ABSTRACT
The San Onofre Nuclear Generating Station (SONGS) was shut down after fluidelastic instability (FEI) produced numerous tube leaks through tube-to-tube impacting. Normally, this instability is expected to occur with tube motion in the direction transverse to the direction of flow. At SONGS, the instability occurred in the plane of the U-bend tubes, a phenomenon never before documented in a nuclear steam generator in service. The authors previously developed a simple theoretical model for streamwise FEI for parallel triangular tube arrays, the results comparing well with existing experimental data. It was shown that streamwise FEI was very sensitive to array pitch ratio and mass damping parameter. In the present paper, that model is extended to the rotated square tube array. The results of comprehensive parametric studies are presented for the effects of pitch ratio, and mass damping parameter on the transverse and streamwise FEI in this array geometry. Computations were carried out for single flexible tubes in a rigid array and multiple flexible tube arrays for tube motion in the transverse and streamwise directions independently. Comparisons are made with existing experimental data. It is seen that array geometry has a significant effect on the tendency for streamwise instability and physical insights are developed to explain the observations.

INTRODUCTION
In U-bend type nuclear steam generators, the area of greatest vulnerability to cross flow-induced vibrations is in the U-bends since the cross flow velocities are very high and the tubes tend to be less well supported than in the straight legs. While turbulence may lead to long term fretting wear problems, by far the flow-induced vibration mechanism of greatest concern in steam generators is fluidelastic instability (FEI) which can lead to tube failures in a very short period of time. As a result, a substantial literature has been developed over the past 45 years, including comprehensive reviews [1, 2, 3] and design guidelines [4].

In designing heat exchanger tube arrays against flow-induced vibrations, the usual approach is to ensure that the tube natural frequencies are sufficiently high. To increase the relative stiffness of U-bend tubes, anti-vibration bars (AVBs) are often
placed radially and, traditionally, tube-to-support clearances have been used to account for manufacturing tolerances, ease of assembly, and thermal expansion. Weaver and Schneider [5] reported a wind tunnel study of a full-scale Bruce B U-bend tube array and found that flat bar AVBs with clearances, placed in the plane of the U-bends, not only restrained the out-of-plane vibrations but also prevented FEI in the in-plane direction. The vast majority of laboratory experiments have been carried out using straight tubes and have indicated that FEI is generally observed in the direction transverse to the direction of flow. These observations and the fact that streamwise fluidelastic instability (SFEI) had never been observed in steam generators in service, even when the computed stability margins were well below unity [6] led to the generally accepted conclusion that, if care was taken in design to prevent transverse FEI, SFEI would not occur. However, the tubes failures at the San Onofre Nuclear Generating Station (SONGS) have brought that assumption into serious question. These replacement steam generators developed serious U-bend tube leaks after only 11 months of service and inspection showed that the leaks were the result of tube-to-tube clashing in their in-plane modes, i.e., SFEI [7].

Weaver and Schneider [5] actually studied the possibility of SFEI in their U-bend experiments. They set up the U-bend test section in the wind tunnel such that the flow was normal to the plane of the U-bends and observed that FEI occurred as expected in the mode with the lowest natural frequency, which was now an out-of-plane mode with the tubes moving in the streamwise direction. Similar results were found in a water tunnel study by Weaver and Koroyannakis [8]. In this case, the tubes were straight and supported on rectangular section beams such that their transverse and streamwise natural frequencies were different and could be selected independently. They found that FEI would occur in whatever direction had the lowest natural frequency, regardless of whether this was in the transverse or streamwise direction to the flow. This is an extremely important observation because it proves that U-bend tubes can become unstable in the in-plane direction. If this has not been observed in operational steam generators with flat bar supports, it must be the result of interactions with the tube supports and not because SFEI cannot occur. Some insight and at least a partial explanation for this is found in the theoretical study by Yetisir and Weaver [9]. They reported numerical simulations for the lowest 36 out-of-plane and in-plane natural vibration modes of a U-bend tube and showed that impacting of the tubes at the flat bar supports excited higher frequency modes which accounted for 70% of the total cumulative modal damping. Thus, excitation of the higher modes by impacting and rather than sliding friction seems to be the dominant damping mechanism. Interestingly, this not only provides insight into the possible reasons for flat bar effectiveness in supporting in-plane modes but it also suggests that impacting at the supports may be necessary for this effectiveness.

