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EXPERIMENTAL STUDY OF FLUIDELASTIC INSTABILITY IN A PARALLEL TRIANGULAR TUBE ARRAY

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ABSTRACT

Fluidelastic instability is a short term failure mode that occurs in tube bundles subjected to cross flow. It is believed that instability occurs due to two possible mechanisms; one is related to fluid coupling of neighboring tubes, the so called "stiffness mechanism", and the other is related to a "negative fluid damping mechanism" i.e., fluidelastic forces in phase with tube velocity. The usage of a single flexible tube in a rigid array will eliminate the stiffness mechanism effect and leave only the damping mechanism, which makes the problem less complex. This paper presents a fundamental study of fluidelastic instability in a parallel triangular tube array subjected to air cross flow. It is found that a single flexible tube located in the third row of a rigid parallel triangular array does become fluidelastically unstable at essentially the same velocity as for a fully flexible array. However, when the single flexible tube is located in the first, second, fourth, or fifth rows, no instability behavior is detected. It is concluded from this work that, the tube location inside the array affects significantly its fluidelastic instability behavior when tested as a single flexible tube in a rigid array. It follows that a single flexible tube can be used for fundamental study of the phenomenon but not generally to generate stability maps for practical use.

Keywords: fluidelastic instability, tube bundle, heat exchanger, parallel triangular array, single flexible tube.

INTRODUCTION

Fluidelastic instability is a critical failure mode in heat exchanger tube bundles which may cause short term failure of the tubes. Such failures are expensive and potentially dangerous, especially for equipments such as nuclear steam generator. The phenomenon occurs when the fluid flowing across the tubes exceeds a certain critical velocity such that energy is transferred to the tubes from the flow and the vibration amplitude rapidly increases to damaging amplitudes. In order to predict and avoid fluidelastic instability in tube bundles, a significant amount of research has been conducted over the last four decades. Several theoretical models have been developed and a number of reviews have been published [1-11]. The theoretical models developed have provided some useful insights to the phenomenon. However, a few aspects of fluidelastic instability remain unresolved and not fully understood, and none of the theoretical models provide reliable prediction of fluidelastic instability [12-14]. This can be attributed to two main reasons; the first is the complex nature of the problem, and the second is the practical importance of the problem such that research has focused more on finding short term answers rather than discovering the underlying physics.

The phenomenon of fluidelastic instability is attributed to two fluid-structure interaction mechanisms [5, 15, 16]. The first mechanism is related to fluid coupling of neighboring tubes and called the "Stiffness Mechanism", and the other is related to a negative fluid damping mechanism i.e., fluidelastic forces in phase with tube velocity and called the "Damping Mechanism". The concept of using a single flexible tube in a rigid array to study fluidelastic instability eliminates the stiffness mechanism effect which helps to reduce the complexity of the problem. It is essential to show that the stability threshold of a single flexible tube in a rigid array is approximately the same as that for a fully flexible array in order to justify using a single flexible tube in a rigid array to study fluidelastic instability.

This paper reports the results of a fundamental study designed to improve our understanding of fluidelastic instability in a tube array. A parallel triangular tube array was designed and constructed to facilitate fine tuning of the problem parameters. Experiments were conducted in the wind tunnel at

McMaster University on both fully flexible array and a single flexible tube located at different locations in the rigid array. The effect of tube location on instability behavior was investigated, and the results obtained using a single flexible tube are compared to the results for a fully flexible tube array and discussed in detail.

EXPERIMENTAL SETUP

Based on a previous study to investigate the behavior of a single flexible tube versus a fully flexible array in different array patterns, it was decided to employ the parallel triangular array geometry in the present research. The array consists of seven rows and five columns of aluminum tubes arranged as shown in Fig. 1. The number of rows and columns in the array was selected based on a previous study by Weaver& El-Kashlan [17] that recommends the minimum dimensions of an array without affecting the stability threshold.

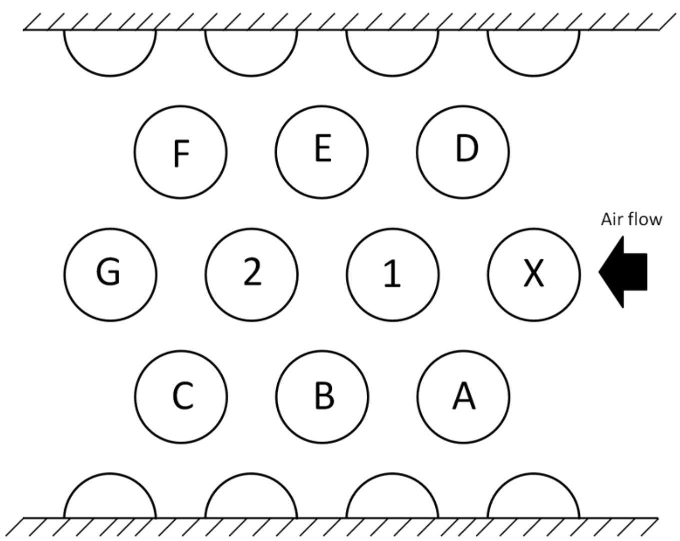

Figure 1. Array geometrical configuration.

