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FLUIDELASTIC INSTABILITY OF A SINGLE FLEXIBLE TUBE IN A RIGID TUBE ARRAY

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ABSTRACT

Tube and shell heat exchangers are commonly used in both fossil and nuclear power plants. The unexpected failure for such components is expensive and potentially dangerous. Of the various excitation mechanisms which can cause excessive tube vibration, fluidelastic instability is the most dangerous and therefore has received the most attention. The present study reviews the experimental work published in the open literature which involves the use of a single flexible tube in a rigid array to study fluidelastic instability. The data are categorized based on the array geometry into four main groups, parallel triangular, normal triangular, rotated square, and square array patterns. It is concluded from this review that the simplification of using a single flexible tube in a rigid array to study fluidelastic instability should be done with great care, and precise control of some parameters is essential to obtain reliable and repeatable results. Fluidelastic instability of a single flexible tube in a rigid array may occur in some cases, and may be used to improve our understanding of the phenomenon. However, it must be noted that this behavior is a special case and not generally useful for determining the stability of tube arrays.

Keywords: Fluidelastic instability, Review, Single flexible tube, Fluid-structure interaction, Tube bundle, Heat exchanger.

INTRODUCTION

Due to the high cost of unplanned outages of power and process plants resulting from component failure, the design of hardware such as tube and shell heat exchangers must account properly for all parameters affecting their reliable operation. Fluidelastic instability in heat exchanger tubes exposed to cross flow is considered to be a critical failure mode that must be avoided [1-8]. Fluidelastic instability is a phenomenon associated with fluid cross flow over tube banks, causing the tube vibration amplitudes to increase dramatically at a certain flow velocity called the critical velocity. This velocity must be known and used with a suitable safety margin in the design of heat exchangers for reliable operation during their working life.

In order to understand and avoid this phenomenon, a significant research effort has been dedicated to this problem over the last four decades. Several theoretical models have been developed to predict fluidelastic instability using different approaches and assumptions [1, 3, 9, 10]. As the problem of fluidelastic instability is quite complex and affected by many parameters such as array geometry, turbulence level, type of working fluid, dynamic coupling, etc, some concepts have been adopted to simplify the problem and to reduce number of parameters. One of these concepts involves using a single flexible tube in a rigid array to study the phenomenon. This concept was based on experimental observations which showed that a single flexible tube placed in a rigid array of tubes underwent fluidelastic instability at essentially the same stability threshold as the same array with all the tubes flexible [11-13]. It is established in the literature that fluidelastic instability is attributed to two main mechanisms [9, 14, 15] one is due to relative tube motion called "The Stiffness Mechanism", and the other is due to negative fluid damping and called "The Damping Mechanism". Applying the concept of a single flexible tube in a rigid array eliminates the effect of relative tube motion and therefore the stiffness mechanism, and this simplification reduces the parameters affecting instability, making it easier to investigate the problem.

Since this simplification was first introduced, a number of studies have been conducted on this basis, including [16-18]. However, a single flexible tube in a rigid array has not shown consistent behavior in all cases even for the same array pattern. This apparent contradiction in experimental observations is the motivation for the present study which reviews the experimental data reported in literature for a single flexible cylinder in a rigid array. The single flexible tube, as referred to in this paper, is generally free to vibrate in both lift and drag directions unless otherwise specified. Based on the common geometrical patterns for tube arrays, as shown in Fig. 1, the study is divided into four sections, Parallel Triangular array, Rotated Square array, Normal Triangular array, and Normal Square array. A critical analysis of the experimental data reported in literature is presented and an attempt is made to establish trends and explain the apparent contradictions.

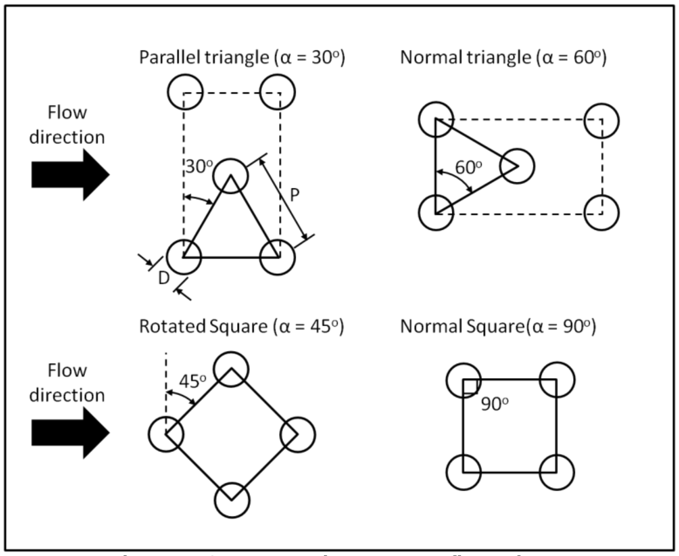

Figure 1. Common tube array configurations.

PARALLEL TRIANGULAR TUBE ARRAY (α= 30^O)

The parallel triangular array pattern has the configuration shown in Fig. 1, where P is the array pitch, and D is the tube diameter. The pitch ratio P_r is defined as shown in Eq. (1). It is important to note here that some authors use the upstream flow velocity U_o as reference while others use the mean gap velocity U_g as reference. The relation between upstream flow velocity and mean gap velocity is given by Eq. (2).

$$P_r = {}^{P}\!/_{D} \tag{1}$$

$$U_g = \frac{P}{(P-D)} U_o \tag{2}$$

Lever and Weaver in 1977 investigated the effect of tuning the array tubes on the fluidelastic stability threshold [13]. Experiments were conducted on a parallel triangular array with a pitch ratio of 1.375 in air. The tubes were suspended on piano wires which facilitated precise control of their frequencies. The authors found that detuning the adjacent tubes as little as 3% of the target frequency could lead to a delay in the stability threshold of about 40%. Increasing the detuning value above 10% had a limited effect on stability threshold as seen in Fig. 2. The observations made during this study suggested that a single flexible tube in a rigid array could become fluidelastically unstable.

To study this issue further, Lever and Weaver [11, 12] conducted a series of experiments on a parallel triangular tube array in air. The array consisted of 12 rows and 11 columns of aluminum tubes with a pitch ratio of 1.375, and the flexible tube was located in the eighth row. The flexible tube was suspended on a piano-wire equipped with a tensioning device and damping device to control the tube frequency and total damping precisely. The experiments showed that a single flexible tube in a rigid parallel triangular array can go unstable essentially at the same stability threshold for the array with all the tubes flexible as shown in Fig. 3. Based on these observations, Lever and Weaver developed their analytical model to predict fluidelastic instability [11, 12, 19].

