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Vibration Excitation Forces in a Rotated Triangular Tube Bundle 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 flow and vibration excitation force measurements in tube bundles subjected to two-phase cross flow are required to understand the underlying vibration excitation mechanisms. Studies on this subject have already been done, providing results on flow regimes, fluidelastic instabilities, and turbulence-induced vibration. The spectrum of turbulence-induced forces has usually been expected to be similar to that in single-phase flow. However, a recent study, using tubes with a diameter larger than that in a real steam generator, showed the existence of significant quasi-periodic forces in two-phase flow. An experimental program was undertaken with a rotated-triangular array of cylinders subjected to air-water cross-flow, to simulate two-phase mixtures. The tube bundle here has the same geometry as that of a real steam generator. The quasi-periodic forces have now also been observed in this tube bundle. The present work aims to understand turbulence-induced forces acting on the tube bundle, providing results on drag and lift force spectra and their behaviour according to flow parameters, and describing their correlations. Detailed experimental test results are presented in this paper. Comparison is also made with previous measurements with larger diameter tubes. The present results suggest that quasi-periodic fluid forces are not uncommon in tube arrays subjected to two-phase cross-flow.

INTRODUCTION

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. To prevent such tube failures, designers and troubleshooters must have guidelines that incorporate flow-induced vibration excitation forces.

In single-phase flow, these forces have been measured and analysed extensively. Tube motion can be generated by three kinds of forces: periodic wake shedding, turbulence-induced forces and motion dependent fluidelastic forces. Experimental data for different fluids and tube bundles have been satisfactorily compared through the use of adequate data-reduction procedures [1-2].

These forces are much less well known in the case of two-phase flow. It is known that there are significant differences between single- and two-phase flow induced forces. It has been shown for instance, that in two-phase flow, well defined Karman vortices do not exist [3]. Some experimental data have been analyzed, assuming that random forces in two-phase flow have relatively flat spectra [4-13].

However, a recent study [14] using tubes with a diameter larger than that in real steam generators, showed the existence of significant quasi-periodic forces in two-phase flow. An experimental program has therefore been undertaken with a rotated-triangular array of cylinders of realistic diameter subjected to air/water flow to simulate two-phase mixtures over many flow conditions.

The experiments showed that these unexpected quasi-periodic forces are still present in a tube array having a realistic geometry. This paper presents the above measurements, and aims to understand vibration excitation mechanisms by comparing the present results with those obtained in previous studies [13-15].

NOMENCLATURE

A	Test section area (m^2)
D	Tube diameter (m)
F_{rms}	R.m.s. force (N/m)
g	Gravity acceleration (m.s^{-2})
G_p	Pitch mass flux (kg.s^{-1}.m^{-2})
G_{pg}	Gas pitch mass flux (kg.s^{-1}.m^{-2})
P	Pitch (m)
S	Strouhal number
V_∞	Upstream flow velocity (m.s^{-1})
V_p	Pitch velocity (m.s^{-1})
W_g	Mass flow (kg.s^{-1})
X	Martinelli parameter
ε	Void fraction
ρ_g	Gas density (kg.m^{-3})
ρ_l	Liquid density (kg.m^{-3})
μ_g	Gas dynamic viscosity (Pas)
μ_l	Liquid dynamic viscosity (Pas)

EXPERIMENTAL CONSIDERATIONS

Test loop. The experiments were done in an air-water loop to simulate two-phase flows. The water runs in a closed-circuit, including a 2500 l tank and a 25 l/s variable speed pump. Water flow is measured with a magnetic flow meter. A 250 l/s compressed air supply system is connected to the loop as shown in Fig. 1. The compressed air is injected below a mixer in order to obtain a homogeneous two-phase mixture in the test section. The loop is operated at room temperature and the pressure in the test section is slightly above the atmospheric pressure.

Test section. As mentioned above, the bundle geometry is that of a prototypical steam generator. The test section shown in Fig. 2 has a rectangular cross section (190.5 mm × 214.6 mm). It consists of nine columns of ten 17.5 mm diameter cylinders. To limit the effects of the boundary conditions, half-cylinders are installed on the walls of the test section, so that the flow path can be similar to that of a whole steam generator. The pitch-to-diameter ratio, P/D, is 1.42 which corresponds to a 7.4 mm gap between the tubes.