Each tube in the array was supported using a piano wire arrangement that contains a spring mechanism to fine tune the tube frequency, and a damping device to precisely control the total damping. The spring tensioning mechanism allows tuning the tube natural frequency with a precision of less than 0.1 Hz. The precision in tuning all the array tubes to the same frequency is essential for obtaining reliable and repeatable results, as was shown by Lever & Weaver [18]. They found that a frequency difference between array tubes as little as 3% can increase the stability threshold as much as 40%. Figure 2 shows a sketch of the tube support arrangement used in the study. The tube natural frequency can be controlled by adjusting the amount of tension in the piano wire according to Eq. (1), where f is tube natural frequency, T is wire tension, m is tube mass, and L is wire free length. A damping device that consists of a cup and a paddle is used to adjust the tube total damping. The cup is filled with oil, and the paddle is mounted on the piano wire such that it has the same motion as the tube. The amount of damping added to the tube can be controlled by controlling the level and viscosity of the oil used in the cups.

$$f = \frac{1}{2\pi}\sqrt{\frac{2T}{mL}} \qquad (1)$$

The tube array has a pitch ratio of P/D=1.54, based on the available standard aluminum tube sizes, the wind tunnel cross-sectional width, and the requirement for an integer number of tubes across the tunnel width. The aluminum tubes used in the array had a diameter D=57mm, length H=305mm, and thickness t=1.2mm. These particular tubes were selected as they have a large diameter, which will give more space for interstitial measurements for a given pitch ratio, and the small thickness reduces the tubes weight.

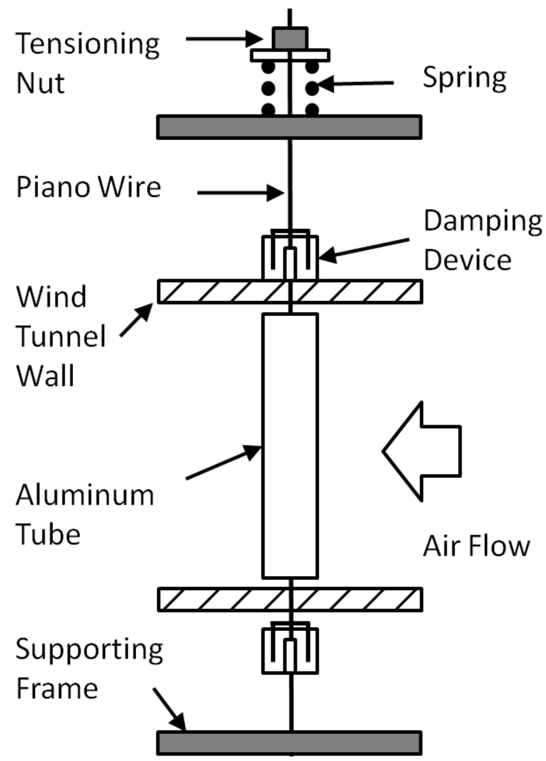

Figure 2. Sketch of the tube support arrangement.

The flow velocity was monitored using a Pitot tube placed 150mm upstream of the array. The Pitot tube was connected to a digital differential pressure transducer to display the flow dynamic head. Two tubes are instrumented during experimentation, namely tube 1 and tube 2 which are located in the third and fifth row respectively as seen in Fig. 1. These two tubes were selected as they are located in the middle of the array where the effect of the side walls is minimized. Removal of the first upstream row, i.e. the tube marked X and the two half tubes on the test section walls, in Fig. 1 moves the monitored tubes 1 and 2 to the second and fourth rows respectively. The upstream turbulence level in the wind tunnel is less than 1% which means that flow disturbances caused by tube motion in the very early tube rows should be detectable over turbulence. It is known that turbulence generated by the tube bundle increases to about the third or fourth tube row and that this will tend to obscure flow disturbances created by tube motion. At the same time, third row tubes typically have the lowest fluidelastic stability threshold [19, 20]. Thus, there is a tradeoff between obtaining a good signal to noise ratio and monitoring a tube with behavior typical of a full tube bundle. The present arrangement supports such an investigation.

