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On the Feasibility of Modeling Two-Phase Flow-Induced Fluidelastic Instability in Tube Bundles

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ABSTRACT

In the 80's a number of theoretical models were developed to model fluidelastic instability, primarily for single phase flows. The models ranged from purely analytical models to semi-empirical models requiring considerable experimental data as input.

While these models were very successful in uncovering the nature of fluidelastic instability and the underlying mechanisms in single phase flow, this work seemed to stop short of getting to the next step of practical application to two-phase flows. During the same period, Connors formula became 'entrenched' in industry to the extent that the formula now forms part of the design norms against fluidelastic instability.

In an ongoing research program the quasi-steady model has been chosen as a possible candidate for modeling fluidelastic instability in two-phase flows. This paper discusses the challenges associated with accurate modeling of fluidelastic instability in two phase flows using this and other models. The unsteady model is shown to have limitations when it comes to measuring accurately the necessary unsteady fluid force coefficients.

A comparison of the stability analysis results with experimental measurements shows that the quasi-steady model can give a reasonable estimate of the instability velocity as well as the inter-tube dynamics.

Finally, the remaining challenges, before the quasi-steady model and possibly other models can be fully implemented for prototypical conditions are discussed. In particular the need for more work to understand the flow itself is highlighted.

1. INTRODUCTION

Fluidelastic instability remains a challenging problem for operating steam generators and heat exchangers. The instability is a self-sustained fluid-structure interaction that can cause tube fretting wear and failure in a short period. The mechanisms behind fluidelastic instability, particularly in two-phase flow remain to be fully elucidated. Thus, while design guidelines are quite conservative, questions remain. Besides causing instability, fluidelastic forces may affect the effective damping of tubes subjected to random turbulence excitation. Indeed as noted by Baj and de Langre (2002) and Hirota *et al.* (2002), flow velocity independent two-phase flow damping does not strictly exist. Thus the effective damping of a tube in a bundle will always depend on the conditions of the surrounding flow. As future generation steam generators are expected to last as long as 60 years, the interaction between fluidelastic forces and turbulence excitation becomes an important factor to be considered as well.

Several theoretical models have been developed for the prediction of fluidelastic instability. An excellent review of these models is given by Price (1995). The models are, however, yet to be implemented in industrial applications. Design engineers presently use the Connors model for design verification against fluidelastic instability. This simple empirical model, based on numerous experimental data, gives a conservative estimate for the fluidelastic instability velocity. The model, however, must be employed with care.

For operating steam generators, estimation of tube wear due to vibration-induced tube-support impacting is vitally important. For fluidelastic excitation this requires a realistic model for the excitation fluid forces. The Connors model cannot be used to estimate the fluid forces during instability; although some (strictly incorrect) attempts have been made to estimate the flow energy from this model. For flow velocities below the instability threshold the model gives no fluidelastic forces. Price (2001) has discussed the shortcomings of the Connors model for fluidelastic instability prediction. The quasi-steady model, developed by Price and Paidoussis (1986) has been shown to give reasonable agreement with experimental results for single phase flow. Recently the authors have presented results of experimental measurements of fluidelastic forces in air-water two-phase flows (Mureithi et al., 2006). The work reported here is part of an ongoing effort to develop two-phase flow fluidelastic instability models based on realistic experimentally measured fluid forces. The paper presents an overview as well as some of the challenges associated with prediction of fluidelastic instability for two-phase flows.

2. TWO-PHASE FLOW PARAMETERS

Several two-phase flow parameters will be regularly referred to in the paper. These parameters are defined here for convenience. The homogeneous void fraction is defined as the ratio of volumetric flow rate to the total volumetric flow rate.

$$\beta = \frac{Q_g}{Q_g + Q_l} \tag{1}$$

Employing the homogeneous void fraction, β , the average fluid density, ρ , and viscosity , ν , are estimated as

$$\begin{aligned} \rho &= \beta\rho_g + (1-\beta)\rho_l \\ \nu &= \beta\nu_g + (1-\beta)\nu_l \end{aligned} \tag{2}$$

The average free stream velocity can be approximated dividing the total volumetric flow rate by the free stream area:

$$U = \frac{Q_g + Q_l}{A} \tag{3}$$

One may also define the homogeneous phase velocities

$$j_g = \frac{Q_l}{A}, \quad j_l = \frac{Q_l}{A} \tag{4}$$

The pitch velocity, based on the homogeneous model, is defined as

$$U_P = U\frac{P}{P-D} \tag{5}$$

The steady force coefficients, presented later, are calculated based on the upstream velocity U as

$$\begin{aligned} C_D &= \frac{F_D}{\frac{1}{2}\rho U^2 S} \\ C_L &= \frac{F_L}{\frac{1}{2}\rho U^2 S} \end{aligned} \tag{6}$$

where F_D and F_L are the measured drag and lift forces, respectively and S the tube frontal area.

