictable [6]. Selected tests [4] have shown that higher critical flowrates do occur for smaller constrictions W' if everything else is the same. The design difficulty is that W' must be very small, on the order of 0.010 in. (0.25 mm), for the geometry of Fig. 1 and Table 1.

The first two methods cited above eliminate second-mode instabilities also. However, the effect of increased second-mode damping is unknown since initial modal damping was $\zeta_2 \sim 0.2\%$ for all previous testing [4,5]. Whereas different length squeeze film ring dampers, located as shown in Fig. 2, were very effective in changing ζ_1 from 0.5 to 6% in the low-frequency, fundamental mode where the motion of the top of the cantilevered tube was primarily translational, the dampers were completely ineffective for the higher-frequency, primarily rotational motion of the second mode. Although control of second-mode damping and testing is planned for the future, investigation of misalignment effects were deemed more important.

III. THE ECCENTRIC SLIP JOINT

The test facility of Fig. 2 was designed to allow concentric alignment of the two tubes by movement of the base of the rigid tube on the upper flange of the main vessel. This same feature provides a means to perform tests with initially eccentric tubes: from concentric (0% eccentricity) to touching tubes (100% eccentric). The eccentricities chosen for testing were EC $\sim 30\%$, 60%, 75%, and 90%. A test with the tubes in contact and preloaded was performed, also. The mechanism for changing eccentricities was very accurate; however, temperature effects and flange loads on the main vessel limited maintenance of the eccentricities to $\pm 4\%$ of the minimum W' desired. Eccentricities were always set in the same direction, the preferred direction of motion for the concentric case. The initial damping ζ_1 was slightly higher [5] normal to the preferred direction.

Not all damping ring configurations were tested; only the two that produced nominal initial damping of $\zeta_1 = 0.5\%$ and 2.2% for the concentric tubes with no fluid in the slip joint. Immediately before and after each test, the ζ_1 in the direction of the eccentricity was measured. As the tubes were made more eccentric, the initial damping in the direction of the eccentricity was expected to increase and demonstrate the beneficial aspects of higher damping in avoiding instabilities. The questions to be answered included

- How much eccentricity is required to increase initial damping significantly,
- Were any new mechanisms created by the eccentricity.

The initially low values of damping chosen were expected to answer these questions best.

The engagement length was tested over the same range included in the concentric tests: $0.3 D$, $0.5 D$, 0.6 , and $1.0 D$. However, not all values were tested for each EC. The lower values of IL were tested most because concentric testing showed short engagements were most sensitive to damping changes and susceptible to elimination of instability mechanisms.

Testing was performed for both upstream and downstream constrictions to determine if a downstream constriction remained a stable configuration in the presence of initial eccentricities. Also, the pressure drop across the slip joint was measured for comparison with the concentric case. For similar conditions, except for eccentricity, a significant increase in pressure drop to achieve the same flowrate would indicate more likely conditions for an instability.

The first-mode total damping ζ_1 in the direction of the eccentricity was measured at each flowrate, as well as at zero flowrate before and after each test. Knowing the total damping as a function of flowrate made measurement of critical flowrates (zero total damping) simple. The instrumentation and test methods used have been reported in detail [5]. Essentially, the flexible tube was plucked over a selected range of initial amplitudes and an average log decrement was determined from three transient decay curves. Damping was not easily measurable in the direction normal to the eccentricity direction or in the second mode; however limited measurements were made to assess whether significant changes occurred for different eccentricities.

IV. CRITICAL FLOWRATES

The most important information for the designer is whether eccentricity makes an instability more or less likely: are the design rules of thumb listed above for a concentric case still valid with eccentricity? The answer for this slip joint and cantilevered tubes is that both fundamental and second-

mode instabilities are less likely, but only marginally until almost 100% eccentricity is realized: the design rules remain valid. Most important, no excitation mechanisms were observed that were not present in the concentric test, and a downstream constriction remained a stable configuration. Also, the stable engagement lengths for a concentric upstream constriction remain stable for the eccentric cases. Details are given below.

Instability critical flowrates for upstream constrictions were mapped, as shown in Fig. 4, for each eccentricity. The format is the same as for Fig. 3 except that the open and solid symbols denote critical flowrates for the fundamental and second modes, but the solid lines of Fig. 3 for nominal initial damping of $\zeta_1 = 0.5$ and 2.2% are repeated for comparison purposes. Table 2 gives more precise relations between the concentric and eccentric critical flowrates for $IL = 0.6 D$.

