Further Study of Quasi-Periodic Vibration Excitation Forces in Rotated Triangular Tube Bundles Subjected to Two-Phase Cross Flow

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ABSTRACT

Two-phase cross flow exists in many shell-and-tube heat exchangers. Flow-induced vibration excitation forces can cause tube motion that will result in long-term fretting-wear or fatigue. Detailed vibration excitation force measurements in tube bundles subjected to two-phase cross flow are required to understand the underlying vibration excitation mechanisms. Some of this work has already been done. Somewhat unexpected but significant quasi-periodic forces in both the drag and lift directions were measured. These forces are generally larger in the drag direction. However, the excitation force frequency is relatively low (i.e., 3-6 Hz) and not directly dependent on flow velocity in the drag direction. On the other hand much higher frequencies (up to 16 Hz) were observed in the lift direction at the higher flow velocities. The frequency appears directly related to flow velocity in the lift direction.

The present work aims at 1) providing further evidence of the quasi-periodic lift force mechanism, 2) determining the effect of cylinder position on such quasi-periodic drag and lift forces, 3) verifying the existence of quasi-periodic drag and lift forces in a more realistic larger tube array. The program was carried out with two rotated-triangular tube arrays of different width subjected to air/water flow to simulate two-phase mixtures from liquid to 95% void fraction. Both the dynamic lift and drag forces were measured with strain gage instrumented cylinders.

1. INTRODUCTION

Two-phase cross flow exists in many shell-and-tube heat exchangers, for instance, in the U-tube region of nuclear steam generators. Flow-induced vibration excitation forces can cause tube motion that will result in long-term fretting-wear or fatigue. To prevent these tube failures in heat exchangers, designers and troubleshooters must have guidelines that incorporate flow-induced vibration excitation forces.

In single-phase flow, these forces have been extensively measured and analyzed. They are related to periodic wake shedding and to the turbulence level created by the tube bundle itself. Experimental data obtained for different kinds of fluids and tube bundles have been satisfactorily compared through the use of adequate data-reduction procedures as in (Axisa et al., 1990; Blevins, 1991).

In the case of two-phase flows, such an extensive study has not been undertaken, though it is known that there are significant differences between single- and two-phase situations. In particular, the relationship between the two phases must be considered in addition to another parameter that is void fraction. This results in different flow regime or patterns of two-phase flow. A few sets of experimental results have been obtained recently, as in (Pettigrew and Taylor, 1994; Nakamura et al., 1995). However the understanding of the physical mechanism that induces these forces is not yet reached as in (De Langre and Villard, 1998). Detailed flow and vibration excitation force measurements in tube bundles subjected to two-phase cross flow are required to understand the underlying vibration excitation mechanisms. Some of this work has already been done by Pettigrew et al. (2005) and Zhang et al. (2007a; 2007b; 2008). The distributions of both void fraction and bubble velocity in rotated-triangular tube bundles were measured and somewhat unexpected but significant quasi-periodic forces in both the drag and lift directions were observed by Pettigrew et al. (2005). These quasi-periodic forces appeared well correlated along the cylinder with the drag force being somewhat better correlated than the lift forces. These quasi-periodic forces are also dependent on the position of the cylinder within the bundle as in (Zhang et al., 2007a). The results of two-phase flow dynamic characteristics and force measurements indicate that quasi-periodic drag and lift forces may be generated by different mechanisms that have not been observed before. The quasi-periodic drag forces appear related to the momentum flux fluctuations in the main flow path between the cylinders. These momentum flux fluctuations are caused by the void fraction fluctuations in the main flow path between the cylinders. The quasi-periodic lift forces, on the other hand, are mostly correlated to oscillation in the wake of the cylinders. The quasi-periodic lift forces are related to local void fraction measurements in the unsteady wake area between upstream and downstream cylinders. The quasi-periodic drag forces correlate well with similar measurements in the main flow stream between cylinders as in (Zhang et al., 2008). The relationships between the lift or drag forces and the dynamic characteristics of two-phase flow are established through fluid mechanics momentum equations. A model was developed to correlate the void fraction fluctuation in the main flow path and the dynamic drag forces. A second model was developed for correlating the oscillation in the wake of the cylinders and the dynamic lift forces. Although still preliminary, each model can predict the corresponding forces relatively well as in (Zhang et al., 2007b).