3. THE GENERAL UNSTEADY MODEL

The general unsteady model of Chen (1983) and Tanaka & Takahara (1981) is in principle the most accurate model for fluidelastic instability prediction. The motion dependent fluid forces (g_j and h_j), in the lift and drag directions, on a given tube j within a tube bundle are expressed as:

$$\begin{aligned} g_j = \sum_{k=1}^{n} \Bigg[& -\rho\pi R^2 \left[\alpha_{jk} \frac{\partial^2 u_k}{\partial t^2} + \sigma_{jk} \frac{\partial^2 v_k}{\partial t^2} \right] \\ & + \frac{\rho U^2}{\omega} \left[\bar{\alpha}_{jk} \frac{\partial u_k}{\partial t} + \bar{\sigma}_{jk} \frac{\partial v_k}{\partial t} \right] + \rho U^2 \left[\bar{\bar{\alpha}}_{jk} u_k + \bar{\bar{\sigma}}_{jk} v_k \right] \Bigg] \end{aligned} \tag{7a}$$

$$\begin{aligned} h_j = \sum_{k=1}^{n} \Bigg[& -\rho\pi R^2 \left[\tau_{jk} \frac{\partial^2 u_k}{\partial t^2} + \gamma_{jk} \frac{\partial^2 v_k}{\partial t^2} \right] \\ & + \frac{\rho U^2}{\omega} \left[\bar{\tau}_{jk} \frac{\partial u_k}{\partial t} + \bar{\gamma}_{jk} \frac{\partial v_k}{\partial t} \right] + \rho U^2 \left[\bar{\bar{\tau}}_{jk} u_k + \bar{\bar{\gamma}}_{jk} v_k \right] \Bigg] \end{aligned} \tag{7b}$$

where Chen's notation is followed for easy referencing. In equation (7) u_k and v_k are the tube displacements in the lift and drag. The fluid forces are grouped into three components, fluid inertia, fluid damping and fluid stiffness forces. To analyze the stability of a fully flexible tube bundle a large number of force coefficients is required since the interaction between each tube and its immediate neighbors must be considered.

3.1 Unsteady Fluid Forces in Single and Two-Phase Flows

In the typical kernel of the triangular tube bundle shown in Fig.1(a) each tube interacts with six neighbors. Assuming symmetry, 10 auto and cross-coupling force components must be measured. For the square array, Fig.1(b), eight force coefficients are needed.

Besides the large number of parameters needed, dynamic tests must be done to obtain them. Dynamic tests are necessary since not only the force magnitude but also the phase difference between tube motion and the fluid force must be measured in order to determine the fluid damping force. What has typically been done, for single phase flow, is to oscillate the 'central' reference cylinder at a given frequency (*f*) and low amplitude. The oscillation frequency and flow velocity (*U*) are varied to yield the force coefficients as functions of the reduced velocity *U/fD,* where *D* is the tube diameter.

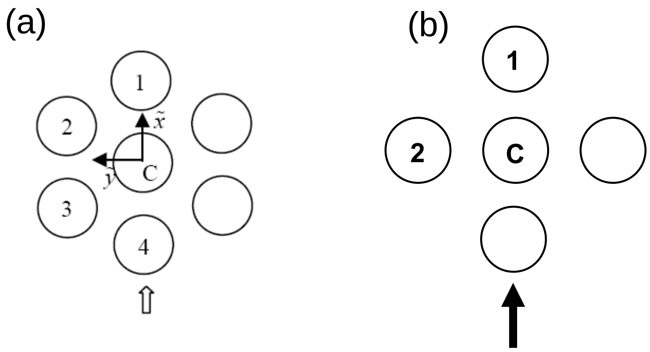

Fig.1 Typical tube bundle kernels for fluid force measurement (a) rotated triangular array, (b) normal square array.

The reduced velocity *U/fD* has been shown to be the important parameter on which these parameters depend – for single phase flows over a reasonable range of Reynolds numbers. Fig.2 shows typical data measured in water flow by Mureithi *et al.* (1996) and Tanaka and Takahara (1980) which confirm the *U/fD* dependence. In the figure the magnitude and phase of the fluid-elastic lift force on a periodically oscillated tube (C in Fig.1(b)) is shown.

Fig.2 confirms the strong variation in force magnitude and particularly phase as the reduced velocity is increased for single phase flow. The interested reader may refer to the complete set of data for square arrays published by Tanaka *et al.* (2002) for single phase flows. For steam-water data, see Mureithi *et al.* (1996, 2002).

Using these unsteady fluid forces, Tanaka and Takahara (1980) and Chen (1983) showed that fluidelastic instability in the corresponding flexible tube bundle could be very accurately predicted by the general unsteady model.

The following question then arises – can similar forces be measured 'with accuracy' for 'reasonably small' tube oscillation amplitudes in two-phase flows?