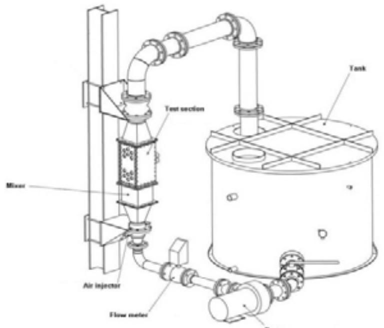

Fig. 1: Test loop

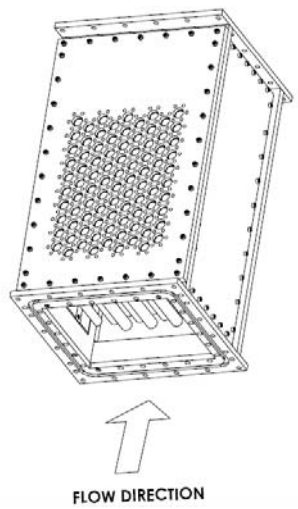

Fig. 2: Test section

Instrumentation. Instrumented tubes have been designed to measure flow-induced forces directly. This was achieved with strain gage instrumented acrylic tubes. The tubes are half-length cantilevered cylinders whose natural frequency in air is around 450 Hz, and 240 Hz in water. For such tubes, the displacement is directly proportional to the applied force at low frequency. An appropriate force spectrum can be obtained below 150 Hz. The tubes are fixed in the test section using newly designed devices as shown in Fig. 3 so that several tubes can be clamped next to each other within the limited space available. The positions of the instrumented tubes are shown in Fig. 4. Each tube has diametrically opposite double strain gages installed to measure either the drag or the lift forces. For some tubes, both drag and lift forces could be measured simultaneously. The strain gages were connected in a full bridge configuration to a strain indicator. The signals were analyzed on an OROS38 8-32 channels real-time multi-analyser/recorder coupled to a laptop computer. The experiments were performed over a void fraction range from 0% to 90% and a pitch flow velocity from 1.0 to 7.3 m/s. The homogeneous model was used to calculate the two-phase flow parameters.

