Journal of Fluids and Structures (1998) **12,** 17–32

THE INFLUENCE OF TRIP-WIRES ON THE FLUID-DAMPING-CONTROLLED INSTABILITY OF A FLEXIBLE TUBE IN A BUNDLE

O. ROMBERG AND K. POPP

Institute of Mechanics, University of Hannover, Appelstrasse 11, 30167 Hannover, Germany

(Received 12 August 1996 and in revised form 29 August 1997)

This paper reports on experimental investigations concerning the influence of disturbed flow on the stability behaviour of normal and rotated triangular tube arrays of different pitch-to-diameter ratios as well as of in-line square arrays. The excitation is due to air cross-flow in a wind tunnel. The experimental apparatus allows the measurement of the stability boundaries of a fully flexible bundle as well as of single flexibly mounted tubes with variable equilibrium position in otherwise fixed arrays as a function of the mass-damping parameter δ_r and the reduced gap velocity V_r. A disturbance of the flow channels between the tubes is achieved by application of thin Prandtl trip-wires with a diameter of $\frac{1}{80}$ of the tube diameter on the top and the bottom of each tube. In most of the cases this leads to a shift of the stability boundaries to higher reduced gap velocities or even to stability in the entire parameter region, depending on the bundle configuration and equilibrium position. To understand these effects a simultaneous flow visualization based on the laser-light-sheet procedure has been carried out.

1. INTRODUCTION

IN HEAT-EXCHANGER TUBE ARRAYS SUBJECTED TO CROSS-FLOW fluidelastic instability is a dangerous excitation mechanism. Because of the resulting large tube amplitudes this phenomenon must be avoided in any case. To represent the stability behaviour, Connors (1970) introduced a diagram which shows the stability boundaries as a function of the mass-damping parameter $\delta_r = \mu\delta/(\rho d^2)$ and the reduced gap velocity $V_r = U/(f_1 d)$. This standard stability diagram gives a general idea of the stability behaviour of tube arrays in cross-flow which is essential for heat-exchanger design. Since a reliable theoretical model is lacking, an experimental investigation of the stability boundaries is required. In Weaver & Fitzpatrick (1987) and Chen (1984) an overview is given of the stability behaviour of tube bundles subjected to cross-flow by means of Connors diagrams.

Fluidelastic instability appears in two different mechanisms: as fluid-damping-controlled (galloping) and as fluidelastic-stiffness-controlled instability, cf. Chen (1983). The galloping mechanism generally results in tube vibrations in the cross-flow direction. For the tube excitation those components of the fluid force are important which are proportional to the tube velocity. In the case of the fluidelastic-stiffness-controlled mechanism the instability results from coupling effects of several tubes in an array by the fluid. The fluid force terms which depend on the displacement of a tube and its neighbours are decisive. Here, the stability investigations require a fully flexible bundle of tubes.

0889-9746/97/010017 + 16 $25.00/fl970121

Which of these two mechanisms is dominant depends on the configuration of the tube array as well as on the fluid density. It is also possible that a combination of the two effects occurs. In the case of the fluid-damping-controlled instability, the equilibrium position of a single flexibly mounted tube becomes unstable. The problem of analysing the stability behaviour of a tube array by investigating only a single flexibly mounted tube in an otherwise fixed row or array is discussed in the literature; cf., for example, Price & Païdoussis (1986). The authors remark that any analysis which attempts to predict the stability behaviour of a complete array of flexible cylinders must take into account the tube coupling and, thus, no theory can be based on a single-flexible-cylinder analysis.

However, the mechanism of fluid-damping-controlled instability (galloping) can be *isolated* using a single flexibly mounted tube in an otherwise fixed array. Moreover, for certain array configurations, where the galloping mechanism is dominant, there is a coincidence of the stability boundaries with that of a fully flexible bundle. Thus, with restrictions, the stability of a fully flexible bundle can be checked by the stability of a single flexibly mounted tube in an otherwise fixed array; cf. Lever & Weaver (1986) and Austermann & Popp (1995). In the last mentioned reference, a comparison of the stability boundaries of one single mounted tube in an otherwise fixed array with that of a fully flexible bundle can be found. The agreement is very good for the rotated triangular tube array ($P/d = 1{\cdot}375$) as well as for the in-line square array ($P/d = 1{\cdot}25$).

Simple analytical models to describe the dynamical behaviour of tube bundles which require no, or only limited, experimental data are rare. For example Païdoussis, Mavriplis & Price (1984) determined the fluid forces from potential theory. Another theoretical model that describes the stability boundaries with respect to the fluid-damping-controlled mechanism is introduced by Lever & Weaver (1982). This analytical model is based on fully developed nonstationary flow channels between the tubes which cause instability. Therefore, the aim of the present study is to disturb these flow channels by trip-wires without influence on the flow capacity and to investigate the influence on the stability behaviour. The first documented attempt to *disturb* the flow field around rigid bodies by using trip-wires is due to Prandtl (1914). He put a thin wire on the surface of a ball and found a tremendous change of the flow detachement due to disturbances of the boundary layer. Later Kraemer (1959) investigated the effects of a trip-wire pasted on a plate, on a single cylinder and on other profiles. Other authors tried to find the optimal position of the trip-wire on the surface for a minimum drag coefficient of the body; cf. Fage & Warsap (1929) or Pearcey, Cash & Salter (1982). Some results showing the influence of the wire diameter have been presented by James & Truong (1972). Moreover, they investigated the change of the boundary layer by using hot-wire anemometers. Heinecke (1978) pasted trip-wires on an in-line square tube array subjected to cross-flow. He investigated the stability behaviour and found a suppression of high amplitudes. Furthermore, Aiba (1992) showed that the heat transmission of a single tube increases by about 20% if a thin wire is pasted at a certain position on its surface.