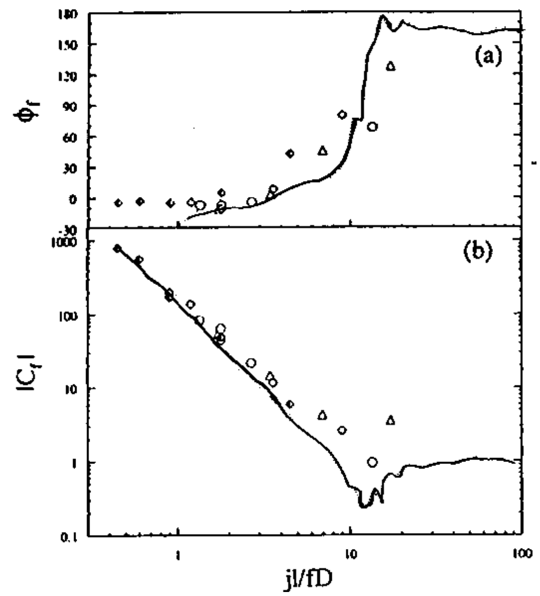

Fig.2 Unsteady fluid forces on an oscillating cylinder measured by Mureithi *et al.* (1996); the solid line shows data by Tanaka & Takahara (1980).

The condition of small oscillation amplitudes is particularly important since, in principle, the theoretical model is based on a stability analysis of the array at its equilibrium position hence the fluid forces should be measured in the neighborhood of 'zero' tube displacement. The caveat of course is that for two-phase flows other fluid forces, unrelated to tube motion, are far from insignificant relative to the motion dependent forces and may even be predominant when tube motions are small. This is the challenge that must be faced during any attempts to measure the unsteady fluid forces for two-phase flows. To the authors' knowledge, this attempt has been made by Mureithi *et al.* (1996, 2002) and Inada *et al.* (2002). We note in addition the work of Baj and de Langre (2003) who, although studying flow-induced damping specifically, did arrive at very noteworthy correlations for damping and in particular dimensionless parameters that could be used to quantify the fluid forces considered here.

Mureithi *et al.* performed unsteady fluid forces measurements in two-phase steam-water flow for both homogeneous and non-homogeneous flows. Tests were conducted on a normal square array with spacing P/D=1.46 at 3.0 & 5.8MPa (homogeneous flow) and 0.5 MPa (non-homogeneous flow). As an example of their results, Fig.3 shows the reference tube displacement and forces measured in the lift direction on the reference tube (C) as well as its neighbors (tubes C, 1 and 2 in Fig.1(b)) at 3.0 MPa.

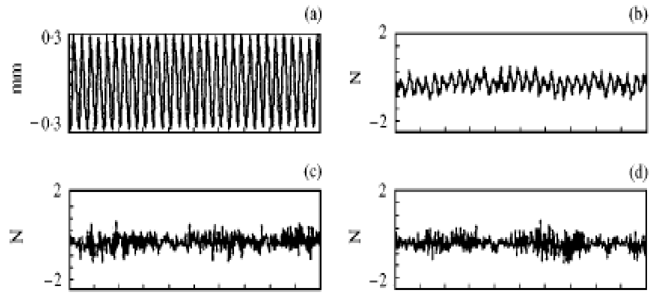

Fig.3 Measurements at 3.0MPa showing (a) tube motion, and lift force on, (b) tube C, (c) tube 1 and (d) tube 2 (from Mureithi et al., 1996, 2002); P/D=1.46.

The reference tube executes periodic motions in the lift direction with amplitude 0.3mm. Note that while the lift force on the tube itself is clearly periodic, the forces on the neighboring tubes are clearly dominated by the motion independent 'turbulence' forces. This was further confirmed by a correlation analysis where the coherence between the reference tube (C) motion and the measured fluid forces on tubes '1' and '2' was well below 50% at the forcing frequency. Clearly one possible solution is to increase the tube oscillation amplitudes during the tests; however, as stated above, this may well compromise the basic assumptions of the theoretical model. Equally, large tube amplitudes may effectively alter the local flow field around the tube again affecting the model accuracy. Clearly further work is needed to answer this question on the limits of the tube oscillation amplitude. The steam-water measurements were compared with measurements in Freon two-phase flow by Hirota et al. (1997); Fig.4 shows an example of the comparison for the reference tube lift force magnitude and phase. Clearly Freon two-phase flow yields fluidelastic forces closely similar to those measured in steam-water. This is a particularly encouraging result since it suggests that fluid forces measured in Freon can be used for the prediction of fluidelastic instability and estimation of tube response in steam-water. Air water-tests have been conducted by Inada *et al.* (2002) where tube oscillation amplitudes up to 7mm (0.318D) were achieved. The authors, however, only measured the forces on the oscillating cylinder and not its neighbors. Some important work was, however, done to investigate the effect of nonlinearities. An amplitude of approximately 0.20D was found to be the limit beyond which the amplitude force relationship became nonlinear. This may be large enough to yield better correlated fluid forces between neighboring tubes. However, see discussion below regarding nonlinear effects.