The motion prior to a first-mode instability was similar to that observed in the concentric test for $EC < 70\%$. The unstable vibration amplitude would build in nearly straight line motion in the preferred direction of motion; the direction of eccentricity. However as the eccentricity was increased beyond 70%, the motion would build in more and more elliptic orbits, until nearly straight line motion normal to the preferred direction occurred at the largest eccentricities. After the instability was initiated, the unstable first-mode motion at higher than critical flowrates was generally the same as for the concentric case because the tubes would statically diverge from each other to allow further motion to build up in either direction.

Fig. 4. Instability Map for (a) $EC = 59\%$ and (b) $EC = 89\%$ with an Upstream Constriction. $\zeta_1 (\%) = 0.5, \square$; and 2.2, ∇ .

Table 2. Ratio of Concentric to Eccentric Critical Flowrates
for IL = 0.6 D with an Upstream Constriction

EC (%)	$\zeta_1 \sim 0.5\%$	$\zeta_1 \sim 2.2\%$	$\zeta_2 \sim 0.2\%$
0%	1.0	1.0	1.0
28%	1.3	1.1	1.4 - 1.6
57%	1.3	1.4	1.2 - 1.3
71%	1.7	1.6	0.9 - 1.3
89%	~ 5	3.7	1.3 - 1.5

Within the repeatability of the testing, the critical first-mode flowrates for EC = 28% were nearly the same as for the concentric case (see Fig. 4a and Table 2). Critical flowrates for f_2 appeared to increase; however, they were hard to repeat, as the second-mode critical flowrate depended on the history of motion in the fundamental-mode instability. This was especially true if the tube impacting started in the fundamental mode. By EC = 57% the trend of increased critical flowrates for the fundamental mode was measurable, and the second-mode instability for IL = 0.5 D and $\zeta_1 \sim 2.2\%$ had disappeared. By EC = 71% no second-mode instabilities were observed for IL = 0.5 D, and the trend of increased flowrates for the fundamental mode was clear. Large increases in critical flowrates, which a designer might take advantage of, did not occur until EC = 89%. However the occurrences of the increases are unreliable for at least two reasons:

- To maintain such increases the tube must remain within 0.004 in. (0.1 mm) of contacting each other, a difficult condition to assure, especially in applications with large temperature variations.

- An eccentric upstream constriction was always accompanied by static divergence of the two tubes, with a trend toward self-centering, prior to the dynamic instability.

The eccentricity for an upstream constriction is shown in the examples of Fig. 5(b) to decrease from the larger initial eccentricities as the flowrate increases. Changes in eccentricity for a downstream constriction were not as large nor necessarily biased toward self-centering, as shown in Fig. 5(a).

Even when the rigid tube was displaced a distance of $\sim 1/2 W'$ beyond initial contact with the flexible tube (EC = 142% ECC), producing a ~ 3.5 lb (15.6 mwt) preload force, the two tubes would lose contact by static divergence at a sufficiently high flowrate and a dynamic instability would ensue. With a nominal initial damping of $\zeta_1 = 0.5\%$, the critical flowrate for the preloaded tubes with IL = 0.6 D or 1 D was ~ 17 gpm ($1.07 \times 10^{-4} \text{ m}^3/\text{s}$).

Fig. 5. The Flexible Tube's Mean Spatial Position with Increased Flowrates for (a) a Downstream Constriction, and (b) an Upstream Constriction at Two Initial Eccentric Positions. (Symbol, IL) = $\circ$, 0.3 D; $\square$, 0.5 D; ∇ , 0.6 D; and Δ , D.

Because the flowrates for lift-off of the tubes for both engagement lengths are higher than the critical flowrates for EC = 89%, evidently the lift-off flowrate becomes the critical flowrate. Obviously more preload could suppress first-mode instability, but such a preload may not suppress the second-mode instability, which occurred between 30-50 gpm ($1.9-3.2 \times 10^{-4} \text{ m}^3/\text{s}$) for both IL. This hypothesis was not investigated because tests could not be performed at higher preloads in the test facility without contact of main vessel support structures.

V. DAMPING

All of the differences between the concentric and eccentric case critical flowrates are explainable in terms of increased initial damping, at least for the fundamental mode. As can be observed from Fig. 4, for example, all first-mode instabilities observed for the concentric case occurred for all the

eccentric cases, only at higher flowrates. Also, the critical flowrate was higher for large eccentricities. The same trends existed for the total damping. If damping decreased to zero with increased flow for the concentric case, then it decreased to zero for all eccentric cases, only at higher flowrates. Also, the initial damping was higher for larger eccentricities. The initial damping increases with eccentricity because the gaps between the tubes are decreased. Note that the damping provided to the lower tube in Fig. 2 by the damper assembly is not affected by eccentric movement of the upper tube.

