VELOCITY AND PRESSURE FLUCTUATIONS ON INCLINED TUBE BANKS SUBMITTED TO TURBULENT FLOW

C. R. Barcellos, C. L. Bartz, L. A. M. Endres and S. V. Möller

PROMEC - Universidade Federal do Rio Grande do Sul
Rua Sarmento Leite, 425, 90050-170 - Porto Alegre, RS, BRAZIL

ABSTRACT

This paper presents the experimental study of pressure and velocity fluctuations and their interdependence, in the turbulent flow impinging on arrangements of yawed circular cylinders simulating inclined tube banks with square arrangement and a pitch to diameter ratio of 1.26. Measurements were performed with hot wires and a pressure transducer. Behavior of fluctuating quantities is described by means of dimensionless autospectral density functions and their interdependence is discussed.

INTRODUCTION

Banks of tubes or rods are found in the nuclear and process industries, being the most common geometry used in heat exchangers. Attempts to increase heat exchange ratios in heat transfer equipments do not consider, as a priority of project criteria, structural effects caused by the turbulent fluid flow, unless failures occur [1]. By attempting to improve the heat transfer process, dynamic loads are increased and may produce vibration of the structures, leading, generally, to fatigue cracks and fretting-wear damage of the components, which are one of the failure sources affecting nuclear power plant performance [2]. While static loads seem to appear mainly due to the strong pressure drop which occurs in the narrow gaps between the tubes, in small aspect ratio tube banks, dynamic loads, arising from the fluctuating pressure field, have a random behavior, without any characteristic frequency [3]. Pressure fluctuations result from velocity fluctuations at several points of the flow field [4].

In shell-and-tube heat exchangers, the cross flow through the banks is obtained by means of baffles, responsible for changing the direction of the flow and for increasing the heat exchange time between fluid and the heated surfaces, the turbulence levels and the heat exchange ratios. Baffles can also be responsible for additional dynamic loads due to boundary layer separation after them, which can travel through the bank, influencing the tube bank and the baffles [5].

Experimental results of velocity and wall pressure fluctuations in the turbulent flow through a simulated tube bank with square arrangement, after passing a baffle plate were performed by Möller et al. [6]. In general, results of wall pressure and wall pressure fluctuations showed higher values than in pure cross flow [7, 8]. The characteristic value of the Strouhal number found was about 0.2. Important additional peak frequencies, appearing in spectra of tube wall pressure fluctuation, could not be associated neither to effects of pure cross flow through the bank nor to effects produced solely by the baffles. The results presented in that paper were, therefore, not conclusive, leading to the need of the experimental study of the flow through inclined tube banks for their correct interpretation.

Former studies of the flow through inclined tube banks, focused more on flow distribution and pressure drop problem using macroscopic theories in the search of constitutive models for multidimensional flow through rod or tube bundles [9,10]. Both references showed the coincidence of the flow incidence angle and the pressure gradient occurred only at 0^o and 90^o (pure axial and cross flow normal to tube axis).

In the study of flow induced vibrations in inclined tube banks, Žukauskas et al. [11] found that hydrodynamic forces exciting the tubes depended on the incidence angle of the flow. The higher the incidence angle, the higher the critical velocity for fluidelastic instabilities. These Author concluded also that the excitation mechanisms were the same for normal or inclined tube banks, depending on the velocity normal to the tube axes.

The purpose of this paper is, therefore, to investigate the wall pressure distribution and the behavior of pressure and velocity fluctuations, and their interdependence, in the turbulent flow impinging on arrangements of yawed circular cylinders simulating an inclined tube bank.

TEST SECTION AND MEASUREMENT TECHNIQUE

The test section was the same described in [7, 8], being a rectangular channel, with 146 mm height and a width of 193 mm. The length of the test section was variable, depending on the bank inclination. All the banks were located at 1600 mm after the settling chamber and had the same outlet length after the bank of 220 mm. Air was the working fluid, driven by a centrifugal blower, passed by a settling chamber and a set of honeycombs and screens, before reaching the tube bank with about 2 % turbulence intensity (Fig. 1).