3.2 Unsteady Fluid Force Parameters

Another important question is with regards to parameter dependence of the fluid forces. Recall that for single phase

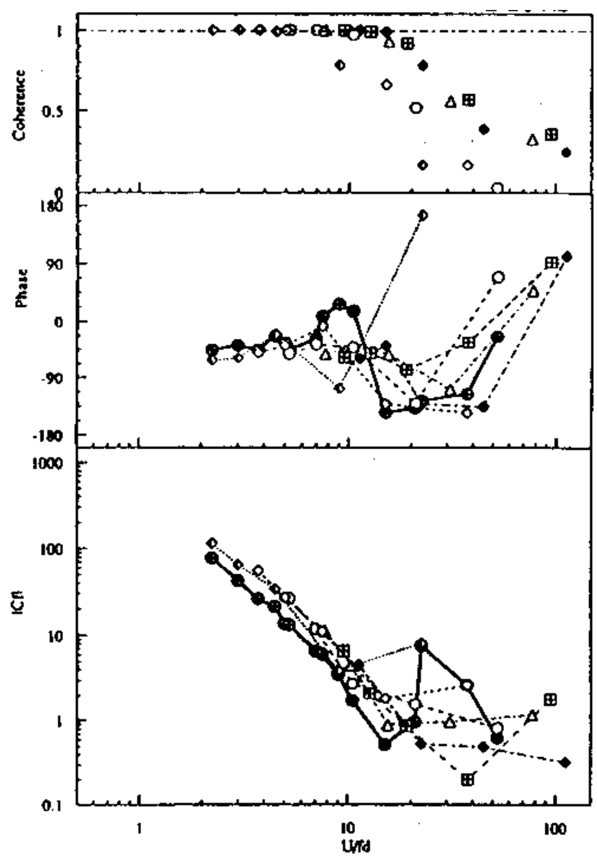

Fig.4 Comparison of unsteady fluid forces in steam-water and Freon two-phase flow; (lift forces on the oscillated central cylinder are shown).

flows, *U/fD* has been shown to be the key parameter on which the forces depend. For two-phase flows, however, Mureithi *et al.* (2002) have shown that U/*fD* is not the (single) governing parameter. Hence, the fluid forces were found to be multiple valued for the same *U/fD* where for two phase flows *U* is the mean homogeneous velocity, defined in Equation 3(a). This can be seen to some extent in Fig.4. The effect was, however, even more drastic for non-homogeneous flows. The reader is referred to Mureithi at al. (2002) for the experimental data. The multiple valued nature of the unsteady fluid forces was not found for single phase flows, e.g.Fig.2; in this case the data collapsed for given *U/fD*. In the two-phase flow tests, Mureithi *et al.* could vary three parameters, the gas and liquid phase velocities and the tube frequency *f*. The homogeneous velocity *U* was kept fixed and the tube oscillation frequency varied. It was found that changing *U* resulted in a well defined shift in the force data. This showed that the homogeneous velocity is not the correct parameter in the case of two-phase flows.

This deficiency of the homogeneous model was also found by Inada *et al.* (2002) in their fluid force measurement tests. The authors replaced the homogeneous model by the drift-flux model of Zuber and Findlay to account for the slip between the liquid and gas phases. Using the drift-flux model based velocity, the authors found very good collapse in the fluid-stiffness dimensionless forces as functions of reduced velocity. Interestingly, such a collapse was not found for the dimensionless fluid-damping force. This suggests that further work is still needed to determine the parameters governing the unsteady forces in two-phase flows.

3.3 Homogeneous and Separated Flow Models

Rather than model the detailed dynamics in each phase during intermittent flow, Feenstra et al. (2003) have recently studied the phenomenon of fluidelastic instability in homogeneous and intermittent flow where their measurements (and those of others – e.g. Pettigrew *et al*.(1989), Joly *et.al* (2009)) show that a significant drop in the reduced instability velocity occurs when the flow pattern changes from homogeneous to intermittent. This is clearly of concern (from a practical point of view) because on the traditional stability map, relating the reduced velocity to the mass-damping parameter, the instability data for intermittent flow falls below the *K*=3 line, where *K* is the Connors constant. Feenstra *et al.* showed that by introducing a more realistic void fraction model, and corresponding flow velocity, good data collapse is achieved, and more importantly the *K* value remains above 3.

While this may be somewhat comforting (since *K*>3 now) it does raise questions regarding the use of the Connors constant for two-phase flows, since the definition of velocity is clearly model dependent. A question which may be even more important is with regard to the true physical nature of fluidelastic instability in intermittent flow as we see next.