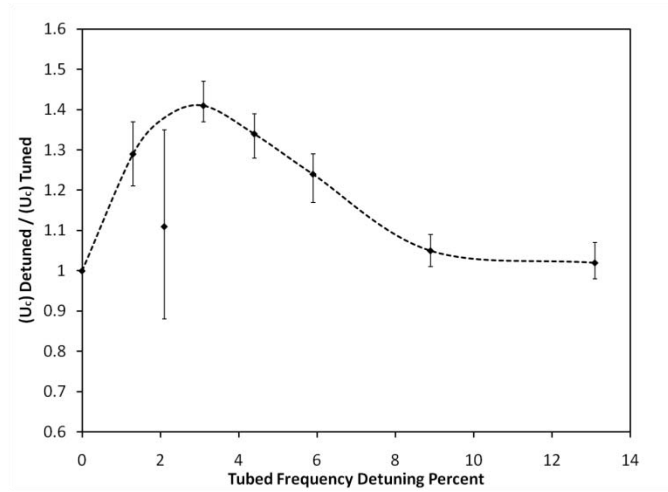

Figure 2. Critical velocity ratio vs frequency difference [13].

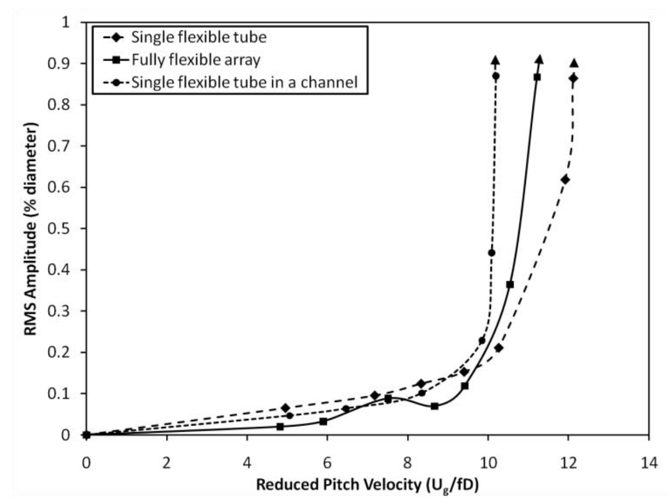

Figure 3. Stability behavior for a single flexible tube and a fully flexible parallel triangular array (P/D=1.375) in air [12].

Little [20] conducted experiments on a parallel triangular array with a pitch ratio of 1.39 in air. The array consisted of 7 rows and 5 columns of cantilevered acrylic tubes D=64mm with the flexible tube located in the third row. This particular location was suggested by Weaver and El-Kashlan [21, 22] to be the least stable location in the array. The array with all tubes flexible showed distinct fluidelastic instability behavior well separated from any Strouhal excitation. The case of a single flexible tube showed instability; however the post stability behavior was different due to the effect of fluid coupling in the case of all flexible tubes as shown in Fig. 4 and Fig. 5. It can be seen that in the case of a single flexible tube as well as the fully flexible array, the critical reduced velocity is about 11.2±0.2. Note that the post stable behavior shows a less rapid increase in RMS amplitude with increasing flow velocity in the single flexible tube case, and that the motion is primarily in the direction transverse to the flow. Thus, for this pitch ratio, fluid coupling has little influence on the stability threshold but a significant effect in the post stable region.

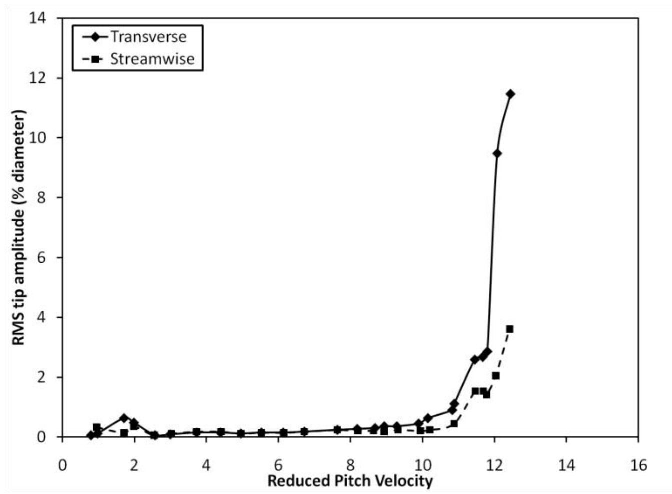

Figure 4. Stability behavior of a fully flexible parallel triangular array (P/D=1.39) in air, Little [20].

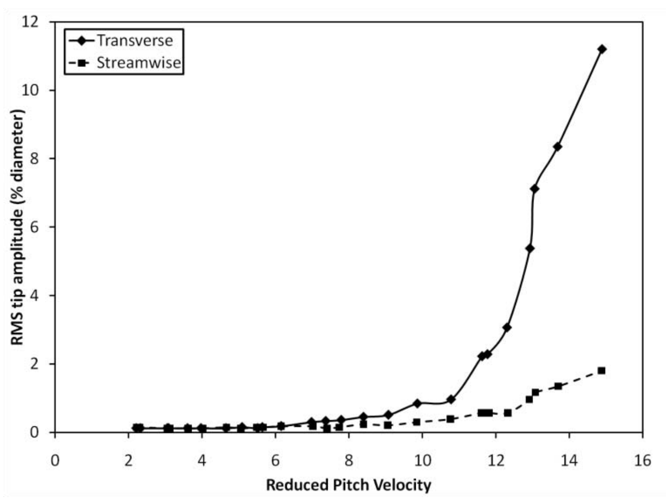

Figure 5. Stability behavior of a single flexible tube in a rigid parallel triangular array (P/D=1.39) in air, Little [20]

Scott [23] conducted experiments on two parallel triangular tube arrays with pitch ratios of 1.375 and 1.73 in water. The first array *P/D=1.375* consisted of 6 rows and 11 columns of acrylic tubes *D=25.4mm* and the flexible tube was mounted in the third row. In the case of a single flexible tube, fluidelastic instability was reported predominantly in cross stream direction, and essentially at the same stability threshold for the array with all tubes flexible as shown in Fig. 6(a) and Fig. 6(b). The response pattern for both the single flexible tube and all flexible tubes cases was similar, where a local response peak was detected in the post stable region, and the tube response frequency increased with flow velocity up to a certain value and then dropped down. This behavior is common in water experiments and is attributed primarily to the change of relative vibration modes between the tubes and the associated changes in fluid added mass. This effect appears in water experiments since the density of water is much greater than air, thus giving the added mass terms more significance. The critical upstream velocity seen in Fig. 6(a) is about 0.13m/s, and the critical velocity for the single flexible tube in this array is essentially the same as seen in Fig. 6(b), albeit the post stable region is only qualitatively similar.