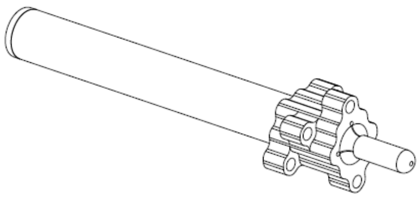

Fig. 3: Instrumented tube

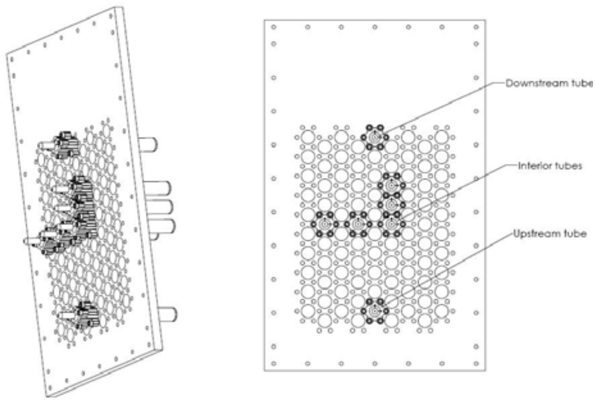

Fig. 4: Position of instrumented tubes

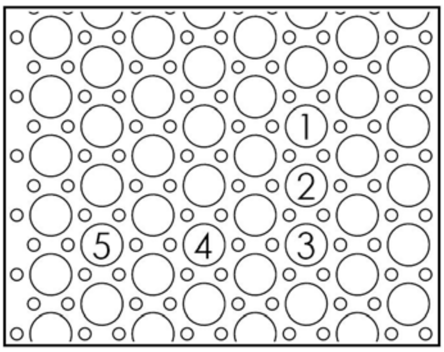

Fig. 5: Relative position of instrumented tubes

RESULTS

Periodic forces. Typical drag and lift power spectral density plots obtained with the interior instrumented tubes (position shown in Fig. 5) for 80% void fraction are presented in Fig. 6-7. V_p is the pitch velocity, defined as $V_p = \frac{P}{P-D} V_\infty$ where V_∞ is the upstream flow velocity. Zhang [14] showed the existence of quasi-periodic forces in two-phase cross flow for the same array geometry but with larger diameter tubes. These forces are significant in both drag and lift directions. The power spectral density graphs show two kinds of quasi-periodic forces. A broader peak is present in all measurements, and a second sharper peak, at lower frequencies is present only above a certain flow velocity. The sharp peak maybe though be related to test section vibration. However, it appears at very different flow velocities depending on the force directions. Besides, Zhang [16] measured sharp low frequency signals in the two-phase flow with an optical probe, so these sharp peaks seem to be actual forces caused by the flow. At 80% void fraction, this peak appears around 5.5 m/s in the lift direction and 1.5 m/s in the drag direction. It also appears that for 60-90% void fraction, which is typical in an actual steam generator, and for the same mass flux, the peak is more significant at lower void fraction. Fig. 8 presents the mean frequency of the higher peak plotted versus pitch velocity. In this case, the lift force plots show a wider peak. These frequencies appear to be proportional to the pitch velocity, with a Strouhal number ($S=fD/V_p$) from 0.08 to 0.12. At low velocity (below 2m/s), the drag periodic forces are close to the lift forces but then, the second low frequency quasi-periodic force become more important. The frequency of this latter force is not strongly related to the flow velocity, increasing from 3 to 4Hz in the flow velocity range from 2.3 to 7.3 m/s.

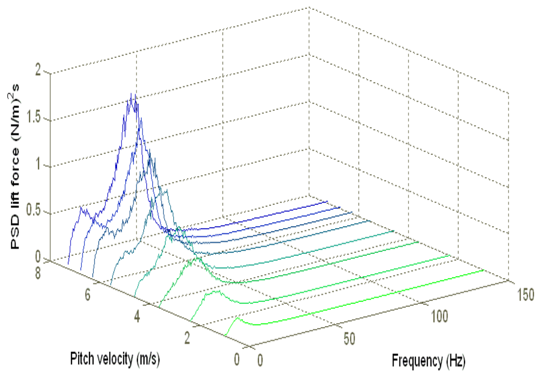

Fig. 6: Typical dynamic Power Spectra Density (PSD) for the interior cylinders (average spectra tubes 1-3) at 80% void fraction: lift force PSD

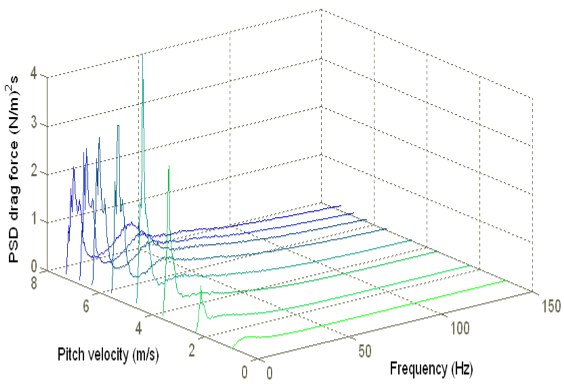

Fig. 7: Typical dynamic Power Spectra Density (PSD) for the interior cylinder (average spectra tubes 3-5) at 80% void fraction: drag force PSD

R.m.s. forces. As shown in Fig.6-7, the drag forces appear larger that the lift forces. However, they remain in the same order of magnitude. R.m.s. drag and lift forces are presented in Fig. 9, for the measurements corresponding to those presented in Fig. 8 for 80% void fraction. These results show that both drag and lift forces are significant. It appears that the lift forces are correlated to the mass flux with the relationship $F_{rms} = a \cdot \mathrm{G_p} + b$ where a=0.0042 m^2/s and b=0.53 N/m. The drag force dependence with mass flux is not so linear. This may be caused by the different behaviour of the two different forces. The force with narrow peak is more important in the drag direction.