Each tube is instrumented with two uni-axial accelerometers oriented in the stream-wise and cross-stream directions to obtain the two normal components of tube motion. The accelerometers have a sensitivity of 10.2 mV/(m/s^2) and range up to 500 m/s^2 which can support vibration amplitudes up to 50% of the tube diameter. Two pressure transducers were mounted inside each tube and located on both sides of the tube along the cross-stream axis. The pressure transducers have a sensitivity of 217.5 mV/KPa and range up to 1720 KPa. The acceleration sensitivity of the pressure transducers is 0.35 Pa/(m/s^2), and this value is used to compensate for vibration effects in the pressure signals acquired. The purpose of these pressure transducers was to provide a measure of the pressure on both sides of the tube, which can be used to monitor the fluid forces acting on the tube. A uni-axial accelerometer is attached to a special rig which can be used to monitor the cross-stream motion of any uninstrumented tube in the array.

The aluminum tubes were tuned to a mean frequency of 20 Hz with standard deviation of 0.3% of the mean value. The total damping of each tube is adjusted to a mean damping ratio of 0.36% with standard deviation of 4.8% of the mean value. Adjusting the total damping of the tubes increases the repeatability of the experiments significantly. The mass ratio of an instrumented tube is $m/\rho D^2=70$, resulting in a mass damping parameter of $m\delta/\rho D^2=1.57$.

A sampling rate of $f_s=512$ Hz was adopted in the measurements. Simultaneous velocity, pressure, and displacement signals from all sensors were collected using a National Instruments data acquisition card NI-DAQ 6015. The signal collected from each sensor was averaged to achieve good repeatability of the results. It was found that the signal RMS value asymptotes after 50 averages, therefore 50 averages were collected from each sensor signal. The time signal collected was transformed to the frequency domain using a fast Fourier transform FFT to obtain the frequency components of each signal. The acceleration signal was calibrated and the acceleration amplitude associated with tube natural frequency was divided by the frequency value squared to obtain the vibration amplitude in meters. The signals obtained from the pressure transducers mounted inside the tubes were calibrated using the sensitivity value mentioned above to obtain the pressure in Pa.

RESULTS FOR A FULLY FLEXIBLE TUBE ARRAY

Experiments were conducted first on a fully flexible tube array to determine the fluidelastic stability threshold as the datum case. The effect of the monitored tube row location was investigated by removing the first row upstream, which will place the instrumented tubes 1 and 2 in the second and fourth rows respectively. The purpose of locating the instrumented tube 1 in the second row of the array was to obtain fluidelastic instability at a location that has low turbulence level and thus high signal to noise ratio for the pressure measurements as discussed above.

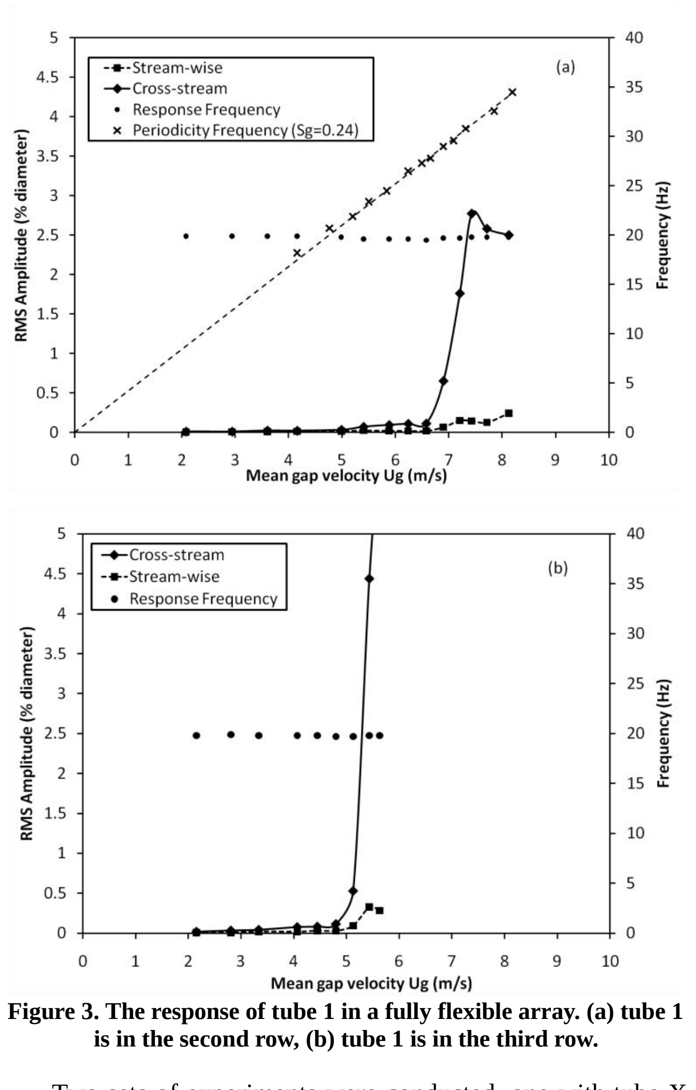

Figure 3. The response of tube 1 in a fully flexible array. (a) tube 1 is in the second row, (b) tube 1 is in the third row.