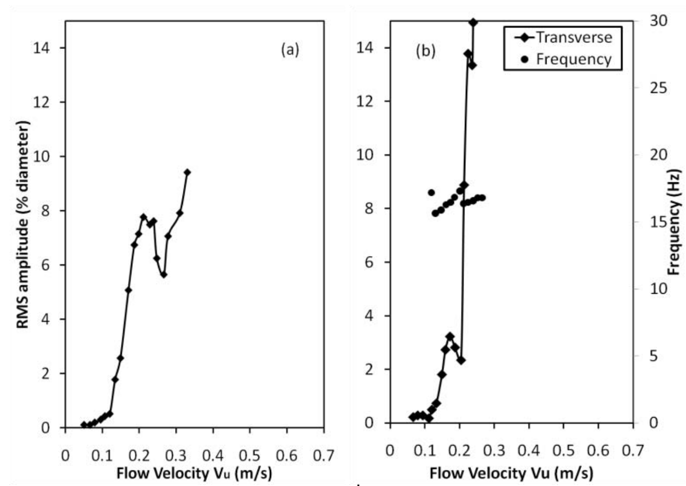

Figure 6. Response of a flexible 3rd row tube in a parallel triangular array P/D=1.375, (a) fully flexible array, (b) rigid array, Scott [23].

The second array investigated by Scott [23] had a pitch ratio of 1.73 and consisted of 6 rows and 9 columns of acrylic tubes *D=25.4mm* and the flexible tube was located in the third row. Fig. 7(a) for the fully flexible array shows a behavior similar to that observed for the smaller pitch ratio with a critical upstream velocity of about 0.2 m/s. Fig. 7(b) presents the response of the single flexible tube in a rigid array and comparison with Fig. 7(a) shows a couple of significant differences. The stability threshold is less clearly defined and delayed about 25% to approximately 0.25m m/s, and the post stable region is also quite different. It seems that pitch ratio is also a factor in determining the significance of fluid coupling of tubes (stiffness mechanism) as relative to the (damping mechanism). Figure 7 also shows the effect of relative tube motions on fluid added mass and, therefore, tube frequency. In the fully flexible array, the variability of tube relative mode is reflected in the significant change in tube frequency with flow velocity as seen in Fig. 7(a). In comparison, the constrained relative mode behavior of the single flexible tube produces a more regular pattern of frequency shifting as well as a reduced frequency range as seen in Fig. 7(b).

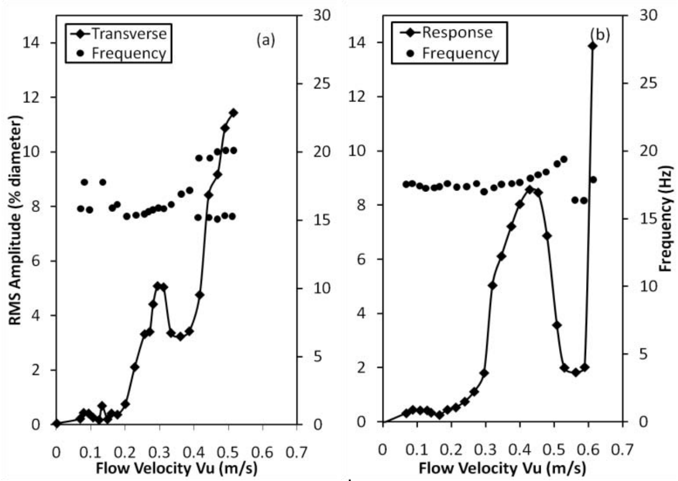

Figure 7. Response of a flexible 3rd row tube in a parallel triangular array P/D=1.7, (a) fully flexible array, (b) rigid array, Scott [23].

Austermann and Popp [16] conducted experiments in air for parallel triangular tube arrays with pitch ratios of 1.25, and 1.375. The first array *P/D=1.25* consisted of 6 rows and 7 columns of aluminum tubes *D=80mm*, and a flexible tube was studied in each one of the first four rows. The results obtained in these experiments showed that a single flexible tube only become unstable in the first row, while a tube in the second, third, or fourth row did not show instability. It was also shown that a static shift in the tube equilibrium position by more than 10% of the gap in the stream-wise direction resulted in instability for the third row tube. The authors reported that the instability of the third row was at a lower critical velocity value which makes it the least stable row. However, they noted that such large disturbances in the array geometry were not practical in real heat exchangers.

The second array *P/D=1.375* consisted of 6 rows and 7 columns of aluminum tubes and showed different stability behavior. In all first four rows, a single flexible tube went unstable. The least critical flow velocity and the largest vibration amplitude were reported at the third row of tubes. It was reported that small shifts in the tube equilibrium position resulted in a slight increase in critical velocity value, which means that the ideal array geometry was the least stable one.

In summary, whether in air or water flows, a single flexible tube in a rigid parallel triangular array has generally been found to become fluidelastically unstable. The mass ratio and strong fluid coupling are seen to have an important effect on the post stability behavior especially in water flows. The pitch ratio seems to be an important parameter in this array geometry, as the small pitch ratio 1.25 showed somewhat inconsistent results, the medium pitch ratio 1.375 showed agreement between single flexible tube behavior and a fully flexible array behavior, and the large pitch ratio 1.7 showed instability but with different behavior prior to instability. The geometrical precision of the array pattern was proven to have an effect on the instability phenomenon and on the stability limit.

ROTATED SQUARE ARRAY (α = 45^{O})

Price et al. [17] conducted experiments to investigate the response of a single flexible tube in a rigid array versus a completely flexible array in both water and air flows for a rotated square array pattern. The experiments were conducted for an array of 7 rows and 13 columns of aluminum tubes with a pitch ratio of 2.12. The mass damping parameter $m\delta/\rho D^2$ for the air experiments was 7 and for the water experiments was 0.065. The instrumented tube was located in the first, second, and fifth rows of the array to investigate the effect of tube location.

The mass damping parameter as well as the flexible tube location seemed to have a little effect on stability behavior for an array subjected to air cross flow. The response frequency of a single flexible tube located in the first or second row of the array changed significantly with upstream flow velocity. Such behavior was not expected, thus the authors abandoned the results from these two locations. The results obtained using a single flexible tube located in the fifth row did not show any instability behavior, and it was concluded that a single flexible tube in a rotated square array did not go unstable due to fluidelastic instability.

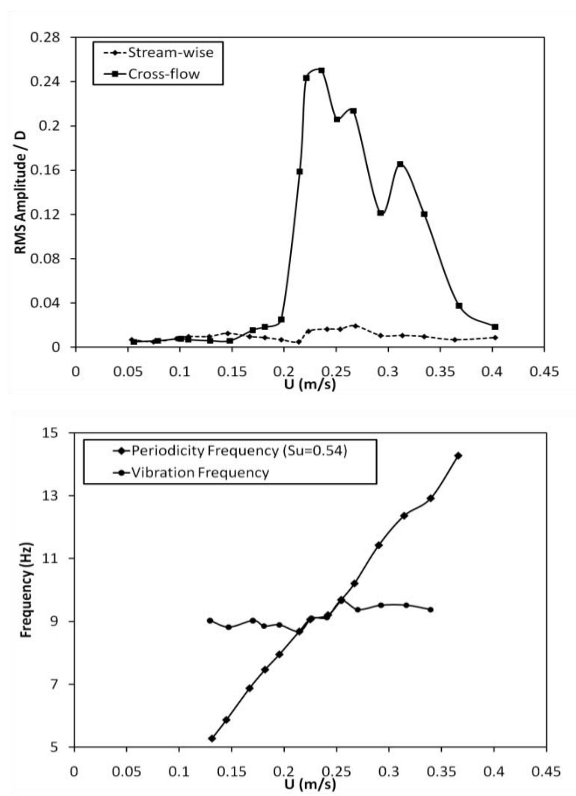

Figure 8. Response of a flexible fifth row tube in a rigid rotated square array in water (P/D=2.12), Price et al. [17].