The angles of incidence of the air on the tubes corresponded to the bank inclination, namely 90^o, 60^o, 45^o and 30^o. The tube banks had square arrangement and were 5 rows deep with 25 tubes in each bank. Figure 2 shows schemes of the tube banks investigated. The flow rate, and thus the Reynolds number, was controlled with help of a gate valve. Before the tube bank a Pitot tube was placed, at a fixed position to measure the reference velocity for the experiments. The mean Reynolds number, calculated with the tube diameter (32.1 mm) and the reference velocity, is $Re = 1.5 \bullet 10^4$.

Mean pressure distribution along the bank was determined by means of a mesh of pressure taps drilled on one side wall and measured with help of H&B pressure transmitters.

Velocity and velocity fluctuations were measured by means of a DANTEC *StreamLine* constant temperature hot wire anemometer. Pressure fluctuations were measured by an ENDEVCO piezo-resistive pressure transducer, mounted inside one of the tubes in the bank, and connected to pressure taps by plastic tubes [12]. Figure 3 shows a scheme of the instrumented tube and of the mounting technique of the transducer. The tube instrumented with the pressure transducer in the bank could be rotated, so that measurements of pressure fluctuations at the tube wall were performed at several angular positions. Previous analysis of the behavior of the test section, by means of METRA accelerometers, and of the measurement technique, allowed to identify peaks in spectra due to resonances not related to the phenomena investigated. A double hot wire probe placed between two tubes of the third row, near the location of the pressure tap, was used for the measurement of two components (parallel and normal to the axis of the test section) of the velocity vector and velocity fluctuations for the correct determination of the direction of these vector quantities. Data acquisition of pressure an velocity fluctuations was performed simultaneously by a Keithley DAS-58 A/D-converter board controlled by a personal computer, which was also used for the evaluation of the results.

For the determination of autospectral density functions, the sampling frequency was of 5 kHz, while the signals of the instruments were high pass filtered at 1 Hz and low pass filtered at 2 kHz. Previous studies of pure cross flow through tube banks showed, for this test sections, to be the frequency range of importance [7, 8].

Analysis of uncertainties in the results have a contribution of 1.4 % from the measurement equipments (including hot wire, pressure transducer and A/D converter). In the measurements of pressure fluctuations, tubings are responsible for 5 % of the uncertainties, leading to a total value for the spectra of pressure fluctuations, up to 1000 Hz, of 6.4 %.

RESULTS

Experimental results of pressure and velocity fluctuations are presented in form of dimensionless mean and RMS-values, as well as auto spectral density functions and cross correlation functions.

Figure 4 a-d shows the mean pressure distribution on one channel side wall, with the presence of the tube bank, as contours. The locations of the tubes in the bank are also indicated in the figures. Results are presented in form of Euler numbers, obtained by means of fluid density, ρ, and a reference velocity. Although some misdistributions of the contour lines are observed, isobaric lines are not parallel to tube axes, indicating that the pressure gradient is neither perpendicular to the tubes, nor parallel to main flow direction [10].

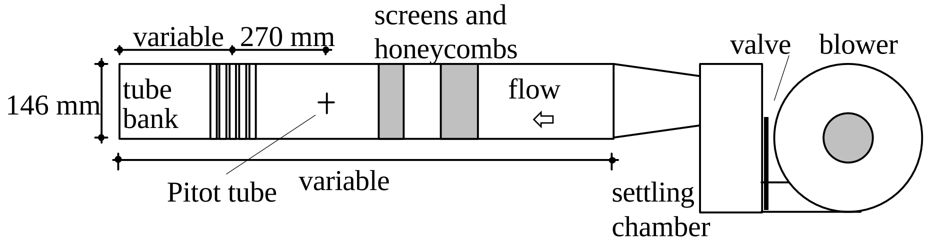

Fig. 1: Test section (schematic).

