Experimental Investigation of Streamwise Fluidelastic Instability in Tube Arrays

by
Ali Aboushita

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ABSTRACT

EXPERIMENTAL INVESTIGATION OF STREAMWISE FLUIDELASTIC INSTABILITY IN TUBE ARRAYS

Ali Aboushita
University of Guelph, 2020

Advisors:
Dr. Marwan Hassan
Dr. Ibrahim Deiab

Fluidelastic instability (FEI) is a major concern in steam generators and continues to be one of the leading causes of structural failure. There has been a general consensus that the phenomenon of FEI occurs only in the transverse direction rather than in the streamwise direction. After a refurbishment of the San Onofre Nuclear Generation Station (SONGS), there was a failure in the steam generator due to streamwise FEI. This has never been reported before and had traditionally not been considered as a factor in the design of nuclear steam generators. Therefore, research efforts are made to understand this phenomenon. In this work, experiments were conducted using a closed-loop wind tunnel. A fully flexible tube array subjected to cross-flow was considered in the current investigation with pitch to diameter ratios of 1.25, 1.4, 1.55, and 1.7. The tubes were mounted over a flexible support in the direction of the flow.
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Symbols

\( f \)    Frequency.

\( m \)    Tube mass per unit length.

\( P \)    Centre to centre pitch.

\( R_e \)  Reynolds number.

\( S_t \)  Strouhal number.

\( U_p \)  Pitch velocity.

\( U_c \)  Critical flow velocity.
δ  Damping logarithmic decrement.
ρ  Density.
ζ  Damping ratio.
K  Connors constant.
1 Introduction

1.1 Flow-Induced Vibration (FIV) in Steam Generators

The rise in the demand for energy as fossil fuels become limited has increased interest in the use of clean energy sources, such as nuclear, wind, and solar power. As of 2012, 15% of Canada's electricity was produced from nuclear energy, and nuclear energy supplies about 50% to 60% of Ontario’s electricity needs [Annual Report of the Canadian Nuclear Safety Commission (CNSC)]. All Canadian nuclear power stations are based on one type of reactor known as the “Canada Deuterium Uranium” (CANDU). In the late 1960s, Atomic Energy Canada Limited (AECL) developed this pressurized water reactor and used deuterium oxide (D2O) as the moderator. The CANDU reactor contains two cycles, as shown in Figure 1-1. Fission reaction inside the reactor uses heavy water in the primary cooling loop. A steam generator transfers the heat to a secondary cooling cycle. Figure 1-2 shows a sketch of a CANDU steam generator. The function of the heat exchanger is to transfer the heat generated from fission to the power loop. There is a phase change occurring within the steam generator. This phase change occurs when the heavy water flows inside the tubes and transfers its heat to the secondary fluid, which flows across and around the tubes. Due to the highly turbulent flow during this operation, the secondary flow interacts with the tubes and can induce vibration. These
vibrations affect the long-term and the short-term life of the steam generator. These vibrations can be induced through several mechanisms: (a) vortex shedding, (b) acoustic resonance, (c) turbulence buffeting, and (d) fluidelastic instability. Since the late 1960s, much attention has been devoted to predicting and understanding the excitation mechanisms that cause flow-induced vibration. In nuclear power plants, FIV became one of the design principles in engineering and received much attention. Fluidelastic instability is the most critical flow-induced vibration mechanism in shell and tube heat exchangers.

This phenomenon is recognized as a significant concern in the design of tube-and-shell heat exchangers. This excitation mechanism can produce significant fluid forces, which can lead to excessive vibrations of the tubes in the heat exchanger. These often result in a collision between a tube and its support. This collision can lead to devastating tube failure due to fatigue or fretting wear. Therefore, flow-induced vibrations are a source of concern in the design of heat exchangers, especially in the nuclear power industry. This has necessitated rigorous safety rules due to the very high costs of unexpected shutdowns and the required repairs to the power plant.
Figure 1-1: Diagram of a CANDU power plant. (Source: www.nuclearfaq.ca)
Figure 1-2: Schematic design of CANDU 6 steam generators (Source: www.canteach.candu.org)
FIV can cause quick and severe failure in a steam generator. Some examples of the damaging effects of FIV on steam generator tubes are shown in Figure 1-3.

*Figure 1-3 Samples of steam generator tube failures due to flow-induced vibrations (modified from Atomic Energy Canada Ltd.)*
1.2 Objectives

The purpose of this research is to provide a better understanding of the phenomenon of fluidelastic instability in the heat exchanger tube bundle. This is achieved by investigating the stability behaviour of a flexible kernel tube in a tube array and the phase lag between the tubes.

1.3 Thesis Outline

This thesis contains five chapters. Chapter 1 provides an introduction to the issue of vibrations in a heat exchanger. Chapter 2 provides a review of fluidelastic instability excitation mechanisms, fluidelastic instability in the streamwise and transverse directions, various models of fluidelastic instability, and the experimental work conducted to understand the mechanism. Chapter 3 provides a description of the experimental facility, the instrumentation, and the methodologies used to conduct the investigation. Chapter 4 provides an explanation of the results obtained through the experimental work. Chapter 5 summarizes the main contributions and the future work.
2 Literature Review

2.1 Flow in a Tube Bundle

Heat exchangers are used to transfer the heat between two or more fluids. The efficiency of the heat exchanger is raised by increasing the surface area of the flow structure interface, which can be achieved by utilizing a large number of highly-packed tubes. To enhance the process of heat transfer, fluid flows around the tubes are designed such that turbulent flow prevails. Four common tube configurations are typically utilized and are shown in Figure 2-1.

![Flow direction](image)

Flow direction

- Inline Square
- Rotated Square
2.2 Excitation Mechanisms

There are four kinds of excitation mechanisms that may trigger extreme vibration in shell-and-tube heat exchangers: (a) vortex shedding, (b) turbulence buffeting, (c) acoustic resonance, and (d) fluidelastic instability. Figure 2-2 shows an example of the response of a tube in a bundle subjected to crossflow.

At low flow velocities, turbulence buffeting is deemed as the primary excitation mechanism. Due to turbulence buffeting, the amplitude of the tube response increases gradually with an increase in the flow velocity. Turbulence buffeting is a random excitation force that prevails over a range of frequencies. Turbulence buffeting might be helpful to enhance the convective heat transfer inside the heat exchanger, but the amplitude of the small vibrations caused by turbulence buffeting should be taken into account.
Vortex shedding and acoustic resonance are known as self-controlled mechanisms in the heat exchanger tube bundle. When the frequency of the vortex shedding coincides with the natural frequency of the tube response, resonance takes place. In addition, in the proximity of the natural frequency, the frequency of vortex shedding locks on the natural tube frequency. While in this lock-on region, the tube can be subjected to comparatively large vibration amplitudes. The frequency of the vortex shedding ($f$) can be determined from Equation 2.1 using the tube diameter ($d$), the flow velocity ($U$), and the Strouhal number ($S_t$):

$$f = S_t \frac{U}{d} \quad (2.1)$$

The Strouhal number is a non-dimensional frequency quantity. In most cases, the vibration excited by vortex shedding can be avoided by operating the heat exchanger far from the lock-on region.
2.3 Fluidelastic Instability in Tube Arrays

Fluidelastic instability (FEI) is considered to be one of the leading causes of structural failure in steam generators. Fluidelastic instability is described as a self-exciting mechanism in which strong feedback between the tube motion and the resulting fluid forces takes place. When the flow velocity reaches a threshold called the critical flow velocity ($U_c$), the tube response dramatically increases, which may lead to catastrophic failure. The earliest study of fluidelastic instability was conducted by Roberts (1966), and resulted in the formulation for the criteria for the critical reduced velocity:

![Figure 2-2 The three main sources of excitation mechanisms](image)
\[ U_c = f d K \left( \frac{\delta m}{\rho d^2} \right)^n \]  \hspace{1cm} (2.2)

where \( m, \delta, d, f, \) and \( \rho \) are the mass per unit length, the damping logarithmic decrement, the diameter of the tube, the natural tube frequency, and the flow density respectively.

Later, experiments for a single row of cylinders were carried out by Connors (1970). A semiempirical correlation for the reduced velocity as a function of the mass damping parameters (MDP) was proposed. The resulting formula is similar to that of Roberts (1966). Connors proposed values for \( n \) and \( K \) to be 0.5 and 9.9, respectively.

\[ \frac{U_p}{f_d} = K \left( \frac{\delta m}{\rho d^2} \right)^n \]  \hspace{1cm} (2.3)

\[ U_p = \frac{p}{p-D} U \]  \hspace{1cm} (2.4)

where \( U_p, U, \) and \( p \) are the pitch flow velocity, the upstream flow velocity, and the array pitch respectively.

As shown in Equation (2.3), the mass damping parameter was defined as a function of the logarithmic decrement \( \delta \), the mass of the tube per unit length \( m \), the pitch flow velocity \( U_p \), the natural frequency \( f \), the density of the fluid \( \rho \), and the diameter of the tube \( d \).

Finding suitable values for the constants \( K \) and \( n \) has been the subject of numerous experimental studies. A guideline for stability threshold was published by Chen (1984), in which the available experimental data and a stability map were constructed.
Standardization of the parameters and the development of modified stability maps were accomplished by Weaver and Fitzpatrick (1988a). Figure 2-3 shows the Weaver and Fitzpatrick (1988a) stability maps for the four standard tube geometries. It was recognized that several parameters affect fluidelastic instability thresholds, such as the tube pitch ratio, the array geometry, the turbulence level, and the relative motion of neighbouring tubes.
Figure 2-3: Critical flow velocity for different geometries of fluidelastic instability: (a) square, (b) rotated square, (c) normal triangle, and (d) parallel triangle arrays. Weaver and Fitzpatrick (1988a)
The design of heat exchanger tube bundles depends on the stability map of ASME guidelines. These guidelines do not account for the fluidelastic instability in different array geometries.