The experiments conducted in water showed a different behavior. A dramatic increase in the tube RMS response was detected at a certain velocity. The fifth row tube showed a similar response to an isolated tube in a cross flow, where a maximum response amplitude occurs when the vortex shedding frequency coincides with the tube natural frequency, thereby producing a resonance response as shown in Fig. 8. The first row tubes showed similar behavior but with a few local peaks before the dramatic increase in response, and these peaks were attributed to vibration mode switching and multiple Strouhal excitations as shown in Fig. 9. It was concluded that the sudden increase in tube RMS response was associated with flow periodicity excitation not fluidelastic instability. The authors concluded from this study also that a single flexible cylinder in a rigid rotated square array did not go unstable due to fluidelastic instability; rather a large RMS tube response is observed due to vortex shedding resonance with the tube natural frequency.

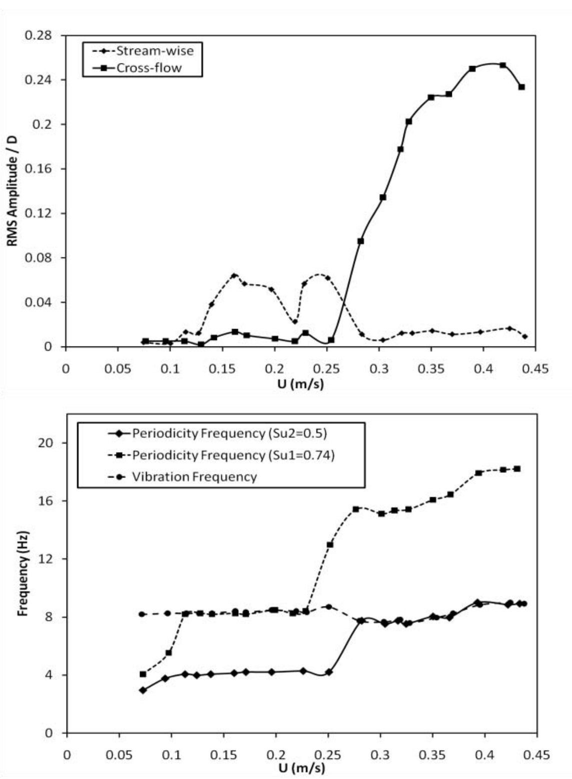

Figure 9. Response of a flexible first row tube in a rigid rotated square array in water (P/D=2.12), Price et al. [17].

Paidoussis et al. [24] conducted similar experiments but for arrays with a pitch ratio of 1.5 in both air and water flows. The tube arrays used in these experiments consisted of 7 rows and 13 columns of tubes. In these experiments the authors monitored a single flexible tube located in the first, second, third, fourth and sixth row while the other tubes in the array were held rigid. The wind-tunnel experiments showed fluidelastic instability behavior in the stream-wise direction for a single flexible tube located in the second row. This unexpected behavior was suspected to be due to a "blow back effect". The drag force drove the tube back, or downstream, into the array, thus distorting the original array geometry. To correct this, the tube under consideration was held in place using strings fixed at an upstream point. When this correction was introduced, no instability was observed up to double the critical flow velocity measured without the strings. The authors suggested that this instability behavior was static divergence and that it was affected by the shift in tube equilibrium position due to the "blow back effect". Experiments conducted with a flexible tube located deeper in the array did not show fluidelastic instability behavior. The authors concluded that a single flexible tube in a rigid rotated square array pattern subjected to air flow did not experience fluidelastic instability. However a static divergence might occur depending on the tube location in the array.

The experiments conducted in water with the flexible tube located in the first, second, third, and sixth rows showed a similar general behavior. The authors reported no fluidelastic instability. However a local peak in the tube response was detected and attributed to Strouhal periodicity not fluidelastic instability. The vibration detected was predominantly in the cross-stream direction, and the maximum vibration amplitude was reported at the second row. The authors concluded from this study that a single flexible tube in a rotated square array did not go unstable due to fluidelastic instability, but did exhibit resonance due to flow periodicity.

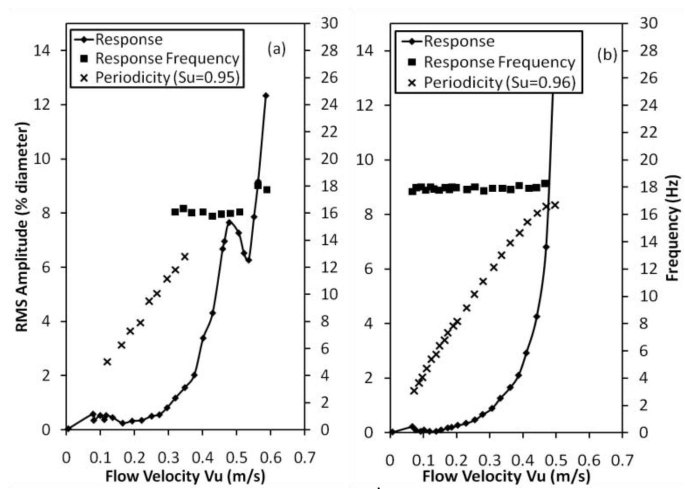

Figure 10. Response of a flexible 3rd row tube in a rotated square array P/D=1.7, (a) fully flexible array, (b) rigid array, Scott [23].

Scott [23] conducted experiments in water flow on a rotated square array with a pitch ratio of 1.7 and consisted of 5 rows and 9 columns of acrylic tubes *D=25.4mm*. The mass damping parameter in these experiments was 0.24. The tubes were supported as cantilevers and tuned within 0.5% of the mean fundamental frequency value. Scott compared the response of a tube in the third row of the array when all the array tubes were flexible with the response of the same tube as a single flexible tube in a rigid array.

A large amplitude response rise starts at about 0.3m/s as shown in Fig. 10(a). The Strouhal number based on upstream flow velocity is 0.95 and the gradual rise in tube response appears to be nearly coincident with vortex shedding resonance. It is not clear whether the response observed represents resonance, a coincidence of vortex shedding resonance and fluidelastic instability, or instability generated by vortex shedding resonance. Fig. 10(b) shows the results for a third row single flexible tube in a rigid array. The rise in response amplitude is very similar to that for the fully flexible array, but occurs before vortex shedding resonance. This implies that the observed phenomenon is fluidelastic instability followed closely by a coincidence of vortex shedding frequency with the tube natural frequency, but this resonance is not the driving force. It was concluded that the single flexible tube becomes unstable at essentially the same velocity as the fully flexible array.