For unstable engagement lengths, where the damping goes to zero at the critical flowrate, the total damping always is greater for the eccentric cases, as illustrated in Fig. 6(c) for nominal initial damping provided by the damping rings of $\zeta_1 = 2.2\%$ and in Fig. 6(a) and (b) for $\zeta_1 = 0.5\%$. However, for stable engagement lengths having an upstream constriction, the total damping at higher flowrates may become less than that of the corresponding eccentric case. One might expect that the total damping would be larger for any eccentric case and any flow. The fact that such is not always the case is believed to be related to the tubes' variable relative position with respect

Fig. 6. Upstream Constriction Flow Damping for (a) EC = 87%, (b) EC = 56%, and (c) EC = 29%, where (Symbol, IL) are: $\circ$, 0.3 D; $\square$, 0.5 D; ∇ , 0.6 D; and Δ , D. Dashed lines are for EC = 0%.

to each other at a given flowrate. As noted earlier (Fig. 5), the eccentric tubes statically diverge from each other with increased flowrate, and the nominal static positions are not repeatable if the flow is stopped and restarted. Thus, there is no reason to expect an eccentric and concentric tube to be in the same position nor have the same ζ_1 for a given flowrate.

The effect of static divergence is most notable in Fig. 6 for the large eccentricities of the stable engagement length $IL = 0.5 D$. The large eccentricity produces a high initial damping, but as the flow is increased, the tubes diverge from each other and the damping reduces dramatically to the damping levels of the concentric case or less. If motion could not occur normal to the preferred direction (parallel to the tube surfaces) and static divergence of the tubes from each other did not occur, then the increased damping due to the large eccentricity would have eliminated the instabilities.

The reason second-mode instabilities disappear for large eccentricities is not understood. As mentioned, the control and accurate measurement of second-mode damping is not possible at present. Based on first-mode results, one would expect the second-mode instabilities to occur for the eccentric case, but at larger flowrates than for the concentric case. One possible reason for their disappearance is that the second-mode excitation may be a forced excitation instead of an instability, and the forced mechanism disappears when the tubes are sufficiently eccentric. Another possibility is that the second-mode instability mechanism, if it exists, may be more sensitive and more easily suppressed by increases in damping than the first-mode mechanism. When the ability to control second-mode damping is added to the facility, this question will be resolved.

Flow damping for the stable configuration of a downstream constriction also is of interest. For the concentric case, the damping always increased significantly with flowrate, and could be used as a design feature to damp forced vibrations. For all eccentricities, the initial damping was as large or larger than that of the concentric case, as discussed previously. For small eccentricities, the damping did increase with flowrate but not always with damping levels as high as those that occur in the concentric case. See Figs. 7(a) and (b) for examples with initial nominal damping of $\zeta_1 = 0.5\%$. For larger initial eccentricity (see Fig. 7(c)), the flow damping often would decrease rapidly at low flowrates because of static divergence of the tubes. But, unlike the upstream configuration, damping lost to divergence was recovered at higher flowrates; a nonzero minimum occurred in the damping curve. In general, the flow damping for the eccentric cases is comparable to that of the concentric case, and initial damping will always be larger.

Fig. 7. Downstream Constriction Flow Damping for (a) $EC = 28\%$, (b) $EC = 57\%$, and (c) $EC = 91\%$, where (Symbol, IL) are: $\circ$, 0.3 D; $\square$, 0.5 D; ∇ , 0.6 D; and Δ , D. Dashed lines are $EC = 0\%$.

VI. FREQUENCIES

Changes in the initial fundamental frequencies were not observed except at the largest eccentricities tested ($EC \sim 90\%$). Even then, reductions in the fundamental frequency were small. Further, the measurements were difficult to repeat because damping was large (only a few cycles per transient), and both the frequency and damping were very sensitive to the small, inherent variations present at all eccentricities.

The fundamental frequencies increased significantly with flowrate as shown in Fig. 8 for an initial damping of $\zeta_1 \sim 22\%$, for example. However, the trend of the increases was the same for all eccentricities, including the previously tested case of $EC = 0\%$ [5]. If the two tubes had converged toward each other with increased flowrate, instead of diverging, then different results for different eccentricities might have occurred. Because the tubes actually diverged with increased flow, the lack of a dependence on eccentricity could have been predicted to be minimal based on the no-flow (initial) damping measurements.

