An overview of vortex shedding and acoustic resonance in tube arrays

D.S. Weaver*

Department of Mechanical Engineering, McMaster University, Hamilton, Ontario L8S 4L7, Canada

Abstract

This paper presents a brief overview of the state of knowledge of vorticity phenomena and acoustic resonance in heat exchanger tube arrays in cross-flow. The mechanics of the vortex shedding process are shown to be strongly dependent on tube array geometry and pitch ratio as well as location in the tube array and Reynolds number.

Keywords: Vortex shedding; Acoustic resonance; Heat exchanger tube arrays; Strouhal number

1. Introduction

Few topics in the field of flow-induced vibrations have been the subject of more confusion and controversy than 'vortex shedding' in tube arrays. While references to problems with heat exchangers in service date back to the early 1950s, the cause was still being debated 25 years later. This situation is very nicely summarized in the review paper by Païdoussis [1]. In describing the attempts to create charts of Strouhal numbers from existing data, Païdoussis states in characteristic humour 'these maps are quite intricate, displaying pockets of high S_{vs} (Strouhal numbers) in otherwise low-lying areas – resembling somewhat the map of Europe at the time of the Thirty Year's War.' He goes on to say that obviously '... circa 1978 there was not only a rather confused state of understanding of the unsteady fluid mechanics of interstitial flow in cylinder arrays, but also an incomplete and often contradictory data base available for practical design purposes.' Païdoussis then summarizes the existing approach to the design of heat exchangers against 'buffeting' and 'vortex shedding' and provides rationalization of the apparently conflicting explanations of these phenomena. Research in the last 20 years has resolved much of the confusion described by Païdoussis. A comprehensive review of the state of knowledge to 1993 was published by Weaver [2]. The present paper provides a brief overview of vortex shedding and acoustic resonance in heat exchanger tube arrays with emphasis on developments since 1993. Design guidance is presented as well as requirements for future research.

2. Vortex shedding mechanisms

One of the reasons for the confusion and apparently contradictory experimental data which marked the earlier research in this field is the huge variety of tube array geometries, pattern and pitch, in common use and the determining effect this has on the generation and evolution of vorticity. Typical 'standard' array geometries are shown in Fig. 1. It is important to note that pitch ratio definitions for staggered arrays are not consistent in the literature and that published Strouhal numbers may be based on either upstream velocity, V_u, or mean velocity in the gap between tubes, V_g, where

$$V_g = [P/P - D]V_u \tag{1}$$

2.1. Staggered arrays

By 1993, the evidence supporting the existence of alternate vortex shedding in staggered arrays was overwhelming [2]. Research since then has been directed towards understanding the complexities of the vortex shedding and how it is affected by location in the array, pitch ratio, and Reynolds number [3,4,5,6]. Basically, the flow development in staggered arrays creates different local flow velocity distributions and effective wake widths in the first few tube rows [3]. Thus, for a given

* Tel.: +1 (905) 525 9140; Fax: +1 (905) 572 7944; E-mail: weaverds@mcmaster.ca

Computational Fluid and Solid Mechanics 2005
K.J. Bathe (Editor)