Two sets of experiments were conducted, one with tube X removed and the other with tube X in place. The response of tube 1 in the second row is shown in Fig. 3(a), while that for the same tube in the third row is shown in Fig. 3(b). Over the range of mean gap velocity U_g=2-6 m/s, the tube response is small, typically less than 0.1% of the tube diameter. The excitation mechanism in this region is turbulent buffeting, and the very small amplitudes can be attributed to the low turbulence level. At about U_g=6.6 m/s, the vibration amplitude in the transverse direction suddenly increased up to about 2.75% of the tube diameter and the tube is considered to have become fluidelastically unstable. Also shown in Fig. 3(a), is a constant Strouhal number line drawn through pressure response peaks in the frequency spectra which increases linearly with flow velocity. The Strouhal number based on mean gap velocity is 0.24 and at the frequency coincidence with the tube natural frequency, no resonance peak is obtained.

A second set of experiments was conducted after reinstalling the first row upstream which places tube 1 in the third row of the array. The response pattern in this case is shown in Fig. 3(b). In the range of mean gap velocity U_g=2-4.8 m/s, a small vibration amplitude is detected caused by turbulent buffeting. At a mean gap velocity of above U_g=5.2 m/s, a dramatic increase in tube response is detected, indicating that the tube has become fluidelastically unstable.

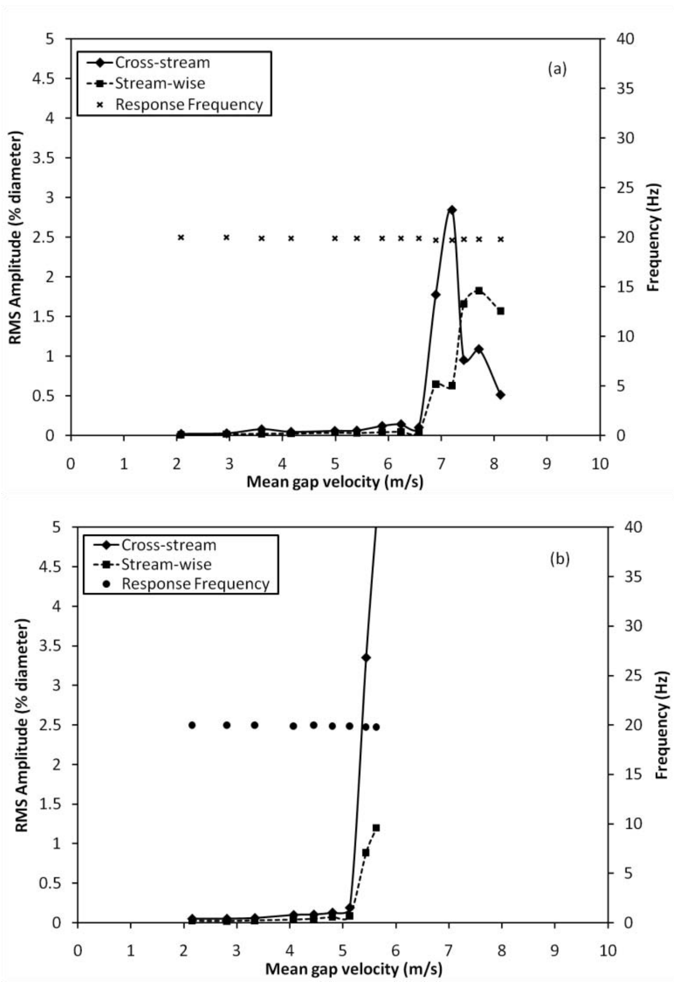

Figure 4. The response of tube 2 in a fully flexible array. (a) tube 2 is in the fourth row, (b) tube 2 is in the fifth row.

