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INFLUENCE OF PITCH RATIO ON THE ACOUSTIC PROPERTIES OF TUBE BANKS

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In boilers and heat exchangers devices, tube banks are used to transfer heat. One of the commonly used arrangement in heat exchangers are staggered tube banks, which consists of tubes arranged in triangular array form. The tube banks are characterized by their longitudinal and transverse pitch ratios, which is the pitch-to- diameter ratio. Based on the pitch ratio the tube bank is considered either a compact or a widely spaced tube bank arrangement. The tube bank may cause acoustic instabilities in the system. In this study, an investigation was performed to analyse the aero-acoustic properties of tube bank samples. Experiments were conducted for three staggered tube bank samples with pitch ratio varying from 1.2 (compact arrangement) to 2 (widely spaced arrangement). Passive properties determine the sound propagation through the system, while the active acoustic properties describe the acoustic source in the system. The attention is in this paper on the passive acoustic properties of staggered tube banks. The experimental results consist of scattering coefficients for samples with different pitch ratios and power balance for all three samples which are compared to see the pitch ratio effect on the acoustic properties.

Keywords: Acoustic instabilities, Staggered tube bank, Pitch ratio, Passive acoustic properties.

1. Introduction

Heat exchanger tubes are an integral part of many combustion systems and automotive radiators. A tube bank is often used to denote crossflow along with the tubes and tube bundle to longitudinal flow across the tubes. Plain tubes are an addition to automotive air conditioning, evaporators, and condensers[1]. In an aeroacoustic instability context, tube banks can act as both acoustic absorbers and generators based on the tube bank pattern and flow conditions. Potentially, tube bank configurations could be designed to control thermoacoustic instabilities in combustion systems and aeroacoustic instabilities in automotive applications.

The tube bank configurations are characterized by the transverse and longitudinal pitch-to-diameter ratio which is also called the pitch ratio. The Tube bank pitch ratio is the most common parameter to vary and the pitch ratio is an important parameter in the design of tube bank structures. Based on the pitch ratio the tube bank is considered either compact or widely spaced. Based on the volume flow in the main duct, for widely spaced tube banks, the flow across the tubes is non-turbulent and for compact tube banks, the flow is mainly turbulent. The instability caused by the flow in combination with sound creates a feedback loop and creates aeroacoustics instabilities.

Literature on the pressure drop across plain and finned tube bundles in heat exchangers with experimental measurements was reviewed [2] A relationship was established between the heat transfer and the pressure drop. The strength of the turbulence within the bundle depends on the velocity of the air and the tube spacing. Thus, these parameters have a strong effect on the pressure drop in the tube bank. When the transverse pitch of the tube was changed, the existence of a clear influence on the pressure drop across the tube bank was observed [3]. Chen and Lai [4] studied the effect of pitch-to-diameter ratio and Reynolds number (Re) number, pressure drop, total drag, and friction drag. The ranges of the pitch-to-diameter ratio and Re number were 1.7–2.0 and 4–40, respectively. With varying pitch ratio there is a large variation in the pressure drop across the tube bank and creation of turbulence. This turbulence around tubes can generate noise from the turbulent flow. The aeroacoustic response of a single row of tubes, with and without cross-flow was analysed [5] by studying the acoustic properties of tubes from the scattering coefficients experimentally and theoretically.

From the earlier research, it can be seen that a lot of work has been performed with tube bank design in the field of fluid or airflow and heat transfer with the dependence of the pitch ratio of the tube bank. Some work has been performed on investigation of acoustic properties of tubes. There is a research gap concerning aeroacoustic instabilities and acoustic properties of tube bank with dependence on pitch ratio. In this paper, the research is focused on the effect of pitch ratio of the tube bank on the passive acoustic properties, like transmission and reflection coefficients.

2. Experimental Modelling

2.1 Tubebank Sample

One of the most commonly used tube bank pattern is the staggered arrangement, where tubes form triangular arrays. The pitch is defined as the shortest distance between two tubes. The pitch ratio (P/D) is the ratio of pitch to diameter of the tubes. In this paper, three configurations consisting of two rows of staggered tubes with 20mm diameter (D) and pitch ratios varying as: 1.2,1.4 and 2 has been used, seen in Fig. 1. A pitch ratio with less than 1.25 is considered a compact tube bank setup and a pitch ratio of 2 is widely spaced arrangement.