The present work aims at 1) providing further evidence of the quasi-periodic lift force mechanism, 2) determining the effect of cylinder position on such quasi-periodic drag and lift forces, 3) verifying the existence of quasi-periodic drag and lift forces in a more realistic larger tube array. An experimental program was carried out with two rotated-triangular tube arrays of different width subjected to air/water flow to simulate two-phase mixtures from liquid to 95% void fraction. Both the dynamic lift and drag forces were measured with strain gage instrumented cylinders.

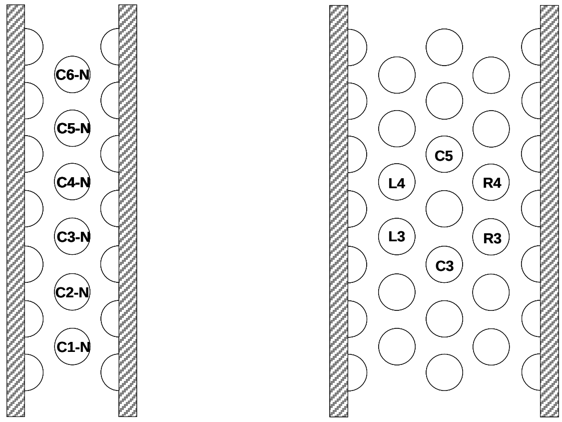
The investigation provided further evidence that the quasi-periodic lift forces are really due to oscillations of the wake between upstream and downstream cylinders. It showed that the quasi-periodic drag and lift forces should not increase with the cylinder position within a rotated triangular tube array. It also showed that quasi-periodic drag and lift forces essentially similar to those observed in the narrow test section also exist in the wider test section.

2. EXPERIMENTAL CONSIDERATIONS

2.1 Test Sections

The experiments were done in an air-water loop to simulate two-phase flows. The loop was described in details by Pettigrew et al. (2005). Compressed air was injected below a suitably designed mixer to homogenize and distribute the two-phase mixture uniformly below the test-section. The air flow was measured with orifice plates connected to a differential pressure transducer and electronic readout system. The loop was operated at room temperature and the pressure in the test section was slightly above atmospheric.

The narrow test section, which has an essentially rectangular cross section (99×191mm), is shown in Fig. 1(a). It consists of a column of six 38 mm diameter cylinders flanked on either side by half cylinders to simulate essentially the flow path in a large array of cylinders in a rotated triangular configuration. The pitch-to-diameter ratio, P/D, was 1.5 resulting in an inter-cylinder gap of 19 mm which allowed sufficient space for detailed flow measurements. The test section length-to-gap width ratio is ten, thus, adequate to maintain essentially two-dimensional flow. The wider test section is similar but includes three columns of cylinders instead of one (Fig. 1(b)). It was used to verify the existence of quasi-periodic drag and lift forces in a more realistic configuration.



(a) *(b)*

Figure1: Test sections

2.2 Instrumentation

Three cylinders in the narrow test section were instrumented with strain gauges to measure the dynamic drag and lift forces due to the two-phase flow. For one test condition, the measurements were done in two steps because of the limited numbers of instrumented cylinders: 1) positions C1-N, C2-N and C3-N, and 2) positions C4-N, C5-N and C6-N. Positions C1-N to C6-N as shown in Fig. 1(a) represent the first to sixth positions from the upstream end of the narrow test section, respectively. Six cylinders located at the positions (L3, L4, R3, R4, C3, C5) in the wider test section were instrumented. Tests were also done for a single cylinder (at position C3-N), and for two in-line cylinders with three different pitches along the flow (1.5D, 3D and 4.5D corresponding to cylinder positions C3-N & C4-N, C3-N & C5-N and C3-N & C6-N, respectively). These tests were conducted in the narrow test section for both single-phase water and two-phase air/water flow. In these cases, the test section was empty except for the test cylinders and the sidewalls were flat. The instrumented cylinders were cantilevered while the others were held at both ends. Two pairs of diametrically opposite strain gages were installed in each instrumented cylinder at 90 deg from each other to measure the forces in the flow direction (drag) and in the direction normal to the flow (lift). The strain gages were connected to strain indicators. The natural frequency of the instrumented cylinders was much higher (i.e., >150Hz) than the excitation force frequencies such that the cantilever cylinder functioned essentially as a dynamic force transducer. The static strain-force relation was determined via a careful calibration. The signals were analyzed with an OR38 8-32 channel real time multi-analyzer/recorder coupled to a laptop computer.