2.4 Models of Fluidelastic Instability

2.4.1 Jet-Switching Model

Roberts (1966) was the first to study the FEI phenomenon. The author found that self-excited streamwise vibration can take place in a staggered row of tubes and attributed the phenomenon to a jet-switching mechanism. The instability occurs for both single rows and double rows that are allowed to vibrate only in the streamwise direction. Using these experimental results, Roberts (1966) developed an analytical model that relates the stability threshold to the tube dynamic parameters and the flow density. In his model, the flow forms a jet between two wakes of different sizes, as shown in Figure 2-4. Roberts solved the pressure profile using the Laplace equation and obtained an expression of the drag force. The fluid moves in the larger wake decreased as the two tubes approach each other. Consequently, the wake is observed to contract and the jet switches direction. The principal contribution of this study was that it formulated the parameter MDP as the controlling parameter of the instability.
2.4.2 Quasi-Static Model

Connors (1970) proposed a quasi-static model, which utilized the experimental data for a tube row subjected to crossflow. The author noted that the tubes oscillate in elliptical orbits over the transverse or the streamwise direction. He attributed the destabilizing effect to this pattern. With the assumption that the movement of the neighbouring tubes occurs in elliptical orbits uniformly and asymmetrically, he measured the coefficients of the fluid forces. Using these fluid force coefficients, Equation (2.3) was derived. This equation is considered to be the most common expression used to predict the phenomenon of fluidelastic instability. The equation proposed by Connors (1970) was based on a single row of tubes and on the assumption that the neighbouring tubes oscillate at the same frequency. Through detuning the neighbouring tubes, Weaver and Lever (1977) attempted to reduce the instability. They found that detuning the neighbouring tubes did not prevent the fluidelastic instability, but it had a stabilizing effect. Price (1995) made a
comparison between the boundaries of stability acquired from a model of quasi-static and experimental results, as shown in

Figure 2-5. He showed that the quasi-static model is not capable of representing the phenomenon of fluidelastic instability correctly. Conners' equation, utilizing the $K$ and $n$ constants is a very crude estimation of the FEI threshold and should not be used when designing heat exchangers.

*Figure 2-5: Theoretical stability boundaries for FIV compared to the experiment: (*) multiple flexible tubes in a liquid flow; (*) multiple flexible tubes in the gaseous flow; ( ) single flexible tube in the gaseous flow; (-) Roberts (1966) solution; (- - -) Connors (1970) solution; (...) Blevins (1974) solution Price (1995)*
2.4.3 Unsteady Models

The unsteady forces of the fluid in a kernel of tubes were measured directly by Tanaka and Takahara (1981) in lieu of theoretical estimations. The authors excited the central tube harmonically and measured the forces of the fluid acting on the surrounding tubes. The measurements of the forces acquired by Tanaka and Takahara (1981) were used by Chen (1983) as an experimental input to a mathematical model that brings together the forces of fluid with the equation of motion of the tube. The model of Chen (1983) obtained stability boundaries. These boundaries had a good agreement with the experimental data acquired by Tanaka and Takahara (1981), as shown in Figure 2-6. One drawback of this method of determining the boundary of instability is that it requires a large amount of data.

![Figure 2-6: Stability boundaries for FEI by Chen (1983a, b) compared to the experiments; (+) multiple flexible tubes in a liquid flow; (*) multiple flexible tubes in gaseous flow; (•), single flexible tube in a gaseous flow; (—) practical stability boundaries; ( - - - ) theoretical stability boundaries Price (1995)
2.4.4 Semi-Analytical Model

In a rigid array, the fact that a single flexible tube has the same threshold of stability as that of a fully flexible array was found experimentally by Lever and Weaver (1982). As such, the authors conducted an analysis of a flexible single tube in a rigid array of tubes subjected to crossflow. As shown in Figure 2-7, the boundaries of instability acquired by Lever and Weaver (1982) followed the trend of the experimental data significantly. These findings imply that the model of Lever and Weaver (1982) captured the physical nature of fluidelastic instability to a certain extent. The theoretical model by Lever and Weaver (1982) was improved on by Yetisir and Weaver (1993). These modifications showed that the instability at a low mass damping parameter (MDP) is attributed mainly to the mechanisms of damping, whereas the instability at a high MDP is attributed to the mechanism of stiffness. The boundaries of instability obtained by the model of Lever and Weaver (1982) showed slight differences as opposed to the boundaries of instability reported by Yetisir and Weaver (1993).
2.4.5 Quasi-Steady Model

Based on the quasi-steady approach, Price and Païdoussis (1984) proposed a model for FEI. They measured the coefficients of fluid forces in a rigid array to represent the forces of fluid on the flexible array. A time delay between the response of the fluid and the tube motion was included by the authors. They identified the response of the tube by coupling the displacement of the tube and the fluid forces via the equation of motion of the system.

Figure 2-7: Boundaries of instability acquired practical; (——), theoretical stability; (- - -), experiment data for parallel triangle; (■■■) by lever and weaver (1982)
Price and Païdoussis (1986) enhanced their model to represent a single tube instability in a rigid array. The boundaries of the instability acquired from the theoretical model of Price and Païdoussis (1984, 1986) showed several regions of stability that have been regarded as impractical. The pragmatic threshold of stability has been identified as shown in Figure 2-8. The model is generally conservative in predicting the stability threshold.

![Diagram](image)

Figure 2-8: Comparison between theoretical boundaries of stability and experimental data; (■△●), by Price and Paidoussis (1986)
2.4.6 Quasi-Unsteady Model

The quasi-unsteady model was introduced by Granger and Païdoussis (1996). They studied the effects of unsteady forces, which had been neglected in the theoretical model of Price and Païdoussis (1984). They predicted the response of the fluid to an impulse in the tube motion and attempted to solve the equations of motion. A more accurate estimation of fluidelastic instability was provided using the quasi-unsteady model than the quasi-steady model. The disadvantage of the quasi-unsteady model is that it is more complex and requires delay time parameters, which have to be obtained from the experimental data.

2.4.7 Computational Fluid Dynamics Model (CFD)

Computational fluid dynamics is an emerging research tool that can be used to obtain a solution for many problems. By the early 1990s, CFD started to gain attention. The recent development of computational power has made the utilization of CFD in the problems of fluid-structure interaction possible. Marn and Catton (1990) studied flow-induced vibration in a tube bundle by using CFD based on a one-dimensional unsteady integration. Marn and Catton (1991) investigated the FIV by considering a two-dimensional analysis; nevertheless, their attempts did not provide a good agreement with the experimental data. Hassan et al. (2010) developed a model that is capable of simulating the interstitial flow inside the tube bundles. In this model, a single tube was given a prescribed motion. The fluid forces acting on the surrounding tubes were calculated. These fluid force
coefficients were compared with these obtained by Tanaka and Takahara (1981) and Chen (1984). The predictions of Hassan et al. (2010) compared well with the experimental data. The authors used these force coefficients and developed an unsteady model to predict the stability threshold. The boundaries of instability obtained by the authors had a good agreement with the experimental data in the literature.

A further application of the techniques of Hassan et al. (2010) was found in the works of Sadek et al. (2018, 2020). El Bouzidi and Hassan (2012) utilized a numerical flow simulation of tube arrays and provided an enhanced time delay model for the flow cell model of Leaver and Weaver. El Bouzidi and Hassan (2015) developed a time delay model to study the phase lag causing fluid elastic instability in a normal triangle array. Anderson et al. (2014) used a CFD model to study the fluidelastic instability forces in a tube array including a boundary layer effect. It was found that the motion of the boundary layer improves the force of the fluid that acts opposite to the tube and the amplitude vibration of the tube. As well, Hassan and Mohany (2016) carried out a simulation of a U-bend tube bundle to model the dynamics of the tube structure including loose support effects. A model simulation was done by El Bouzidi et al. (2015) to investigate the effect of the clearance between the tube and the support and predict tube leakage in the steam generator. This investigation can be used to estimate the crack and leakage life for steam generators.

Significant enhancements in the research of computational fluid dynamics have made it possible to solve numerous advanced engineering problems. It has not been possible to
use CFD to solve the fluid flow equations coupled with the tube equation of motion for practical values of flow rates. In the near future, it is expected that numerical codes will be developed to predict the tube response without modelling the flow field or the tube motion.

2.5 Streamwise Fluidelastic Instability

2.5.1 Early Observations

Numerous investigations and experiments have been devoted to the study of the instability of flexible tube bundles. All of these studies concluded that instability can occur in the transverse direction only. Nevertheless, several tests have shown that instability can occur in the streamwise direction. A wind-tunnel investigation of the effect of flat bar supports on the stability of U-bend tubes was reported by (Weaver and Schneider (1983). The authors found an interesting outcome when the experiment was conducted. The instability had occurred in the streamwise direction when the flow direction was perpendicular to the U-bend plane. They concluded that instability occurs in the direction with the lowest natural frequency, whether that be in the transverse or the streamwise direction. Another experimental study confirmed the possibility of the streamwise fluidelastic instability as reported by Weaver and Koroyannakis (1983). The authors conducted an experimental study on a parallel triangle straight tube array with a pitch to diameter ratio of 1.375. They found that tubes with an asymmetric stiffness
became fluid elastically unstable in the streamwise direction when the stiffness in the transverse direction was much larger than in the streamwise direction.

2.5.2 Other Experimental Studies

The lack of stability of a single flexible tube in a rigid array in the streamwise direction was confirmed by Mureithi et al. (2005). An experiment involving a fully flexible array with a restricted number of flexible tubes was conducted. The results showed that a single flexible tube within a rotated triangle array cannot be unstable in the flow direction; meanwhile, the other configuration of the bundle was shown to be unstable. An experimental study of fluidelastic instability of U-bend tube bundles was reported by Janzen et al. (2005). All the tests were conducted in two-phase cross-flow. The results showed that fluidelastic instability was found in the in-plane and out-of-plane directions in an air-water flow with a 25% void fraction. Violette et al. (2005) performed another experimental study of flow-induced vibrations for three different configurations of flexible tubes in a two-phase flow. The results showed that the instability was found at 80%, 90%, and 95% for two flexible columns and for a fully flexible bundle, respectively. They also noted that all the instabilities were at much higher pitch velocities than expected.