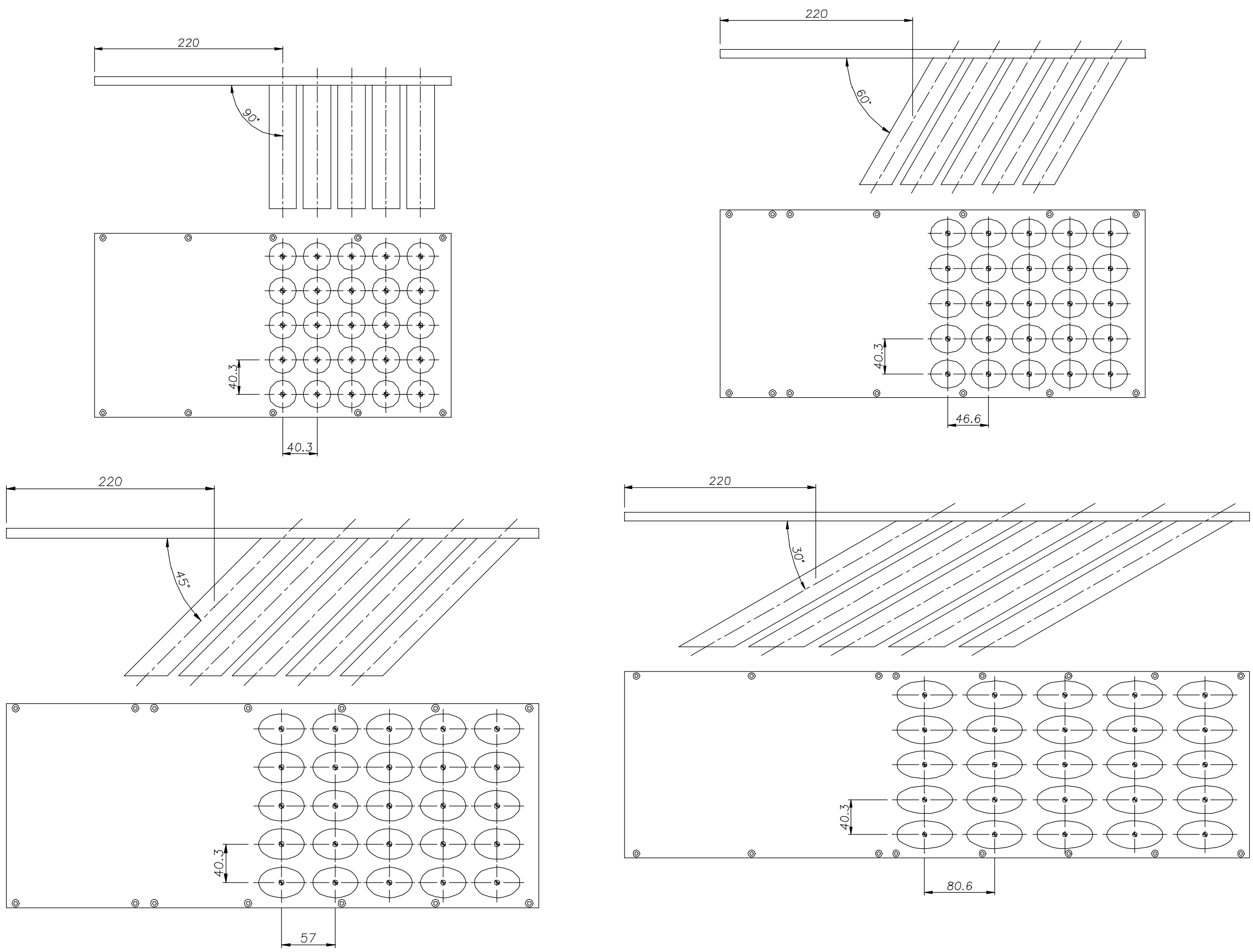

Fig. 2: Scheme of the tube banks with all yaw angles investigated (dimensions in mm).

