THE PINNING FORCE TO PREVENT IN-PLANE FLUID ELASTIC INSTABILITY

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ABSTRACT
The in-plane (stream-wise) fluid elastic instability (FEI) of triangular tube arrays caused tube-to-tube wear (TTW) indications observed in U-bend regions of tube bundles of San Onofre Unit-3 steam generators. In the U-bend region of steam generators, flat bar type tube supports (e.g. Anti-Vibration Bars: AVB) have not been designed to support tubes in the in-plane directions. In order to prevent the in-plane fluid elastic instability, U-bend tubes have to be supported in the in-plane direction or support structures have to generate sufficient damping against in-plane motion. To support and pin a tube at an AVB in the in-plane direction, the contact force pressing the tube against the AVB must be sufficient to overcome both the out-of-plane fluid forces acting to lift the tube off the AVB's surface and the in-plane fluid forces acting to slide the tube along the surface of the AVB. This paper defines the pinning force at a tube-to-AVB intersection is the tube-to-AVB contact force necessary to prevent the FEI and its threshold should be established.

NOMENCLATURE
- $F_{lift}$: Component of the reaction force that would cause the tube to lift off of the adjacent AVB
- $F_{pin}$: Pinning force, contact force necessary to pin a tube
- $F_{slide}$: Component of the reaction force that would cause the tube to slide along the AVB
- $F_z$: Component of $F_{slide}$ in the tube axial direction
- $F_y$: Same as $F_{lift}$
- $F_c$: Component of $F_{slide}$ in the tube perpendicular direction
- $\mu$: Kinetic coefficient of friction

1. INTRODUCTION
(1) In-Plane Fluid Elastic Instability
On January 31, 2012, a leak was detected in a steam generator (SG) in Unit 3 of the San Onofre Nuclear Generating Station (SONGS). SG tube-to-tube wear (TTW) resulted in the leakage. “Southern California Edison has determined the mechanistic cause of the TTW in Unit 3 was FEI, resulting from the combination of localized high steam velocity, high steam void fraction, and insufficient contact forces between the tubes and the AVBs.... The FEI resulted in a vibration mode of the SG tubes in which the tubes moved in the in-plane direction, parallel to the AVBs, in the U-bend region” [1]. The FEI in the in-plane direction has never been observed in the U-tube SGs before its occurrence in the SONGS SGs, as M. K. Au-Yang states that “In-plane modes have never been observed to be unstable even though the computed fluid-elastic stability margins are well below 1” [2]. However, a recent study after the SONGS RSG leakage revealed that the in-plane FEI can occur in triangular array bundle [3]. The contact forces between the tubes and AVBs have to be sufficient to prevent the FEI and its threshold should be established.

(2) Contact Force and Pinning Force
Effectiveness of AVBs depends on the contact force. We defines the contact force necessary to pin a tube is the pinning force. The “pinning force” is defined as the contact force needed to
prevent tube liftoff and sliding at a particular tube-to-AVB intersection for a specific loading and tube support condition. It is mathematically defined in terms of reaction forces. Reaction force is the force experienced at a pinned tube-to-AVB intersection due to the fluid forces applied to the tube. The component of the reaction force that would cause the tube to lift off of the adjacent AVB is referred to as \( F_{lift} \). The component of the reaction force that would cause the tube to slide along the AVB is referred to as \( F_{slide} \). To pin the tube against an adjacent AVB, the force pressing the tube against the AVB must overcome both \( F_{lift} \) and \( F_{slide} \).

2. PINNING FORCE CALCULATION METHOD

(1) Definition of Pinning Force

The figure below shows a tube pinned to an AVB with three forces acting on the tube. It depicts (1) \( F_{lift} \), the force acting to lift the tube off of the AVB; (2) \( F_{slide} \), the force acting to slide the tube off of the AVB; (3) the friction coefficient, represented by the symbol \( \mu \), between the tube and the AVB; and (4) \( F_{pin} \), which is an out-of-plane force perpendicular to the tube that presses the tube against the AVB.