The instability in the streamwise direction occurs at higher velocities than in the transverse direction, and the probability of instability in the in-plane direction is much less (Janzen et al., (2005), Mureithi et al., (2005), and Violette et al. (2005)). Up to this
point, streamwise fluidelastic instability had only been found in laboratory experiments and had never been observed in operating nuclear steam generators. This changed when the San Onofre Nuclear Generating Station (SONGS) was shutdown in 2012 due to leaks in the tubes caused by instability in the streamwise direction. Since that time, instability in the in-plane direction has received more attention from scientists.

In-plane fluidelastic instability of a triangular tube array subjected to airflow was reported by Hirota et al. (2013). The authors studied the relationship between the critical flow velocity and the pitch to diameter ratio of the tube in the streamwise direction. They demonstrated the possibility of fluidelastic instability in the streamwise direction and found that the critical flow velocity of the inflow was larger than that in the cross-flow direction.

Unsteady and steady fluid forces acting on a parallel triangle tube bundle subjected to two-phase flow were reported by Olala et al. (2014). The coefficient of magnitude of the unsteady fluid forces in the streamwise direction was found to depend on the reduced flow velocity. The coefficient of the steady fluid forces for all the void fractions was found to increase with tube displacement.

Nakamura et al. (2011, 2014, 2017, 2018) carried out several wind tunnel experiments to establish the conditions under which tube arrays are prone to streamwise fluidelastic instability. The results showed that the critical flow velocity depends on the pitch to diameter ratio of the arrays. It was also noted that the tube-to-tube coupling is very
important for inflow fluidelastic instability to occur, and that streamwise fluidelastic instability never occurred in a square tube array.

Feenstra et al. (2017) studied streamwise fluidelastic instability subjected to air crossflow at two different locations. The test rig was equipped with a variable clearance of flat bar supports to investigate the effect of the supports and the tube configuration. They concluded that clusters of tubes, which include a small number of rows, were vibrating at different frequencies and had different instability thresholds. Streamwise fluidelastic instability occurred only in a cluster of tubes and did not occur in the case of a single flexible tube. Table 2-1 illustrates all the experimental parameters extracted from the previous works.
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<th>Test condition</th>
<th>MDP</th>
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<th>Vr</th>
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<td>6.62</td>
<td>0.027</td>
<td>Kernel flexible</td>
<td>7.5</td>
<td>6.98</td>
<td>16.7</td>
</tr>
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<td></td>
<td>6.62</td>
<td>0.024</td>
<td>Kernel flexible</td>
<td>7.5</td>
<td>6.98</td>
<td>16.7</td>
</tr>
<tr>
<td>2018</td>
<td>Hirota et al. (2018)</td>
<td>SF6-ethanol</td>
<td>PT</td>
<td>1.3</td>
<td>-</td>
<td>9.53</td>
<td>stainless steel</td>
<td>6.63</td>
<td>6.60</td>
<td>0.035</td>
<td>0.35</td>
<td>Kernel flexible</td>
<td>14.5</td>
<td>6.98</td>
<td>12.3</td>
<td></td>
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<tr>
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<td>6.68</td>
<td>0.039</td>
<td>Kernel flexible</td>
<td>17.9</td>
<td>6.98</td>
<td>16.7</td>
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<td></td>
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<td></td>
<td></td>
<td>6.62</td>
<td>0.027</td>
<td>Kernel flexible</td>
<td>17.9</td>
<td>6.98</td>
<td>16.7</td>
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<td></td>
<td></td>
<td>6.62</td>
<td>0.024</td>
<td>Kernel flexible</td>
<td>17.9</td>
<td>6.98</td>
<td>16.7</td>
</tr>
</tbody>
</table>

- **Flexible Columns.**
- **Kernel (13 tubes)**
- **One column (5 tubes)**
- **Vc (m/s)**
- **Stainless steel**

References:
- Hirota et al. (2018)
- Mureithi et al. (2010)
- Khalvatti et al. (2018)
- Hirota et al. (2013)
- Hirota et al. (2010)
- Nakamura et al. (2011)
- Nakamura et al. (2014)
- Nakamura et al. (2005)
- Muniruzz et al. (2005)
- Khalvatti et al. (2013)
- Nakamura et al. (2013)

**Table Notes:**
- MDP: Multiple Points
- Vc: Critical Velocity
- Vr: Reduced Velocity
- €: Cost
2.5.3 Theoretical Work

The first analytical investigation of a tube array subjected to streamwise FEI was conducted by Hassan and Weaver (2015). In this study, the impacts of the surrounding turbulence level, the initial loading of the tube to the support, the friction of the sliding support, and the clearance of the tube to the support on the critical flow velocity for inflow fluidelastic instability were investigated. The results showed that the effect of tube damping was increased due to the sliding contact of the tube to its support, which led to an increase in the stability threshold. They confirmed that the effect of the tube-to-support clearance was small in the transverse direction as long as the supports were active. It was also determined that a decrease in the clearance led to a significant destabilization effect on the streamwise fluidelastic instability. The critical flow velocity for streamwise FEI was reduced substantially by increasing the ambient turbulence level. Hassan and Weaver (2016) developed a model to study the stability of the array in both the streamwise and transverse directions. Their model predicted that the tube array would become unstable in the transverse direction if the natural frequency of the tubes was lower than or equal to the natural frequency of the streamwise direction. The array of tubes could become unstable in the streamwise direction if the natural frequency of the tube array in the streamwise direction was 20% lower than that in the transverse direction. Hassan and Weaver (2017) studied the impact of the geometry of a tube array on the streamwise fluidelastic instability in both the in-plane and out-of-plane directions for a normal triangle and a square inline array.
Hassan and Weaver (2019) extended this model to include all tube array geometries and study the behaviour of streamwise fluidelastic instability as a function of mass and pitch ratio. They found that at high mass damping parameters, the parallel triangle array is vulnerable to streamwise fluidelastic instability, particularly for a small pitch ratio. The transverse fluidelastic instability of a rotated square array occurred at a lower flow velocity, and in-plane fluidelastic instability could develop. Their work also explained why the square inline array is very stable in the streamwise direction.

2.6 Summary

The literature shows that streamwise fluidelastic instability has become one of the major problems leading to structural failure in heat exchangers. There are very few models that are capable of predicting the stability threshold, but much more work is required to enhance this model. All the experimental studies were done to understand the reasons which lead to streamwise fluidelastic instability in a tube bundle. However, in the streamwise direction, FEI still needs more investigation to obtain a better understanding of the phenomenon.

The current work carries out a systematic investigation to understand this phenomenon. An experimental investigation was conducted using a closed-loop wind tunnel. Several fully flexible tube arrays subjected to cross-flow were considered with various pitch to diameter ratios.
3 Experimental Facility

This experimental study was carried out to shed light on the streamwise FEI phenomenon. The experimental setup was designed and manufactured with high precision to facilitate the control of the array parameters and to provide more thorough measurements of the interaction among tubes and the flow. Furthermore, it enabled studying both transverse and streamwise directions separately.

3.1 Wind Tunnel Facility

All the experiments are conducted on a subsonic closed-loop wind tunnel design built at the School of Engineering at the University of Guelph, as shown in Figure 3-1 Elhelaly (2019). The air is drawn by an axial fan which derived from an AC motor (20 HP). The speed of the motor is controlled through a variable frequency drive (VFD), which can vary the frequency from 0 to 50 Hz with an increment 0.1 Hz. Flexible hoses (2) were installed on both sides of the fan to prevent any vibration transmission from the fan to the wind tunnel. The incoming air from the fan flows into a diffuser (4). This diffuser is designed to provide a transition from the round housing of the fan to the square cross section of the duct of the wind tunnel. After the flow enters the diffuser, it passes through two corners each of which is equipped with guide vanes (5). These guide vanes were
installed to minimize the power losses, the turbulence and force a smooth turn of the airflow. The flow then passes through a settling chamber (8) before entering the test section. The settling chamber was designed to eliminate the large-scale eddies associated with the strong secondary flows produced by the turns in the tunnel. To provide a uniform flow velocity distribution, a honeycomb (7) and a mesh screen were installed. The honeycomb has a cell diameter of 12.7 mm and 100 mm in length. Then, the flow enters a contraction duct (9) before entering the test section. Additional mesh screen was added (19) for farther conditioning of the flow. All the mesh screens were selected to have a 40% open area in order to induce a pressure drop in order to increase uniformity of the velocity distribution across the test section. Past the test section the flow enters another diffuser (14) followed by another two corners before entering the fan. Vibration isolators were installed to minimize vibration transmission through the ground. There is no significant vibration signal detected when testing the test section at full flow capacity.
3.2 Model Design

3.2.1 Tube Array Geometry

The design of the tube array has three objectives.
1. Proper modeling of the tube array dynamics.

2. The ability to study fully flexible tubes in addition to a single flexible tube in a rigid array.

3. Ensuring the uniformity of the flow that crosses the tube bundle.

Weaver and El-Kashlan (1981) investigated the effect of the dimensions of the tube array on the stability threshold and recommended that at least five rows and three columns of tubes are required to capture the phenomenon.