Price, et al. [18] conducted experiments on a single flexible tube in a rigid rotated square array in air with a pitch ratio of 2.12 but with 7 columns and 2 rows of tubes only. A single flexible tube was found to become unstable essentially at the same stability threshold as for the fully flexible array. However when a third row was added to the array, no instability was observed.

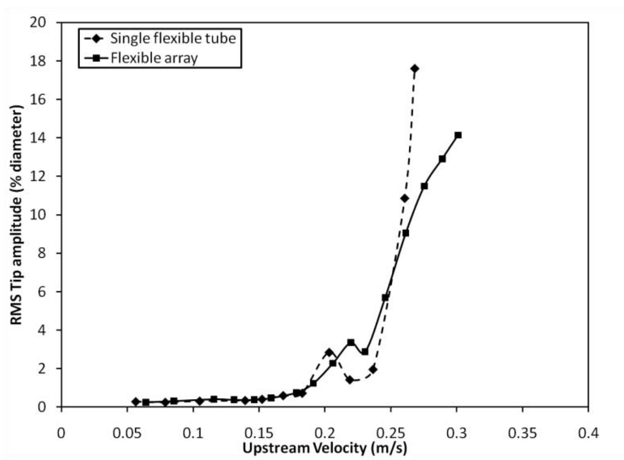

Figure 11. Response of a fifth row tube in a rotated square array (P/D=1.5), Weaver and Yeung [25].

Weaver and Yeung [25, 26] conducted experiments on a rotated square array of $P/D=1.5$ in water. The array consisted of 11 rows and 11 columns of aluminum tubes $D=12.7mm$ mounted as cantilevers on a rotating table. The results showed that a single flexible cylinder in this array went unstable essentially at the same stability threshold as for the fully flexible array as seen in Fig. 11.

Austermann and Popp [16] conducted experiments in air with a rotated square tube array with a pitch ratio of 1.25. The array consisted of 7 rows and 8 columns of aluminum tubes, and the flexible tube was tested in each one of the first four rows. In all these cases, no fluidelastic instability behavior was observed.

In summary, the experiments reported for rotated square arrays seem to be contradictory. Price et al. [17] concluded that, for their 2.12 pitch ratio array, the dramatic increase in tube response was due to the "lock-in" with flow periodicity. The tube frequency response supports this argument, and the Strouhal numbers reported were $S_{u1}=0.74$, and $S_{u2}=0.5$ which are within 14 % of the Strouhal numbers reported by Weaver et al. [6] of $S_{u1}=0.64$, and $S_{u2}=0.44$ respectively. The mass damping parameter for the experiments conducted by Price et al. [17] in water, as shown in Fig. 8 and Fig. 9, was 0.064, and the reduced velocity at which the increase in tube response took place was $U_g/fD=1.84$. Projecting these values on the stability map developed by Weaver and Fitzpatrick [10], shows that the corresponding reduced velocity for a mass damping parameter of $m\delta/\rho D^2=0.064$ is expected to be above $U_g/fD=2$. These findings support the Price et al. [17] conclusion that the response was due to flow periodicity and not fluidelastic instability. However, note that the difference between vortex shedding resonance and fluidelastic instability threshold is in order of only 10%.

Comparison of these findings with the results of Scott [23] and Weaver and Yeung [25, 26] are very revealing. It becomes clear that vortex shedding is significant in rotated square arrays in water flow and is nearly coincident with the fluidelastic stability threshold. As the pitch ratio becomes smaller, it appears that the vortex shedding resonance tends to occur after the stability threshold. In air flow, no fluidelastic instability was observed for a single flexible tube in a rigid array. Thus, mass ratio and pitch ratio are critical parameters in the fluidelastic stability of a single flexible tube in a rigid rotated square array.

NORMAL TRIANGULAR TUBE ARRAY (α = 60^{O})

Scott [23] conducted experiments in water on normal triangular arrays with pitch ratios 1.33 and 1.5. The arrays consisted of 5 rows and 17 columns of cantilevered acrylic tubes $D=25.4mm$. The response reported using a fully flexible tube array with a pitch ratio of 1.33 is shown in Fig. 12(a). Since the tubes were relatively light acrylic material and the pitch ratio was small 1.33, the added mass effects were significant and, therefore, there were significance variations in natural frequency with relative mode shapes. While there is no clear constant Strouhal excitation frequency, the large peak at about 0.25m/s has the appearance of vortex shedding resonance response. The results for a third row flexible tube in a rigid array are shown in Fig. 12(b). Here, there is clear vortex shedding at a Strouhal number based on upstream velocity of 2.8, associated with a small resonance peak at a velocity of 0.15m/s. It is interesting to note that the relatively small tube motion in the fully flexible array appears sufficient to suppress the coherent vortex shedding observed in the rigid bundle, perhaps because of the large variation in fluid coupled tube natural frequencies as observed in Fig. 12(b).

The experiments conducted for the same array pattern with *P/D=1.5* showed a very similar behavior to the previous case. The response pattern in the case of a fully flexible array showed local peaks which were attributed to switching in relative tube vibration modes. However, the case of a single flexible tube showed only small vibration amplitude due to turbulence buffeting, and no instability behavior was observed. Generally, a single flexible tube in a normal triangular tube array with small pitch ratios did not become fluidelastically unstable.

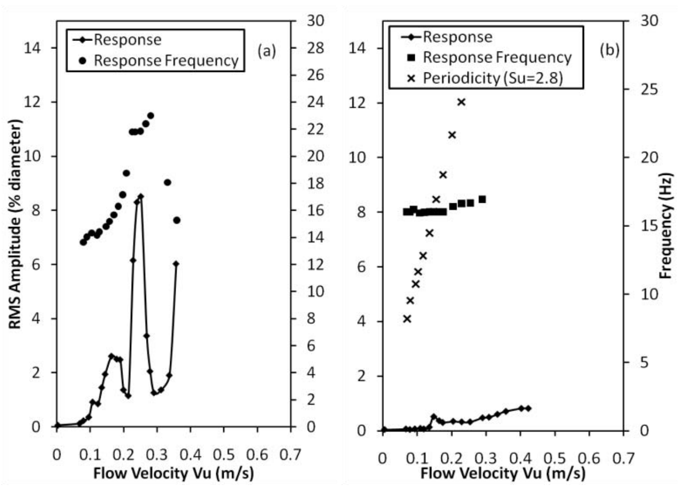

Figure 12. Response of a flexible 3rd row tube in a normal triangular array P/D=1.33, (a) fully flexible array, (b) rigid array, Scott [23].

Austermann, and Popp [16] conducted experiments in air with normal triangular tube arrays which had pitch ratios of 1.25 and 1.375. The first array with a pitch ratio of 1.25 consisted of 4 rows and 13 columns of aluminum tubes D=80mm, and the flexible tube was located in each of the first three rows. The second row tube did not go unstable even by shifting its static equilibrium position by 15% of the gap. The authors reported that a single flexible tube in the first or third row did go unstable with the lowest threshold for a tube in the third row. It was also found that small geometrical imperfections had an effect on the stability threshold for the first row, while it did not seem to have much effect on the stability in the third row.