2. FLOW CHANNELS WITHIN A TUBE ARRAY

Figure 1 shows the fully developed nonstationary flow channels for a rotated triangular tube configuration assumed by Weaver & Yetisir (1988). These channels are essential for the "wavy wall rigid channel model" introduced by Lever & Weaver (1982). This simple linear analytical model provides the stability boundaries of a flexibly mounted tube in an

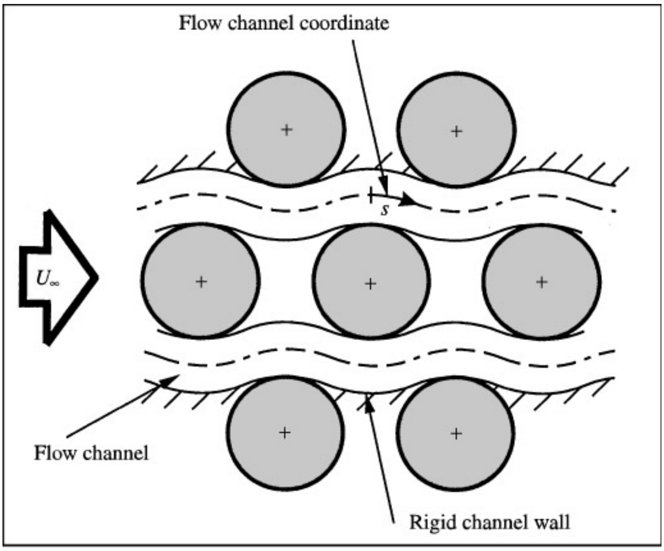

Figure 1. Flow pattern in the "wavy wall rigid channel model", by Weaver & Yetisir (1988).

otherwise fixed array in the form of

$$\delta_r = F(V_r). \tag{1}$$

The model assumes an unsteady cross-section $A(s, t)$ of a one-dimensional flow channel. The nonstationary continuity equation yields the flow velocity $u(s, t)$ and the nonstationary Bernoulli equation provides the pressure distribution $p(s, t)$. The integration over the pressure distribution $p(s, t)$ on the tube surface delivers the fluid force for the equation of motion of the tube. Here, the locations of flow-attachment and flow-separation are decisive parameters. If the term of the total damping disappears, the stability boundary of the tube is reached. This results in equation (1).

3. EXPERIMENTAL APPARATUS

The experimental investigations were carried out with both apparatuses used by Andjelić & Popp (1989) as well as by Austermann & Popp (1995).

The arrays consist of aluminium tubes with an outside diameter of $d = 80$ mm and a length of $l = 800$ mm. The arrays are mounted within the test-section of a wind tunnel. The side walls of the test-section allow the realization of the tube patterns which are commonly used in heat exchangers; see also Figure 2 and Table 1.

The coincidence of the stability boundaries of a single flexibly mounted tube in an otherwise fixed array with that of a fully flexible bundle is a matter of fact for certain tube configurations, cf. Austermann & Popp (1995). Therefore, with respect to the rotated triangular arrays, $P/d = 1{\cdot}375$ and $P/d = 1{\cdot}25$ and the in-line square array, $P/d = 1{\cdot}25$, only one flexibly mounted tube in an otherwise fixed bundle has been investigated. In the experiments it is possible to vary row number, equilibrium position and damping of the flexible tube.

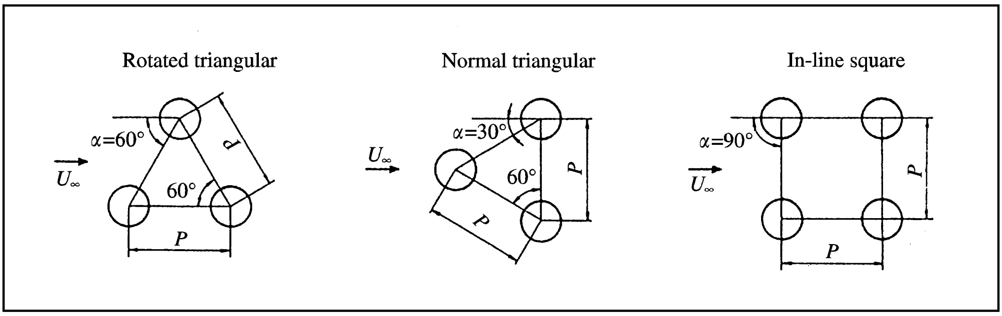

Figure 2. Tube configurations in heat exchangers investigated here.

TABLE 1
Tube configurations investigated in this paper

Symbol	Tube array	P/d	Experimental set-up
△	Rotated triangular	1·375	One flexible tube
△	Rotated triangular	1·25	One flexible tube
◁	Normal triangular	1·25	Fully flexible bundle
□	In-line square	1·25	One flexible tube

With respect to the rotated triangular arrays, the tested configuration consists of six rows of 15 cylinders altogether and six half-tubes. For the investigations of the in-line square array, a bundle of 20 tubes and eight half-tubes has been used.

It has been shown that the stability boundaries for a fully flexible normal triangular array do not coincide with that of one flexibly mounted tube within a fixed array; cf. Austermann & Popp (1995). Therefore, the investigations with respect to the normal triangular array ($P/d = 1{\cdot}25$) are carried out using a fully flexible bundle of 18 flexibly mounted tubes (and four fixed half-tubes) where nine of them have linear iso-viscoelastic mountings and variable damping. The tube motions in both apparatuses are determined by a set of strain gauges; cf. Andjelić & Popp (1989) and Austermann & Popp (1995).

To determine the relation between the upstream velocity U_∞ and the gap velocity U, the basic array configurations shown in Figure 2 have to be considered. Applying the continuity equation to normal triangular arrays and in-line square arrays it yields

$$U = U_\infty P/(P - d). \tag{2}$$

For the rotated triangular pattern, the relation

$$U = U_\infty P \sin\alpha/(P - d) \tag{3}$$

is used, where α denotes the relative flow angle; cf. Figure 2.

To disturb the flow channels between the tubes (see Figure 1), each tube of the array has been equipped with thin Prandtl trip-wires on the surface, parallel to its longitudinal axis. Some preliminary investigations concerning the position and the diameter of the wires gave optimal conditions for the stability behaviour of the tubes and the influence on flow capacity. It has been found that a trip-wire diameter of $\frac{1}{80}$ of the tube diameter is enough to get a strong influence on the stability behaviour of the tube. In this case, the influence on the gap velocity U as well as the wire mass can be neglected.

The trip-wires are pasted at the top and the bottom of each tube. This is a compromise with respect to a possible application of this damping phenomenon in real heat exchangers.

4. FLOW VISUALIZATION

To investigate the flow channels that should be disturbed and to make the effect of the wires on the fluid visible, a flow visualization has been carried out on the same experimental set-ups. A fog made of water and glycerol has been used as visible medium. The fog has been put into the air of the wind tunnel far upstream of the working section.

Figure 3 shows schematically the experimental set-up for the flow visualization based on the laser-light-sheet procedure. The visualization has been carried out for all mentioned tube array configurations at Reynolds numbers in the range of 1000–100 000. Distinct flow channels have been found only for *aligned* array configurations.