As shown in Figure 3-2, the tube bundle consists of a base plate, half tubes, seven flexible tubes and a number of rigid tubes. The number of rigid tubes depends on the geometry of the array. The base plate of the bundle was designed to be suitable to work in both streamwise and transverse directions. The flexible tubes consist of a rigid cylinder made from acrylic (0.0254 m diameter) which is attached to a flexible base. The base of the flexible tube is made from aluminum and has a rectangular cross-section (13 mm x 1.6 mm) to be oriented such that the tube can be flexible in the either streamwise or transverse direction, as shown in Figure 3-3. The half tubes were added to the sides of the test section to reduce the effect of the boundaries layer.

In order to have facilitated sufficient tube spacing, a suitable tube diameter has been selected. The diameter was chosen based on the available standard size of the tube.
Twelve base plates for holding the tubes were manufactured to facilitate the study of the four array geometries and pitch to diameter ratios. The manufacture of all base plates was carried out using a CNC milling machine to achieve maximum precision for the location of the tubes.

*Figure 3-2: Model of the tube bundle*
3.3 Test section

The test section consists of a top plate, bottom plate, two sides, rubber flanges, a contraction and an expansion section as shown in Figure 3-4. Twelve sets of contraction and expansion sections were manufactured to accommodate the various array/pitch to diameter ratios combinations. A slot has been cut at the top plate of the test section and a polished Acrylic sheet installed to facilitate visualization of the tube array. Another slot was made at one side of the test section, and another acrylic sheet is installed at this slot to allow the light to illuminate the test section. The rubber flanges were installed from the diffuser and contraction section of the wind tunnel to seal and isolate the section from any ambient vibration. The upstream and downstream flow area of the test section have
Figure 3-4: Test section a) Expanded 3D view b) Elevation view
an area of (0.3m x 0.3m). The height of the section is 0.3m, while the width is varied according to the pitch ratio and the type of the array. The test section was designed to permit switching each tube array from being flexible to rigid. Table 3-1 shows a list of all test section dimensions and the corresponding contraction ratio. The tube bundles were fixed in a steel frame separately from the test section to prevent any vibration coming from the wind tunnel being transferred to the bundle of the tubes.

### Table 3-1: Summary of test section parameters

<table>
<thead>
<tr>
<th>Array</th>
<th>P/D</th>
<th>Total number of full tubes</th>
<th>Test section width [mm]</th>
<th>Contraction ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Triangle</td>
<td>1.25</td>
<td>13 + 10 half tubes</td>
<td>110</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>1.40</td>
<td>13 + 10 half tubes</td>
<td>123</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>1.55</td>
<td>13 + 10 half tubes</td>
<td>136</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>1.70</td>
<td>13 + 10 half tubes</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>Normal Triangle</td>
<td>1.25</td>
<td>17 + 6 half tubes</td>
<td>127</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>17 + 6 half tubes</td>
<td>142</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>1.55</td>
<td>17 + 6 half tubes</td>
<td>158</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>1.70</td>
<td>17 + 6 half tubes</td>
<td>173</td>
<td>1.7</td>
</tr>
<tr>
<td>Rotated Square</td>
<td>1.25</td>
<td>10 + 6 half tubes</td>
<td>90</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>10 + 6 half tubes</td>
<td>101</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.55</td>
<td>10 + 6 half tubes</td>
<td>111</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>1.70</td>
<td>10 + 6 half tubes</td>
<td>122</td>
<td>2.5</td>
</tr>
</tbody>
</table>
3.4 Instrumentation

3.4.1 Strain gauges

In all the experiments, the motion of two tubes was monitored. The two tubes were instrumented with strain gauges to measure the vibration of the tubes. Strain gauges were mounted to the beam near the clamped end, as shown in Figure 3-5: schematic drawing of the tubes. The strain gauges were calibrated by applying a known displacement at the tip of the tube. A full-bridge strain gauges circuit was used to obtain a better sensitivity during the measurements. The strain gauge signal conditioners include an amplifiers to boost the signal level to increase measurement resolution and to improve signal-to-noise ratios. The measurement signal is then acquired by the real-time-processing computer via an A/D-converter.

![Figure 3-5: schematic drawing of the tubes](image)

Figure 3-5: schematic drawing of the tubes
3.4.2 Flow Velocity Instrumentation

The velocity of the flow was measured by using a pitot tube as shown in Figure 3-6: schematic drawing of the pitot tube. The pitot tube was placed in the upstream in front of the tubes bundle. A digital pressure transducer was connected to the pitot tube. The velocity of flow may be obtained by calculating the dynamic head via Bernoulli’s equation as follows:

\[ U_0 = \sqrt{\frac{2 \Delta P}{\rho}} \]  \hspace{1cm} (3.1)

where \( \Delta P \) is the dynamic head and \( \rho \) is the density of air. The flow velocity was obtained with an accuracy of 0.001 m/s. The range of air flow velocities covered through this study is less than 20 m/s with an average temperature of the room of about 21 °C.

![Figure 3-6: schematic drawing of the pitot tube](image-url)
3.5 Vision System

Figure 3-7 in shows the Visual Image Processing System utilized in this study. The system consists of a high-speed camera, lighting source, and a data acquisition system (DAC). The high-speed camera captured the images of the tube motion with 200 frames per second (FPS) and is connected to a computer to store the images for farther analysis using an image processing software (Dynamic Studio).

*Figure 3-7: The vision system*
3.6 Image post-processing

The images captured by the high-speed camera were analyzed and converted to videos. A MATLAB module was used to process the images and extract the tube motion. This was done by first selecting feature points within the tube area. The feature points are then tracked from each frame and the change in the position of these tracking points was recorded. This process is done by using the Lucas-Canada tracking algorithm. To start the tracking process, an initializer must be used to set the location of the point and begin with the first video frame. The data collected from the software is transformed into displacement vs time records. This data was calibrated using a static test to be able to convert the pixel to mm. Figure 3-8 presents an overview of the process. The data collected from the image processing code was used to calculate the phase shift and lag among the motion of the tubes.
Figure 3.8: An overview of the process

Region and point selected

The values of training from several points

The mean value of the point

Get The Phase Shift Between The Tubes

Applying Fast Fourier Transform (FFT)
4 Results and Discussion

This chapter presents the results of the experimental work which was conducted to examine the stability behaviour and the phase shift in tube array.

All the tests started with low flow velocity and then increased incrementally. For each velocity, the data acquisition started after the system reaches a steady-state. The process is repeated until the amplitudes of the tube became large enough, and the stability threshold was reached. The process of the data collection has been repeated at least three times to ensure the repeatability of the data. In addition to the displacement, the tube motion was recorded by taken videos for documenting the behaviour of the array and phase analysis.

4.1 Tube Array Tuning

In order to ensure the reliability of the obtained data, all the tubes must have the same natural frequency and damping ratio. The frequency of each tube was tuned by adding or removing a small mass from the cap of the tube. Each tube was individually tested by imposing an initial displacement to the tube, and the free response of the tube was recorded. The natural frequency of the tube was obtained by examining the response spectrum of the recorded signal. This process was repeated ten times for each tube. All the flexible tubes were tuned to have the same natural frequency of 9.14 Hz with ±
0.05Hz. The logarithmic decrement of damping in air, found from a simple pluck test, was found to be 0.01 +/- 0.001.

Table 4-1 shows the tube's natural frequency and damping ratio.

Table 4-1: Tube natural frequency and Damping ratio

<table>
<thead>
<tr>
<th>Tube</th>
<th>Natural Frequency</th>
<th>Damping Ration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.17</td>
<td>0.0011</td>
</tr>
<tr>
<td>2</td>
<td>9.17</td>
<td>0.0011</td>
</tr>
<tr>
<td>3</td>
<td>9.13</td>
<td>0.0011</td>
</tr>
<tr>
<td>4</td>
<td>9.13</td>
<td>0.0012</td>
</tr>
<tr>
<td>5</td>
<td>9.17</td>
<td>0.0011</td>
</tr>
<tr>
<td>6</td>
<td>9.13</td>
<td>0.0011</td>
</tr>
<tr>
<td>7</td>
<td>9.13</td>
<td>0.0012</td>
</tr>
<tr>
<td>Mean</td>
<td>9.14</td>
<td>0.0011</td>
</tr>
<tr>
<td>STD</td>
<td>0.021</td>
<td>4.8E-05</td>
</tr>
</tbody>
</table>
4.2 Parallel Triangle Array

4.2.1 Transverse direction

Before starting the data collection for streamwise direction, experiments were conducted for the stability threshold in the transverse direction. The amplitude vs the time trace for the centre tube, at different flow velocities, was plotted as shown in Figure 4-1. Figure 4-1a and b show the tube response in the pre-stable region when the response is dominated by random motion due to turbulence excitation. Figure 4-1a and b show the tube response in the pre-stable region when the response is dominated by random motion due to turbulence excitation. Beyond the stability threshold (Figure 4-1c and d), the tube response was found to be periodic with approximately constant amplitude. Figure 4-2 shows the plot of RMS amplitude versus the reduced flow velocity for the transverse direction for the central tube with a pitch to diameter ratio of 1.25. The results showed that the RMS amplitude was very low in the range from 0 to 10 reduced flow velocity ($U_r$). Beyond a value of $U_r = 10$, the amplitude response increases rapidly with a small increment in the flow velocity and the critical flow velocity was found to be 11.5. The transverse stability map was plotted against previously collected experimental data according to the guidelines of the design suggested by Weaver and Fitzpatrick (1988). The current data of the transverse stability threshold showed a good agreement with the available data, as shown in Figure 4-3.
Figure 4-1: The centre tube response at different velocities (a) $Ur=10$ (b) $Ur=11$ (c) $Ur=12$ (d) $Ur=13.5$
Figure 4.2: The tube response of the transverse direction vs reduced flow velocity of parallel triangle array with P/D=1.25

Figure 4.3: Comparison with current experimental data for parallel triangular arrays (transverse direction)
4.2.2 Pitch to diameter ratio of 1.25

The RMS amplitude vs the reduced flow velocity for the streamwise direction for the central tube with a pitch to diameter ratio of 1.25 is plotted in Figure 4-4. The results showed that the RMS amplitude was very low in the range from 0 to 15 reduced flow velocity ($U_r$) and increased rapidly beyond reduced flow velocity value of ($U_r = 15$). In this case, the critical flow velocity was found to be 18.5. After this reduced flow velocity, the amplitudes of the tubes became very large; therefore, tests were immediately stopped to avoid tube damage.