The response of tube 2 showed a similar behavior to tube 1 as seen in Fig. 4(a) and 4(b). When tube 2 was located in the fourth row, it became unstable at about 6.6 m/s and reached RMS amplitude of above 3% of the diameter, then the amplitude dropped down for velocities above 7 m/s as seen in Fig. 4(a). When the first row upstream is placed back in position, tube 2 is in the fifth tube row and its response is shown in Fig. 4(b). In this case the tube is seen to become fluidelastically unstable at about 5.2 m/s.

The experiments were repeated four times to determine the repeatability of the results. It was found that the general behavior was the same in all cases, and the stability threshold was repeatable within ±1%. It should be noted that the dominant response of both tube 1 and 2 was in the cross-stream direction. Additionally, the vorticity excited resonance observed in the second and third rows has a limited effect and disappeared by the fourth tube row.

In summary, when the first row upstream is in place, tubes 1 and 2 are in the third and fifth rows respectively, the stability threshold is about 5.2 m/s and the post stable response is typical of that expected from previous experiments with fully flexible arrays [21-23]. When the first row is removed, tubes 1 and 2 are now in the second and fourth rows respectively, not only the stability threshold is delayed to about 6.6 m/s, but also the post stability response is limited and irregular. The same tube behaves differently depending on whether or not an upstream row is in place.

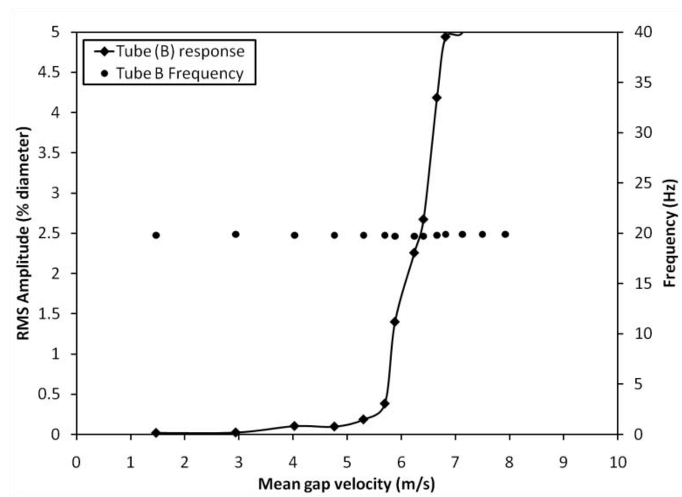

Figure 5. The response of tube B when located in the third row of a fully flexible array.

In an attempt to understand and explain these observations, the behavior of all tubes in the array was observed during an experiment. It was found that when the first tube row upstream was removed, the tubes in the third row, either tube B or tube E as seen in Fig. 1, always became unstable first followed by the rest of the tubes. To investigate this observation further, an accelerometer was attached to the third row tube B to monitor the tube displacement, and the amplitude response is shown in Fig. 5. The third row tube is seen to become unstable at about 5.8 m/s. This compares with the experiments corresponding to tube 1 and 2 in Fig. 3(a) and 4(a) respectively, which become unstable at about 6.6 m/s. Thus, it appears that the third row tube becomes unstable to large amplitudes and then triggers instability in other tubes in the array.

When the first row is put in place such that tube 1 is in the third row, tube 1 becomes unstable at about 5.2 m/s as seen in Fig. 3(b). When the first tube row upstream is removed, the third row tube is located beside the wall which could explain the delayed stability threshold seen in Fig. 3(a) and 4(a) as well as the irregularities in response. In order to investigate this behavior further, a single flexible tube was studied at different locations in an otherwise rigid tube array.

RESULTS FOR A SINGLE FLEXIBLE TUBE

The same experimental procedure discussed in the previous section was used to carry out the experiments for studying the behavior of a single flexible tube in a rigid array. The purpose of these experiments was to determine the response of a single flexible tube at different locations in a rigid array. The response of tube 1 as a single flexible tube located in the second and third row is shown in Fig. 6(a) and 6(b) respectively.