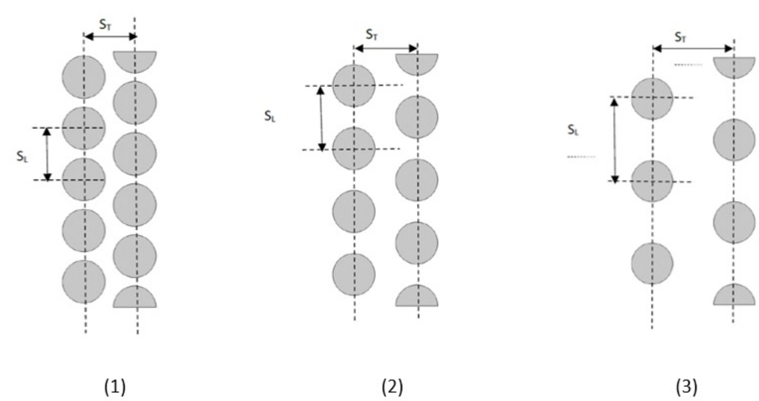

Figure 1: Staggered tube samples with pitch ratios (1) P/D = 1.2 (2) P/D = 1.4 and (3) P/D = 2.

2.2 Experimental Setup

The experimental setup used in this work consists of a rectangular duct with tube row samples at the centre as shown in the schematic diagram in Fig.2. Acoustical excitation is created by loudspeakers on the upstream and downstream side respectively. The upstream end is connected to an anechoic chamber where pressurized flow is generated by the flow rig. The downstream end is connected to a muffler to reduce the end reflections. The acoustic pressure fluctuations upstream and downstream of the sample were recorded using eight flush mounted microphones, four on either side of the sample.

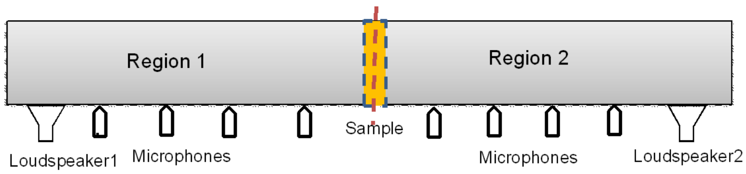

Figure 2: Experimental Setup.

The microphone signals passed through signal conditioners to the data acquisition system. The DAQ also acted as signal generator for the loudspeakers; these were driven with a variable amplification. The flow velocity on the upstream side was measured using a pitot tube and a pressure transducer.

3. Experimental Methodology

Experiments were conducted on the staggered tube bank samples to investigate the passive acoustic properties. The scattering coefficients were determined using stepped sine excitation for frequencies from 100 Hz to 2000 Hz with 50Hz steps, for different flow speeds.

3.1 The Scattering Matrix

In the experiments, the measured data is obtained from four microphones, on each side of the sample, see Fig.1. The acoustic pressure field within the duct can be expressed as a superposition of forward and backward travelling waves. A two-port multi-microphone measurement technique [6] was used to obtain the acoustic pressure amplitudes of the waves. Using Equation (1), the upstream and downstream pressure amplitudes can be evaluated. The scattering matrix, can be determined by:

$$\begin{bmatrix} p_1^+ \\ p_2^- \end{bmatrix} = \begin{bmatrix} T_{1-2}^+ & R_2^- \\ R_1^+ & T_{2-1}^- \end{bmatrix} \begin{bmatrix} p_2^+ \\ p_1^- \end{bmatrix} \tag{1}$$

Here, R is the reflection coefficient of waves propagating towards that region 1 or region 2 as shown in Fig.2, and T is the transmission coefficient of waves from upstream to downstream or vice-versa. Here, regions 1 and 2 represents upstream and downstream.

3.2 The Power Balance

The power balance is calculated from the scattering coefficients (1). The power balance helps to understand the sound attenuation and sound amplifications of the test sample caused by flow acoustic interaction. It is defined as the ratio of the outgoing power to the incoming power as shown below in equations (2) (3), where, w refers to the acoustic power,

$$\frac{w_{out}^1}{w_{in}^1} = \frac{|R_1|^2 (1-M)^2}{(1+M)^2} + |T_{1-2}|^2 \tag{2}$$

$$\frac{w_{out}^2}{w_{in}^2} = \frac{|R_2|^2 (1+M)^2}{(1+M)^2} + |T_{2-1}|^2 \tag{3}$$

4. Results

4.1 The Scattering Matrix

Experiments were conducted on the staggered tube bank samples with pitch ratios 1.2, 1.4 and 2 for different flow speeds from 6 m/s to 40 m/s. Fig. 3 presents the scattering matrix elements as defined in (1) of the tube bank samples for the lowest flow speed 6 m/s.