![Figure 4-4: The tube response of the streamwise direction vs reduced flow velocity of parallel triangle array with P/D=1.25](image)
Figure 4-5 and Figure 4-6 show the time trace for each of the flexible tubes before being unstable and at instability, respectively. The motion of Tube one was plotted against each tube in the kernel to illustrate the phase. As shown in Figure 4-5, the response of the tube in the pre-instability did not show a fixed phase lag relationship among the tubes. In addition, it was noted that the amplitude response for each tube was not constant. The response of the tube kernel in the post-stability region is shown in Figure 4-6. The response of each tube was constant, but the tubes were not vibrating with the same amplitude. Figure 4-6a shows the response of Tube 1 and 2. The amplitude of Tube 1 is larger than that of Tube 2. The amplitude of Tube 1 was found to be the largest in the kernel. The amplitude of Tubes 3 and 4 were similar but lower than the amplitude of Tube 1 by 60%. Tubes 5 and 6 were vibrating with approximately the same amplitude but lower than the amplitude of Tube 1 by 40%, as seen in Fig4-6d and e. In Figure 4-6f, the amplitude of Tube 7 was approximately the same as Tube 6 in Fig 4-6e. Figure 4-7 summarizes the phase angle obtained for each tube at the condition of instability. It was noted that under the instability condition Tubes 1 and 2 were in phase and approximately 180° out of phase with Tubes 7 and 6. Similarly, Tubes 3, 4 and 5 were out of phase of 251°, 272° and 97°, respectively with Tube 1. On the other hand, before the instability, all the tubes do not show a fixed phase lag relationship. It was noticed that the phase angle between Tubes 6 and 7, and Tubes 4 and 3 is approximately 30°. Which indicated a specific pattern of movement for two adjacent tubes of the same column. The matrix below illustrates the phase angles for all the flexible tubes.
\[
[\phi] = \begin{bmatrix}
0^\circ & 6^\circ & 109^\circ & 88^\circ & -97^\circ & 155^\circ & -169^\circ \\
-6^\circ & 0^\circ & 103^\circ & 82^\circ & -103^\circ & 149^\circ & -175^\circ \\
-109^\circ & -103^\circ & 0^\circ & -21^\circ & -154^\circ & 46^\circ & -82^\circ \\
-88^\circ & -82^\circ & 21^\circ & 0^\circ & -185^\circ & 67^\circ & -103^\circ \\
97^\circ & 103^\circ & 154^\circ & 185^\circ & 0^\circ & 108^\circ & -72^\circ \\
-155^\circ & -149^\circ & -46^\circ & -67^\circ & -108^\circ & 0^\circ & -36^\circ \\
169^\circ & 175^\circ & 82^\circ & 3^\circ & 72^\circ & 36^\circ & 0^\circ 
\end{bmatrix}
\]

[\Phi] is the phase matrix which represents the inter-tube modal pattern. The phase matrix [\phi] is a 7 x 7 matrix where each individual element \(\phi_{ij}\) represents the phase difference between Tube i and j.
Figure 4-5: Comparison of displacement vs time trace for P/D = 1.25  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 before instability
Figure 4-6: Comparison of displacement vs time trace for P/D= 1.25  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 at the instability
Figure 4-7: Tube phase vectors for $P/D = 1.25$ at the instability
4.2.3 Pitch to Diameter ratio of 1.4

The variation of the RMS amplitude with respect to flow velocity for the streamwise direction for the central tube with a pitch to diameter ratio of 1.4 was plotted, as shown in Figure 4-8. The RMS amplitude was found to be small until the reduced flow velocity reached a value of $U_r = 17$. After the value of $U_r = 17$ the amplitudes response increases rapidly with the flow velocity, as illustrated in Figure 4-8 the critical flow velocity was found to be 19.5. Beyond the value of 19.5, the RMS amplitudes of the tubes became very large.

*Figure 4-8: The tube response of the streamwise direction vs reduced flow velocity of parallel triangle array with P/D=1.4*
Before and at the point of instability, the time trace for each tube was plotted, as shown in Figure 4-9 and Figure 4-10, respectively, respectively, by taking the motion of Tube one as a reference. As shown in Figure 4-9, before reaching the critical flow velocity, most of the tubes did not show a fixed phase lag relationship between the tubes and the amplitude of each tube was not constant. At the point of instability, as shown in Figure 4-10 the response of each tube was constant, but the tubes were not vibrating with the same amplitude. Fig4-11a and c show the amplitude of Tube 1 was approximately the same as Tube 2 and 4. Tube 3 was vibrating with an amplitude bigger than Tube one by 36 %, as seen in Fig4-11b. In the kernel, Tube 3 was found to has the largest amplitude. Tube 5 and Tube 7 were vibrating with the same amplitude but different than Tube 1 by 50 %. Tube 6 was vibrating with an amplitude smaller than Tube 1 by 75 %. Figure 4-11 summarizes the phase angle obtained for each tube at instability. It was observed that at instability, Tubes 4 and 6 are in phase and out of phase approximately 180° with Tubes 1 and 2. Similarly, Tubes 3, 5 and 7 are out of phase with 130°, 79° and 261° of Tube 1, respectively. Examining the phase angle between Tubes 6, 7 and Tubes 3, 4 reveals that the phase between Tubes 6 and 7 is approximately 65° and the phase between Tubes 3 and 4 is also approximately 65°. The matrices below illustrate the phase angles for all the flexible tubes between each other.
\[
\phi = \begin{bmatrix}
0^\circ & 27^\circ & -130^\circ & 174^\circ & -79^\circ & 169^\circ & 99^\circ \\
-27^\circ & 0^\circ & -157^\circ & 147^\circ & -106^\circ & 142^\circ & 72^\circ \\
-130^\circ & 157^\circ & 0^\circ & 304^\circ & 51^\circ & 61^\circ & 131^\circ \\
-174^\circ & -147^\circ & -56^\circ & 0^\circ & 107^\circ & -4^\circ & -75^\circ \\
79^\circ & 106^\circ & -51^\circ & 107^\circ & 0^\circ & 248^\circ & 178^\circ \\
-169^\circ & -142^\circ & 61^\circ & 5^\circ & 112^\circ & 0^\circ & -70^\circ \\
99^\circ & -72^\circ & 131^\circ & 75^\circ & -178^\circ & 70^\circ & 0^\circ
\end{bmatrix}
\]
Figure 4-9: Comparison of Displacement vs time trace for P/D=1.4  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-10: Comparison of displacement vs time trace for P/D = 1.4  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4.11: Tube phase vectors for P/D = 1.4 at the instability
4.2.4 Pitch to Diameter ratio of 1.55

Figure 4-12 shows the RMS response of the central tube in the kernel of a pitch to diameter ratio of 1.55. As shown in the Figure, the RMS amplitude was very low in the range of reduced flow velocity ($U_r$) from 0 to 25. The response of the amplitude beyond $U_r = 25$, increased rapidly with the flow velocity. It appeared that the phenomenon of fluidelastic instability occurred when $U_r = 28.5$ and the amplitude of the tubes vibration became very large after this velocity.

*Figure 4-12: The tube response of the streamwise direction vs reduced flow velocity of parallel triangle array with P/D=1.55*

Figure 4-13 and Figure 4-14 depicts the time trace for each tube at the h pre-instability regime and at instability regime, respectively. The motion of Tube 1 was plotted with
each tube to clarify the phase change. Figure 4-13 shows, shows that, most of the tubes have a fixed phase shift since the data were taken at pre-instability regime. The response of each tube was constant, and the tubes were not vibrating with the same amplitude, as illustrated in Figure 4-14. It was observed that Tube 1 at pre-instability and instability regimes has the largest amplitude. Both Figures 4-13 and 4-14 shows the behaviour of the tubes are the same in the instability and pre-instability regimes but with differences in the amplitude response. The phase angle obtained for each tube at the pre-instability and instability regimes was summarized in Figure 4-15 and Figure 4-16, respectively. It was noted that Tubes 6 and 2 are in phase and 180° out of phase approximately with Tubes 3 and 4. Similarly, Tubes 5 and 7 are 119° and 280° out of phase with Tube 1, respectively. At the pre-instability, the phase lag for most of the tubes was approximately the same as at instability. The phase angle between Tubes 6 and 7 and Tubes 4 and 3 is equal to approximately 30°. The matrix below illustrates the phase angles for all the flexible tubes between each other.
$$\Phi = \begin{bmatrix}
0^\circ & 60^\circ & -133^\circ & 156^\circ & -119^\circ & 23^\circ & 80^\circ \\
-60^\circ & 0^\circ & 193^\circ & 98^\circ & -179^\circ & -37^\circ & 20^\circ \\
133^\circ & -193^\circ & 0^\circ & 71^\circ & 14^\circ & 156^\circ & 147^\circ \\
-156^\circ & -96^\circ & 71^\circ & 0^\circ & -275^\circ & -133^\circ & -76^\circ \\
119^\circ & 179^\circ & -14^\circ & 85^\circ & 0^\circ & 142^\circ & 199^\circ \\
-23^\circ & 37^\circ & -156^\circ & -133^\circ & -142^\circ & 0^\circ & 57^\circ \\
-80^\circ & -20^\circ & 147^\circ & 76^\circ & -119^\circ & -57^\circ & 0^\circ
\end{bmatrix}$$
Figure 4-13: Comparison displacement vs time trace for P/D=1.55  a) Tube 1&2  b) Tube 1&3  c) Tube 1&4  d) Tube 1&5  e) Tube 1&6  f) Tube 1&7 at pre-instability
Figure 4.14: Comparison of displacement vs time trace for P/D = 1.55  
(a) Tube 1&2  b) Tube 1&3  c) Tube 1&4  d) Tube 1&5  e) Tube 1&6  f) Tube 1&7 at the instability
Figure 4-15: Tube phase vectors for P/D =1.55 at pre-instability

Figure 4-16: Tube phase vectors for P/D =1.55 at the instability
4.2.5 Pitch to Diameter ratio of 1.7

Figure 4-17 shows the data of the central tube RMS response for the cases of kernel flexible in the streamwise direction for 1.55 pitch to diameter ratio. The results showed the RMS response is very low until reduced flow velocity reached a value of $U_r = 27$. Subsequently, the amplitude response increased rapidly with the flow velocity. The critical flow velocity, $U_r$, in the streamwise direction was around 31. The amplitude of the tubes vibration became very large after reaching the critical flow velocity.