4. THE NAKAMURA MODEL

Perhaps one the most innovative models developed for two-phase flow fluidelastic instability is that by Nakamura *et al*. (2002). This was the first attempt to explicitly take into account the different flow patterns or to distinguish homogeneous flows from non-homogeneous (intermittent) flows. For the intermittent flows the fluid force acting on the tube is changed according to whether the tube is instantaneously in liquid or gas flow. The corresponding excitation forces F_l and F_g are computed based on the particular fluid phase. An energy balance method is then used to establish the stability boundary. By treating the phases separately, the authors showed that it was possible for 'intermittent fluidelastic instability' to occur either in the liquid or gas phase depending on the phase flow velocities. Their experimental tests showed that intermittent fluidelastic instability was the primary instability observed for intermittent flows. The latter means that instability was caused by only one of the phases – and the tube would be effectively stable (temporarily) when surrounded by the non-destabilizing phase. This conclusion seems to be supported by experiments.

5. THE QUASI-STEADY MODEL

5.1 Model Outline

The quasi-steady theory (Price and Paidoussis, 1986) provides an approximate semi-empirical approach for the estimation of the fluid components in the cross-flow and inflow directions, assuming small displacements are be expressed as:

$$F_y = \frac{1}{2}\rho S U_\infty^2 \left(C_L - 2\frac{\dot{x}D}{aU_\infty} C_L - \frac{\dot{y}D}{aU_\infty} C_D \right)$$
$$F_x = \frac{1}{2}\rho S U_\infty^2 \left(C_D - 2\frac{\dot{x}D}{aU_\infty} C_D + \frac{\dot{y}D}{aU_\infty} C_L \right) \quad (8)$$

where C_D and C_L are, respectively, the drag and lift force coefficients and U_∞ the upstream flow velocity. The factor '*a*' relates the gap velocity to the upstream velocity (Price and Paidoussis, 1986). The quasi-steady theory takes into account the time (τ_i) required for the fluid force field to readjust to a new cylinder position. The induced incidence and the time delay effect lead to apparent displacements, χ_i, η_i in the x- and y-directions, respectively, of the neighbouring cylinders relative to the reference cylinder. The fluid force coefficients are expressed as first order Taylor series based on these relative displacements. For the central cylinder in the tube array shown in Fig.1(a) for instance, this leads to the expressions

$$C_{DC} = C_{D0} + \tilde{g}\sum_{C,i=1}^{6}\left(\chi_i \frac{\partial C_{DC}}{\partial \chi_i} + \eta_i \frac{\partial C_{DC}}{\partial \eta_i}\right),$$
$$C_{LC} = C_{L0} + \tilde{g}\sum_{C,i=1}^{6}\left(\chi_i \frac{\partial C_{LC}}{\partial \chi_i} + \eta_i \frac{\partial C_{LC}}{\partial \eta_i}\right), \quad (9)$$
$$\tilde{g} = \exp(-\lambda\tau) \text{ and } \tau = \mu D / aU_\infty .$$

The fluid force coefficients of eq.(9) have recently been measured for air-water mixtures by the author and co-workers (Shahriary, 2007, and Shahriary *et al*., 2007). The homogeneous model was used to represent the two-phase mixture. The simplest form of the time delay is also used, hence $\mu = 1$ in equation (9) above. Shahriary (2007) has tested the effect of varying μ on the predicted stability velocity found that the predicted critical velocity, particularly for a single flexible cylinder can vary considerably. Currently ongoing work indicates that the velocity U_∞ should perhaps be replaced by the liquid phase velocity U_l for a better representation of the underlying flow effects. The velocity U_l needs to be estimated from a void fraction model. The promising model at the moment is that of Feenstra et al. (2003). Note that for the case of multiple flexible cylinders, the effect of the time delay is less important because the inter-tube phase plays a predominant.

5.2 Measured Fluid Forces

The force measurements were conducted on a rotated triangle tube array having dimensionless pitch spacing *P/D*=1.5. Referring to Figure 1(a), the effect of tube '*C*' displacement on the lift and drag force coefficients on the five tubes '*C*',1-4 was considered.

Figure 5 shows the measured lift (C_{LC}) and drag (C_{DC}) coefficients for tube 'C' for 80% and 60% void fractions as well as in liquid flow for comparison. Previous air-flow results (for a smaller spacing, *P/D*=1.375) by Price and Paidoussis (1986) are also indicated by dashed lines. The lift coefficient shows strong dependence on the dimensionless transverse displacement ($\tilde{y} = y / D$).

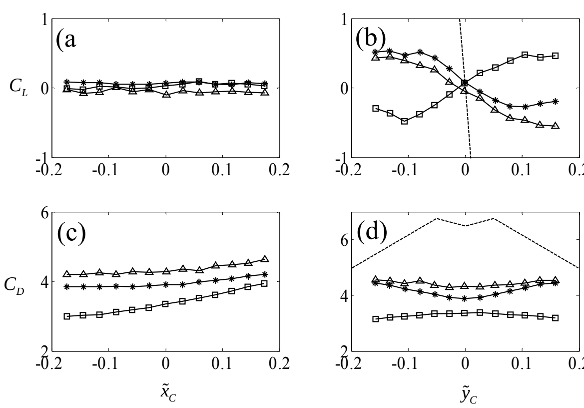

Fig.5. Measured lift (a,b) and drag (c,d) for tube 'C', △ $\beta = 80\%$,* $\beta = 60\%$,□ $\beta = 0\%$., ----- air flow in Re=1.4x10^4 , P/D = 1.375 (Shahriary et al.2007).