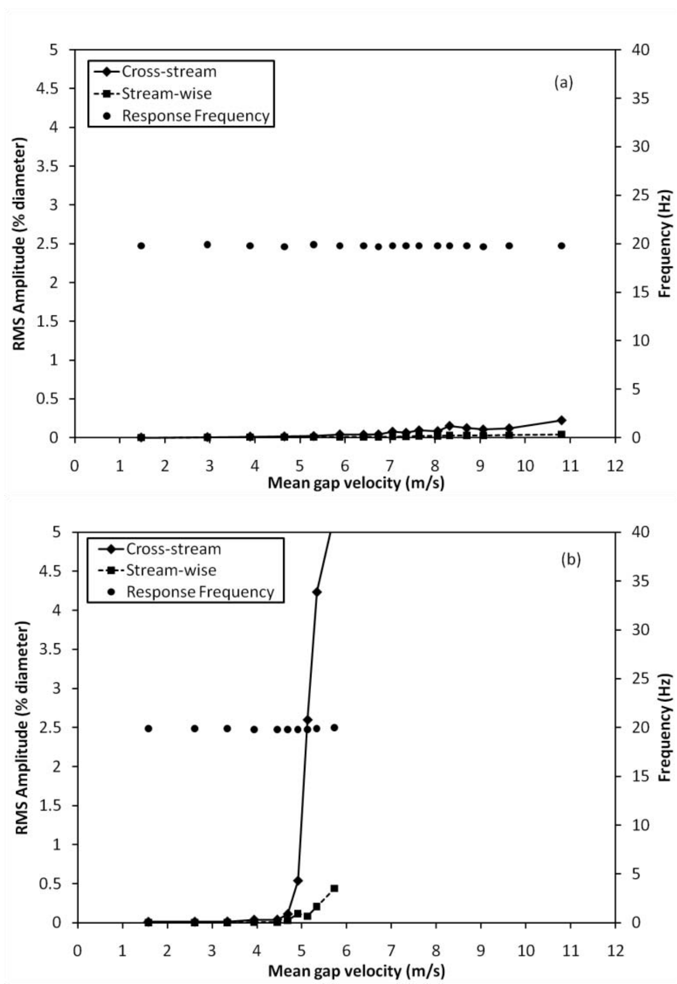

Figure 6. The response of tube 1 as single flexible tube in a rigid array. (a) tube 1 is in the second row, (b) tube 1 is in the third row.

As seen in Fig. 6(a), when tube 1 is in the second row, no instability is detected up to a mean gap velocity of U_g=11 m/s which is twice the critical velocity found for the fully flexible array. The response of the same tube located at the third row, by adding the upstream tube X indicated in Fig. 1, is completely different. Clear fluidelastic instability, primarily in the cross-flow direction, is seen at a mean gap velocity U_g=5 m/s as seen in Fig. 6(b). It seems that when tube 1 is the only flexible tube in the otherwise rigid array, it is completely stable when in the second row and unstable when it is in the third row. Furthermore, the stability threshold in the latter case is slightly below the value of 5.2 m/s found for the case of a fully flexible array.

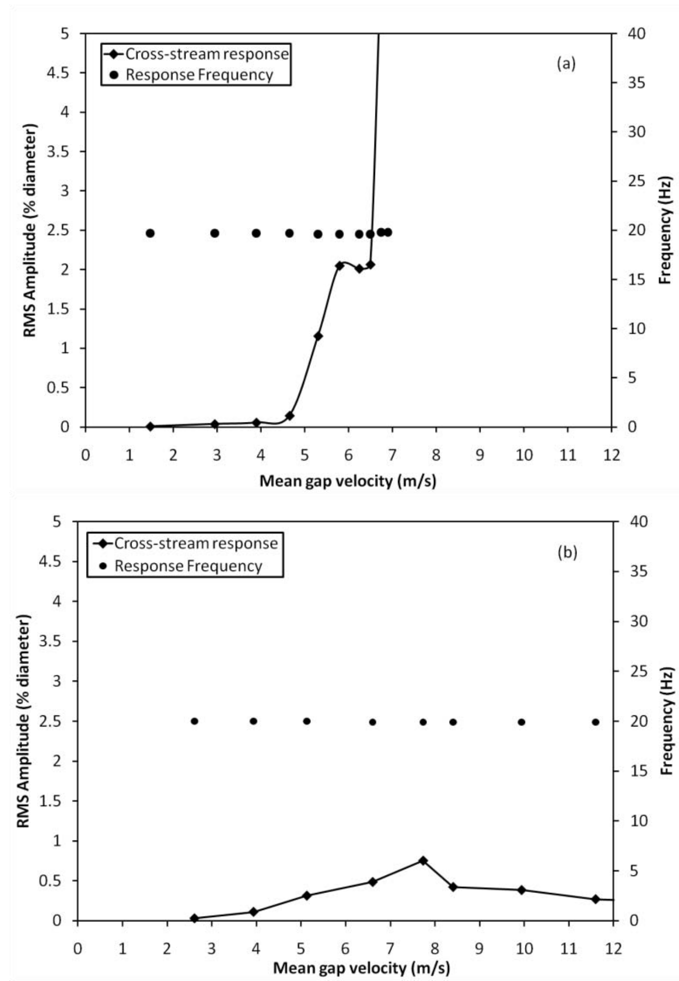

Figure 7. The response of tube B as a single flexible tube in a rigid array. (a) tube B is in the third row, (b) tube B is in the fourth row.