The second array had a pitch ratio of 1.375 and consisted of 5 rows and 11 columns of aluminum tubes. The tube array behavior was somewhat different. The first row tube was stable for the investigated range of reduced velocity, while the second, third, and fourth row tubes could become unstable. The third row tube was the least stable tube up to a mass damping parameter $m\delta/\rho D^2=30$, and beyond this the least stable row was the second row as shown in Fig. 13. In all investigated tubes for this array, the instability was not affected by shifts in the equilibrium position up to (13%) of the gap.

Meskell, and Fitzpatrick [27] conducted experiments in air on normal triangular tube arrays with pitch ratios of 1.3 and 1.58. The arrays consisted of 5 rows and 13 columns of aluminum tubes *D=38mm* with only one flexible tube located in the third row. The authors reported that a single flexible tube in a rigid array showed fluidelastic instability behavior. The authors also noted that there could be coupling between vortex shedding and the excitation of the first acoustic mode of the test section.

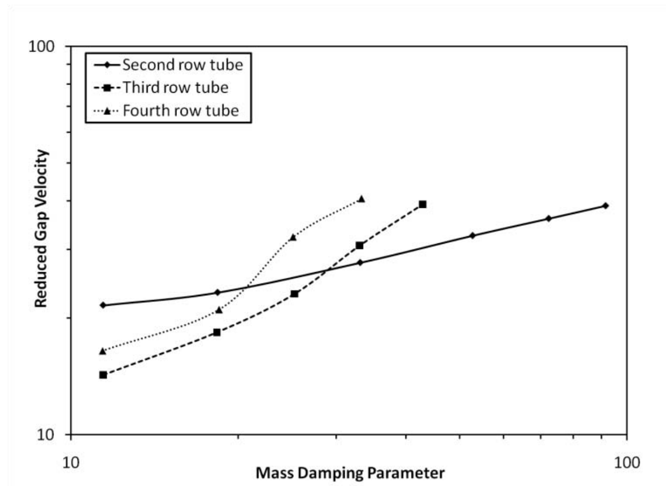

Figure 13. Stability diagram for one flexible tube in a rigid normal triangular array, (P/D=1.375), Austermann and Popp [16]

The experiments discussed above showed that generally, a single flexible cylinder in a rigid normal triangular array can go unstable when tested in air, but not in water. The range of pitch ratios for the different experiments was relatively small and similar. Thus, for this series of experiments, the differences cannot be explained by the pitch ratio parameter. It seems that the most obvious difference is mass ratio, smaller mass ratios apparently being stable.

NORMAL SQUARE TUBE ARRAY (α = 90^{O})

Price and Paidoussis, [28] conducted experiments on a 5 rows and 6 columns in-line tube array with a pitch ratio of 1.5 in both air and water flows. Aluminum tubes with a diameter of 25.4mm and suspended on piano wires were used in air, while in water, 12.7mm diameter tubes were mounted as cantilevers. For a single flexible tube located in any of the first five rows of the array in air, fluidelastic instability was observed at values higher than the typical critical flow velocity for this array. The instability was predominantly in the cross flow direction, and the stability threshold was not significantly affected by upstream turbulence. The experiments in water showed similar behavior to the experiments in air. The authors concluded from this work that a single flexible cylinder in a square in-line array could go unstable at a critical velocity which was higher than the threshold for a fully flexible array. It was found that the stability threshold varied with the flexible tube location in the array, and the least stable location was the second row. However, in their water-tunnel experiments, the position of the flexible tube had a very minimal effect on the stability threshold. The authors also found that the upstream turbulence level did not have a significant effect on the array stability threshold, and that the interstitial turbulence caused by array pattern overwhelmed the upstream turbulence.

Weaver and Yeung [25, 26] conducted experiments on an in-line tube array with a pitch ratio of 1.5 in water. The array consisted of 8 rows and 8 columns of aluminum tubes *D=12.7mm* mounted as cantilevers on a rotating table. The authors reported that a single flexible tube could go unstable at a threshold within about 20% of the threshold for the same array with all flexible tubes as shown in Fig. 14. The results also showed two significant response peaks at about 0.15 m/s and 0.24 m/s as seen in Fig. 14 which are attributed to vorticity phenomenon.

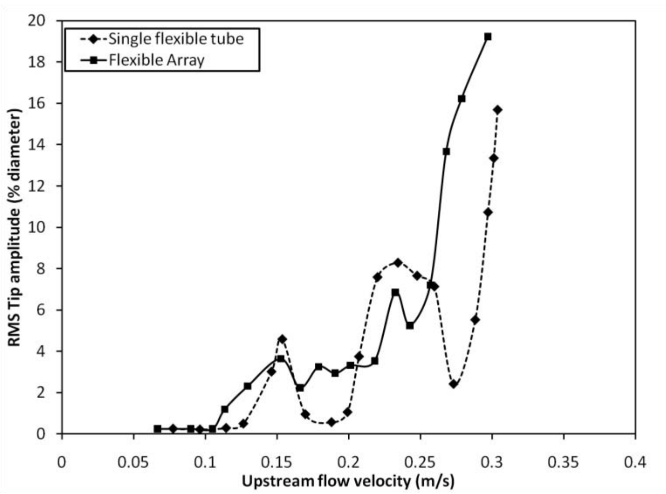

Figure 14. Response of a fifth row tube in a fully flexible and in a rigid in-line array (P/D=1.5), Weaver, &Yeung [25].

Scott [23] conducted experiments on a square in-line array *P/D=1.33* in water. Four rows and 10 columns of acrylic tubes *D=25.4mm* were used, and the tubes in the second and third row were monitored. In the experiments with all the tubes flexible, the second and third row tubes showed similar behavior, and the tube vibration amplitudes were greater at the second row. In both locations, fluidelastic instability occurred at a point very close to a local peak in tube response, making it difficult to determine the stability threshold precisely as seen in Fig. 15(a). There is a clear vorticity excitation with a Strouhal number, based on upstream velocity, of 2.8. The small peak at a velocity about 0.13 m/s may be due to vorticity resonance but this cannot explain the other local peaks. These are apparently associated with relative mode frequency shifting due to changes in fluid added mass. This behavior is discussed in more detail for a parallel triangular array of tubes in water by Weaver and Koroyannakis [29].

The response of a third row tube as a single flexible tube in the same rigid array was quite different as seen in Fig. 15(b). The absence of fluidelastic instability in this case was attributed to the lack of precise alignment of the tubes and to the small pitch ratio. However, Austermann and Popp [16] also did not observe fluidelastic instability in their wind tunnel study of an in-line array with a pitch ratio of 1.25. The array consisted of 4 rows and 7 columns of aluminum tubes. Note that the response frequency did not shift around or drift substantially with increasing flow velocity because of the lack of fluid coupling between adjacent tubes. Strongly varying fluid added mass with the varying tube modes only occurs when all the tubes are free to vibrate because of the switching in tube vibration modes.