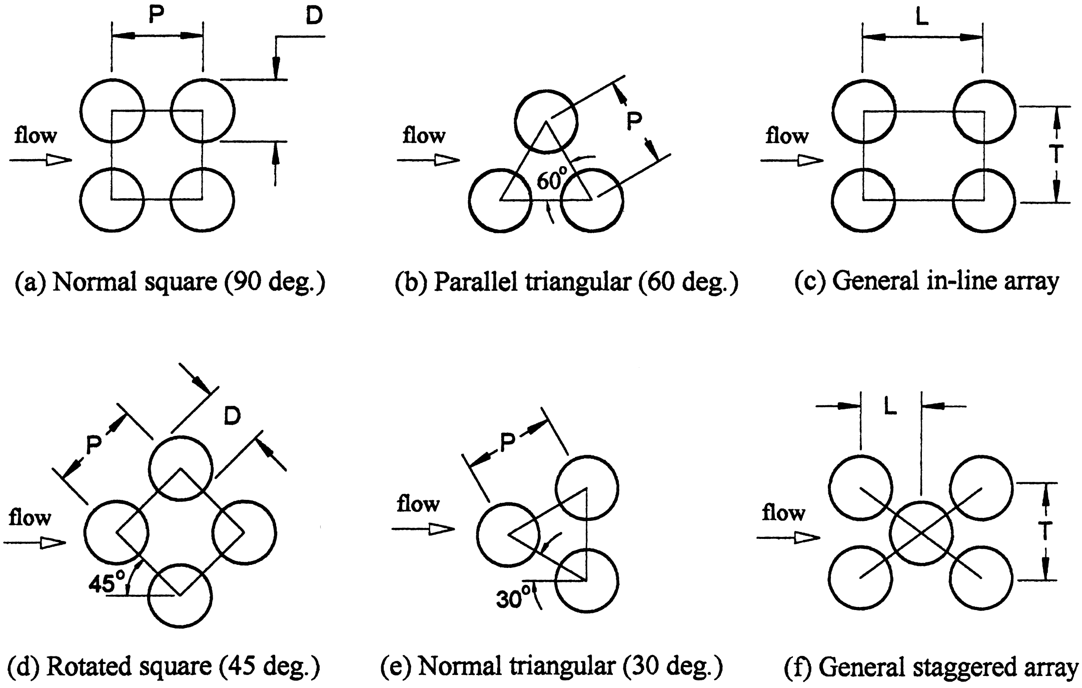

Fig. 1. Standard tube patterns and array geometry definitions.

upstream velocity, the frequency of vortex shedding observed behind the first and second tube rows is different, giving rise to multiple Strouhal numbers. The relative strength of the vortex shedding depends on pitch ratio, tube pattern and Reynolds number. It is characteristic of vortex shedding in staggered arrays that, in the absence of tube vibration or acoustic resonance, the vortices produced in the early tube rows become distorted, stretched out and dissipated as they pass subsequent tube rows. Thus, under non-resonant conditions, discrete vorticity peaks in the interstitial flow of staggered arrays are strongest in the early tube rows. Strouhal number data are plotted against pitch ratio for rotated square, normal triangular and parallel triangular arrays in Figs 2, 3 and 4 respectively. These graphs have been adapted from references [3], [5] and [6] respectively, and contain data from numerous sources in the literature (for details, see original references).

2.2. In-line tube arrays

In a remarkable series of papers [7,8,9], Ziada and Oengoren showed that vorticity phenomena in in-line tube arrays are fundamentally different from those in staggered arrays. The straight 'flow lanes' through in-line tube arrays permit the development of jets which exhibit symmetric vortex shedding behind the pairs of tubes on either side of the jet along the flow lane. Thus, in contrast to the wake instability in staggered arrays which dissipates with row depth, jet instability in in-line arrays tends to grow in strength with row depth. Also sharply contrasting with staggered arrays, the Strouhal numbers associated with jet instabilities in in-line arrays as measured at off-resonant conditions are not related to those observed under acoustic resonance conditions.

3. Effects of vortex shedding

3.1. Tube vibration

Theoretically, at least, when the frequency of vortex shedding in a tube array coincides with a tube natural frequency, resonance occurs. However, the lift coefficients tend to be small and no resonant tube vibration response is observed in gas flows [2]. The same is true in two-phase flows where even small amounts of the vapour phase suppresses vortex shedding [10]. In liquid flows, some resonance response has been observed in the early tube rows of in-line arrays [11] and normal triangular arrays [12]. However, the author is not aware of any case where tube failures in a heat exchanger have been proven to have been caused by vortex shedding resonance.

3.2. Acoustic resonance

The vast majority of acoustic resonance problems in heat exchangers are associated with acoustic modes that are transverse to both the tube axes and the direction of flow. Defining this dimension as the duct width, W, the lowest acoustic natural frequency, f_{a1}, will have a wavelength $2W$. The nth duct acoustic natural frequency is then

$$f_{an} = \frac{nC_e}{2W}, n = 1, 2, 3... \tag{2}$$

where C_e is the equivalent speed of sound in the duct accounting for the presence of the tubes. Parker [13] computed C_e in terms of the volume fraction of the duct filled by the tubes, σ, and the speed of sound in an open duct, C, as

$$C_e = C/(1+\sigma)^{1/2} \tag{3}$$

The actual sound speed in a tube array lies between C and C_e because of the spilling out and decay of the transverse acoustic mode into the duct upstream and downstream of the tube array [14,15].