The results are documented in video films and photographs. Figure 4 shows the undisturbed flow pattern for a rotated triangular tube array with $P/d = 1{\cdot}375$ scanned out of a film. In the middle of the lower half of Figure 4 the tube in the critical third row can be seen. The photo shows the free undisturbed flow channel that causes fluid-damping-controlled instability; cf. Lever & Weaver (1982, 1986).

Figure 5 shows the corresponding disturbed flow, where trip-wires have been pasted on each tube in the bundle. On the surface of the third row, one of the trip-wires can be seen which influences the flow channel visibly. The flow seems to be more turbulent as well as more attached. The corresponding film shows also the stabilization of an oscillating tube due to pasted trip-wires.

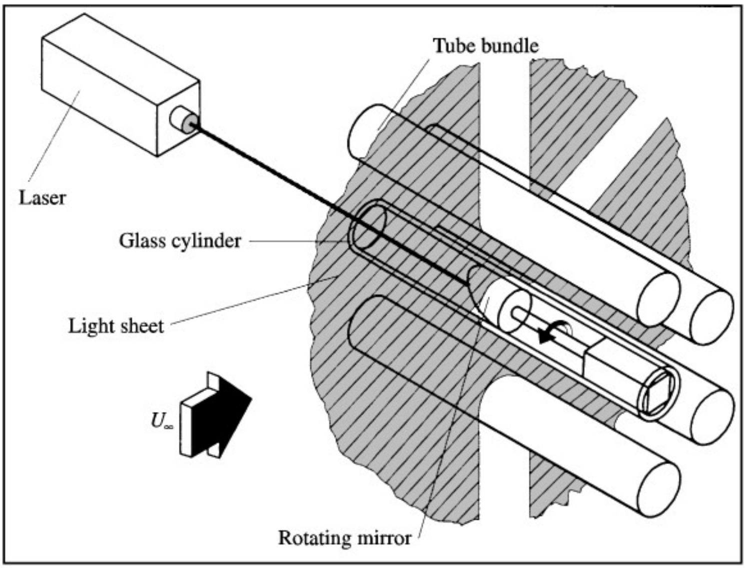

Figure 3. Schematic illustration of the laser-light-sheet procedure.

Figure 4. Visualization of the flow channel in the first four rows of a rotated triangular array with a pitch-to-diameter ratio $P/d = 1{\cdot}375$ for *undisturbed flow*; Re $\sim$ 25 000.

5. INFLUENCE ON THE STABILITY BEHAVIOUR

A reliable determination of stability boundaries demands the exact knowledge of the vibration behaviour of the system considered and requires a stability criterion; cf. Chen (1988). In this study the amplitude criterion used also by Austermann & Popp (1995) has been applied. The stability is investigated considering the amplitude behaviour depending on the reduced gap velocity V_r for a fixed mass-damping parameter. A sudden change to large amplitudes characterizes the stability boundary. For more details see Austermann & Popp (1995). In this study four different tube configurations have been investigated; see Table 1.

In the diagrams the symbols of the first column of Table 1 have been used. For the rotated triangular array and the in-line square array, different mid-point positions of the flexibly mounted tube in the otherwise fixed array have been adjusted to check the sensitivity to geometry changes.

5.1. Rotated Triangular Array ($P/d = 1{\cdot}375$ and $P/d = 1{\cdot}25$)

We start with the investigation of the rotated triangular array with $P/d = 1{\cdot}375$. Figure 6 shows the amplitude behaviour of a single flexibly mounted tube in the third row in an otherwise fixed array with and without flow disturbance by trip-wires.

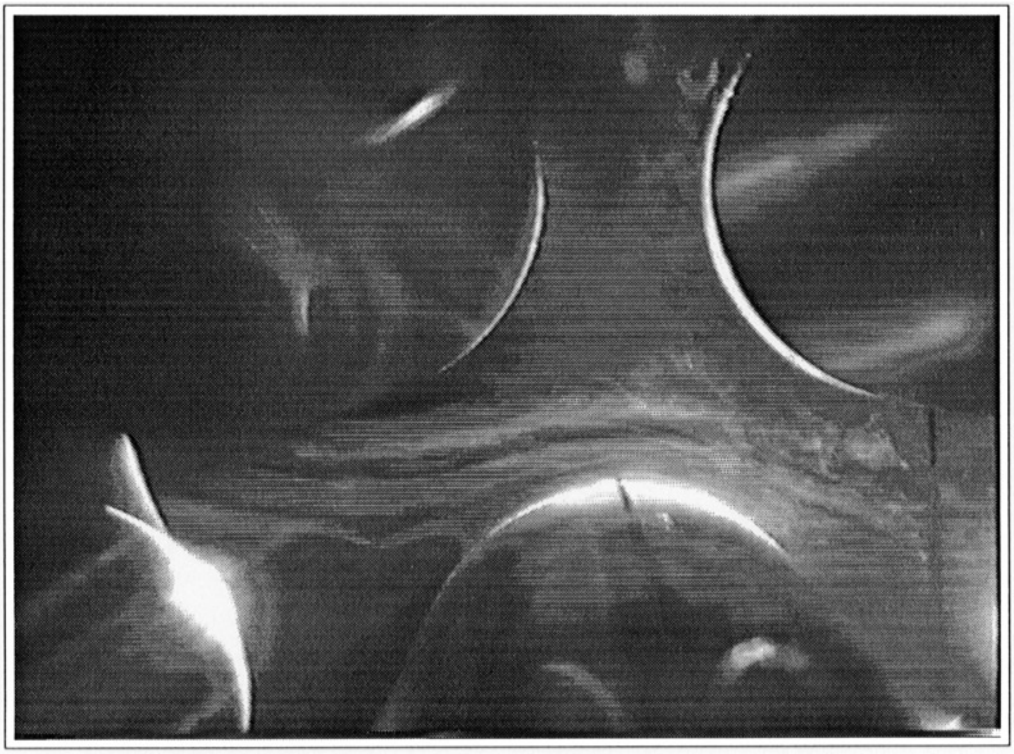

Figure 5. Visualization of the flow channel in the first four rows of a rotated triangular array with a pitch-to-diameter ratio $P/d = 1{\cdot}375$ for *disturbed flow* due to trip-wires; Re $\sim 25\,000$, $\delta_r = 8{\cdot}2$.