Interest in SFEI has been rekindled in recent years, especially after the SONGS RSG tube failures. Mureithi et al [10] reported a wind tunnel study of a tube array in which the tubes were supported in a way that effectively prevented them from vibrating in a direction transverse to the flow. The results were clear and supported those earlier studies which demonstrated that SFEI could occur. Similar studies have been carried out in two phase flows: U-tubes in air-water (Janzen et al. [11], straight tubes in air and air-water (Violette et al. [12] and straight tubes in refrigerant 11 (Feenstra et al. [13]). Hirota et al [14] carried out an air flow study of a parallel triangular array of straight tubes restrained to move only in the in-plane or out-of-plane directions. They found that their array became unstable in the in-plane direction and that, for their pitch ratio of 1.34, the ratio of Connors constants for the in-plane to out-of-plane directions was 1.5. These results agreed with those of Nakamura et al [15]. Nakamura et al. [16, 17] showed experimentally that streamwise FEI in parallel triangular arrays is dependent on the number of tubes considered in the array and was strongly dependent on the pitch ratio. Indeed, these experiments indicated that a single flexible tube in a tube array would not become unstable in the streamwise direction and that SFEI could become critical at very low pitch ratios.

Olala et al [18] carried out a study of a single flexible tube in a parallel triangular array with a pitch ratio of 1.5 and subjected to an air-water 2 phase flow. The tube was constrained to move only in the streamwise direction and never became fluidelastically unstable, at least for this tube array geometry and pitch ratio. These results confirmed that the fluid stiffness mechanism is dominant in SFEI. Olala and Mureithi [19] extended this work to determine the quasi-steady fluid force coefficients for a kernel of flexible tubes in the same array and included the effect of the cross-coupling forces and phase measurements used to determine the time delay. Olala and Mureithi [21] used these force coefficients in a quasi-steady analysis to study the streamwise stability of a kernel of tubes in 2 phase air-water flow ranging from 0 to 90% homogeneous void fraction. Their predicted critical velocities agreed reasonably well with the experimental results of Violette et al [12]. They examined a variety of cases with different numbers of tubes, concluding that the critical velocity decreased with an increase in the number of adjacent flexible tubes. This, of course, reflects the fact that fluid coupling is the dominant excitation mechanism in SFEI. This also explains their observation that frequency detuning had a stabilizing effect on their array.

Feenstra et al [22] reported an experimental study of streamwise damping of U-tubes moving in the plane of the anti-vibration bars (AVBs). The experimental rig employed a full-scale sectional model of 22 tubes in a parallel triangular array with a pitch ratio of 1.5 and the results showed that the damping of the tubes moving in the plane of wet AVBs was substantially less than existing guidelines suggested. This experimental facility was then used to study SFEI in air flow by Feenstra et al [23]. SFEI was observed in most of the configurations tested and when the AVB clearances were sufficiently large, amplitude limited FEI was observed in the lift direction. The SFEI results with
small clearances showed substantial hysteresis with the most consistent critical velocity measurements being obtained with decreasing velocity. In some cases, large initial disturbances were required to initiate instability.