The first important observation is that the force coefficients are very well defined functions of tube position. This is a highly desirable result for stability analysis. Furthermore the 60% superficial void fraction force coefficients are close to those measured for 80% void fraction, particularly for the all important lift coefficient shown in Fig.5(b). It is remarkable that the trend of the water-flow test is very different.

The nonlinear relation between force and displacement in the lift direction, Fig.5(b), is also important to note. Referring to the dynamic tests by Inada *et al.* discussed above, we notice here that linearity may only be guaranteed for tube displacements of only up to 10% D.

The complete set of measurements (see Shariary et al., 2007) shows that tube 'C' displacement has the strongest effect on tubes in the same column, i.e. tubes 1 and 4 (see Fig.1(a)) as well as tube 'C' itself. Tubes 2 and 3 in the neighboring column show significantly less sensitivity to tube 'C' displacements. This suggests that there is reduced interaction between tubes in different columns particularly in the lift direction; tube 2 drag was, however, found to be significantly affected by tube 'C' transverse ($\tilde{y}$) displacement. This interaction between tube 'C' and its neighbors is depicted schematically in Fig.6 where the size and direction of arrows indicates the level and direction of interaction. Open arrows indicate that the cylinder 'C' direction of motion is normal to the cylinder force direction, hence transverse tube 'C' displacement significantly affects the drag force on tube 2.

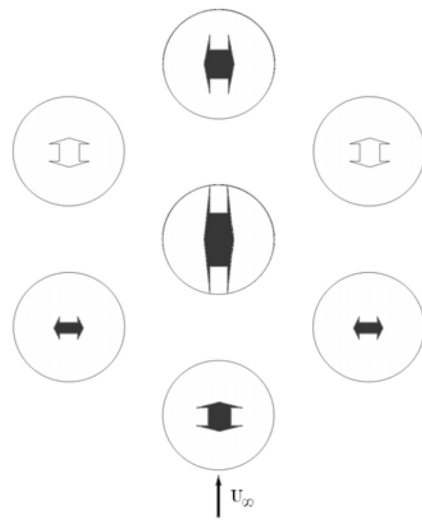

Fig.6 Influence of tube 'C' on its neighbors for $\beta = 80\%$ each arrow indicates the magnitude and direction of the most important force derivative. Open arrows indicate that the cylinder 'C' direction of motion is normal to the cylinder force direction.

5.3 Quasi-Steady Model Based Stability Analysis

The fluidelastic instability velocity for a single flexible tube as well as a flexible cluster of 7 tubes within the rigid array was determined for the same tube array considered in the force measurements. In the flexible cluster experiments, the seven vibrating cylinders were flexibly mounted on cantilevered flexible supports. Details of the fluidelastic instability tests and results may be found in Violette et al. (2006). For accurate comparison between theory and experiments, the complete 14 degree-of-freedom problem was solved in the theoretical analysis.

Fig.7 shows a comparison of the predicted versus measured dimensionless instability velocities as functions of the void fraction for a 7-tube flexible cluster within a rigid array. The results are also presented in Table 1. Further details may also be found in Shariary et al. (2007). The predicted critical velocities are within 30% of the measured velocities. This is significantly better than previous theoretical estimates which have, to date, been based on single phase flow considerations. The quasi-steady model also predicts the correct trend as a function of void fraction which is encouraging. The single flexible tube case can be a tougher challenge for the quasi-steady model due to the stronger influence of the poorly known time delay. Fig.8 shows the results for the single flexible tube where comparison is made with experiments, as well as with Connors equation assuming K=3.

Table 1 Comparison of the predicted reduced velocity with the dynamic measurements for the 7 tube cluster

β	Total mass-damping parameter	Reduced velocity prediction	Reduced velocity Measured
0%	0.126	1.68	2.29
60%	1.32	3.49	5.2
80%	1.46	4.54	6.52

The latter equation cannot be expected to predict the correct instability velocity, however, it is important here to show that the equation also gives the incorrect trend in the variation of the critical flow velocity with homogeneous void fraction.

Perhaps most importantly, the present results confirm that the quasi-steady theory is a feasible model for the prediction of fluidelastic instability in two-phase flow. This is clearly a consequence of the fluid forces which show very well defined trends with tube position, void fraction and flow rate.

6. DISCUSSION

The agreement between the quasi-steady theory and experiments is, however, not perfect as seen in Figs.7-8, even for this controlled test case where fluid force measurements and stability tests are conducted using the same test setup. This suggests that the two-phase flow itself must be studied more closely to facilitate model improvement. It was also noted that the application of the more complex unsteady fluidelastic instability theory raises some real practical challenges, particularly with regards to measurement of the unsteady fluid forces.