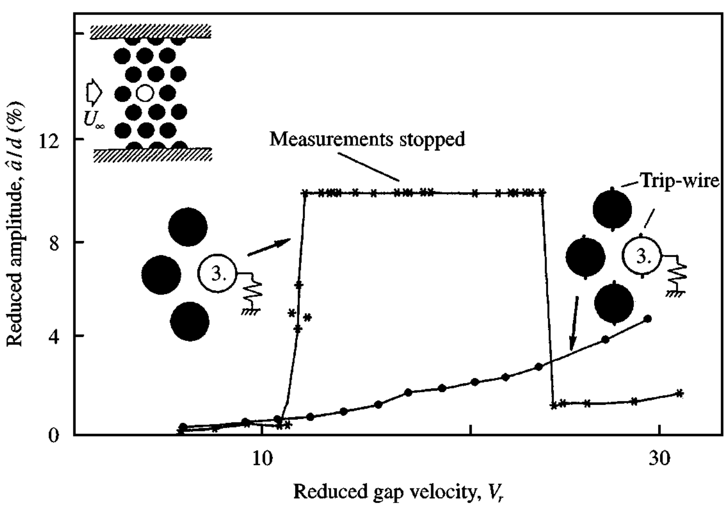

Figure 6. Amplitude of a single flexibly mounted tube in an otherwise fixed array for tubes with and without trip-wires, as a function of V_r.

The large amplitudes of the tube without trip-wires are suppressed by thin trip-wires pasted on the top and the bottom of each tube. Figure 7 shows the measured reduced amplitudes for undisturbed flow as a function of the reduced gap velocity V_r and the mass-damping parameter δ_r for the same tube and ideal geometry. In the stable region the tube moves with small amplitudes in cross- and in-flow direction (turbulent buffeting). In the unstable mode the tube executes galloping motions exclusively in cross-flow direction. To protect the experimental apparatus the measurements have been stopped if the tube reaches a reduced amplitude of about 12%. The measured amplitude behaviour corresponds to the results of Austermann & Popp (1995).

After the application of the described thin Prandtl trip-wires on the same experimental set-up with the same array configuration and parameters, the system shows the amplitude behaviour presented in Figure 8. It can easily be seen that the unstable mode is fully suppressed. Small distortions of the trip-wire position due to tube rotations lead to the same stabilization effect.

However, if the trip-wires were pasted solely on the single flexible tube, this leads to a slight shift of the stability boundary to higher reduced gap velocities only, but not to total stability. The trip-wires pasted on the tubes which lie upstream to the test tube have much more influence.

In Figure 5 it can be seen that the flow with trip-wires seems to be more attached compared with Figure 4. However, a calculation using the Lever & Weaver-model with changed geometry parameters due to trip-wires does not show this trend of stabilization.

The investigations were carried out at the first four rows of the tube array, but the mentioned third row is the critical one in the case of undisturbed flow. This can also be seen from the stability diagram presented by Austermann & Popp (1995) for the same tube configuration; cf. Figure 9. In this case, an array with an ideal geometry is most sensitive to fluidelastic instability. In the critical third row, not only do the largest amplitudes occur but also the smallest values of the critical reduced gap velocity are found.

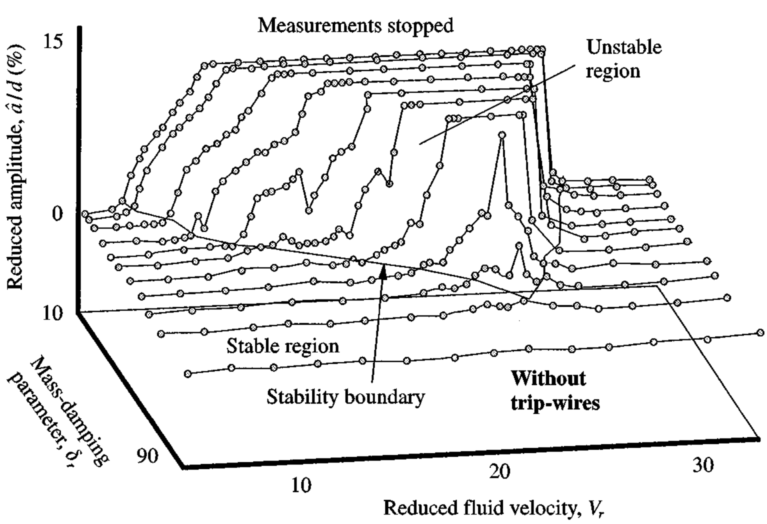

Figure 7. Measured reduced amplitudes as a function of V_r and δ_r for one single flexibly mounted tube in the critical third row of an otherwise fixed array with ideal geometry, without trip-wires.

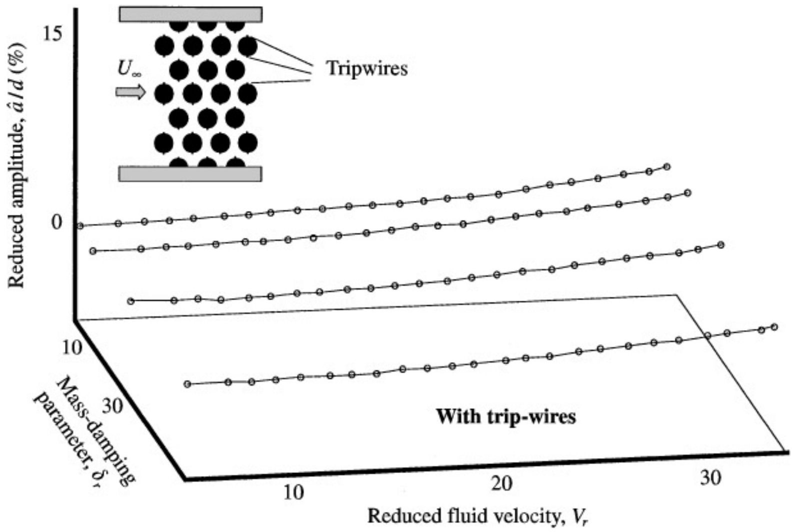

Figure 8. Measured reduced amplitudes as a function of V_r and δ_r for one single flexibly mounted tube in the critical third row of an otherwise fixed array with ideal geometry, with trip-wires.