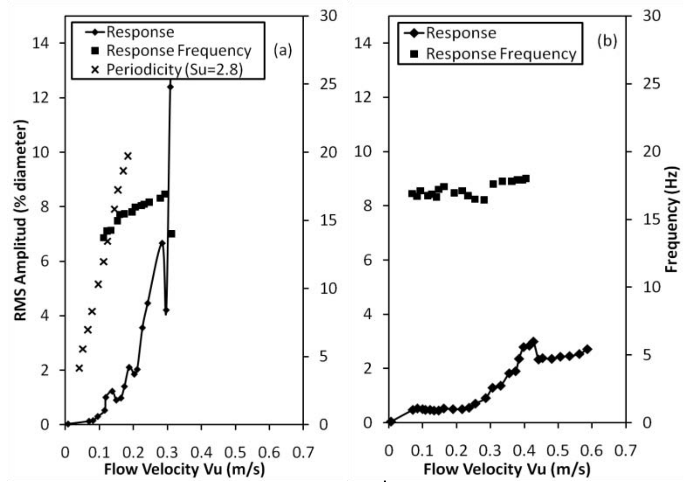

Figure 15. Response of a flexible 3rd row tube in an in-line array P/D=1.33, (a) fully flexible array, (b) rigid array, Scott [23].

In summary, local peaks are observed in the tube response curves for in-line square arrays which are attributed to coherent vorticity in the tube lanes. As noted by Weaver [30], this excitation mechanism is different from that in staggered arrays, being associated with jet instability down the tube lane. A single flexible tube in a rigid array become unstable in large pitch ratio arrays but the stability threshold may be difficult to establish precisely because of the vorticity phenomena. The results in both air and water for pitch ratios 1.33 or smaller suggest that a single flexible tube in a rigid array does not become unstable.

DISCUSSION

In an attempt to better understand the results presented above, Tables 1 through 4 are developed to summarize these observations for the parallel triangular, the rotated square, the normal triangular, and the in-line square array patterns respectively. Six parameters are compared in each table: the array pitch ratio *P/D*, the type of working fluid used in the experiment, the single flexible tube location in the array, the mass damping parameter $m\delta/\rho D^2$, the reduced velocity for instability of a single flexible tube in a rigid array $U_{cs}=U_g/fD$, and the ratio of the stability threshold for a single flexible tube to the stability threshold for a fully flexible array U_{cs}/U_{cf}.

Table 1. Parallel Triangular Array (α = 30°)

Reference	*P/D*	*Fluid*	*Location*	$m\delta/\rho D^2$	U_{cs}	U_{cs}/U_{cf}
Lever, and Weaver [11-13]	1.375	Air	Row 15	1.8	9.8	9.8/9.5=1.03
Grover, and Weaver [31, 32]	1.375	Air	Row 15	1.8	9.3	9.3/8.75=1.06
Little [20]	1.39	Air	Row 3	2.4	11.6	11.6/11.2=1.02
Scott [23]	1.375	Water	Row 3	0.18	1.15	1.15/1.15=1.0
	1.73			0.28	1.55	1.55/1.24=1.25
Austermann, and Popp [16]	1.25	Air	Row 1	11.7	30	No Data
	1.375		Rows 1,2,3, and 4	11.7	28, 19, 10, 14	

Table 2. Rotated Square Array (α = 45°)

Reference	*P/D*	*Fluid*	*Location*	$m\delta/\rho D^2$	U_{cs}	U_{cs}/U_{cf}
Price et al. [17]	2.12	Water	----	0.065 - 0.117	Stable	----
		Air	----	4.2 - 40	Stable	----
Paidoussis et al. [24]	1.5	Water	----	0.065	Stable	----
		Air	----	10.36	Stable	----
Scott [23]	1.7	Water	Row 3	0.24	2.42	2.42/2.24=1.08
Austermann, and Popp [16]	1.25	Air	----	11.7	Stable	----
Weaver, and Yeung [25, 26]	1.5	Water	Row 6	0.21	3.0	3.0/2.66=1.13

Table 3. Normal Triangular Array (α = 60°)

Reference	*P/D*	*Fluid*	*Location*	$m\delta/\rho D^2$	U_{cs}	U_{cs}/U_{cf}
Meskell, and Fitzpatrick [27]	1.32	Air	Row 3	180	56	No Data
	1.58	Air	Row 3	19	32	No Data
Scott [23]	1.33	Water	----	0.24	Stable	----
	1.5		----	0.24	Stable	----
Austermann, and Popp [16]	1.25	Air	Row 3	11.7	14	No Data
	1.375	Air	Row 3	11.7	15	No Data

Table 4. Square Array (α = 90°)

Reference	*P/D*	*Fluid*	*Location*	$m\delta/\rho D^2$	U_{cs}	U_{cs}/U_{cf}
Price, and Paidoussis [28]	1.5	Water	Row 3	0.0379	1.41	No Data
		Air	Rows 1, and 2	7	67	No Data
Weaver, and Yeung [25, 26]	1.5	Water	Row 5	0.21	2.52	2.52/2.38=1.06
Scott [23]	1.33	Water	----	0.24	Stable	----
Austermann, and Popp [16]	1.25	Air	----	11.7	Stable	----

While the individual data appear rather confusing and contradictory, a careful overall examination produces some interesting trends. All researchers have found fluidelastic instability for a single flexible tube in a rigid parallel triangular (30°) array regardless of working fluid, albeit with some sensitivity to tube frequency tuning and precision of array geometry. For rotated square (45°) arrays, a single flexible tube in a rigid array is observed to become fluidelastically unstable in water flows but not in air flows. This implies that tube-to-tube coupling is necessary for fluidelastic instability in air flows but not for the higher density fluid. Moreover, in water flows, strong vortex shedding excitation is nearly coincident with fluidelastic instability so that it becomes difficult to distinguish between them and to define the stability threshold. In contrast, the behavior of a single flexible tube in a rigid normal triangular (60°) array defies expectations with clear instability in air flows and no instability in water flows. Thus, as the staggered tube array progresses from 30°, through 45° to 60°, for the same pitch ratio, the wavy path of the flow through the array tends to become more torturous and, apparently, the potential for a single flexible tube in a rigid array to become fluidelastically unstable is reduced. This suggests that the nature of the excitation mechanism is affected by length of the flow attachment on a tube as well as the stream-wise distance between tube rows.

For square in-line arrays, where the flow path down the tube lanes is straight, the instability of a single flexible tube in air or water flows seems to occur only for pitch ratios of 1.5 or greater. However, jet instability down these tube lanes in in-line arrays is known to produce strong tube coupling, especially of stream-wise modes, which distinguish this geometry from staggered array geometries when it comes to vorticity phenomena [33]. This behavior can also obscure the fluidelastic excitation response in water flows. It follows that array geometry, pitch ratio, and fluid density are all significant parameters in determining the fluidelastic stability threshold of a single flexible tube in a rigid array, i.e., the relative importance of the "Damping" and "Stiffness" excitation mechanisms.