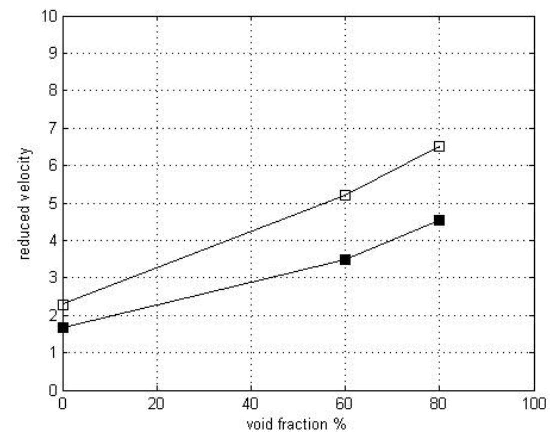

Fig.7 Comparison of measured (□) and predicted (■) instability velocities in single phase (water) and two-phase (air-water) flows for a fully flexible array.

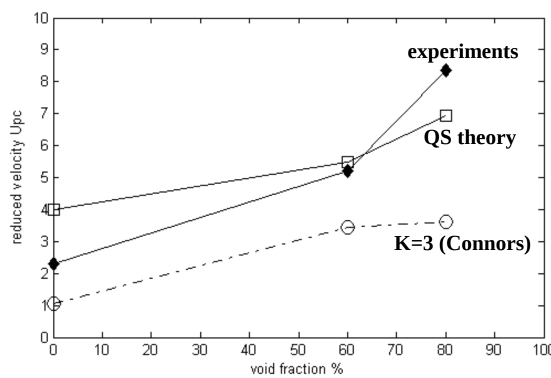

Fig. 8 Comparison of predicted instability with experimental results and Connors model, for a single flexible tube in a rotated triangular array.

6.1 Nonlinear effects in the fluidelastic forces

The work of Inada *et al.* showed that for the inline array (P/D=1.5), a linear relation exists between the unsteady fluid force amplitude and the oscillation amplitude up to 0.2D. This is, however, a significantly large amplitude when compared with typical amplitudes at the onset of and during fluidelastic instability. From a stability analysis point of view, the tube cannot be deemed to be in the vicinity of its equilibrium point which may make the measured fluid forces questionable. The maximum allowable amplitude depends on the nonlinearity of the fluid force. For the rotated triangular array, for instance, the steady lift forces is strongly nonlinear as a function of tube position in the lift direction as was shown in Fig.5. Note that in the range +/-0.2D the lift force undergoes a large variation, and linearity holds only up to 0.1D. One can expect that the resulting unsteady fluid force would be significantly affected by this nonlinear variation in the average lift force.

6.2 Limitations of the homogeneous flow model

In the quasi-steady analysis, homogeneous model based two-phase flow parameters are used. Ongoing work, however, indicates that this model is often far from representative of the fluid dynamics. In general, the liquid phases tends to play a much more important role. As mentioned above, the time delay introduced in the quasi-steady model seems to be better related to the liquid phase velocity than the homogeneous mixture velocity. More concretely, Inada *et al.* (2002), Nakamura *et al.* (2002), Mureithi *et al.* (2002) and others have shown that homogeneous model based parameters do not capture the correct flow physics, particularly for intermittent flows. The dynamic force measurements of Mureithi et al. and Inada et al. show that the homogeneous model cannot be valid for intermittent flow. Separated flow models have been shown by Inada *et al.* (2002) and Feenstra *et al.* (2003) to be invaluable. The model of Feenstra et al. has been shown to be very accurate and makes it possible to access the true phase velocities thus better modeling the flow physics. The work of Baj and de Langre (2002) is also notable. The authors have introduced dimensionless parameters which show good collapse of the measured damping forces with a newly defined reduced velocity.

6.3 Flow Visualization

Many of the results presented and much of the discussion points to the fact that there is still preciously little known about the detailed dynamics of two-phase flows in geometries as complex as tube bundles. This problem is exacerbated when interactions with moving structures come into play. Much more work therefore needs to be done to quantify two-phase flows in tube bundles. Accurate two-phase flow pattern maps for tube bundles are badly needed for instance. Ongoing developments in numerical and experimental methods may also begin to bear fruit.