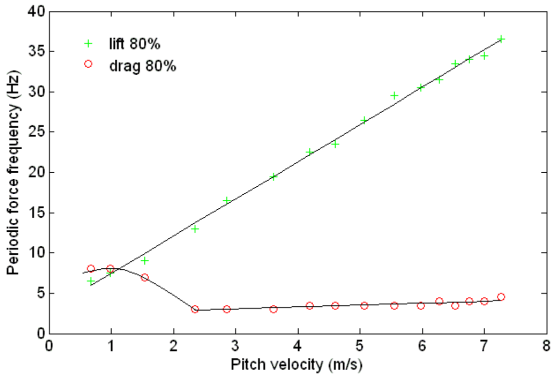

Fig. 8: Relationship between main peak frequency and pitch velocity

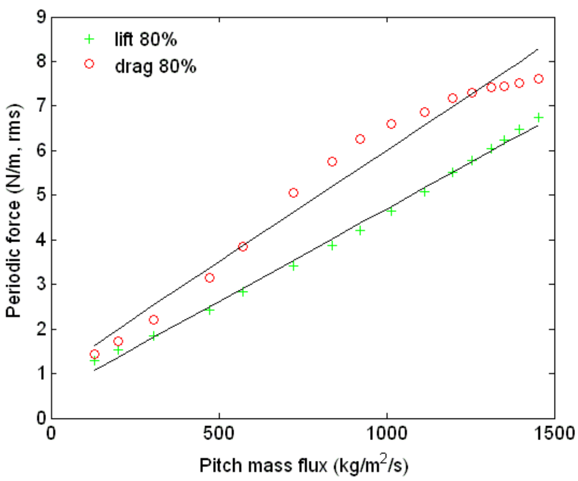

Fig. 9: Relationship between r.m.s. periodic forces and mass flux

Effect of tube position. There are no significant differences between the vibration response PSDs of the different interior tubes (tubes 1-5 in Fig. 5) for the same test conditions. However, Fig. 10-11 show noticeable differences between spectra of interior, downstream and upstream tubes, for a test performed at 80% void fraction and 6.8 m/s pitch velocity. Table 1 shows r.m.s. forces measured in the drag and lift directions for each tube. In the lift direction, the interior tube is clearly subjected to the larger forces. For this tube, the two kinds of quasi-periodic forces are present, as expected from Fig. 6-7 data. On the other hand, the upstream tube spectrum shows a sharp quasi-periodic drag force frequency peak at 6 Hz and a smaller broad peak at higher frequency. Its mean frequency is higher than that for the interior tube (44 Hz for the upstream tube instead of 35 Hz for the interior tube). Of the three principal tube positions, the downstream tube is subjected to the lowest forces. There is no significant sharp quasi-periodic force at low frequency for this tube. However, the tube seems to be subjected to a broad quasi-periodic force at the same frequency as that of the interior tube. Other tests performed for various velocities and void fractions from 70% to 90% show the same characteristics. The vibration spectra of the tubes in different position appear to be different whether in the lift or the drag direction. Indeed, the upstream tube is subjected to larger drag forces. It shows a significant sharp peak at low frequency. However, this frequency is higher than that of the interior tube. There is no significant second quasi-periodic force for the upstream tube, whereas there is for the interior tubes. The downstream tube is also subjected to the lowest drag force. The spectrum is similar to that for the interior tube. However, there is no second quasi-periodic force peaks. These observations have also been confirmed with other tests performed between 70% and 90% void fraction. The results of the relative force magnitudes as a function of tube position are in agreement with Zhang's results [14].

Table 1: Drag and lift r.m.s. forces measured for each tube, for an 80% void fraction and 6.8m/s pitch velocity

	Upstream	Interior (tube n°3)	Downstream
Drag force r.m.s. (N/m)	7.8	7.2	5.6
Lift force r.m.s. (N/m)	4.6	5.7	2.4