![Figure 4-17: The tube response of the streamwise direction vs reduced flow velocity of parallel triangle array with P/D=1.7](image-url)
Figure 4-18 and Figure 4-19 show the response of each flexible tubes before reaching the instability zone and at instability, respectively. Figure 4-18 shows that, before instability, most of the tubes do not show a fixed phase lag. In Figure 4-19 the response of each tube was constant at the instability and the tubes were not vibrating with the same amplitude. Fig4-21a, e and f show the amplitude of Tube 1 was approximately the same as Tubes 2, 6 and 7. The amplitude response of Tube 3 was lower than the amplitude of Tube 1 by 40%, and the amplitude of Tube 1 was bigger than the amplitude of Tube 5 by 50 %, as shown in Fig4-21 b and d. Figure 4-20 shows synopsis of the phase angle obtained for each tube at instability. Before the instability, as mentioned earlier, the tubes did not show a fixed phase lag. It was noted that at the instability Tubes 7 and 5 are in phase and 180° approximately out of phase with Tubes 3 and 4. Similarly, Tubes 2 and 6 are 326° and 109° out of phase with of Tube 1 respectively. Also, by looking at the phase angle between Tubes 6, 7 and Tubes 3, 4. Tube 7 lag Tube 6 by a phase angle of approximately 40° and the lag between Tube 3 and 4 was also approximately at 40°. This indicates that there is a specific pattern of movement for two adjacent tubes of the same column. The matrix below illustrates the phase angles for all the flexible tubes.
\[
\phi = \begin{bmatrix}
0^\circ & 34^\circ & 151^\circ & 118^\circ & -45^\circ & -100^\circ & -58^\circ \\
-34^\circ & 0^\circ & 117^\circ & 84^\circ & -79^\circ & -134^\circ & -92^\circ \\
-151^\circ & -117^\circ & 0^\circ & -33^\circ & -196^\circ & 109^\circ & 151^\circ \\
-118^\circ & -84^\circ & 33^\circ & 0^\circ & -163^\circ & 142^\circ & -176^\circ \\
45^\circ & 79^\circ & 164^\circ & 163^\circ & 0^\circ & -55^\circ & -13^\circ \\
100^\circ & 134^\circ & 109^\circ & 142^\circ & 55^\circ & 0^\circ & 42^\circ \\
58^\circ & 92^\circ & 151^\circ & 176^\circ & 13^\circ & -42^\circ & 0^\circ 
\end{bmatrix}
\]
Figure 4-18: Comparison of displacement vs time trace for P/D=1.7  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 before instability
Figure 4-19: Comparison of displacement vs time trace for P/D = 1.7  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 at the instability
Figure 4-20: Tube phase vectors for $P/D = 1.7$ at the instability
4.2.6 Discussion

For parallel triangle array, the critical flow velocities were found to be 18.5, 19.5, 20 and 31 for a pitch to diameter ratio 1.25, 1.4, 1.55 and 1.7, respectively. It was noted that decreasing the pitch to diameter ratio of the array resulted in decreasing the stability threshold. This trend agrees with the results of experimental and theoretical studies reported earlier in the open literature. The amplitude response of the tubes before instability was not constant and changed with time. At instability, each tube was vibrating with a different constant amplitude, and the same phase lag. At 1.55 pitch to diameter ratio, a comparison was made between the tubes at pre-instability and instability. It was noted that the behaviour of the tubes at pre-instability was almost the same that at instability. There is a specific pattern of movement for two adjacent tubes of the same column.
4.3 Normal Triangle Array

4.3.1 Pitch to Diameter ratio of 1.25

The vibration response for the streamwise direction for the central tube with a pitch to diameter ratio of 1.25 was plotted, as shown in Figure 4-21. The graph shows a low gradual increase for the velocity range of reduced flow velocity ($U_r$) from 0 to 35. The RMS amplitude started to increase substantially after a value of flow velocity $U_r = 35$. The critical flow velocity was found to be 40. After this reduced flow velocity, the amplitudes of the tubes became very large.

![Figure 4-21: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.25](image)
Figure 4-22 and Figure 4-23, show the response with respect to time for each of the flexible tubes during pre-instability and at instability regimes, respectively. It must be stated here that as per previous cases Tube 1 was taken as a reference. As shown in Figure 4-22, most of the tubes showed a fixed phase lag with a very low amplitude of vibration. During pre-instability, the tubes showed a steady amplitude that differs from one tube to another. In Figure 4-23, the response of each tube was constant with a different vibration. Both Figures 4-25 and 4-26 show that the behaviour of the tubes are the same in the instability and pre instability regimes but with differences in amplitude response. Figure 4-24 and Figure 4-25 show a description of the phase angle variation obtained for each tube at pre-instability and at instability, respectively. It was noted that at instability, Tubes 3 and 5 are in phase and approximately 180° out of phase with respect to Tubes 7 and 2. Similarly, Tubes 6 and 4 are 55° and 242° out of phase, respectively. At instability, the upstream Tubes 7 and 2 had a lag with the adjacent down stream tubes 6 and 3 in a different row by approximately 110°. This indicated that there is a specific pattern for the movement of the flexible tube. The matrix below has seven rows and seven columns, which depicts the phase angles of all the seven flexible tubes with respect to each other.
\[ \phi = \begin{bmatrix}
0^\circ & -146^\circ & -21^\circ & 118^\circ & -19^\circ & -55^\circ & -165^\circ \\
146^\circ & 0^\circ & 125^\circ & 96^\circ & 127^\circ & 91^\circ & -19^\circ \\
21^\circ & -125^\circ & 0^\circ & 139^\circ & 12^\circ & -34^\circ & -144^\circ \\
-118^\circ & 96^\circ & -139^\circ & 0^\circ & -137^\circ & -173^\circ & 77^\circ \\
19^\circ & -127^\circ & -2^\circ & 137^\circ & 0^\circ & -36^\circ & -146^\circ \\
55^\circ & -91^\circ & 34^\circ & 173^\circ & 36^\circ & 0^\circ & -110^\circ \\
165^\circ & 19^\circ & 144^\circ & 77^\circ & 146^\circ & 110^\circ & 0^\circ 
\end{bmatrix} \]
Figure 4.22: Comparison of displacement vs time trace for P/D=1.25  
(a) Tube 1&2  
(b) Tube 1&3  
(c) Tube 1&4  
(d) Tube 1&5  
(e) Tube 1&6  
(f) Tube 1&7 pre-instability
Figure 4-23: Comparison of displacement vs time trace for $P/D = 1.25$  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 at instability
Figure 4-24: Tube phase vectors for $P/D = 1.25$ pre-instability

Figure 4-25: Tube phase vectors for $P/D = 1.25$ at the instability
4.3.2 Pitch to Diameter ratio of 1.4

The RMS amplitude vs the reduced flow velocity for the streamwise direction of the central tube with a pitch to diameter ratio of 1.4 was plotted, as shown in Figure 4-26. The results showed that the RMS amplitude was very low in the range of reduced flow velocity \( U_r \) from 0 to 50. Beyond \( U_r = 50 \), the amplitude response increases rapidly with increasing the flow velocity. The critical flow velocity was found to be 71.

![Figure 4-26: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.4](image)
The amplitude versus time was plotted for each tube with respect to the reference tube (Tube 1), as shown in Figure 4-27 and Figure 4-28 before being unstable and at instability, respectively. Figure 4-27 depicts the motion of the tubes before instability. A variable phase lag was observed, and the amplitude response was not constant and kept changing with time. Figure 4-28 shows that some of the tubes vibrated with constant amplitude and the others vibrated with change in the amplitude. As shown in Figure 4-28 a, b, and c, the amplitude response change with time. By contrast, Fig4-28 d, e and f vibrate with constant amplitude and fixed phase lag. The phase angle was plotted for each tube at instability as shown in Figure 4-29. Tubes 2 and 3 were found to be in phase and approximately 180° out of phase with Tube 7. Similarly, Tubes 3, 5 and 4 were 180° out of phase with respect to Tube 7. On the other hand, Tube 1 and Tube 7 were approximately 180° out of phase with each other and Tube 1 and 5 were at the same phase. It was noticed that the relative movement of Tubes 2, 3, 4, and 5 have a well-pattern, and the phase angle of the two adjacent tubes in the same or different row was approximately about 20°. Tubes 7 and 6 did not have the same pattern as the other tubes. The phase angle of all the tubes with respect to each others is illustrated in the matrix below.
\[ \phi = \begin{bmatrix}
0^\circ & 62^\circ & 24^\circ & -22^\circ & -9^\circ & 87^\circ & -175^\circ \\
-62^\circ & 0^\circ & -38^\circ & -84^\circ & -71^\circ & 25^\circ & -123^\circ \\
-24^\circ & 38^\circ & 0^\circ & -46^\circ & -33^\circ & 63^\circ & -161^\circ \\
22^\circ & -84^\circ & 46^\circ & 0^\circ & -13^\circ & 109^\circ & 153^\circ \\
9^\circ & 71^\circ & 33^\circ & -13^\circ & 0^\circ & 96^\circ & -166^\circ \\
-87^\circ & -25^\circ & -63^\circ & -109^\circ & -96^\circ & 0^\circ & -98^\circ \\
175^\circ & 123^\circ & 161^\circ & 153^\circ & 166^\circ & 98^\circ & 0^\circ 
\end{bmatrix} \]
Figure 4.27: Comparison of displacement vs time trace for $P/D = 1.4$ a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-28: Comparison of displacement vs time trace for P/D = 1.4  a) Tube 1&2  b) Tube 1&3  c) Tube 1&4  d) Tube 1&5  e) Tube 1&6  f) Tube 1&7
Figure 4-29: Tube phase vectors for P/D = 1.4 at instability
4.3.3 Pitch to Diameter ratio of 1.55

In this case the same procedure that was followed earlier was followed. The vibration response for the central tube for kernel array with a pitch to diameter ratio of 1.55 was plotted as shown in Figure 4-30. The results show the amplitude response of the tube was very low until a reduced flow velocity ($U_r$) of 35. Beyond this value ($U_r = 35$), the amplitudes response was increasing rapidly as the flow velocity increased. The critical flow velocity was found to be 58. After this critical reduced flow velocity, the vibration amplitude of the tubes became very large.