To ensure that this behavior was not tube specific, additional similar experiments were carried out with other tubes, varying the location of each tube by adding or removing the upstream tube row. For example, tube B and E, as seen in Fig. 1, were studied as a single flexible tube located in the third row when the first row upstream was removed, and in the fourth row when the first row upstream was installed. The response of tube B in the third and fourth tube rows is shown in Fig. 7(a) and 7(b) respectively.

At a mean gap velocity of about 5 m/s, tube B, when in the third row, became unstable as seen in Fig. 7(a). This is about the same critical velocity as found for tube 1 when it was in the third row. The small fluctuation in tube response over the range of mean gap velocity U_g=5.9-6.9 m/s is attributed to confinement wall effects as this tube is near the test section wall. When the first row upstream is installed, tube B is now in the fourth tube row and shows a completely different behavior. The response of tube B is primarily due to turbulent buffeting and while the RMS amplitude rises to about 0.5% of the diameter near 8m/s, no clear fluidelastic instability is seen up to a mean gap velocity of 12 m/s. this peak suggests that some fluidelastic forces exist but are unable to overcome the system damping to produce instability.

Similar experiments conducted on a single flexible tube located in the first, second, fourth, and fifth tube rows, and a similar trend is observed. Low response amplitudes are detected in all cases up to a mean gap velocity of U_g=17 m/s where the dominant mechanism is turbulence buffeting. Changing the location of the single flexible tube in the array does not affect the response behavior unless it is located at the third tube row of tubes.

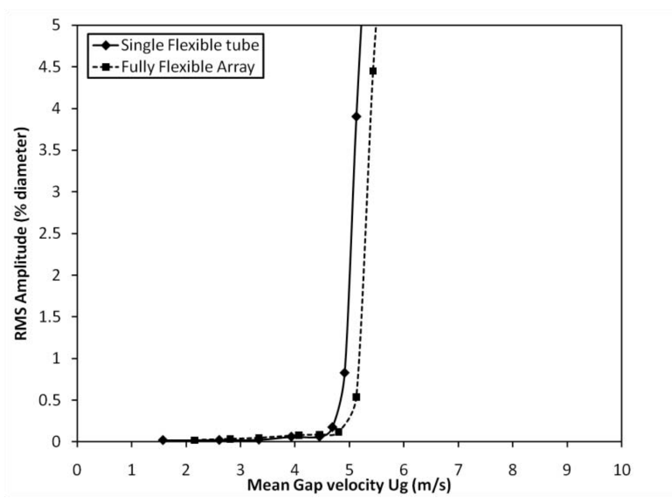

Figure 8. The stability behavior of tube 1 located in the third row for both single flexible tube and fully flexible array cases.

In this study, a single flexible tube in a rigid array only becomes fluidelastically unstable if it was located in the third row of the array. By monitoring the same tube and changing its location in the array, by adding or removing the upstream tube row, the effect of tube-to-tube variability was removed and the observed effect on stability can only be attributed to tube row location. Furthermore, as seen in Fig. 8, the stability threshold for tube 1 in the third row of a rigid array is essentially the same, even slightly lower than that for tube 1 in the third row of the fully flexible array. These results support the observation made while testing a fully flexible array that the instability seems to develop in the third row of tubes first and then propagates through the array.

EFFECT OF HOLDING THE THIRD ROW TUBE FIXED

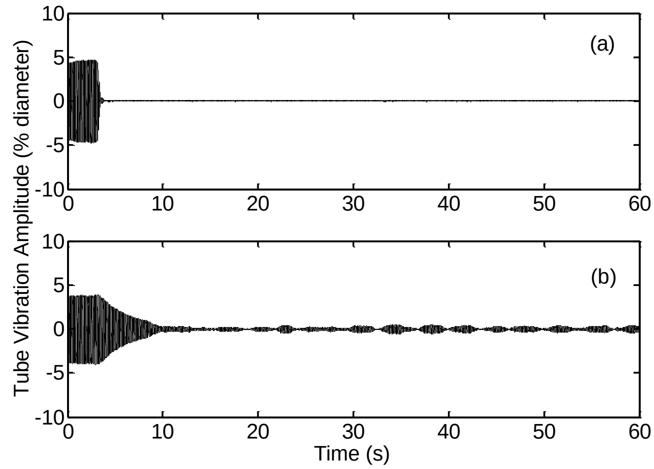

Figure 9. The effect of holding the third row tube rigid during instability onset of a fully flexible array. (a) response of tube 1 in the third row, (b) response of tube 2 in the fifth row