Hassan and Weaver [24] reported a theoretical study of the effects support clearance, tube-to-support preload and flow turbulence on transverse and streamwise SFEI of loosely supported tubes. The results indicated that these parameters have very different effects on transverse and streamwise SFEI because of the difference in damping mechanisms at the supports (sliding friction, stick-slip, and impacting). In particular, increasing normal load and friction between the tube and support have stabilizing effects while increased tube-to-support clearance has little effect on transverse SFEI but is destabilizing to streamwise SFEI. These simulations appeared to explain some of the observations on the SONGS tube failures but the results were obtained using an artificial flow excitation mechanism. Thus, they followed this study up with the development of a first principles theoretical model [25] based on the simple wavy wall stream tube approach of Lever and Weaver [26]. A kernel of 7 flexible tubes in a parallel triangular array with a pitch ratio of 1.5 was studied for a mass damping parameter value of 50. The tube frequencies and motion were unconstrained so that their amplitude and frequency response were free to evolve with increasing flow velocity in both the lift and drag directions. The results showed that, at least for this array geometry, pitch ratio and mass damping parameter, the instability always occurred in the lift direction if the natural frequencies were the same in both directions. However, if the streamwise natural frequency were about 20% lower than the transverse natural frequency, SFEI occurred in the streamwise direction. It was also clear that the fluid coupling between tubes is an important component of SFEI, i.e., the ‘stiffness’ excitation mechanism is dominant. Hassan and Weaver [27] then extended this study to examine the effects of pitch ratio and mass damping parameter on the transverse and streamwise stability of parallel triangular tube arrays. The results indicated that streamwise SFEI could become critical for small pitch ratio arrays operating at high values of the mass damping parameters. These are, in fact, the precise conditions under which the SONGS failures occurred. The theoretical predictions agreed very well, both qualitatively and quantitatively, with the experimental results of Nakamura et al. [17], showing that fluid coupling is an important driving mechanism for SFEI and predicting its sensitivity to pitch ratio. Weaver and Hassan [28] adapted this model to study SFEI in normal triangular and in-line square tube array geometries and found that parallel triangular tube arrays were most vulnerable to SFEI and, in agreement with the experimental results of Nakamura et al [29], predicted that the tubes in normal square arrays would not become unstable in the streamwise direction.

It is clear that SFEI is strongly dependent on tube array geometry, pitch ratio and mass ratio, and since no theoretical studies for SFEI in rotated square arrays have been carried out, that is the subject of this paper. The Lever and Weaver model as developed for SFEI in Hassan and Weaver [25], was extended to model rotated square array tube bundles and computations were carried out for transverse and streamwise SFEI for a single flexible tube in a rigid array and for a kernel of multiple flexible tubes while varying pitch ratio and the mass damping parameter. The results are compared to available experimental data and to other standard array geometries.

MODEL DEVELOPMENT

The theoretical model utilized in this work is based on the original tube-in-channel model developed by Lever and Weaver [26]. The full description of the model can be found in the paper by Hassan and Weaver [25]. However, a brief presentation of the model will be presented here. The complex flow inside the tube bundle can be simplified by a series of flow channels. A kernel of flexible tubes surrounded by rigid tubes are considered as shown in Fig. 1. Each tube is in contact with two flow channels. The flow in these channels was idealized as one-dimensional incompressible flow. The width of the flow channel (Δ) and the location of flow attachment, S_a, and flow separation, S_w, with each tube can be obtained from flow visualization (Fig. 2). The wake regions behind each tube are ignored as their contribution to the fluid forces acting on the tubes is negligible.

The governing equations of motion for the tube bundle can be expressed as:

\[
[M] \ddot{w} + [C] \dot{w} + [K] w = \{F_{fei}\}
\]

where \([M]\), \([C]\), and \([K]\), represent the system mass, damping, and stiffness, respectively. \(\dot{w}\), \(\ddot{w}\), and \(w\) are the tube acceleration, velocity, and displacement, respectively. For \(N\) flexible tubes the response \(w\) is a 2N\times1 vector that includes both the transverse \(w_L\) and streamwise \(w_D\) fluidelastic forces. The transverse \(F_L\) and streamwise \(F_D\) fluidelastic forces are included in the \(F_{fei}\) force vector.

The motion of each tube in the transverse \(w_L\) and streamwise \(w_D\) directions is thought to create a flow perturbations \(a_L\) and \(a_D\) that travel upstream and downstream of the tube. These perturbations will alter the flow channel width creating an unsteady flow forces that are coupled with the tube motion. The instantaneous flow channel width is expressed as:

\[
A(s,t) = A(s) + a(s,t)
\]

where \(A(s)\) and \(a(s,t)\) are the steady state and perturbation components of the flow channel width. Similarly, these perturbation will cause perturbations in the flow velocity \(u(s,t)\) and pressure \(p(s,t)\). The perturbation due to the transverse tube motion is a function of the tube displacement, time lag and its location \(s\) with respect to the source of the disturbance as follows:

\[
a_L(s,t) = w_L(t - \tau_L)\gamma_L(s)
\]

where \(\gamma_L(s)\) is a decay function and \(\tau_L\) is the time delay that reflects the speed at which the perturbation propagates. Similarly, the streamwise perturbation can be expressed in terms of magnitude, phase, and decay rate.