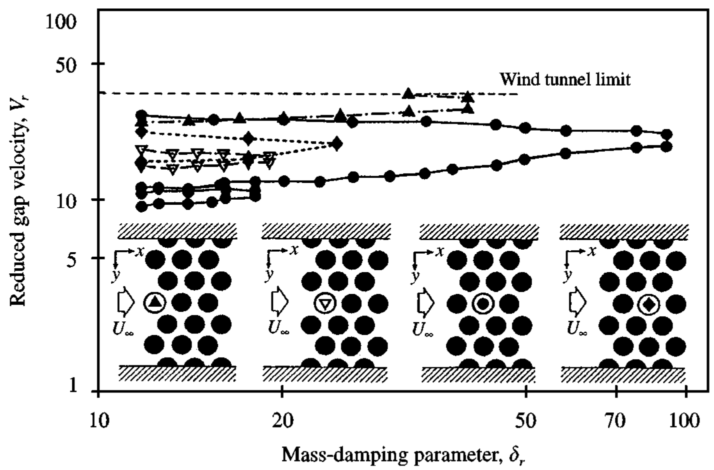

Figure 9. Stability diagram for one flexibly mounted tube in an otherwise fixed rotated triangular array ($P/d = 1{\cdot}375$), without tripwires, from Austermann & Popp (1995).

Figure 10 shows the stability diagram for the array configuration considered in Figure 9, but with trip-wires pasted on each tube. For very small values of the mass-damping parameter δ_r only the first row becomes unstable. The stability boundaries of the second, third (see also Figures 7 and 8) and fourth row disappear for the ideal geometry of the array. To investigate the sensitivity of the stability boundaries with respect to the tube geometry, the mid-point position of the flexible tube has been varied. Figure 11 shows the applied shifts for a pitch-to-diameter ratio of $P/d = 1{\cdot}375$. Only at high shifts of the equilibrium position (20% of the gap or $\pm$ 6 mm) definite stability boundaries could be found for the

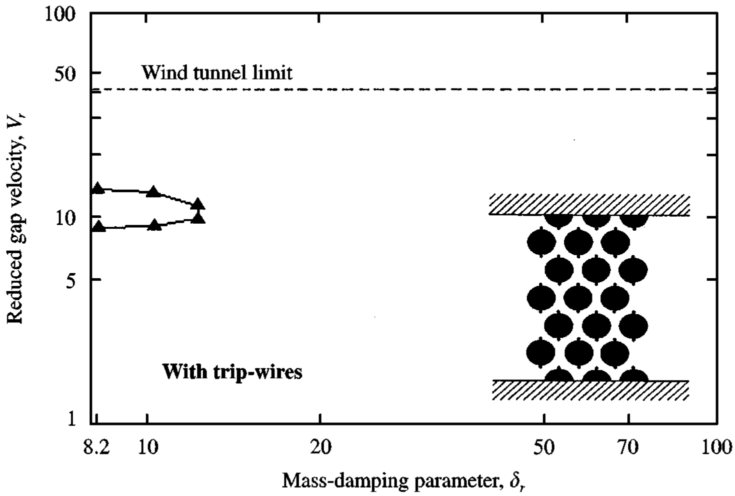

Figure 10. Stability diagram for one flexibly mounted tube in an otherwise fixed rotated triangular array ($P/d = 1{\cdot}375$), with tripwires.

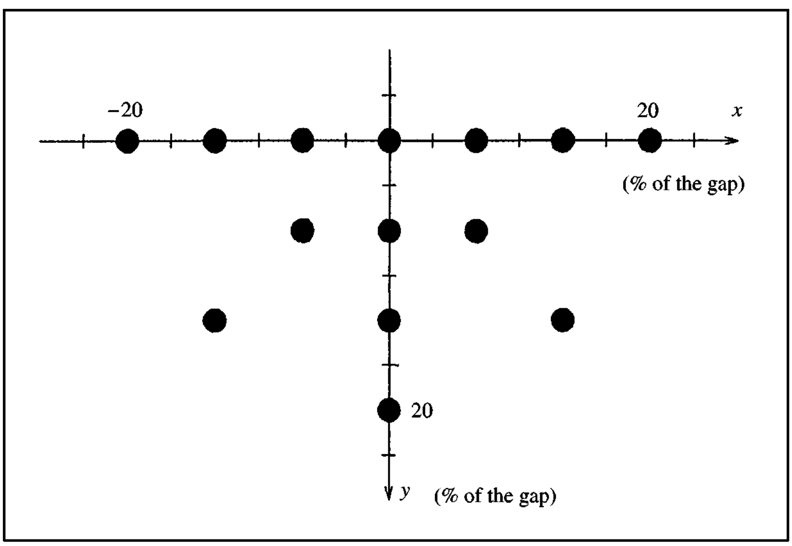

Figure 11. Investigated shifts of the equilibrium position of the flexible tube; rotated triangular array $P/d = 1{\cdot}375$.

first two rows; see Figure 12. The third and fourth row remained stable for almost all considered shifts of the equilibrium position.

The trip-wires on the surfaces of the tubes do not suppress the unstable behaviour generally. A reduction of the pitch-to-diameter ratio to $P/d = 1{\cdot}25$ leads in some cases to a decreased critical gap velocity as shown in the following. For an ideal array geometry with $P/d = 1{\cdot}25$ and undisturbed flow, only a flexibly mounted tube in the first row becomes unstable, while a free tube located in the second, third and fourth row shows stochastic motions due to turbulent buffeting. The third row becomes unstable only for a shift of the equilibrium position; see Austermann & Popp (1995) and Figure 13.

Figure 14 shows the stability diagram of the same array with ideal geometry and pasted trip-wires. It can be seen that the stability boundary of the first row is decreased compared with Figure 13. Additionally, a stability boundary for a tube in the second row occurs, with finite amplitudes in both the streamwise and cross-flow directions.

In contrast to the stability behaviour due to the undisturbed flow, tubes in the third row are stable for all investigated shifts of the equilibrium position. But tubes in the fourth row show a stability boundary at small mass-damping parameters and high reduced gap velocities.