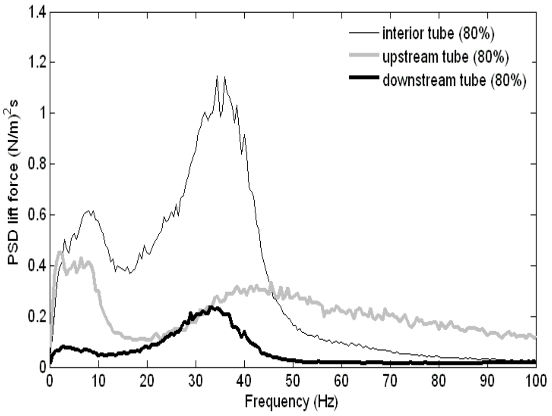

Fig. 10: Comparison of PSDs obtained for upstream, interior and downstream tubes for 80% void fraction at 6.8 m/s pitch velocity: lift force PSD

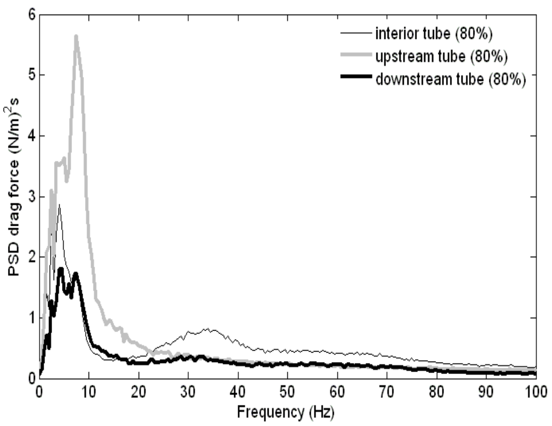

Fig. 11: Comparison of PSDs obtained for upstream, interior and downstream tubes for 80% void fraction at 6.8 m/s pitch velocity: drag force PSD

Correlations between vibration excitation forces. Force coherences have also been obtained for the interior tubes. Fig. 5 indicates the position of each tube. The gap between the tubes is 43.0 mm in the transverse direction and 24.6 mm in the flow direction. Fig. 12-15 show the coherence between lift and drag forces for Tubes 1-2-3 and Tubes 3-4-5. The global behaviour of the coherence spectra appears to confirm Nakamura et al.'s and Heilker et al.'s results [4, 10]. As expected, the pairs of tubes separated by the same distance show no significant difference in coherence. However, as expected, the coherence decreases with the distance between the tubes. The correlation between two adjacent tubes in a column is very strong (Fig. 12-13), particularly in the drag direction, where two adjacent tubes have more than 90% coherence up to 150 Hz. In the lift direction, the coherence is above 90% up to 40 Hz, and then it decreases. Within a row of tubes, the forces are less well correlated. This was expected since the distance between tubes in the transverse direction is larger than in the flow direction, but above all because of the rotated-triangular configuration, which tends to isolate each column of tubes. In the lift direction (Fig. 14), the coherence is very small at very low frequencies (below 4Hz). It then increases to reach 90% at 12 Hz, followed by a rapid decrease. Thus, there is low coherence for frequencies corresponding to the broad quasi-periodic force. Similar coherence trends have been obtained by Zhang [14]. In the drag direction (Fig. 13, 15), low-frequency forces (below 10 Hz) are well correlated, and, interestingly, the low-frequency coherence is still strong between Tubes 3-5. Above 10 Hz, the transverse coherence decreases very quickly.

These results indicate that low-frequency forces seem to be well correlated in all directions, while the higher-frequency quasi-periodic forces are well correlated along the tube columns (in the flow direction) but not in a tube row (perpendicular to the flow direction). Other tests performed at various void fractions and flow velocities show that the coherence increases with flow velocity and with void fraction.