The experiments were performed over a pitch flow velocity range from 1 m/s to 10 m/s at 80% void fraction for two-phase flow and 0.25 m/s to 2 m/s in 0.25 m/s increment for water flow, respectively.

3. RESULTS AND DISCUSSION

3.1 Comparison between periodic vortex shedding forces in water and quasi-periodic lift forces in air/water flow

3.1.1 Periodic vortex shedding forces in water

Lift force spectra for a single cylinder (C3-N), two cylinders with different pitches along the flow (1.5D, 3D and 4.5D, corresponding to cylinder positions C3-N & C4-N, C3-N & C5-N and C3-N & C6-N, respectively) in the narrow test section are shown in Fig. 2 for 1 m/s pitch flow velocity in water flow. All the force spectra show very well defined vortex shedding peaks. For the case of two cylinders at 1.5D pitch, the magnitude of the peak for the upstream cylinder (at C3-N) is relatively less than that for the single cylinder (Fig. 2(d) vs. Fig. 2(a)). It indicates that the vortex shedding from the upstream cylinder was affected by the downstream cylinder due their proximity. For the cases at 3D and 4.5D pitches (Fig. 2(b) vs. Fig. 2(a) and Fig. 2(c) vs. Fig. 2(a)), the space between cylinders is sufficient so that not much effect on the upstream cylinder occurs. Interestingly, the periodic lift force for the downstream cylinder is larger than that for the upstream cylinder. It is also larger than that for the single cylinder except for the smallest pitch case.

3.1.2 Quasi-periodic lift forces in air/water flow

Lift force spectra for a single cylinder (C3-N), two cylinders with different pitches along the flow (1.5D, 3D and 4.5D, corresponding to cylinder positions C3-N & C4-N, C3-N & C5-N and C3-N & C6-N, respectively) in the empty narrow test

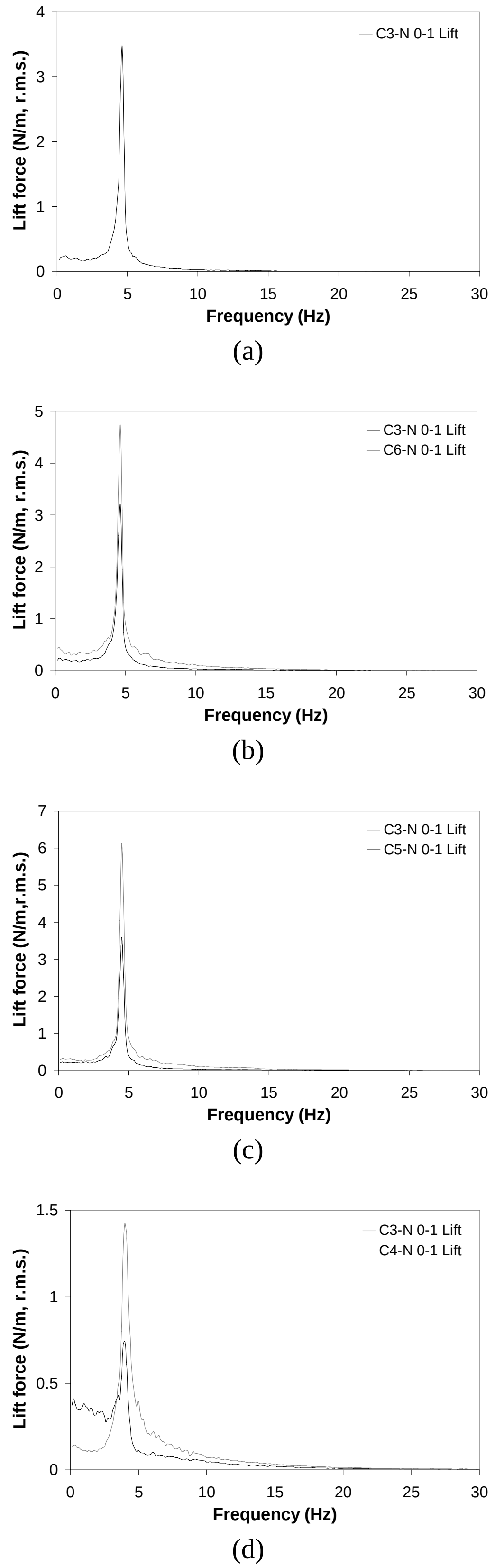


Figure 2: Typical dynamic lift force spectra for water flow at 1 m/s pitch flow velocity: (a) single cylinder, (b), (c) and (d) two cylinders at different pitches (4.5D, 3D and 1.5D, respectively)