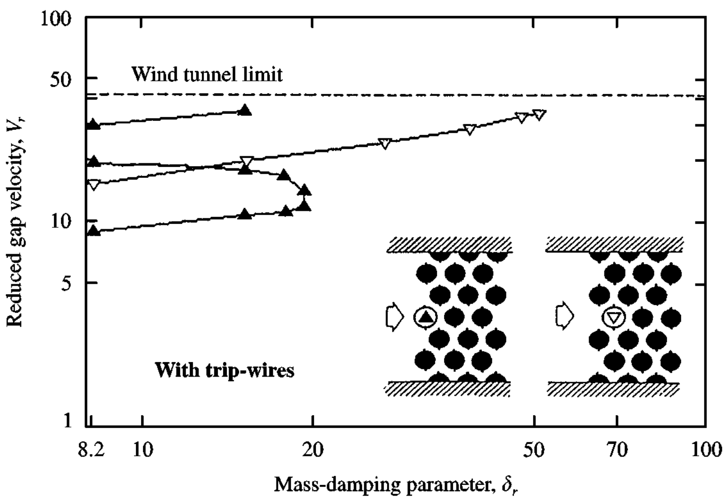

Figure 12. Stability diagram for one flexibly mounted tube in an otherwise fixed rotated triangular array ($P/d = 1{\cdot}375$) with trip-wires and a shift of the equilibrium position of 20% in in-flow direction ($\Delta x = 6$ mm) for the *first row* and 20% in cross-flow direction ($\Delta y = 6$ mm) for the *second row.*

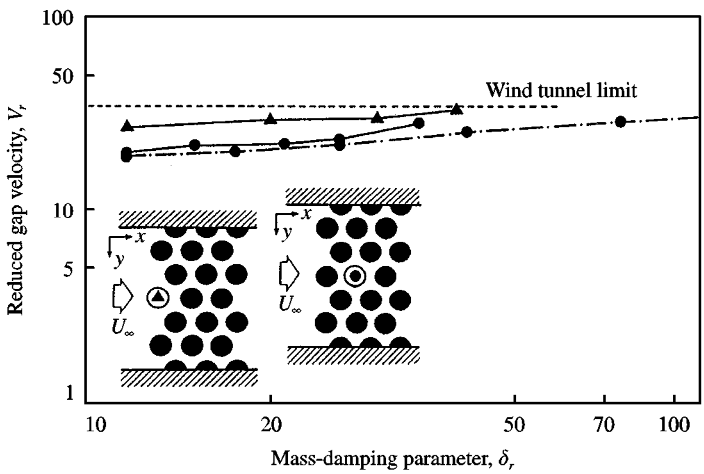

Figure 13. Stability diagram for one flexibly mounted tube in an otherwise fixed rotated triangular array ($P/d = 1{\cdot}25$) for ideal geometry and shifts of the equilibrium position of the third row, without trip-wires, from Austermann & Popp (1995): –●–, shift in equilibrium position $\Delta x = 2$ mm, $\Delta y = 0$; –·–●–·–, $\Delta x = 4$ mm; $\Delta y = 0$.

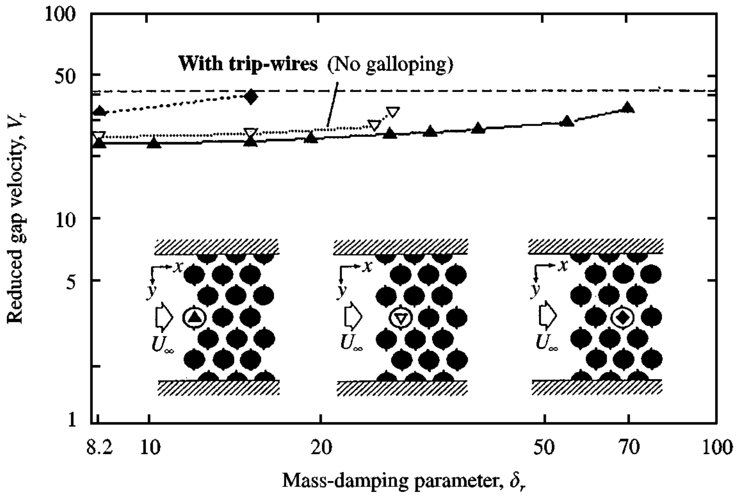

Figure 14. Stability diagram for one flexibly mounted tube in an otherwise fixed rotated triangular array ($P/d = 1{\cdot}25$) for ideal geometry, with trip-wires.

The investigations of varied tube mid-point positions for the array with $P/d = 1{\cdot}25$ were limited to 10% of the gap or ± 2 mm in the x- and y-direction.

For the first row there is no influence on the stability behaviour for shifts of the equilibrium position and pasted trip-wires. The tube moves exclusively in the cross-flow direction. For tubes in the second row the stability behaviour reacts sensitively upon geometrical changes. Thus, for tube arrays with a pitch-to-diameter ratio of $P/d = 1{\cdot}25$ there is an influence but not a stabilization by flow disturbances due to trip-wires. This holds for arrays with an ideal geometry, as well as for shifts of the equilibrium position.

5.2. In-Line Square Array ($P/d = 1{\cdot}25$)

If a tube is flexibly mounted in the first or third row of an in-line square array with undisturbed flow, only stochastic tube motions (turbulent buffeting) occur in the range of parameters and shifts of the equilibrium position investigated. Also, for a tube in the second row with an ideal geometry, only limit-cycle motions with very small amplitudes can be observed; cf. Austermann & Popp (1995).

A shift of the equilibrium position results in increasing amplitudes. Figure 15 presents two different tube positions where the array geometry is disordered. The application of trip-wires yields a suppression of fluidelastic instability in the range of parameters investigated. No stability boundary has been found, also for the ideal geometry. However, the turbulent buffeting is more pronounced, as in the case without trip-wires.

Figure 16 presents the amplitude behaviour in the case of tubes with trip-wires for several shifts of the equilibrium position up to 20% of the gap or ± 4 mm.

5.3. Normal Triangular Array ($P/d = 1{\cdot}25$)

In this case, the investigations were carried out using a fully flexible bundle, because there is no sufficient coincidence of the stability behaviour with that of a single flexibly mounted

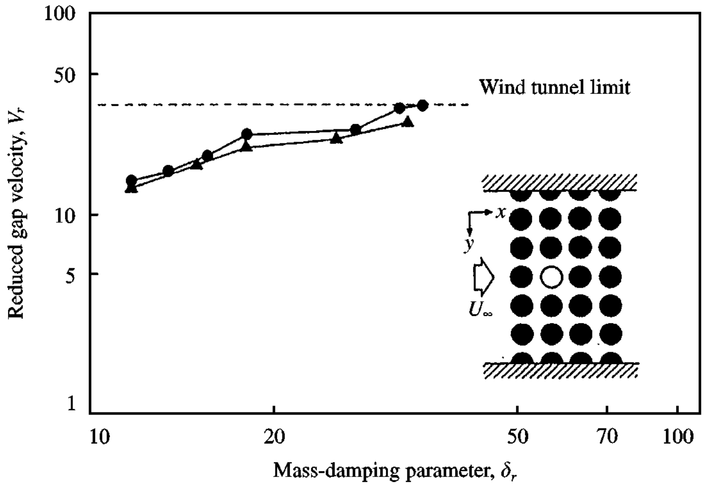

Figure 15. Stability diagram for one flexibly mounted tube in the second row of an otherwise fixed in-line square array ($P/d = 1{\cdot}25$) for shifts of the equilibrium position, without tripwires, from Austermann & Popp (1995): ●, $\Delta x = -3$ mm, $\Delta y = 0$; ▲, $\Delta x = 0$, $\Delta y = -3$ mm.