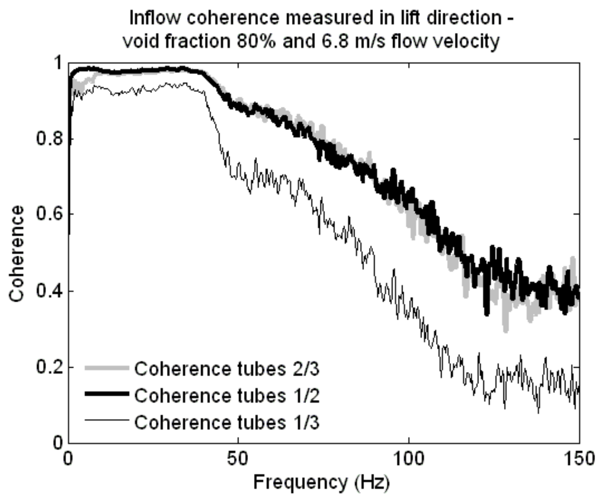

Fig. 12: Inflow coherence in lift direction

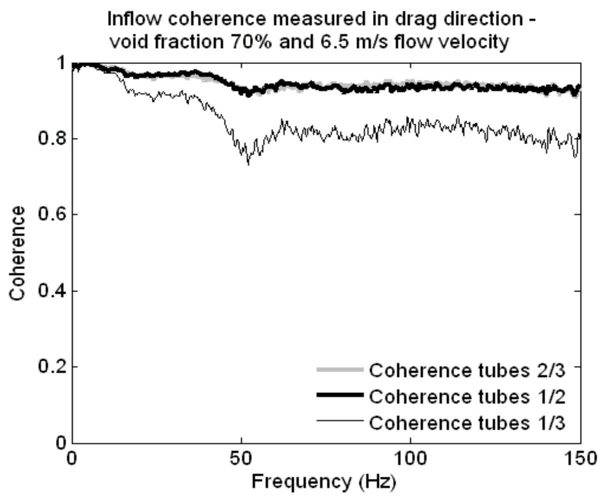

Fig. 13: Inflow coherence in drag direction

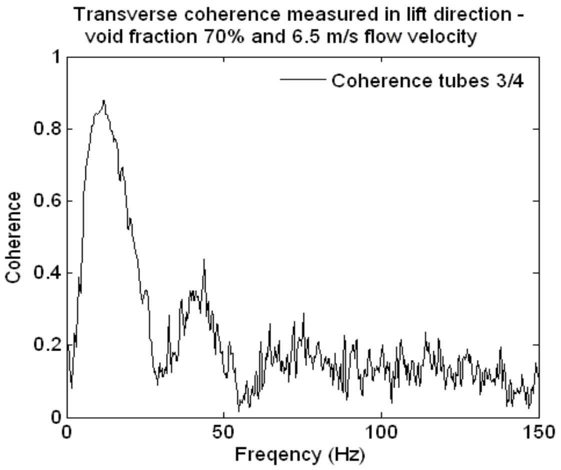

Fig. 14: Transverse coherence in lift direction

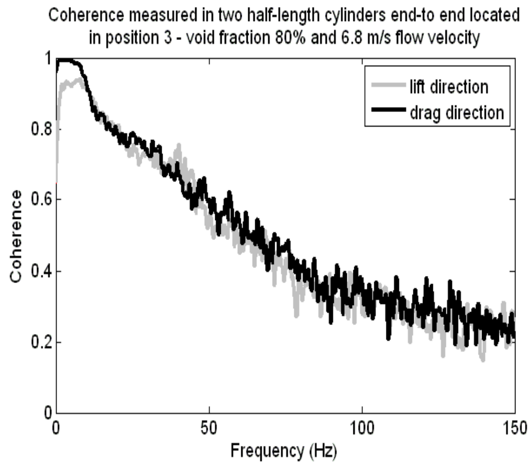

Fig. 16: Coherence between two end-do-end half cylinders

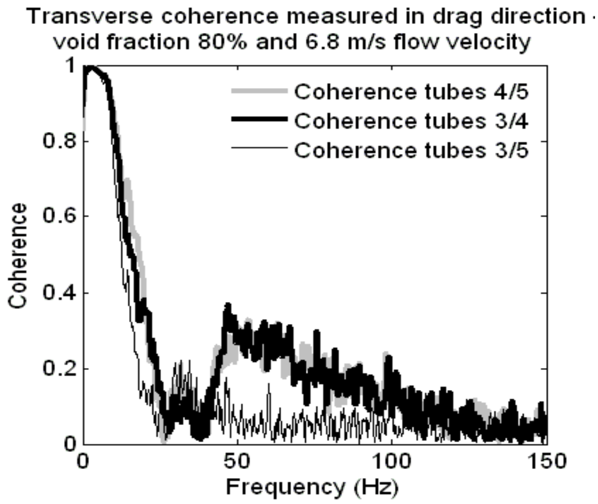

Fig. 15: Transverse coherence in drag direction

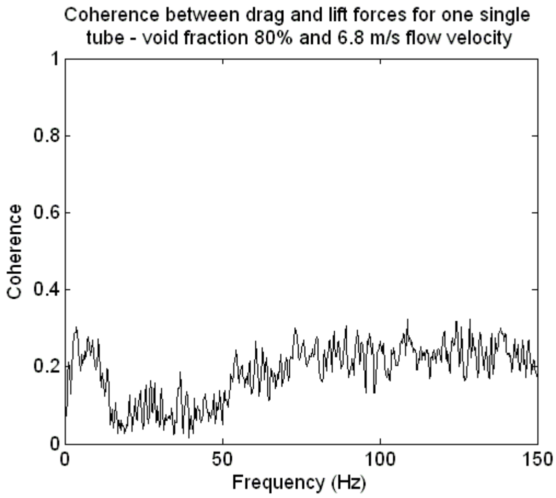

Fig. 17: Drag/lift force coherence for the same single tube

Fig. 16 shows both the drag and lift coherence between two half-length cylinders located end-to end. The coherence spectra appear very similar, but there is still better coherence (almost 100%) in the drag direction for 0-10 Hz frequencies.

The drag and lift forces are not significantly correlated, as seen in Fig. 17. While potentially a two-phase flow force could act in both directions in the same way, this graph confirms that drag and lift forces have to be taken into account separately, as suggested by Zhang [16], since the underlying mechanisms are different.

DISCUSSION