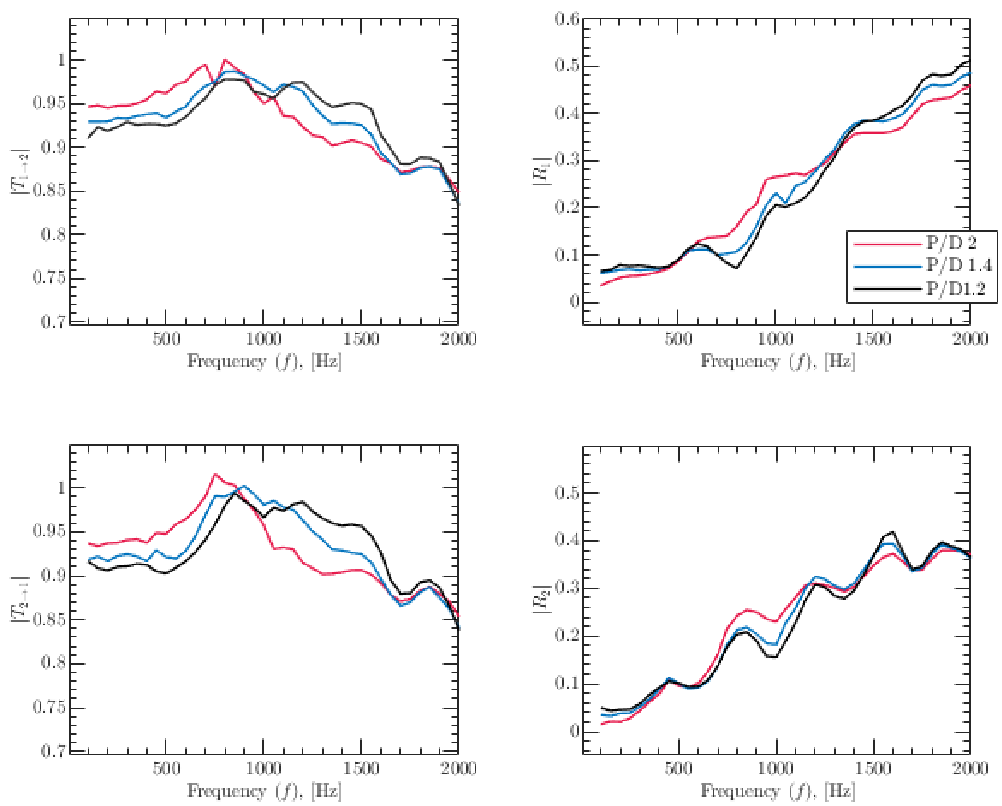

Figure 3: Transmission and reflection coefficients as defined in (1) for the staggered tube bank with a flow speed of 6m/s.

In Fig.3, it is observed that the reflection coefficient increases with the frequency starting from approximately *R=0*, as expected as for low frequencies as these are less hindered than high frequency waves when propagated through a constriction [7]. The transmission coefficient is observed to have a maximum in a certain frequency range. This frequency range is clearly shifting with the smaller pitch ratio. This can be observed for all the flow cases. For 6 m/s flow velocity in Fig.3 , the transmission coefficient peak starts around 600 Hz for widely spaced (i.e, P/D 2) and the peak range moves to higher frequency ranges for the compactly packed sample. This shifting of peaks is related to flow speed change in between tubes with respect to the pitch ratios variation. For a compact tube bank sample the flow speed between the tubes is higher compared to the widely spaced sample and this cause this shifting of the maximum.