In staggered tube arrays, the 'vortex shedding' is a wake instability which occurs for a constant Strouhal number(s), St, as measured at off-resonant conditions,

$$St = \frac{f_{vs}D}{V} \tag{4}$$

where f_{vs} is the frequency of vortex shedding and Strouhal number and flow velocity must consistently be defined as upstream or gap between tube values (see Eq. (1)). Acoustic resonance occurs at frequency coincidence, $f_{an} = f_{vs}$, and the velocity range for acoustic resonance in the nth mode, V_{crn}, is typically taken as ± 20 percent of the velocity at $f_{an} = f_{vs}$:

$$0.8\frac{f_{an}D}{st} \leq V_{crn} \leq 1.2\frac{f_{an}D}{St} \tag{5}$$

The appropriate Strouhal numbers can be obtained from maps such as Figs 2–4.

Unfortunately, in-line tube arrays and some parallel triangular arrays [6] do not lend themselves to such simple analysis since the symmetric jet instabilities in the flow lanes occurring at off-resonant conditions do not generate acoustic resonance. Rather, acoustic resonance in such arrays is associated with asymmetric wake instabilities which are usually not observed at off-resonant conditions [6,7,8,9]. Additionally, the onset velocity for acoustic resonance appears to be affected by damping, suggesting that the wake instability is self-excited and a unique acoustic Strouhal number may not exist. An alternative design approach uses the flow Mach

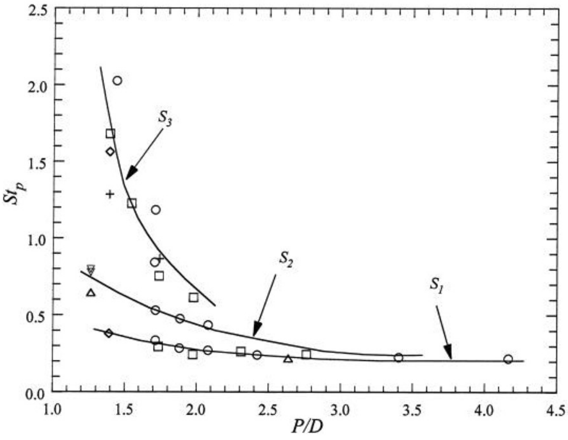

Fig. 2. Strouhal number versus pitch ratio for parallel triangular arrays (adapted from [6]).

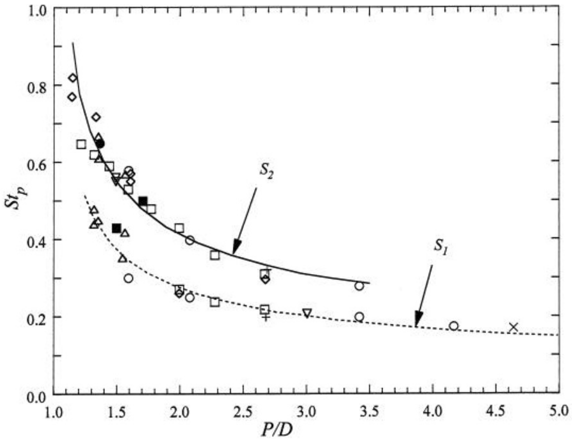

Fig. 3. Strouhal number versus pitch ratio for normal triangular arrays (adapted from [5]).

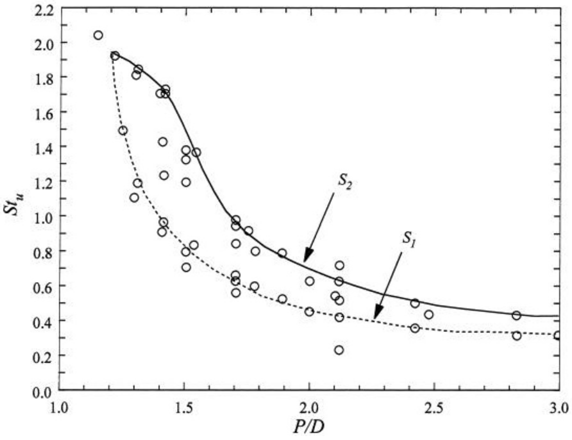

Fig. 4. Strouhal number based upon upstream flow velocity for rotated square arrays as a function of pitch ratio (adapted from [3]).

number and pressure drop across the array to predict the maximum acoustic pressure [16]. While this approach based on input energy appears to provide reasonable predictions, Eisinger et al. [17] show that none of the predictive methods are totally reliable. The problem is that frequency coincidence or energy input are not sufficient for the generation of acoustic resonance. Some measure of acoustic damping is also required and no reliable models exist. This is an important area for future research.