section are shown in Fig. 3 for 80% void fraction at 5 m/s pitch flow velocity. The spectrum of the single cylinder is largely broad band random in appearance (Fig. 3(a)). For the case of two cylinders at 4.5 D pitch, some periodicity appears for the downstream cylinder (C6-N), while the spectrum of the upstream cylinder (C3-N) shows random and broad band characteristics typical of turbulence forces (Fig. 3(b)). For the case of two cylinders at 3D pitch, more prominent periodicity appears for the downstream cylinder (C5-N), while the spectrum of the upstream cylinder (C3-N) is still broad band random in appearance (Fig. 3(c)). For the case of two cylinders at 1.5D pitch, periodicity in the downstream cylinder (C4-N) is more dominant and the peak is sharper than other cases, while the magnitude of the spectrum for the upstream cylinder is significantly increased. It indicates that the periodicity in the lift forces is much affected by the space between upstream and downstream cylinders. The wake oscillation in the relatively narrow space is the source of this periodicity. It can be concluded that the mechanism of the quasi-periodic lift force in air/water flow is significantly different than that of vortex lift force in water flow.

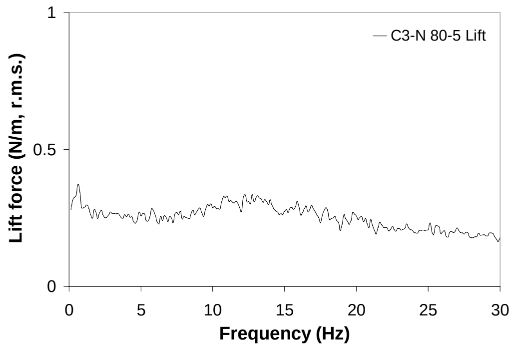
3.2 Effect of cylinder position on the quasi-periodic drag and lift forces

3.2.1 Typical lift forces

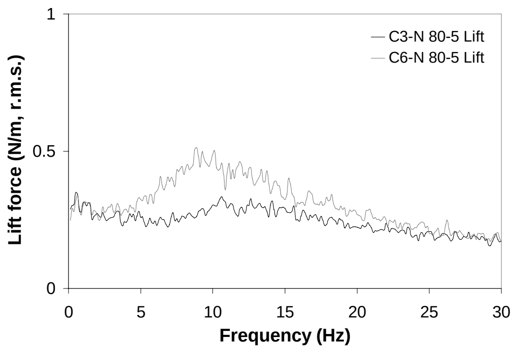
Lift force spectra for all the six positions in the narrow test section are shown in Fig. 4(a) for 5 m/s pitch flow velocity at 80% void fraction. The force spectrum magnitudes in the lift direction are relatively small in the upstream positions (C1-N & C2-N) but much larger in the interior (C3-N & C4-N) and in the downstream positions (C5-N & C6-N). The periodicity for the most upstream position (C1-N) is less prominent, but the force spectrum shows random and broad band characteristics of turbulence forces. This is because these quasi-periodic lift forces are mostly correlated to oscillations in the wake of the upstream cylinder and there is no cylinder upstream of C1-N as in (Zhang et al., 2008). The behavior of the interior cylinders is quite similar to that of the downstream cylinders (Fig. 4(a)). It implies that the periodic lift force peak amplitude would not increase further with increasing tube bundle depth.

3.2.2 Typical drag forces

Drag force spectra for all the six positions in the narrow test section are shown in Fig. 4(b) for 5 m/s pitch flow velocity at 80% void fraction. The force spectra are quite similar for all cylinders, except that the peak amplitude for the most upstream position (C1-N) is a little larger than those of other



(a)



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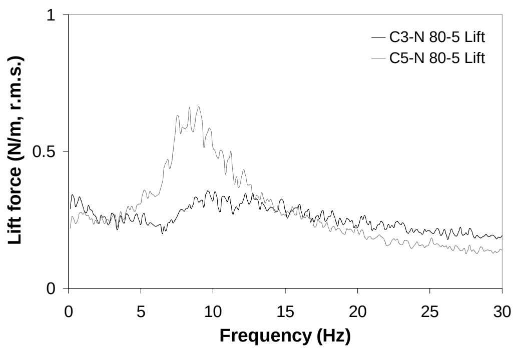
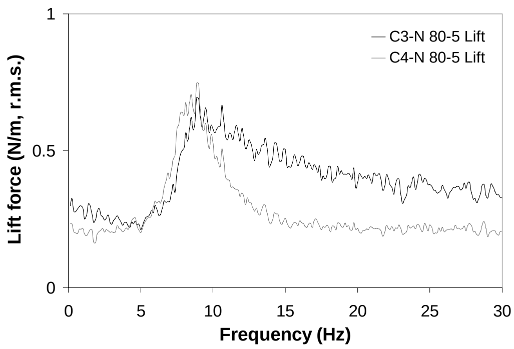