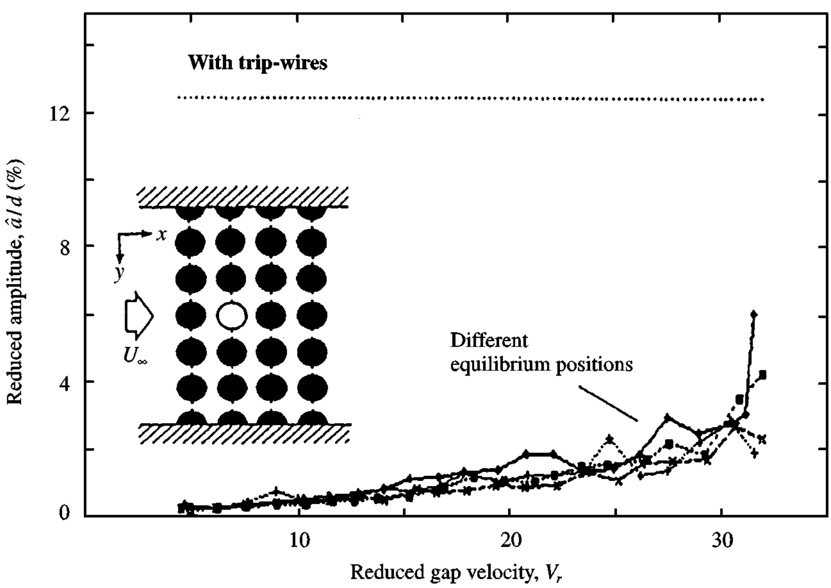

Figure 16. Measured reduced amplitude as a function of V_r for one flexibly mounted tube in the second row of an otherwise fixed in-line square array ($P/d = 1{\cdot}25$) for different shifts of the equilibrium position, with trip-wires, $\delta_r = 8{\cdot}2$.

tube in an otherwise fixed array. Austermann & Popp 1995. Note, that it is generally assumed that for this configuration the fluid-damping-controlled instability (galloping) is not the dominant mechanism. Here, the effect of fluidelastic coupling of several tubes is decisive.

The amplitude criterion mentioned above is applied for any flexibly mounted tube that becomes unstable. The measured stability boundary for the undisturbed flow corresponds to the stability behaviour measured by Andjelić & Popp (1989). Figure 17 shows that the

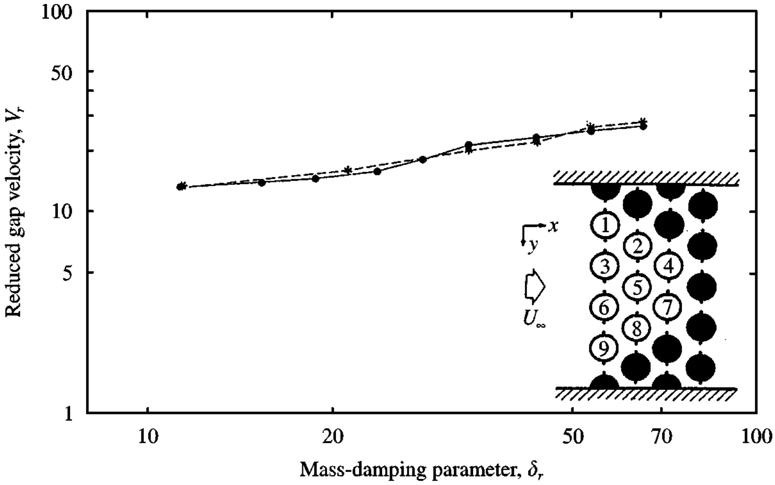

Figure 17. Stability diagram for a fully flexible tube bundle of a normal triangular array ($P/d = 1{\cdot}25$), with and without trip-wires: –●– without trip-wires; –*–, with trip-wires.

flow disturbance has no influence on the stability behaviour in this case. A possible explanation is a higher turbulence for undisturbed flow in this tube configuration as well as the predominance of another excitation mechanism. This results confirm the hypothesis that the fluid-damping-controlled instability caused by developed flow channels is not dominant for this tube configuration.

6. CONCLUSIONS

The motivation of the present investigation is to give an answer to the question, how do disturbances of the flow in tube bundles influence the stability of the tubes. Usually, fully developed nonstationary flow channels between the tubes are assumed which cause instability. These flow channels are the basic part of the well-known model introduced by Lever & Weaver (1982). This model is able to predict the stability boundaries for *a single flexibly mounted tube in an otherwise fixed array* under special assumptions. The qualitative agreement of measurements (Austermann & Popp 1995) with theoretical results based on this model leads to the question of the influence of disturbances of these channels on the stability behaviour.

To verify the existence of flow channels, a flow visualization for relevant Reynolds numbers and several tube-bundle configurations has been carried out. Distinct flow channels have been found only for aligned array configurations. As an example, in this paper the flow field of the rotated triangular array ($P/d = 1{\cdot}375$) for disturbed and undisturbed flow is shown. Here, the fluid-damping-controlled instability (galloping) is the dominant excitation mechanism.

Disturbances caused by trip-wires pasted on the surface of tubes have an influence on the stability behaviour of a single flexibly mounted tube in an otherwise fixed array depending on the bundle configuration. For a *rotated triangular tube array* with a pitch-to-diameter ratio $P/d = 1{\cdot}375$ and an *in-line square array* with a pitch-to-diameter ratio $P/d = 1{\cdot}25$ it has been found that the pasted trip-wires disturb the flow channels and have a significant stabilizing effect. However, for the *rotated triangular array* with a pitch-to-diameter ratio $P/d = 1{\cdot}25$ the wires can also cause instabilities for tubes in a certain row number and for shifts of the equilibrium position.