As an example, recent developments in Particle Image Velocimetry (PIV) show that the method, when carefully applied, can provide additional information on the flow structure in tube bundles. The author, together with co-workers have recently carried out tests to visualize the two-phase flow within a rotated triangle configuration at low void fractions. The particle image velocimetry (PIV) method was employed in an air-water experimental loop which has a 10cm x 10cm x 2m test section made of transparent Plexiglas. A close-up view of the test section and PIV system is shown in Figure 9. Aluminum half cylinders are mounted on the inner wall to simulate a single flow path within a rotated triangular tube array with P/D=1.5. A laser light sheet is introduced, in the middle section containing transparent half-cylinders, perpendicular to the tube axes. The air-water mixture flows vertically upward. To visualize the two phases

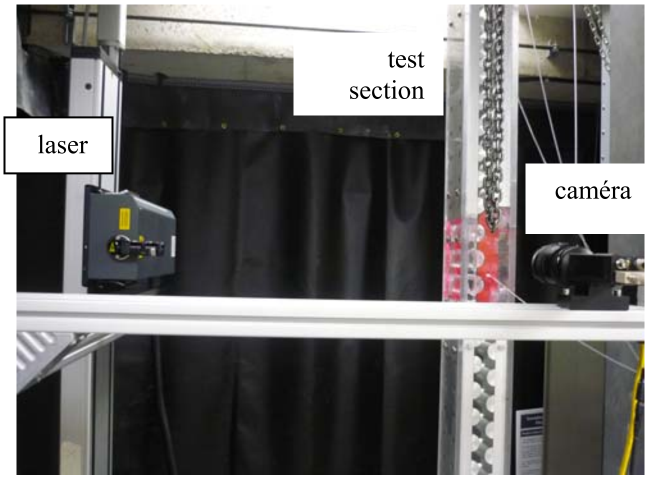

Figure 9 View of test section with laser and one camera in place.

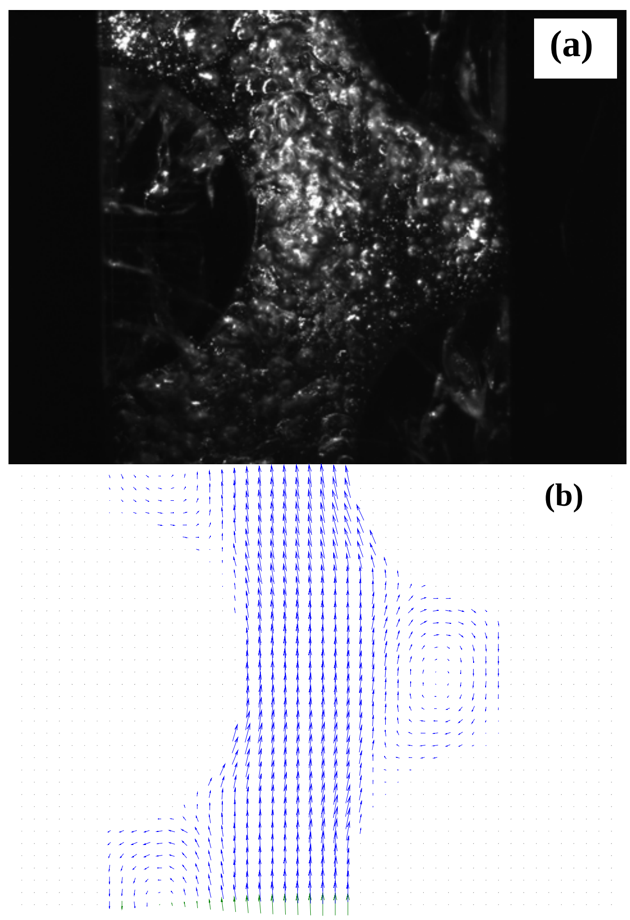

Figure 10 (a) Flow image and (b) average gas phase velocity field for, β=39%.

separately, a pair of cameras fitted with green and orange filters, respectively, is used to image the gas and liquid phases. The liquid phase (water in this case) is seeded with buoyant microscopic fluorescent particles. A typical image of the gas phase for a low void fraction of 39% is presented in Fig.10. Note direct measurement of the gas phase velocity makes it possible to accurately the void fraction. The non-uniformity of the instantaneous flow is evidenced the large scale structures visible in the main flow channel. Such structures, involving bubble coalescence and separation, can be expected to generate significant unsteady excitation. The average velocity vector field shown in Fig.10(b) on the other hand suggests that the tube will also be subjected to a well defined average force field despite the unsteady flow structures of Fig.10(a). This can be viewed as an encouraging result with respect to applicability of the quasi-steady model for stability analysis of tube bundles (if similar results are obtained at higher void fractions). Clearly, however, this is only a starting point and much work needs to be done to better understand the complex two-phase flow in tube bundles.

7. CONCLUSION

An overview of the challenges associated with accurate modeling of fluidelastic instability in two-phase flows using existing models developed for single phase flows has been presented. The unsteady model was shown to have limitations when it comes to the accurate measurement of the unsteady fluid forces. Careful consideration of not only the dimensionless parameters but also nonlinear effects is needed.

A comparison of the stability analysis results with experimental measurements shows that the quasi-steady model can give a reasonable estimate of the instability velocity as well as the inter-tube dynamics. This model therefore holds potential for two-phase flow applications. There are, however, remaining challenges before the quasi-steady model can be fully implemented. In particular the need for more work to understand the flow itself is highlighted. Several researchers have already proposed separated flow models which hold promise for the quantification of the two-phase fluid forces. However, it is not clear yet, whether unsteady fluid forces, practically useful for a stability analysis, can be obtained.

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