Fig. 8. Frequencies for (a) an Upstream Constriction with EC ~89% and (b) a Downstream Constriction with EC ~88%.

As for the concentric case, the cantilevered beam's second-mode frequency remained the same regardless of the flowrate as long as the tubes did not contact (see Fig. 8). Preload contact or contact initiated by a second-mode instability changed the boundary conditions at the joint toward a fixed-pinned beam vibrating in a fundamental mode with a frequency close to, but smaller than, the cantilever's second mode frequency.

VII. PRESSURE DROP

The pressure drop versus flowrate relationships for all the eccentric cases and the concentric case [5] were the same within the accuracy of the measurements. Results are shown in Fig. 9 for the extreme cases of eccentricity. As expected, based on concentric case results, the pressure drops were the same for an upstream or downstream constriction and were independent of engagement length and initial damping; the narrow annulus is the main source of pressure losses in the slip joint.

Some dependence of pressure drop on eccentricity was expected at large EC, but the increased divergence of the tubes with increased flow must minimize the effect. Some differences in ΔP for EC ~28% (Fig. 9(a)) and EC ~89% may exist at the lowest flowrate, before the tubes diverge significantly, but the accuracy of the instrumentation is poor in this range and the

Fig. 9. Pressure Drop Across the Slip Joint for (a) EC ~28% and (b) EC ~89%.

readings are unreliable. Regardless, differences do not exist at practical flowrates for such a flexible tube.

VIII. SUMMARY

Leakage flowrates were determined that cause dynamic instability of the much more flexible (4 Hz fundamental frequency) tube of a pair of telescoping cantilevered tubes (Fig. 2) **eccentrically** engaged at their free ends by the slip joint of Fig. 1 and Table 1. The major feature of the slip joint is a constriction formed by the short, raised diameter on the inside of the outer tube. Tests were performed at eccentricities of ~25, 50, 75, and 90%, where 0% is a concentric and 100% is a fully eccentric (just contacting tubes) slip joint. Compared with previous results obtained for a concentric slip joint (Fig. 3), the eccentric slip joint is less likely to result in unstable vibrations (Fig. 4). In particular, the design rules to avoid instabilities remain the same--Maintain

- a downstream flow constriction, or
- a downstream annulus length LD less than $1.25 L$, or
- sufficient initial modal damping (Fig. 3).

Differences between the eccentric and concentric slip joints were found in the initial modal damping that appear to explain at least the slightly diminished range of flowrates for which unstable motion occurs in the first mode.

As the initial (no flow) eccentricity of the tubes is increased, the initial modal damping in the direction of the eccentricity increases (Fig. 6), but not significantly until almost 90% eccentricity is achieved. Increased initial damping is reflected in increased critical flowrates for upstream constrictions, but, as for initial damping, the increases are not significant until 90% eccentricity. However, the significant increases in damping or critical flowrates are not reliable, because maintenance of the very small gaps between the tubes at 90% or more eccentricity that produce the significantly larger initial damping is difficult. Any small movement of the tubes due, for example, to a support variation or thermal expansion could greatly reduce the eccentricity and damping. Such reductions were seen at small flowrates (Figs. 6(a) and 7(c)), because the tubes statically diverge from contacting each other as the rate is increased.

Static divergence of the tubes occurs for both upstream and downstream constrictions (Fig. 5), but the divergence is much more pronounced for an upstream constriction, where it nears or surpasses self-centering at higher flowrates in some cases. For both constrictions the divergence is greater for larger flowrates. Thus, any effects due to initial eccentricity can be expected to diminish rapidly with flow. The fundamental frequencies (Fig. 8) and the pressure drops across the slip joint (Fig. 9) for the eccentric cases were essentially the same as for the concentric case except at nearly zero flow. Further, all the instabilities in the fundamental mode that occurred for concentric tubes occurred for eccentric tubes. In fact, instability occurred for one case of preloaded contacting tubes created by 142% eccentricity.

Further testing is required to understand why second-mode instability mechanisms were eliminated by eccentricity at the engagement length of $1/2 D$, the smallest length for which second-mode instabilities occurred for a concentric tube (compare Figs. 3 and 4). The motion at the slip joint in the second mode is known to be primarily rotational, whereas it is primarily translational in the first-mode. Also, measurement and control of second-mode frequency ($f_2 \sim 21$ Hz) and initial damping ($\zeta_2 \sim 0.25\%$) were not possible, and neither changed unless the tubes contacted. Control and measurement of second-mode damping is necessary to gain an understanding of the second-mode phenomenon.

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