In case of a *fully flexible normal triangular tube array* with a pitch-to-diameter ratio $P/d = 1{\cdot}25$ the trip-wires have no influence on the stability behaviour.

The reasons for the different effects depending on the array configuration can be: (i) different dominant excitation mechanisms–fluid-damping-controlled (galloping) or fluidelastic-stiffness-controlled; (ii) different shapes of the flow channels; (iii) different sensitivities to changes of the geometry; (iv) different levels of self-induced turbulence; (v) different spatial correlations of the fluid forces.

With respect to the important last two items further experimental investigations are necessary. Ongoing research based on pressure measurements shows that the trip-wires seem to reduce the large spatial correlation (correlation length) of the fluid forces acting on the tube, while galloping occurs. In the authors' opinion it is too early to discuss the technical application of the effects described in this paper.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support for this research work by the DFG (Deutsche Forschungsgemeinschaft, contract number Po 136/17/1).

References

Aiba, S. 1992 Heat transfer around a circular cylinder with a single trip wire. In *Heat Transfer – Japanese Research*, Vol. 21, No. 5, pp. 466–482.

Andjelić, M. & Popp, K. 1989 Stability effects in a normal triangular cylinder array. *Journal of Fluids and Structures* **3,** 165–185.

Austermann, R. & Popp, K. 1995 Stability behaviour of a single flexible cylinder in rigid tube arrays of different geometry subjected to cross-flow. *Journal of Fluids and Structures* **9,** 303–322.

Chen, S. S. 1983 Instability mechanisms and stability criteria of a group of circular cylinders subjected to cross-flow. Part I: Theory *ASME Journal of Vibration, Acoustics, Stress and Reliability in Design* **105,** 51–58.

Chen, S. S. 1984 Guidelines for the instability flow velocity of tube arrays in crossflow *Journal of Sound and Vibration* **93,** 439–455.

Chen, S. S. 1988 Some issues concerning fluidelastic instability of a group of circular cylinders in crossflow. In *Proceedings of 1988 International Symposium on Flow Induced Vibration and Noise, Vol. 3: Flow-Induced Vibration and Noise in Cylinder Arrays* (eds M.P. Païdoussis, S. S. Chen & M. D. Bernstein), pp. 1–24. New York: ASME.

Connors, H. J. 1970 Fluidelastic vibration of tube arrays. In *Flow Induced Vibrations in Heat Exchangers* (ed. D. D. Reiff) pp. 42–56. New York: ASME.

Fage, A. & Warsap, J. 1929 The effects of turbulence and surface roughness on the drag of a circular cylinder. *Aeronautical Research Council R&M No. 1283.*

Heinecke, E. P. 1978 Fluid-elastic vibrations in heat exchangers with tubes in cross-flow. In *Proceedings International Conference on Vibration In Nuclear Plant Keswick, U.K. Session 2*: Flow induced vibrations in heat exchangers, Paper 2.4.

James, D. & Truong, Q.-S. 1972 Wind load on cylinder with spanwise protrusion. *ASCE Journal of the Engineering Mechanics Division* **1,** 72–81.

Kraemer, K. 1959 Umschlagmessungen hinter Stolperdrähten. In *Bericht 59/A/21, Aerodynamische Versuchsanstalt Göttingen*, Göttingen, Germany (in German).

Lever, J. H. & Weaver, D. S. 1982 A theoretical model for fluidelastic instability in heat exchanger tube bundles. *ASME Journal of Pressure Vessel Technology* **104,** 147–158.

Lever, J. H. & Weaver, D. S. 1986 On the stability of heat exchanger tube bundles. Part I: Modified theoretical model. *Journal of Sound and Vibration* **107,** 375–392.

Paidoussis, M. P., Mavriplis, D. & Price, S. J. 1984 A potential flow theory for the dynamics in cylinder arrays in cross-flow. *Journal of Fluid Mechanics* **146,** 227–252.

Pearcey, H., Cash, R. & Salter, I. 1982 Flow past circular cylinders: simulation of full-scale flows at model scale. NMI R 131 and OT-R-8208.

Prandtl, L. 1914 Der Luftwiderstand von Kugeln. In *Göttinger Nachrichten der Gesellschaft für Wissenschaften*, Klasse 1914, Göttingen, Germany, 177–190 (in German).

Price, S. J. & Paidoussis, M. P. 1986 A constrained-mode analysis of the fluid elastic instability of a double row of flexible circular cylinders subject to cross-flow: a theoretical investigation of system parameters. *Journal of Sound and Vibration* **105,** 121–142.

Weaver, D. S. & Fitzpatrick, J. A. 1987 A review of flow induced vibrations in heat exchanger. In *Proceedings BHRA Conference on Flow-Induced Vibrations* (ed. R. King), Bowness-on-Windermere, U.K. pp. 1–17.

Weaver, D. S. & Yetisir, M. 1988 On an unsteady theory for fluidelastic instability of heat exchanger tube arrays. In *Proceedings International Symposium on Flow-Induced Vibration and Noise*, Vol. 3: *Flow-Induced Vibration and Noise in Cylinder Arrays* (eds M. P. Païdoussis, S. S. Chen & M. D. Bernstein), pp. 181–195. New York: ASME.

APPENDIX: NOMENCLATURE

A	cross-section of the flow channel (m^2)
$\hat{a}$	peak amplitude (zero-to-peak) (m)
$\hat{a}/d$	reduced amplitude (%)
d	tube outside diameter, $d = 0{\cdot}08$ m
f_1	first natural tube frequency, $f_1 = 9{\cdot}3$ Hz
l	tube length, $l = 0{\cdot}8$ m
P	tube pitch (m)
p	pressure distribution (N/m^2)
Re	Reynolds number, $\mathrm{Re} = Ud/\nu$
t	time (s)
U_∞	undisturbed upstream velocity (m/s)
U	gap velocity (m/s)
u	fluid velocity in the flow channel (m/s)
V_r	reduced gap velocity, $V_r = U/(f_1 d)$
x	shift of tube in in-flow direction (% of the gap)
y	shift of tube in cross-flow direction (% of the gap)
α	relative angle of undisturbed flow (deg)
δ	logarithmic decrement of damping
δ_r	mass-damping parameter, $\delta_r = \mu\delta/(\rho d^2)$
μ	tube mass per unit length, $\mu = 3{\cdot}04$ kg/m
ν	kinematic viscosity, $\nu = 0{\cdot}151\ cm^2/s$
ρ	fluid density $\rho = 1{\cdot}197\ kg/m^3$