4. Finned tubes

In order to enhance heat transfer in modern heat exchangers, finned tubes are more commonly being used. They can take a variety of forms from integrally formed to spirally wound and welded serrated fins. Fin height and density are also parameters. The literature is fairly sparse and some of the results are conflicting. It appears that the effects of the fins on the vortex shedding around finned tubes can be approximately scaled using an equivalent tube diameter, D_e, based on total projected area as proposed by Mair et al. [18]:

$$D_e = \frac{1}{s}\left[(s-t)D + tD_f\right] \tag{6}$$

where s is the fin spacing, t is the fin thickness, D is the bare tube diameter and D_f is the fin diameter. Fins can also produce surprising effects such as enhancing vortex strength and correlation length [19], thereby generating more intense acoustic resonance. On the other hand, platen fins can eliminate vortex shedding but reduce the stability threshold for fluidelastic instability [20]. More research is required to understand the effects of various fin arrangements in tube arrays.

References

[1] Païdoussis MP. A review of flow-induced vibrations in reactors and reactor components. Nuclear Eng Design 1982;74:31–60.

[2] Weaver DS. Vortex shedding and acoustic resonance in heat exchanger tube arrays. In: Au-Yang MK, principal editor, ASME Technology for the 90s. ASME, 1993, pp. 776–810.

[3] Weaver DS, Lian HY, Huang XY. Vortex shedding in rotated square arrays. J Fluids Struct 1993;7:107–121.

[4] Polak DR, Weaver DS. Vortex shedding in normal triangular tube arrays. J Fluids Struct 1995;9:1–17.

[5] Oengoren A, Ziada S. An in-depth study of vortex shedding, acoustic resonance and turbulent forces in normal triangular tube arrays. J Fluids Struct 1998;12:717–758.

[6] Ziada S, Oengoren A. Flow periodicity and acoustic resonance in parallel triangle tube bundles. J Fluids Struct 2000;14:197–219.

[7] Ziada S, Oengoren A. Vorticity shedding and acoustic resonance in an in-line tube bundle, part 1: vorticity shedding. J Fluids Struct 1992;6:271–292.

[8] Oengoren A, Ziada S. Vorticity shedding and acoustic resonance in an in-line tube bundle, part II: acoustic resonance. J Fluids Struct 1992;6:293–309.

[9] Ziada S, Oengoren A. Vortex shedding in an in-line tube bundle with large tube spacings. J Fluids Struct 1993;7:661–687.

[10] Feenstra PA, Weaver DS, Nakamura T. Vortex shedding and fluidelastic instability in a normal square tube array excited by two-phase cross flow. J Fluids Struct 2003;17:793–811.

[11] Weaver DS, Abd-Rabbo A. A flow visualization study of a square array of tubes in water cross flow. ASME J Fluids Eng 1985;107:354–363.

[12] Weaver DS, Yeung HC. The effect of tube mass on the flow-induced response of various tube arrays in water. J Sound Vibr 1984;93:409–425.

[13] Parker R. Acoustic resonances in passages containing banks of heat exchanger tubes. J Sound Vibr 1987;57:245–260.

[14] Ziada S, Oengoren A, Buhlmann ET. On acoustical resonances in tube arrays. I. Experiments. J Fluids Struct 1989;3:293–314.

[15] Blevins RD. Acoustic modes of heat exchanger tube bundles. J Sound Vibr 1986;109:19–31.

[16] Blevins RD, Bressler MM. Experiments on acoustic resonance in heat exchanger tube bundles. J Sound Vibr 1993;164:503–533.

[17] Eisinger FL, Francis JT, Sullivan RE. Prediction of acoustic vibration in steam generator and heat exchanger tube banks. ASME J Pressure Vessel Tech 1996;118:221–236.

[18] Mair WA, Jones PDF, Palmer RKM. Vortex shedding from finned tubes. J Sound Vibr 1975;39:293–296.

[19] Jebodhsingh D, Ziada S, Weaver DS, Eisinger FL. The effects of fins on vortex shedding from a cylinder in cross flow. In: de Langre E, Axisa F, editors, Flow-Induced Vibration, Vol. II, Proc of the 8th International Conference on FIV, Paris, France, 2004, pp. 469–747.

[20] Weaver DS, Ziada S, Sun Z, Feenstra P. The effect of platen fins on the flow-induced vibrations of an in-line tube array. ASME J Pressure Vessel Tech 2001;123:437–441.