![Figure 1: Definition of Pinning Force](image1)

The perpendicular force pinning the tube to the AVB must be large enough to overcome both the out-of-plane \( F_{lift} \) force and the in-plane \( F_{slide} \) force. The out-of-plane force acting to lift the tube off the AVB \( (F_{lift}) \) is in the direction opposite to the pinning force. Therefore, the force required to prevent the tube from lifting off of the AVB is equal and opposite \( -F_{lift} \). However, the in-plane sliding force is more complex. Before the sliding force \( (F_{slide}) \) can produce sliding, it must overcome the resistance against sliding produced by the friction between the tube and the AVB. The friction force resisting the lateral sliding force is equal to the out-of-plane perpendicular force pressing the tube against the AVB multiplied by the kinetic coefficient of friction, \( \mu \), between the tube and the AVB. Therefore, the perpendicular force required to prevent the tube from sliding in any directions is equal to the sliding force divided by the coefficient of friction, i.e., \( F_{slide} / \mu \). The pinning force is mathematically represented by the equation below.

\[
F_{pin}(t) = F_{lift}(t) + \frac{F_{slide}(t)}{\mu}
\]

(1)

Because the fluid forces acting on the tube are constantly changing due to the turbulent nature of the flow near the tube, \( F_{lift} \) and \( F_{slide} \) – and therefore \( F_{pin} \) – are also constantly changing.

(2) Pinning Force Calculation Method

A rigorous statistical analysis of the time dependent forces attempting to lift the tube from an AVB is performed, as well as those attempting to slide the tube along an AVB. These statistical analyses yielded statistical distributions for the three-dimensional components of the reaction force \( (F_x, F_y, \text{and} F_z) \) from which a Probability Density Function ("PDF") for the pinning force is developed. A PDF describes the probability that a random variable will take on a given value. The pinning force PDF is developed in three steps. First, as discussed above, the pinning force time history data are calculated by the tube response analysis for each of the three-dimensional components of the reaction force \( (F_x, F_y, \text{and} F_z) \). A PDF for each of the three-dimensional components of the reaction force is created based on the calculated time history output. Fig. 2 below shows examples of the PDFs for the \( F_x \), \( F_y \), and \( F_z \) reaction force components for an intersection on a tube. Each of these PDFs shows the likelihood (expressed on the vertical axis as a probability) that the \( F_x \), \( F_y \) or \( F_z \) reaction force (expressed in Newtons on the horizontal axis) will be experienced at the intersection on the tube. Second, then the PDFs of the reaction forces in the \( x \) and \( z \) directions are statistically combined to arrive at a PDF that reflects \( F_{slide} \), which is shown in Fig. 2b below. Finally, the \( F_{slide} \) PDF is statistically combined with the PDF of \( F_{lift} \). This combination yields the pinning force PDF, which is shown in Fig. 2c below.

![Figure 2: Example of Statistical Combination of Reaction Forces to Determine the Pinning Force PDF](image2)
3. PINNING FORCE TEST

(1) Test Apparatus

A mockup was constructed from the perspective of in-plane natural frequency in the SONGS RSGs. This mockup contained the tube itself and AVB segments that closely replicated the existing SONGS AVBs. More specifically, the mockup incorporated a tube identical to those in Row 142 of the SONGS RSGs, which are the tubes with the largest radius. From the perspective of tube vibration, the SONGS Row 142 tubes are the most-limiting tubes because they have the longest unsupported span lengths (i.e., the length of the tube between consecutively-numbered AVBs). The longer the unsupported span length, the lower the tube's displacements and reaction forces at tube-to-AVB intersections.

The Test tube was mounted on a vertical wall using brackets to closely replicate TSPs 6, 7 and the 14 AVB segments. Figures 3 and 4 show the apparatus used for the Tests (“Test assembly”). The Test tube was clamped (i.e., fixed) at brackets representing TSPs 6 and 7 such that the tube could not vibrate at those intersections. Operators could adjust the tube-to-AVB gap sizes at every tube-to-AVB intersection to increase the gap, decrease the gap, or apply contact forces to the tube.