Periodic force frequencies. The results presented in Fig. 8 are compared to Zhang's results [14] for the experiments performed with 80% void fraction. To compare these data which are obtained with a different bundle geometry, the lift data is presented in Fig. 18 in terms of a Strouhal number. In the lift direction, both experiments have comparable Strouhal numbers. In the drag direction, the frequencies presented in Fig. 19 are directly comparable without normalising with a Strouhal number. In these experiments the lift frequencies are mostly related to the larger peak, while the drag frequencies correspond to the sharp low frequency forces. This can explain the difference in behaviour between the two kind of quasi-periodic forces. It suggests that drag direction force is not dependent on the bundle geometry.

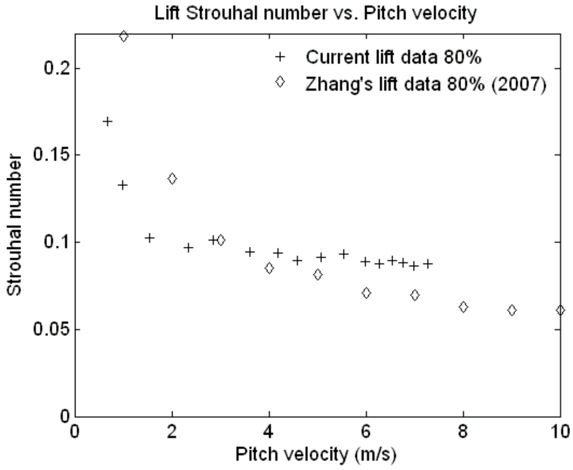

Fig. 18: Comparison of Zhang's Strouhal numbers obtained in the lift direction [14] with the present results, tests performed with 80% void fraction

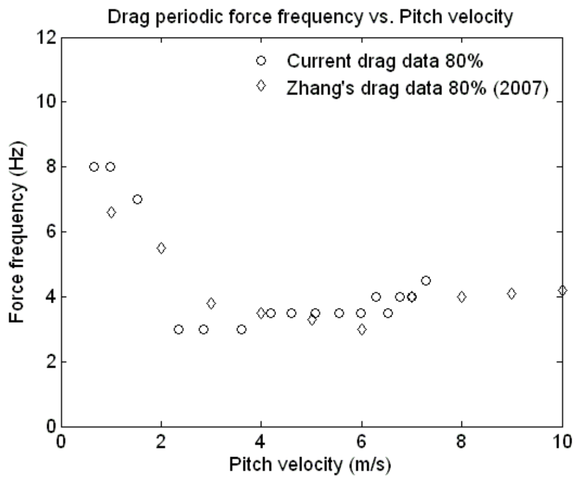

Fig. 19: Comparison of Zhang's frequencies obtained in the drag direction [14] with the present results, tests performed with 80% void fraction