Due to the motions of the multiple tubes within the bundle, the perturbation at any point within a flow channel is considered
to be a linear summation of all perturbations originated at the surrounded tubes.

\[ a(s, t) = \sum_{j=1}^{N} \left( a_{L_j}(s, t) + a_{D_j}(s, t) \right) \]  

(3)

Once the perturbation along the flow channel is calculated, the unsteady continuity equation is utilized to calculate the velocity perturbations:

\[ u_i(s, t) = \frac{1}{A_i(s, t)} \left[ A_i(-s_0, t)U_i(-s_0, t) - U_i(s)A_i(s, t) - \int_{-s_0}^{s} \frac{\partial \sum_{j=1}^{N} A_{j}(s, t)}{\partial t} ds \right] \]  

(4)

These velocity perturbations are then used to obtain the pressure perturbations utilizing the unsteady momentum equation:

\[ p_i(s, t) = \rho \left[ 0.5(U_i(s))^2 - U_i(s, t)^2 - \int_{-s_0}^{s} \frac{\partial u_i(s, t)}{\partial t} ds - \frac{\rho_0}{2s_0} \int_{-s_0}^{s} U_i(s, t)^2 ds \right] \]  

(5)

As shown in Fig. 3, each tube is in contact with two flow channels. The net pressure acting on the tube \( \Delta p = p_1 - p_2 \) is calculated utilizing the pressure equation (5). The transverse and streamwise fluid forces are calculated as:

\[ F_t = \int_{-s_0}^{s} \Delta p \cos \beta \, ds \]

\[ F_D = \int_{-s_0}^{s} \Delta p \sin \beta \, ds \]  

(6)

Once the two force components are estimated, the equations of motion are integrated using the central difference method and the tube response is calculated.

**FIGURE 1:** ROTATED SQUARE TUBE ARRAY MODEL. FLEXIBLE TUBES ARE LABELED 1-7.

**FIGURE 2:** FLOW VISUALIZATION PHOTO AND DRAWING AND THE IDEALIZED FLOW CHANNELS

**FIGURE 3:** FLOW CHANNELS AND PRESSURE OVER THE LENGTH OF THE CHANNEL IN CONTACT WITH THE TUBE.

**SIMULATIONS**

A substantial advantage of the modelling approach used here is that comprehensive parametric studies can be carried out with no new empirical data and relatively modest computational effort. A set of tube array parameters are selected and, for a given flow velocity, a disturbance was given to the tubes and a transient time tube response analysis is carried out until a steady state condition is achieved. This takes from 10 to 100 seconds with time steps in the range 0.1 ms to 0.01 ms, depending on the number of flexible tubes being considered, their direction of motion, and stability condition. The tube response frequency is not constrained to their no flow natural frequency but rather is free to respond to the flow current flow conditions. The velocity is then incremented in small steps until the stability threshold has been clearly established. The process, including time traces of transient response and velocity vs response amplitude are illustrated in [25].

Previous studies by the authors [26, 27] have demonstrated the sensitivity of the stability threshold to tube array pitch ratio, P/D, and mass damping parameter (MDP). Thus, in the present study, simulations were carried out for a range of these governing parameters for the cases of a single flexible tube in a rigid array and a kernel of 7 flexible tubes as shown in fig 1. The response behaviour is studied for both transverse and streamwise...
directions by having the excitation mechanism in the model active in either direction independently.

**Simulation Results for Transverse FEI**

Simulations were carried out for the stability of a single flexible tube in a rigid array in the transverse direction for a range of MDP from 1 to 110 and for pitch ratios from 1.2 to 1.7, as plotted in Fig. 4. Clearly, a single flexible tube in a rigid array is predicted to become unstable throughout the parameter range simulated, with a jump near MDP = 3.5. Interestingly, below this value, the stability is seen to increase very gradually with increasing MDP and to be nearly independent of the pitch ratio. For MDP > 3.5, the stability increases with both MDP and P/D.