The Test assembly replicated existing AVBs by attaching short segments of AVBs, made from the same material as those in the SONGS RSGs, to a mounting assembly as shown in Fig.5. The design of the mounting assembly allowed operators to adjust the size of the tube-to-AVB gap or apply contact forces to the tube (which were measured by the load cell at that intersection). The contact conditions (contact forces or gaps) at each tube-to-AVB intersection were adjusted by sliding the load cell mount along the guide plate toward or away from the tube.

FIGURE 3: PHOTOGRAPH OF TEST ASSEMBLY

The Test tube was vibrated in the in-plane direction by an in-plane exciter (located near AVB B09, approximately 30 degrees off of the vertical) and in the out-of-plane direction by an out-of-plane exciter (located at the apex of the U-bend). This is shown in Fig.4. Each exciter was connected to the tube by a thin rod and applied a predetermined level of excitation to the tube, which allowed operators to excite the tube in both the in-plane and out-of-plane directions. A tri-axial load cell was attached to the AVB at the tube-to-AVB B09 intersection to measure the reaction forces at that intersection in three dimensions, as shown in Fig.4. One-dimensional load cells were placed at the remaining tube-to-AVB intersections to measure reaction forces in the out-of-plane direction. A two-dimensional laser displacement scanner was used to measure the in-plane relative displacement between the tube and AVB B09. Figure 6 shows a schematic of the three-dimensional load cell at the AVB B09 intersection, the in-plane exciter, and the two-dimensional in-plane laser displacement scanner.

FIGURE 4: SCHEMATIC OF THE TEST APPARATUS

FIGURE 5: SCHEMATIC OF THE TEST TUBE PASSING THROUGH A PAIR OF AVBS

FIGURE 6: SCHEMATIC OF THE IN-PLANE EXCITER, TRI-AXIAL LOAD CELL, AND TWO-DIMENSIONAL IN-PLANE LASER DISPLACEMENT SCANNER
(2) Confirmation of Effectiveness of Contact Force

a) Test Conditions

The first test was done to demonstrate the effectiveness of contact forces that would effectively pin the tubes and prevent in-plane FEI. For this test, the Test tube was vibrated in both the in-plane and out-of-plane directions by mechanical exciters in a variety of contact force conditions, to (1) determine the tube’s in-plane natural frequency, and (2) measure the tube’s displacement at both its apex and at AVB B09. A range of contact forces was applied at the six key intersections to determine the effect of different contact forces on the tube’s in-plane natural frequency and tube displacement. The Test was performed with a 20 mil diametral gap at each intersection where contact forces were not applied.

Operators adjusted the positioning of the load cell mounts for S01 and S02 (as shown in Fig.5) to contact the Test tube and to exert the desired contact force as measured by load cells at the tube-to-AVB S01 and S02 intersections. Because S01 is located between B03 and B04, and because S02 is located between B09 and B10, contact forces applied at S01 and S02 are distributed across B03 and B04, and B09 and B10, respectively, with each experiencing contact forces of approximately one half of the magnitude of those at S01 and S02. Thus, where S01 and S02 each exert approximately 60 N of contact force, approximately 30 N of contact force exists at the other four key intersections. A 20 mil diametral gap was set for the non-key tube-to-AVB intersections.

After confirming the contact force conditions, the operators excited the tube in the in-plane and out-of-plane directions and measured the tube’s in-plane natural frequency and displacement at both the apex and at the tube-to-AVB B09 intersection. Operators then adjusted the load cells for S01 and S02 (as shown in Fig.5) to increase the contact forces present at the key intersections and again measured the tube’s in-plane natural frequency and tube displacement at the tube-to-AVB B09 intersection. This process was repeated with the same in-plane and out-of-plane excitation for a range of contact forces at the S01 and S02 intersections (as shown in Table 1). The Test tube was excited with the in-plane and out-of-plane exciters to conservatively bound the vibration that the tube would experience in an operating SONGS RSG at full power, which is calculated by using the turbulence excitation force PSD and the flow condition shown in Figure 7.

b) Test Results

For the conditions described above, the Pinning Force Test results show that:

Tube Frequency:

- Where no contact force was present at the tube to AVB B03, B04, B09, and B10 intersections, the tube’s in-plane natural frequency was approximately 5 Hz.
- Where 10 N of contact force was applied at the B03, B04, B09, and B10 intersections, the tube’s in-plane natural frequency became approximately 43 Hz.