Figure 16 shows a stability plot from the theory of Paidoussis and Price [34] for a parallel triangular tube array with a pitch ratio of 1.375. Mechanism *I* is negative damping while Mechanism *II* is the so called stiffness mechanism or tube-to-tube coupling. It is seen that negative damping is the dominant mechanism for mass damping parameters less than about 200 while fluid stiffness is dominant at much higher values of this parameter. Fig. 17 shows similar results from the theory of Yetisir and Weaver [35, 36] along with experimental data from the review paper of Weaver and Fitzpatrick [10]. Despite their different approach, the theories of both Paidoussis and Price and Yetisir and Weaver provide qualitatively similar predictions, although the transition between excitation mechanisms occurs at somewhat lower values of mass damping parameter in the Yetisir and Weaver theory. Taking this predicted transition to occur near $m\delta/\rho d^2 \approx 100$, then nearly all of the data in Tables 1-4 should be damping mechanism dominant, i.e., a single flexible tube in a rigid array is expected to become unstable. Clearly these expectations are not met, at least for some of the arrays. Thus, while the essence of fluidelastic instability in tube arrays seems to be captured by the theoretical models, some details required for good quantitative agreement must be missing.

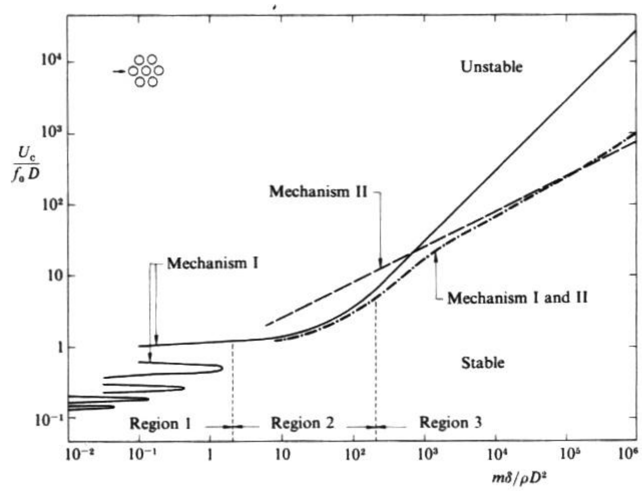

Figure 16. Region of fluidelastic instability mechanisms for pitch to diameter ratio (P/D=1.375), Paidoussis and Price [34].

The concept of "negative fluid damping" and "fluid stiffness" mechanisms driving fluidelastic instability is a useful mathematical construct to assist in explaining the phenomenon. In reality, however, both mechanisms are active simultaneously and cannot be separated. The data from experiments with a single flexible tube in a rigid array demonstrate the importance of array geometry, pitch ratio, and fluid density in determining the operative mechanism for fluidelastic instability in tube arrays.

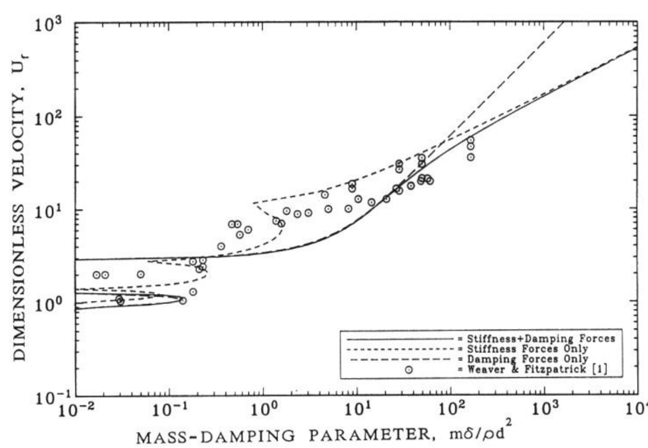

Figure 17. Instability boundaries developed based on different mechanisms (P/D=1.5), Yetisir and Weaver [35, 36].

CONCLUSIONS

The experimental observation that a single flexible tube in a rigid array could become fluidelastically unstable at essentially the same flow velocity as the fully flexible array offered the possibility of greatly simplifying the physical and mathematical modeling of the phenomenon. Such modeling considers only the "fluid damping" mechanism of fluidelastic instability and assumes that fluid coupling between the tubes, "fluid stiffness", is not an essential component of the overall excitation mechanism. This is demonstrably true for those cases where the stability threshold for a single flexible tube in a rigid array is the same as that for the fully flexible array. While this has often been observed, there are many cases where it has not. Indeed, there are a number of cases for which a single flexible tube in a rigid array appears never to become unstable, i.e., where fluid coupling between tubes is essential for instability.

This paper has critically reviewed all of the available data in an attempt to understand the apparently contradictory results and provide guidance for future fundamental studies of fluidelastic instability in tube arrays. While the available data are not exhaustive, some general conclusions can be drawn.

1. The relative importance of the "fluid damping" and "fluid stiffness" mechanisms of fluidelastic instability in tube arrays is strongly dependent on array geometry and pitch ratio, as well as the theoretically predicted mass ratio.

2. The most consistent results for fluidelastic instability of a single flexible tube in a rigid array in both air and water flows are for parallel triangular (30^o) arrays.

3. As the staggered array geometry moves from 30^o through 45^o to 60^o, the behavior of a single flexible tube in a rigid array becomes less consistent. In water flows, vortex shedding resonance in rotated square (45^o) arrays nearly coincides with fluidelastic instability and the stability behavior becomes obscured. For normal triangular (60^o) arrays, the stability behavior of a single flexible tube in a rigid array is opposite to that expected, being stable at low mass ratios (water flows), and unstable at high mass ratios (air flows). This suggests that the instability is fluid stiffness (coupling) dominant at low mass ratios, and fluid damping dominant at high mass ratios.

4. As found for the case of vorticity phenomenon in square in-line arrays, the straight open tube lane flows tend to create distinctive fluidelastic instability behavior for this array geometry. Of particular significance is the large amplitude coupled tube response associated with vorticity phenomenon in water flows which tend to obscure the stability behavior, especially at small pitch ratios.

5. For repeatable and reliable fluidelastic stability data from tube arrays, great care needs to be taken to tune all the tubes to the same frequency (within 1% is recommended) and to maintain the array geometry precisely. Experiments have shown that small detuning of adjacent tubes in an array has stabilizing effects, and that relatively small distortion of array geometry (dislocation of tube from its perfect array position) can affect the stability of a single flexible tube in a rigid array.

6. A single flexible tube in a rigid array is a useful concept for fundamental studies in fluidelastic instability but is not generally suitable for establishing the stability threshold for tube arrays.

NOMENCLATURE

α	Array pitch angle.
D	Tube diameter.
δ	Logarithmic decrement.
f	Tube fundamental frequency.
m	Tube mass per unit length including fluid added mass.
P	Array pitch.
P_r	Pitch ratio.
ρ	Fluid density.
S_u	Strouhal number based on upstream flow velocity.
U_g	Mean gap velocity.
U_o	Upstream flow velocity.
U_c	Critical flow velocity.
U_{cs}	Critical flow velocity using a single flexible tube.
U_{cf}	Critical flow velocity using fully flexible array.

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