The stability of the kernel of 7 flexible tubes shown in Fig. 1 was then studied over the same parameter ranges as for Fig. 4, the results being shown in Fig 5. It is seen that the stability behaviour is qualitatively the same as for a single flexible tube in the rigid array and to make quantitative comparison simpler, the results for both cases are repeated in Fig 6 for an array with a pitch ratio of 1.5. These results are very revealing. The stability threshold for a single flexible tube in a rigid array is always higher than that for a fully flexible array which shows the importance of tube-to-tube coupling for FEI in normal square tube arrays, over the entire range of MDP and P/D. The jump in the stability boundary is also delayed to higher MDP values and, as seen in Fig 5, is quite sensitive to pitch ratio for fully flexible arrays. This indicates that the increased coupling associated with higher MDP and lower P/D both have significant destabilizing effects.

The reason for the step in the stability threshold observed in Fig. 4 – 6 inclusive is not understood. Figure 7 shows schematic sketches of the relative modes of the kernel of flexible tubes observed for a P/D of 1.5 in fig 5. The markers on the trajectories indicate the phase relationships. At MDP values below the step, it appears that all tubes in a streamwise column are essentially in-phase and approximately 180 degrees out-of-phase with their adjacent columns. Above the step, the phase relationships have changed with there no longer being simple in-phase and out-of-phase modes, although the modal relationships appear to be well organized. Thus, the step in the stability threshold with increasing MDP is associated with a change in modal behaviour for a fully flexible array but, the existence of a similar step for a single flexible tube indicates that the relative mode shape is not the cause of the step.
Simulation Results for Streamwise FEI

Since streamwise FEI has become such a concern after the failures at SONGS, simulations were also conducted separately to investigate the streamwise stability of rotated square tube arrays over the same parameter ranges as for transverse stability by simply activating the streamwise excitation mechanism while disengaging the transverse mechanism in the model. The results are summarized in Fig. 7 for a pitch ratio of 1.5 for a single flexible tube and a fully flexible tube array. The results for all other P/D over the range 1.2 to 1.7 show exactly the same trend with the critical velocity for a given MDP increasing with pitch ratio. This is exactly what one would expect. Increasing pitch ratio reduces tube-to-tube coupling forces and therefore has a stabilizing effect. It is seen that a single flexible tube can become unstable for the entire range of MDP studied but that the stability of a fully flexible array is always lower for a given MDP. This shows that a single flexible tube can become fluidelastically unstable in a rotated square tube array but that fluid coupling has a destabilizing effect, regardless of P/D and MDP.

For quantitative comparison, the stability results for a fully flexible array in the transverse direction are also plotted in Fig. 7. The streamwise FEI threshold is always significantly higher than that for a multiple flexible tube array. These results indicate that, while streamwise FEI is possible in rotated square arrays, it is unlikely to be a practical problem in heat exchangers unless the streamwise natural frequencies are much lower than those in the transverse direction.

COMPARISON WITH EXPERIMENTS

While the experimental data for fluidelastic instability in rotated square arrays in the open literature is rather sparse, some data do exist and are shown in Fig. 9 [reference], along with the present predictions for a fully flexible array with P/D = 1.5. While the data is rather scattered, typical of data in the literature, the predictions of the simulations are remarkably good, especially given the simplicity of the model.

CONCLUSIONS

The Hassan and Weaver tube-in-channel model, originally developed from the Lever and Weaver model to study both transverse and streamwise fluidelastic instability in parallel triangular tube arrays, was extended to consider the stability of rotated square tube arrays. Simulations were carried out for a single flexible tube in a rigid array and for a kernel of 7 flexible for both transverse and streamwise FEI. Parametric studies of the stability of the arrays were carried out over a range of pitch ratio.
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and mass damping parameter and compared with available experimental data in the open literature. While the model is very simple and primarily expected to predict stability trends with parameter changes, the quantitative comparison of the predictions with the available experimental results is remarkably good. The specific conclusions drawn from these simulations are:

1. Streamwise fluidelastic instability can occur in rotated square tube arrays but for the same tube natural frequency in the lift and drag directions, transverse FEI is always critical.

2. A single flexible tube in a rigid array is predicted to become unstable in the streamwise direction but its stability threshold is higher than that for a multiple flexible tube array in the streamwise direction, and much higher than that for a multiple flexible tube array in the transverse direction.

3. Tube-to-tube coupling is not essential for streamwise FEI in normal triangular tube arrays but its effects are significant over the entire range of pitch ratio and mass damping parameter studied. These coupling effects increase with both decreasing pitch ratio and increasing mass damping parameter.

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