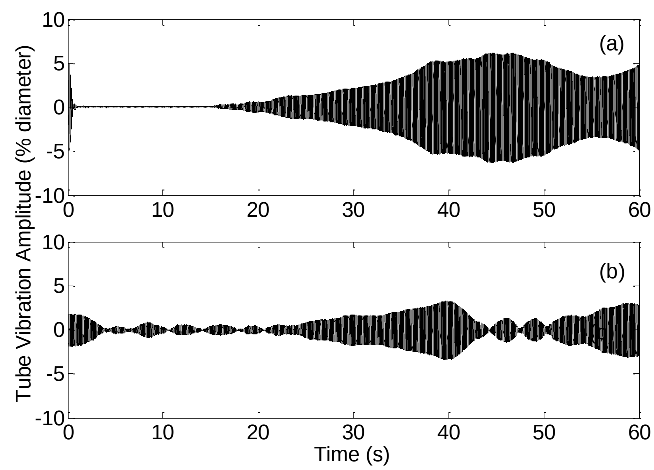

Figure 10. The effect of releasing the third row tube during the instability onset of a fully flexible array. (a) response of tube 1 in the third row, (b) response of tube 2 in the fifth row.

An additional set of experiments was conducted to confirm that fluidelastic instability in the array originates from the third row of tubes. A fully flexible tube array was subjected to a cross flow velocity of U_g=7 m/s, which is above the critical flow velocity. Then, while the array tubes were oscillating at significant amplitudes, the third row tube was suddenly held rigid and the responses of other tubes were monitored as seen in Fig. 9. When the time-amplitude trace of tube 1, in the third row, shows a sudden drop in vibration amplitude, the trace of tube 2 shows that it has been stabilized within about 7 seconds. When the same third row tube is released, as seen in Fig. 10, an exponential growth of its response amplitude is observed, and the other tubes in the array became unstable as well with the amplitude modulations typical of fluidelastic instability in tube bundles.

A similar behavior was reported by Austermann & Popp [24] when studying a parallel triangular array with a pitch ratio of 1.25. They found that a single flexible tube located at the second, third, or fourth row of a rigid array does not become fluidelastically unstable, however, a single flexible tube located at the first row of the rigid array does become unstable. The same study showed that for a parallel triangular array with pitch ratio 1.375, a single flexible tube located at the first, second, third, or fourth row of a rigid array does become fluidelastically unstable. They also determined experimentally that the least stable tube was the third row tube, and these observations agree with previous research [19, 20, 22, 25] which was also carried out for a pitch ratio of 1.375. Thus, it appears that the stability of a single flexible tube in a rigid array is not only dependent on its tube row location but also dependent on array pitch ratio.

CONCLUSIONS

Experiments using a parallel triangular tube array with a pitch ratio of 1.54 were conducted in the wind tunnel facility at McMaster University as part of a fundamental study of the mechanisms of fluidelastic instability in tube arrays. Tube response was monitored for both cases of a fully flexible array, and a single flexible tube in a rigid array. The single flexible tube location was varied to investigate the effect of tube location on fluidelastic instability.

The original intent was to make the physical model as precise as possible so that the effect of single parameter variation could be studied. The use of a single flexible tube in a rigid array removes the effect of dynamic fluid coupling between tubes, thereby leaving only the negative damping mechanism of fluidelastic instability. The use of one tube in the upstream tube row would reduce the array generated turbulence, and thereby reduces the noise on the velocity and pressure measurements in the interstitial flow.

The experimental results showed that a single flexible tube in a rigid parallel triangular array of tubes with a pitch ratio of 1.54 can only become fluidelastically unstable if it is located in the third tube row. It was also found that a third row tube in a fully flexible array is the least stable and, when it becomes unstable, it appears to trigger the rest of the array. Comparing these results with those of the published literature suggests that this behavior is strongly dependent on pitch ratio for parallel triangular array geometry.

It is concluded that simplified models for fluidelastic instability in tube arrays can have substantial benefits for developing an understanding of the underlying fluid excitation mechanisms as well as demonstrating the true complexity of the phenomenon. The relative importance of the damping and stiffness mechanisms is strongly dependent on tube array geometry and pitch ratio as well as on the tube location within the array. It follows that great care must be taken in interpreting the results and in making generalizations about the observed behavior.

NOMENCLATURE

D	Tube diameter.
δ	Logarithmic decrement.
f	Tube natural frequency.
f_s	Sampling frequency.
H	Tube length.
L	Piano wire free length.
m	Tube mass.
P	Pitch ratio.
ρ	Fluid density.
t	Tube wall thickness.
T	Piano wire tension force.
U_g	Mean gap velocity.

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