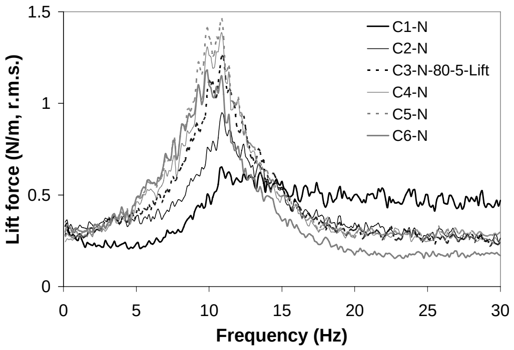
(c)



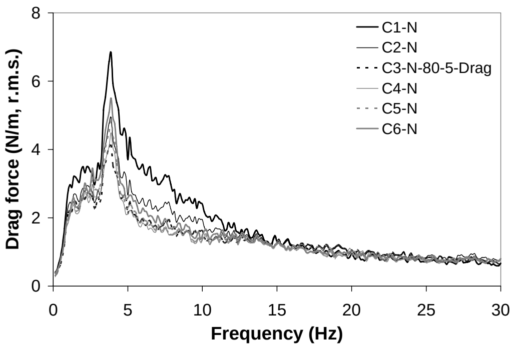
(d)

Figure 3: Typical dynamic lift force spectra for 80% void fraction at 5 m/s pitch flow velocity: (a) single cylinder, (b), (c) and (d) two cylinders at different pitches (4.5D, 3D and 1.5D, respectively)

positions. This is probably due to the fact that the cylinder at C1-N is directly exposed to the upstream two-phase flow fluctuations. The drag periodic forces do not appear to increase with tube bundle depth beyond the first upstream tube.



(a)



(b)

Figure4: Typical dynamic lift and drag force spectra for 80% void fraction at 5 m/s pitch flow velocity: (a) Lift force spectra and (b) Drag force spectra

3.3 Quasi-periodic drag and lift forces in the wider test section

One may have the opinion that our recent observations as in (Zhang et al., 2007a; 2008) with the narrow test section are possibly an artifact of this particular experimental set-up and would not be observed in a wider array of the same geometry under similar flow conditions. To answer these questions we conducted some tests with a similar but wider test section including three columns of cylinders instead of one (Fig. 1(b)). Six cylinders located in the positions (L3, L4, R3, R4, C3, C5) were instrumented with strain gages. Similar results were found as in (Zhang et al., 2007a; 2008).

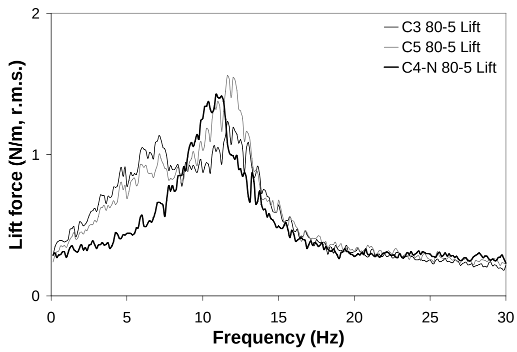
3.3.1 Typical lift forces

Typical lift force spectra in the wider test section are shown in Figs 5(a), (b), (c) for 5 m/s pitch flow velocity at 80% void fraction. The lift force spectra reveal narrow band or quasi-periodic forces similar to those in the narrow test section. The lift periodic frequency in the center column is a little higher than that in the narrow test section, although the amplitudes are quite similar. On the other hand, the lift periodic frequencies in adjacent columns (left and right columns) are similar to those in the narrow test section, although the amplitudes are a little less (Figs 5(a), (b), (c)). The difference in frequency may be related to the fact that the flow paths on each side of the columns are not identical. The two adjacent columns have a solid flow boundary on one side and an open flow boundary on the other side. On the other hand the center column has two open flow boundaries. Interestingly, some components of the drag force frequency may be found in the lift force spectra. Further tests revealed that the presence of drag force components in the lift force spectra is much less pronounced when the pitch flow velocity is less than 5 m/s.