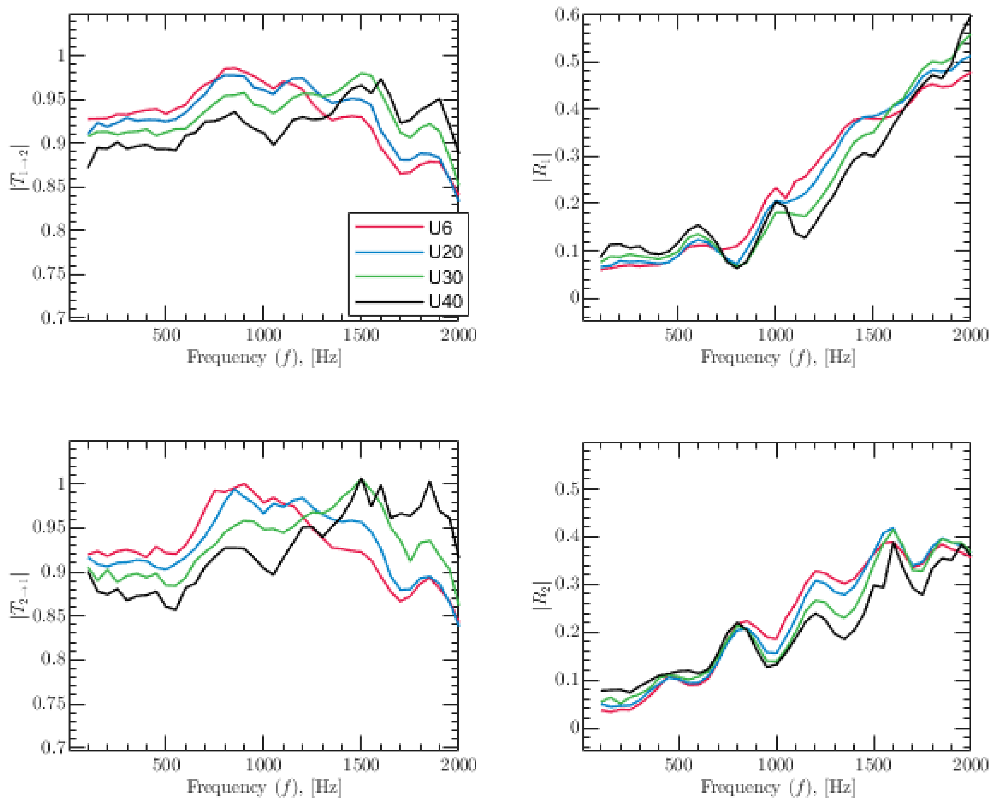

Figure 4: Transmission and reflection coefficients of a sample with pitch ratio of 1.4 for different flow speeds 6m/s, 20m/s, 30m/s and 40m/s.

Figure.4 shows the transmission and reflection coefficients for the tube bank sample of pitch ratio (P/D) 1.4 for different flow velocities of 6m/s, 20m/s, 30m/s and 40m/s. The transmission coefficient have a maximum that shift towards higher frequency with increasing flow velocities in a manner similar to the results in Fig.3 . The reflection coefficients are increasing with the frequency.

4.2 The power balance

As discussed before, the power balance helps to understand the amplification or attenuation based on the scattering coefficients. The power balance ratio will be larger than unity for amplification and smaller than unity for attenuation of the incident power. The power balance curves for the sample with P/D 1.4 is shown in Fig.6. There, it can be observed that the power balance is larger than one in certain frequency ranges. For lower flow velocity (6m/s) the value is larger than one at lower frequency and for higher flow velocities at higher frequencies.

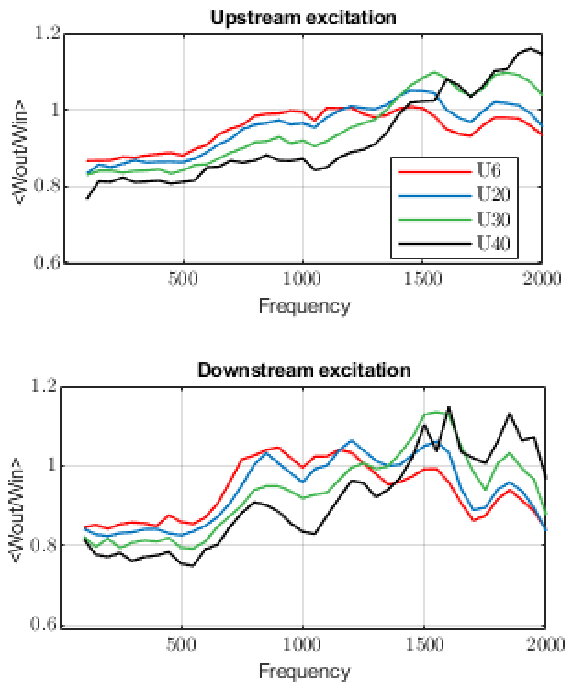

Figure 5: Power balance curves from excitation from the upstream and downstream side respectively for the sample with pitch ratio 1.4 for different flow speeds 6m/s, 20m/s, 30m/s and 40m/s.