The application of various contact forces at B03, B04, B09, and B10 exceeding 10 N produced no appreciable change in the tube’s in-plane natural frequency. Once the unsupported span of a tube has been shortened (which causes the shift in in-plane natural frequency), the application of additional contact forces at the same locations does not change the length of that unsupported span, and therefore does not change the tube’s newly-established in-plane natural frequency. To increase the in-plane natural frequency of the tube beyond 43 Hz, additional support points (i.e., at other AVBs) would be required.

**FIGURE 8:** EFFECT OF CONTACT FORCES ON THE TUBE’S IN-PLANE NATURAL FREQUENCY

 Tube Displacement:

Figure 9 below shows the effect of the contact forces on displacement at the apex of the Test tube. Specifically, the Test shows that:

- The relative displacement at the Test tube’s apex decreases rapidly with the application of a small contact force. In the zero contact force condition, the tube displacement at the apex was close to 0.3 mm RMS. By adding as little as 1 or 2 N, the

**TABLE 1:** Contact Force Test Matrix

<table>
<thead>
<tr>
<th>Contact Force, N</th>
<th>S01 and 02</th>
<th>B03, B04, B09 and B10</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>120</td>
</tr>
</tbody>
</table>

**FIGURE 7:** TURBULENCE EXCITATION PSD AND FLOW CONDITION

(a) Non-dimensional PSD

(b) Flow velocity and density distribution
displacement decreased by an order of magnitude to about 0.03 to 0.04 mm RMS.

The displacement at the Test tube’s apex continues to decrease with increasing contact force. At 10 N, the RMS displacement at the apex was approximately 0.01 mm RMS.

![Graph](image)

**FIGURE 9: EFFECT OF CONTACT FORCE ON TUBE DISPLACEMENT MEASURED AT THE TEST TUBE’S APEX**

(3) Reaction Force Measurements

In addition to the case above (Case A-1), 6 cases were performed for a range of excitation levels that both approximated and conservatively bounded the excitation that a SONGS RSG tube would experience during operation as shown in Table 2. Both excitors were adjusted to achieve the measured reaction forces at AVB B09. Contact forces were applied at the six pinned intersections such that the tube was pinned to the adjacent AVBs for the different excitation levels applied. Two sets of tube support conditions were specified (of 4 mil and 20 mil diametral gaps) at the unpinned tube-to-AVB intersections, as described in Table 2.

**TABLE 2: Test Cases with Measured Reaction Forces**

<table>
<thead>
<tr>
<th>Case</th>
<th>Diametral gap at unpinned AVBs, mm</th>
<th>Sliding force</th>
<th>Lifting force (F_{Lift})</th>
<th>Contact force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>0.5</td>
<td>1.5, 3.0</td>
<td>3.4, 3.6</td>
<td>1.2</td>
</tr>
<tr>
<td>A-2</td>
<td>0.1</td>
<td>1.2, 2.7</td>
<td>3.0, 2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>B-1</td>
<td>0.5</td>
<td>1.2, 2.1</td>
<td>2.4, 4.2</td>
<td>0.5</td>
</tr>
<tr>
<td>B-2</td>
<td>0.5</td>
<td>2.2, 3.5</td>
<td>4.2, 5.7</td>
<td>0.5</td>
</tr>
<tr>
<td>B-3</td>
<td>0.5</td>
<td>1.6, 3.1</td>
<td>3.5, 4.1</td>
<td>0.5</td>
</tr>
<tr>
<td>B-4</td>
<td>0.5</td>
<td>2.4, 4.1</td>
<td>4.8, 5.2</td>
<td>0.5</td>
</tr>
<tr>
<td>B-5</td>
<td>0.5</td>
<td>2.8, 5.2</td>
<td>5.9, 6.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4. COMPARISON BETWEEN TEST AND CALCULATION

(1) Analytical Model and Inputs

IVHET is a computer program that calculates the vibration response of a steam generator tube that is excited by fluid flow forces. The single-tube mockup described above is utilized to obtain measured values for reaction forces, and it then compared those values with the values calculated by IVHET to confirm the IVHET code’s accuracy. Figure 10 and Table 3 describe the analytical model geometry and input parameters. IVHET modeled the Test tube as a beam element fixed at both ends and modeled unpinned tube-to-AVB intersections using gap elements. The mechanical properties associated with these elements are provided in Table 3. Because the mockup employed a 4 mil (0.1 mm) or 20 mil (0.5 mm) diametral gap for unpinned tube-to-AVB intersections, the gap on each side of the tube was modeled in IVHET as 2 mils or 10 mils, respectively.