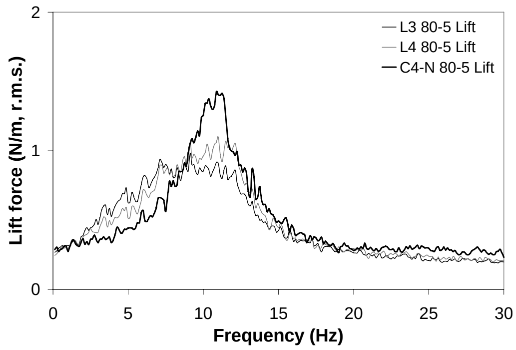
3.3.2 Typical drag forces

Periodicity was also observed in the drag direction as shown in Figs 5(d), (e), (f) for 5 m/s pitch flow velocity at 80% void fraction. The drag periodic frequency in both adjacent columns (L3, L4 and R3, R4) and for the centre column (C3, C5) is coincident with that in the narrow test section, although the amplitude seems smaller than that in the narrow test section (Figs 5(d), (e), and (f)).

In summary, quasi-periodic lift and drag forces essentially similar to those in the narrow test section also exist in the wider test section.



(a)



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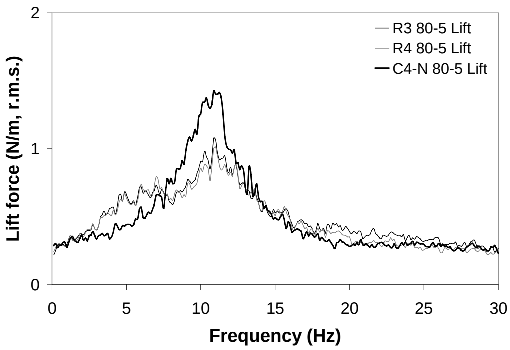
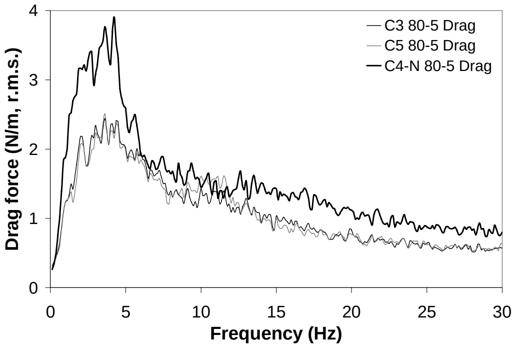


(c)



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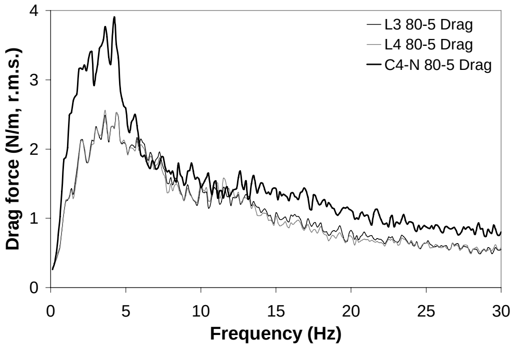

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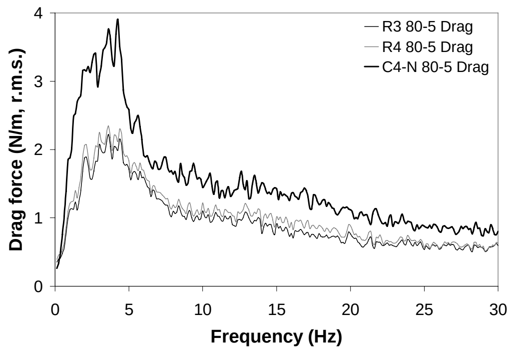

(f)

Figure 5: Comparison of the dynamic lift and drag forces between the wider test section and the narrow test section for 80% void fraction at 5 m/s pitch flow velocity; (a), (b) and (c) for lift forces, and (d), (e) and (f) for drag forces (The letter N in the nomenclature is for the narrow test section)

4. CONCLUSION

This investigation provided further evidence that the quasi-periodic lift forces are really due to oscillations of the wake between upstream and downstream cylinders. It showed that the observed quasi-periodic drag and lift forces should not increase with cylinder depth within a rotated triangular tube array. It also showed that quasi-periodic drag and lift forces essentially similar to those observed in the narrow test section also exist in the wider test section.

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