As a preliminary analysis of a possible governing Strouhal number and to understand the flow-acoustic interaction, it is useful to find a scaling factor. So, we choose the peak frequencies (where the power balance is greater than one) of the power balance from measurements by visual inspection, for various flow velocities, shown in Fig 6. Figure 6 depicts these Frequencies of three samples plotted against mean flow speeds. It can be observed that the frequency of the maxima changes with change in the pitch ratios.

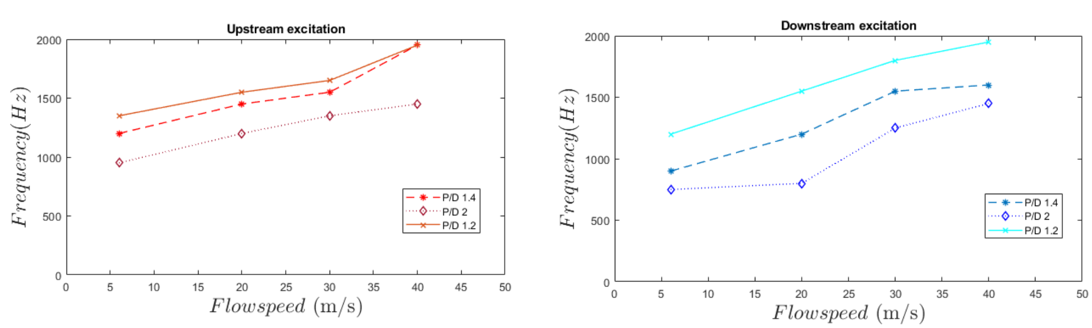

Figure 6: Peak frequency vs flow velocity in the duct for tube bank sample of P/D 1.4.

5. Conclusion

The passive acoustic properties of the staggered tube bank samples were experimentally investigated, to the possibility of tube bank design playing a vital role for controlling of the instabilities were being analysed, where the pitch ratio is one of the important parameters in the tube bank design. In the present paper, the acoustic properties of staggered tube banks with three different pitch ratios 1.2, 1,4 and 2 are examined. The scattering coefficients are determined from experimental data. It is observed that the scattering coefficient maxima shifts with varying pitch ratio and with increase in the mean flow velocity. For widely spaced samples, the maximum occurs at a lower frequency range where as for compact samples it shifts to a higher frequency range. In the case, of different flow speeds for the sample with pitch ratio 1.4, the maxima shift with increasing velocity. From the analysis of the power balance, it can be observed that the power balance is greater than one for low flow speeds at lower frequencies and for higher flow speeds at higher frequencies. Preliminary analysis were done to analyse the flow acoustic interaction to find a relation between the power balance peak frequencies to flow speed for all the three samples.

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REFERENCES

1. A Tahseen, MM Rahman, and M Ishak. Effect of tube spacing, fin density and reynolds number on overall heat transfer rate for in-line configuration. *International Journal of Automotive & Mechanical Engineering*, 12, 2015.

2. Tahseen Ahmad Tahseen, MM Rahman, and M Ishak. Heat transfer and pressure drop prediction in an in-line flat tube bundle by radial basis function network. *International Journal of Automotive and Mechanical Engineering*, 10:2003–2015, 2014.

3. A Nir. Heat transfer and friction factor correlations for crossflow over staggered finned tube banks. *Heat Transfer Engineering*, 12(1):43–58, 1991.

4. Han-Taw Chen and Jian-Rong Lai. Study of heat-transfer characteristics on the fin of two-row plate finned-tube heat exchangers. *International Journal of Heat and Mass Transfer*, 55(15-16):4088–4095, 2012.

5. Aswathy Surendran, Maria A Heckl, Luck Peerlings, Susann Boij, Hans Bodén, and Avraham Hirschberg. Aeroacoustic response of an array of tubes with and without bias-flow. *Journal of Sound and Vibration*, 434:1–16, 2018.

6. Mats Åbom. Measurement of the scattering-matrix of acoustical two-ports. *Mechanical systems and signal processing*, 5(2):89–104, 1991.

7. Ann P Dowling, MM Sevik, and JE Ffowcs-Williams. Sound and sources of sound. 1984.