![Graph showing vibration response](image)

*Figure 4-30: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.55*
Figure 4-31 and Figure 4-32, illustrate the time trace for each tube before being unstable and at the instability in kernel array, respectively. As shown in Figure 4-31 before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and kept changing with time. At instability, Tubes 1, 3 and 7 did not vibrate with a constant amplitude, but Tubes 2, 6 and 5 were vibrating with a constant amplitude, as seen in Figure 4-32. The tube at the instability always shows a fixed phase lag. The amplitude of Tube 5 was found to be the largest in the kernel. Also, Tubes 1 and 2 were vibrating with a low amplitude at instability.

Figure 4-33 shows the summary of the phase angle obtained for each tube at instability. It was noted that at instability, Tubes 2, 6 and 7 were in phase and approximately 180° out of phase with respect to Tubes 5 and 3. Similarly, Tubes 4 was 204° out of phase with respect to Tube 1. Also, in this case, the relative movement of Tubes 7, 2 and 6 had a specific pattern, and the lag between them was approximately 20 deg. In contrast, Tubes 5, 4 and 3, had different patterns. The matrix below illustrates the phase angles for all the flexible tubes with respect to each other.

\[
\phi = \begin{bmatrix}
0 & 61 & -133 & 156 & -119 & 23 & 80 \\
-6 & 0 & -194 & 95 & -180 & -38 & 19 \\
-109 & -166 & 0 & 71 & 14 & 156 & 147 \\
-88 & -95 & -71 & 0 & -85 & -133 & -76 \\
97 & 180 & -14 & 85 & 0 & 142 & 161 \\
-155 & 38 & -156 & 133 & -142 & 0 & 57 \\
169 & -19 & -147 & 76 & 161 & -57 & 0
\end{bmatrix}
\]
Figure 4-31: Comparison of displacement vs time trace for P/D=1.55  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-32: Comparison of displacement vs time trace for P/D = 1.55  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-33: Tube phase vectors for P/D = 1.55 at the instability
4.3.4 Pitch to Diameter ratio of 1.7

The variation of the RMS amplitude with respect to flow velocity for the streamwise direction for the central tube with a pitch to diameter ratio of 1.7 was plotted, as shown in Figure 4-34. In the range from 0 to 35 of the reduced flow velocity ($U_r$) the response was very low. The amplitudes response increased rapidly with the flow velocity after reach a reduced flow velocity of $U_r = 35$. The result show that the critical flow velocity in the streamwise was 81. After this reduced flow velocity, the amplitudes of the tubes became very large. Consequently, tests were immediately stopped to prevent tube damage.

![Graph: NT-1.7 (Streamwise)](image)

*Figure 4-34: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.7*
The motion of Tube 1 was plotted against each tube in the kernel to illustrate the phase before and after the instability, as shown in Figure 4-35 and Figure 4-36, respectively. Figure 4-35 depicts the tubes before instability; it doesn’t show a constant phase lag. As shown, the amplitude response was not fixed and kept changing with time. At instability, Tubes 7, 6 and 5 were vibrating with high amplitude in contrast Tubes 1, 2, 3 and 4, as shown in Figure 4-36. Also, the tubes did not show constant phase lag. It was noted that Tubes 7 and 6 were going unstable first, and the experiment was stopped before the other tubes became unstable to avoid damage.

Figure 4-37 shows the summary of the phase angle obtained for each tube at instability. It was observed that at instability, Tubes 2 and 6 are in phase and out of phase of approximately 180° with Tubes 7 and 4. Also, it was noted that Tube 3 is out of phase of Tube 5. Tubes 5 and 3 are at a phase of 71° and 288°, respectively, with Tube 1. The matrix below illustrates the phase angles for all the flexible tubes with respect to each other. By looking at the figure, it is clear that the lags among two adjacent tubes in the same row or in a different row were approximately the same. The phase angle between Tubes 2, 7, 6, and 5 was approximately 100, which suggest that there is a specific pattern for the movement of the flexible tube. The matrix below has seven rows and seven columns, which depicted the phase angles of all the seven flexible tubes between each other.
\[
\phi = \begin{bmatrix}
0^\circ & 6^\circ & 72^\circ & 113^\circ & -71^\circ & 2^\circ & -117^\circ \\
-6^\circ & 0^\circ & 66^\circ & 107^\circ & -77^\circ & -4^\circ & 111^\circ \\
-72^\circ & -66^\circ & 0^\circ & 41^\circ & -143^\circ & -70^\circ & 45^\circ \\
-113^\circ & -107^\circ & 41^\circ & 0^\circ & 176^\circ & -111^\circ & 4^\circ \\
71^\circ & 77^\circ & 143^\circ & -176^\circ & 0^\circ & 73^\circ & -172^\circ \\
-2^\circ & 4^\circ & 70^\circ & 111^\circ & -73^\circ & 0^\circ & 115^\circ \\
-117^\circ & -111^\circ & -45^\circ & -4^\circ & 172^\circ & -115^\circ & 0^\circ 
\end{bmatrix}
\]
Figure 4.35: Comparison of displacement vs time trace for P/D=1.7 a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-36: Comparison of displacement vs time trace for P/D=1.7 a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-37: Tube phase vectors for P/D = 1.7 at the instability
4.3.5 Discussion

For normal triangle array, the critical flow velocities for each pitch to diameter ratio 1.25, 1.4, 1.55 and 1.7 were found to be 40, 73, 58, 81, respectively. The results followed the same trend when the pitch to diameter ratio decreases, the stability threshold decreases except for the pitch to diameter ratio of 1.4. At pitch to diameter ratio of 1.25, the result was taken at instability and pre-instability. The behaviour of the tubes is the same at instability and pre-instability, but with differences in amplitude response. At pitch to diameter ratio of 1.4, before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and was changing with time. At instability, some of the tubes vibrate with constant amplitude and the others vibrated with changing in the amplitude.

For a pitch to diameter ratio 1.55 at instability, Tubes 1, 3 and 7 did not vibrate with a constant amplitude, but Tubes 2, 6 and 5 were vibrating with a constant amplitude. The tube at the instability always shows a fixed phase lag. For a pitch to diameter ratio of 1.7, before instability, the tubes did not show a fixed phase lag and the amplitude response was not constant and was changing with time. It was noted that Tube 7 and 6 were going unstable and thus the experiment was stopped before the other tube was going unstable to avoid tube damage, and that is why the tube did not show fixed phase lag.
4.4 Rotated Square Array

4.4.1 Pitch to Diameter ratio of 1.4

In Figure 4-38 the RMS amplitude was plotted against the reduced flow velocity for the case of kernel array of a pitch to diameter ratio of 1.4. The RMS amplitude was very small until the reduced flow velocity of $U_r=30$. After this reduced flow velocity; the amplitude response increased rapidly with the flow velocity. The critical flow velocity was found to be 32. After this reduced flow velocity, the amplitudes of the tubes become very large.

![Graph showing the RMS amplitude vs reduced flow velocity for a normal triangle array with P/D=1.4](image)

*Figure 4-38: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.4*
Figure 4-39 and Figure 4-40, show the time trace for each tube of the flexible tubes before being unstable and at instability, respectively. Before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and kept changing with time, as seen in Figure 4-39. Figure 4-40 shows that Tubes 7, 2 and 3 at instability were vibrating with high amplitude by contrast Tubes 1, 4, 5 and 6. Also, Tubes 7 and 2 started to go unstable first. Before the other tubes start to become unstable, the experiment is stopped to avoid the damage.