![Diagram](image)

**FIGURE 10: IVHET Analytical Model**

**TABLE 3: Analytical Model Specifications**

<table>
<thead>
<tr>
<th>Tube diameter</th>
<th>19.05 mm</th>
<th>Contact stiffness</th>
<th>3800 N/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube wall thickness</td>
<td>1.09 mm</td>
<td>Tangential stiffness</td>
<td>590 N/mm</td>
</tr>
<tr>
<td>Tube Radius</td>
<td>1937.3 mm</td>
<td>Contact damping</td>
<td>110 Ns/m</td>
</tr>
<tr>
<td>Tube material</td>
<td>Alloy 690</td>
<td>Coefficient of friction</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of AVBs</td>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(2) Reaction Force

The tube in the IVHET model is excited by the turbulence-induced excitation force. IVHET outputs time history curves for the three orthogonal components of the reaction force \(F_z\), \(F_y\), and \(F_x\) at each pinned tube-to-AVB intersection. \(F_z\) is the reaction force in the out-of-plane direction acting to lift the tube off of the AVB (i.e., \(F_{Lift}\)). The in-plane components of the reaction force acting to slide the tube along the AVB are \(F_x\) in the tube axial direction and \(F_y\) in the direction normal to the tube axis, which are combined to calculate \(F_{Slide}\).

Figure 11 and Table 4 show the reaction forces calculated by IVHET and those measured by the Reaction Force Test.
Calculation  

Test  

Fx  

Fx  

Fy  

Fy  

Fz  

Fz  

Pinning Force  

Pinning Force  

TABLE 4: EXAMPLE OF PROBABILITY DISTRIBUTION FUNCTION (COMPARISON BETWEEN CALCULATION AND TEST IN CASE A-1)  

5. DISCUSSIONS  

Based on the first test results, it is apparent that the application of even small contact forces of one or two N at the key intersections greatly diminishes the tube's vibration amplitude and eliminates the natural frequency peak at 5 Hz. With the application of contact forces on the order of 10 N at the key intersections, the in-plane natural frequency of the Test tube is firmly established at 43 Hz. A small contact force has a great role to change the tube vibration responses.

Figure 11 demonstrates that the calculated reaction forces are consistent with the measured reaction forces and confirm IVHET's ability to calculate reaction forces. The reaction forces calculated by IVHET in the lift direction are (on average) 15% higher than what was measured in the Reaction Force Test. The reaction forces calculated by IVHET in the sliding direction are (on average) 15% lower than what was measured in the Reaction Force Test. Considering the uncertainties associated with the test measurements and variations in the input parameters used in the IVHET analysis, this result is good agreement with the test results and IVHET has an ability to obtain the pinning force. As shown in Table 4, although the pinning force is variable, the probability of the pinning force exceeding 30 N is negligibly small.

6. CONCLUSIONS  

The results of the tests and the analyses lead to the following conclusions:

(1) The application of small contact forces (e.g. 5 N) reduce the tube displacement and increase the tube natural frequency. That means the AVB intersection with the contact force is effective as pin the tube in the in-plane direction. Consequently, the in-plane FEI is able to be prevented by the contact forces.

(2) The threshold of the pinning force can be determined based on the PDF. The probability of the pinning force exceeding the threshold (the probability of the tube slippage at the AVB intersection) is able to be calculated mathematically. If the probability is negligibly small and the tube wear due to the turbulence induced vibration during long term operation is not significant, the threshold is appropriate.

(3) In addition, it is confirmed that the probabilities of the pinning force and the reaction forces can be predicted by numerical calculations.

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