Flow regimes. For each vibration test, the flow regime depends on the flow parameters. To determine the flow regime, the test flow conditions can be plotted on the Grant flow pattern map [17] used in various studies on flow-induced vibration in heat exchangers [18-21]. Fig. 20 shows the Grant flow pattern map with the present experimental condition superposed for 80% void fraction. On this map, the abscissa corresponds to the Martinelli parameter, *X*, defined as [22]:

$$X = \left(\frac{1-\varepsilon}{\varepsilon}\right)^{0.9} \left(\frac{\rho_l}{\rho_g}\right)^{0.4} \left(\frac{\mu_l}{\mu_g}\right)^{0.1}$$

The ordinate, U_g is the dimensionless gas velocity and is expressed by:

$$U_g = \frac{G_{pg}}{\left(2\left(P-D\right)g\rho_g\left(\rho_l-\rho_g\right)\right)^{0.5}}.$$

G_{pg} is the gas pitch mass flux defined as $G_{pg} = \frac{W_g}{A}\frac{P}{\left(P-D\right)}$ with W_g the gas mass flow rate and A the section area.

Fig. 20 shows that the measurements are actually taken near the boundary between bubbly and intermittent flow. The emergence of the sharp quasi-periodic force then can probably be explained by the change of flow regime, going from intermittent to bubbly when the flow velocity increases, or when the void fraction decreases. However the difference between the drag and lift spectra indicates that there are both tube-scale and bundle-scale flow regimes inside the test section.

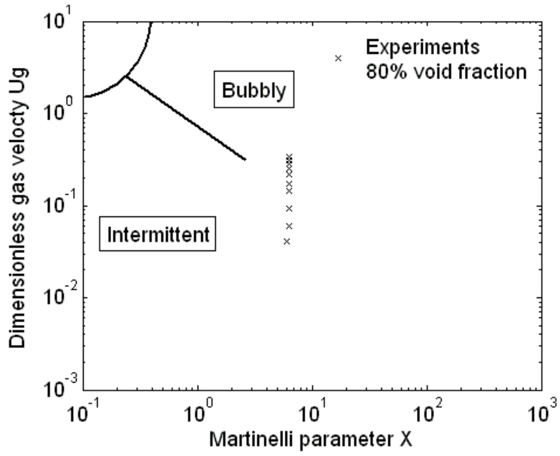

Fig. 20: Grant’s flow pattern map [17]

The coherence graphs have shown that random forces in a tube bundle subjected to a two-phase cross-flow are surprisingly well-correlated. It appears that unlike in single-phase flow, where the correlation length is supposed to be small [1, 2, 23], in two-phase flow, forces remain correlated for significant distances. The correlation length is different whether drag or lift forces are considered, and whether in the flow direction or perpendicular to it.

FUTURE WORK

The experiments revealed the existence of two types of quasi-periodic forces. The first showing quite a broad frequency spectrum, has a frequency directly related to the flow velocity. The second appears when the flow pattern becomes bubbly. Its spectrum is sharp and its mean frequency is almost constant, between 3 and 4Hz. Further studies on these two kinds of quasi-periodic forces have to be done to be able to characterize them properly, taking into account changes in local flow regime.

The two-phase cross-flow induced forces appear to be well spatially correlated. A detailed study of these correlations should lead to an estimate of the correlation length, which seems to depend on the flow direction and also the force direction.

CONCLUSION

Detailed force measurements in a rotated-triangular tube bundle subjected to two-phase cross-flow are presented in this paper. The experiments confirm the existence of significant quasi-periodic forces in a tube bundle having a realistic steam generator geometry. It shows that the two-phase cross-flow spectra are not flat as in the case of single-phase cross-flow. These quasi-periodic forces should be taken into consideration when calculating the power spectral density of forces in two-phase cross-flow.

The broad peak observed in both drag and lift force PSDs depends on the flow velocity. The resulting quasi-periodic force can reach frequencies as high as 40 Hz. It could therefore potentially induce resonance problems in practice.

The forces seem to be well spatially correlated, particularly in the drag direction.

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