Figure 4-41 shows the summary of the phase angle obtained for each tube at instability. It was noted that at instability, Tubes 2, 6 and 7 are in phase and out of phase of approximately 180° with Tubes 5, 6, 4 and 3. By looking at the figure, it was clear that Tubes 1, 6, 4 and 5 have approximately the same phase. That reason for this is that the upstream tubes have became unstable first, and the experiment was stopped to avoid tubes damage. The phase angle of all the tubes is shown in the following matrix.

\[
\phi = \begin{bmatrix}
0^\circ & -157^\circ & 4^\circ & 47^\circ & -14^\circ & -13^\circ & -133^\circ \\
157^\circ & 0^\circ & 161^\circ & 156^\circ & 143^\circ & 144^\circ & 29^\circ \\
-4^\circ & -161^\circ & 0^\circ & 43^\circ & -18^\circ & 17^\circ & -137^\circ \\
-47^\circ & 156^\circ & -43^\circ & 0^\circ & -61^\circ & 60^\circ & -180^\circ \\
14^\circ & -143^\circ & 18^\circ & 61^\circ & 0^\circ & 1^\circ & -119^\circ \\
13^\circ & -144^\circ & 17^\circ & 60^\circ & -1^\circ & 0^\circ & -120^\circ \\
133^\circ & -24^\circ & 137^\circ & 180^\circ & 119^\circ & 120^\circ & 0^\circ 
\end{bmatrix}
\]
Figure 4-39: Comparison of displacement vs time trace for P/D=1.4 a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-40: Comparison of displacement vs time trace for P/D = 1.4  a) Tube 1 & 2  b) Tube 1 & 3  c) Tube 1 & 4  d) Tube 1 & 5  e) Tube 1 & 6  f) Tube 1 & 7
Figure 4-41: Tube phase vectors for $P/D = 1.4$ at the instability
4.4.2 Pitch to Diameter ratio of 1.55

The RMS amplitude with respect to the reduced flow velocity for the streamwise direction for the central tube with a pitch to diameter ratio of 1.55 was plotted, as shown in Figure 4-42. The results show that the RMS amplitude was very low in the range of reduced flow velocity ($U_r$) from 0 to 70. Beyond $U_r = 70$, the amplitude response increased rapidly with the flow velocity. The critical reduced flow velocity was found to be 80. After this reduced flow velocity, the amplitudes of the tubes became very large; therefore, experiments were immediately stopped to avoid tubes damage.

![Figure 4-42: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.55](image)
Figure 4-43 and Figure 4-44 show the time trace for each of the flexible tubes before being unstable and at critical flow velocity, respectively, by taking the motion of tube one as a reference. As shown in Figure 4-43 before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and kept changing with time. At instability, the tube showed fixed phase lag, but it is not vibrating with a constant amplitude as seen in Figure 4-44. The amplitude of Tube 7 was found to be the largest in the kernel.

Figure 4-45 shows the summary of the phase angles obtained for each tube at instability. It was noted that at instability, Tubes 6 and 4 are in phase and both are approximately 180° out of phase with Tube 3. Similarly, Tube 2 is 230° out of phase with Tube 1. Also, Tubes 7, 6, and 1 are have the same phase. The phase lag between the adjacent downstream tubes of different columns was approximately the same. In contrast, the upstream tubes did not show the same phase angle, indicating that in this case the tubes do not have a specific pattern. The phase angle of all the tubes, with respect to each other, is illustrated in the following matrix.
\[
\phi = \begin{bmatrix}
0^\circ & 130^\circ & -140^\circ & 57^\circ & 77^\circ & 35^\circ & -13^\circ \\
-130^\circ & 0^\circ & -270^\circ & -73^\circ & -53^\circ & -95^\circ & 143^\circ \\
140^\circ & 270^\circ & 0^\circ & 163^\circ & -143^\circ & 175^\circ & 153^\circ \\
-57^\circ & -73^\circ & 163^\circ & 0^\circ & -20^\circ & -22^\circ & -70^\circ \\
-77^\circ & 53^\circ & 143^\circ & -20^\circ & 0^\circ & -42^\circ & -90^\circ \\
-35^\circ & -95^\circ & -175^\circ & 22^\circ & 42^\circ & 0^\circ & -48^\circ \\
13^\circ & 143^\circ & -127^\circ & 70^\circ & 90^\circ & 48^\circ & 0^\circ 
\end{bmatrix}
\]
Figure 4-43: Comparison of displacement vs time trace for $P/D=1.55$  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-44: Comparison of displacement vs time trace for P/D = 1.55  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7 at the instability
Figure 4.45: Tube phase vectors for $P/D = 1.55$ at the instability
4.4.3 Pitch to Diameter ratio of 1.7

In this section, the same procedure as the previous sections was followed. The vibration response for the central tube of the kernel array with a pitch to diameter ratio of 1.7 was plotted, as shown in Figure 4-46. The graph shows a low gradual increase in the velocity range from 0 to 40 of the reduced flow velocity ($U_r$). The RMS amplitude started to increase noticeably after the $U_r = 40$. The critical flow velocity was found to be 62. After this reduced flow velocity, the vibration amplitude of the tubes became very large. At this point, the shutdown of the experiments was necessary to avoid tube damage.

![Graph showing tube response vs reduced flow velocity](image)

*Figure 4-46: The tube response of the streamwise direction vs reduced flow velocity of normal triangle array with P/D=1.7*
Figure 4-47 and Figure 4-48 show the time trace for each tube of the flexible tubes before being unstable and at instability, respectively, by taking the motion of Tube 1 as a reference. As shown in Figure 4-47 before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and kept changing with time. Figure 4-47 and Figure 4-48 show that the amplitude response for each individual tube was constant, and the tubes had a fixed phase lag. Figure 4-49 shows the summary of the phase angle obtained for each tube at instability. It was noted that at instability, Tubes 6 and 4 are in phase and out of phase approximately 180° with Tubes 7 and 3. Similarly, tube 5 is out of phase of 271° with respect to Tube 1. Again the tubes before instability did not show a fixed phase lag. This case showed the same behaviour as the case of 1.55 Pitch to diameter ratio. This means tubes of different columns approximately have the same phase lag. In contrast, the upstream tubes did not show the same phase angle, demonstrating that, in this case, the tubes do not have a specific pattern. The phase angle for all the tubes is illustrated, matrix below.

\[ \phi = \begin{bmatrix} 0^\circ & 64^\circ & -165^\circ & 57^\circ & 89^\circ & 42^\circ & -149^\circ \\ -64^\circ & 0^\circ & 131^\circ & -7^\circ & 25^\circ & 22^\circ & 147^\circ \\ 165^\circ & -131^\circ & 0^\circ & 138^\circ & 106^\circ & 153^\circ & 16^\circ \\ -57^\circ & 7^\circ & -138^\circ & 0^\circ & 32^\circ & 15^\circ & -154^\circ \\ -89^\circ & -25^\circ & -106^\circ & -32^\circ & 0^\circ & -47^\circ & -122^\circ \\ -42^\circ & 22^\circ & -153^\circ & 15^\circ & 47^\circ & 0^\circ & -169^\circ \\ 149^\circ & -147^\circ & -16^\circ & 154^\circ & 122^\circ & 169^\circ & 0^\circ \end{bmatrix} \]
4.4.4 Discussion

For rotated square array, the critical flow velocities for each of pitch to diameter ratios 1.4, 1.55 and 1.7 were found to be 32, 80, 62, respectively. Also, the results follow the same trend when the pitch to diameter ratio decreases where the stability threshold decreases except for the pitch to diameter ratio of 1.55. For a pitch to diameter ratio 1.4, 1.55 and 1.7 before instability, the tubes did not show a fixed phase lag, and the amplitude response was not constant and kept changing with time. At pitch to diameter ratio of 1.4 Tubes 7 and 2 started to become unstable first, and before the other tubes started to become unstable, the experiment was stopped to avoid the damage. For a pitch to diameter ratio of 1.4, 1.55 and 1.7 at instability, the tubes showed fixed phase lag but they were vibrating with constant amplitude. The method of getting the phase lag between the tube motion may also be used to predict the instability threshold of the fluidelastic instability.
Figure 4-47: Comparison of displacement vs time trace for P/D = 1.7  a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-48: Comparison of displacement vs time trace for P/D = 1.7 a) Tube 1&2 b) Tube 1&3 c) Tube 1&4 d) Tube 1&5 e) Tube 1&6 f) Tube 1&7
Figure 4-49: Tube phase vectors for P/D = 1.7 at instability
5 Conclusions

The current work reports a methodical investigation to uncover the fundamental aspects of the fluidelastic instability phenomenon in the streamwise direction. An experimental study was conducted using a closed-loop wind tunnel on a parallel triangle, normal triangle and rotated square arrays with a pitch to diameter ratio 1.25, 1.4, 1.55 and 1.7. In addition, a set of experiments using a visual image processing system were conducted to study the phase lag between the motion of the tubes and the phenomenon of fluidelastic instability.

- All the flexible tubes were tuned to have the same natural frequency of 9.14 Hz with ± 0.05 Hz, and the damping ratio was 0.001 with ± 0.0001
- Initial experiment was done for fluid elastic instability in the transverse direction and the results showed a good agreement with the data available in the open literature.
- Parallel triangle array tests revealed critical flow velocities of 18.5, 19.5, 20 and 31 for a pitch to diameter ratio 1.25, 1.4, 1.55 and 1.7, respectively. Decreasing the pitch to diameter ratio of the array resulted in decreasing the stability threshold. This reveals the effect of the pitch to diameter ratio on the stability threshold.
- Normal triangle array tests for pitch to diameter ratio of 1.25, 1.4, 1.55 and 1.7 revealed critical flow velocities of 40, 73, 58, 81, respectively. The results showed the same trend obtained in case of parallel triangle array such that when the pitch to diameter ratio decreases the stability threshold decreases except for the pitch to diameter ratio of 1.4.

- For rotated square array, the critical flow velocities for each of pitch to diameter ratio of 1.4, 1.55 and 1.7 were found to be 32, 80, 62, respectively. Also, the results followed the same trend such that when the pitch to diameter ratio decreases the stability threshold decrease except for the pitch to diameter ratio of 1.55.

A visual image processing system was used to get the phase lag between the adjacent tubes. The method used to collect the data is a non-contact measurement method. This method has many advantages such as easy installation and can be used to testing a number of tubes simultaneously. The results showed that for all the arrays and pitch to diameter ratios studied in this investigation when the tubes were vibrating at the critical flow velocity, a number of tubes are out of phase with approximately 180° with respect to each other. In contrast, the tubes before instability did not show a fixed phase lag relationship. This method may also be used to predict the instability threshold of fluidelastic instability.
6 References


[28] V. Janzen, E. Hagberg, M. Pettigrew, and C. Taylor, “Fluidelastic instability and