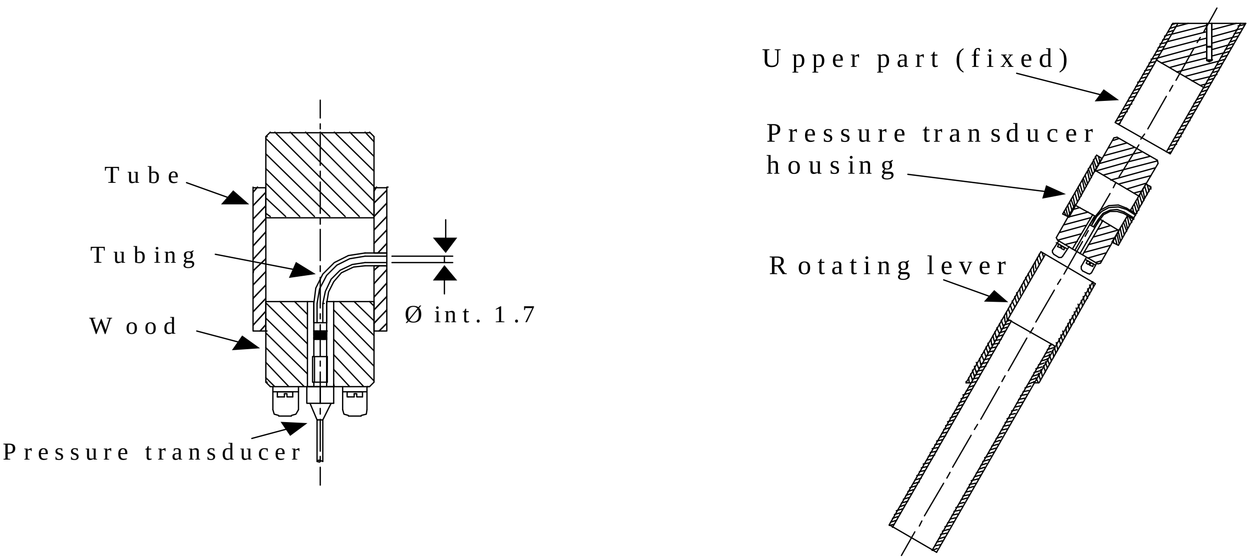

Fig. 3: Instrumented tube (schematic).

Figures 5 a-b show dimensionless values of the mean wall pressure and RMS-values of pressure fluctuations, also, in form of Euler numbers. Results are presented as functions of the angular position of the instrumented tube: 0^o corresponds to the position facing the main flow. Mean pressure distribution for all investigated incidence angles have similar distribution as in the flow perpendicular to a single cylinder, with increasing dimensionless absolute values as the incidence angle decreases. The values become negative at about 30^o. RMS values show local maxima at about 30^o and 110^o indicating the incidence of shedded vortexes from upwind tube row and the shedding process occurring in that tube. The first local maxima coincides with the change of signal of mean values.

Figure 6 shows autospectral density functions of the wall pressure fluctuation in the tube banks investigated for angular positions from 0^o to $180^{°}$. While the tube bank with 90^o incidence angle show spectra with uniform decay, in the spectra measured in the banks with 60^o incidence angle or less, peaks appear, with the highest values at the 45^o bank. The highest peak in the plots of 60^o, 45^o and 30^o occur at angular positions of 30^o and $120^{°}$ coinciding with the local maxima observed in the RMS plots, Fig. 5-b. Dimensionless frequencies, in form of Strouhal numbers, defined with gap velocity increase, as the incidence angles decrease. After a Strouhal number of about 2.10^{-1} they show the same decay until values of about 2.10^{0} where the resonance peaks from tubings occur. These peaks can be fully disregarded.

Similar behavior is observed also in the spectra of velocity fluctuations measured in the narrow gap between two tubes of the third row, Fig. 7: Peaks appear at about the same values of the Strouhal number, with the highest peaks at the bank with 45^o incidence angle. The highest energy values occur for this bank until a Strouhal number of about 2.10^{-1}. After this value all spectra have the same behavior.

Figure 8 presents results of cross correlations between velocity fluctuations, measured at the narrow gap between two tubes of the third row and wall pressure fluctuations at that location. Cross correlation measured in the bank with 90^o incidence angle, presents a peak with negative value. The magnitude of this peak increases in the 60^o bank, while some

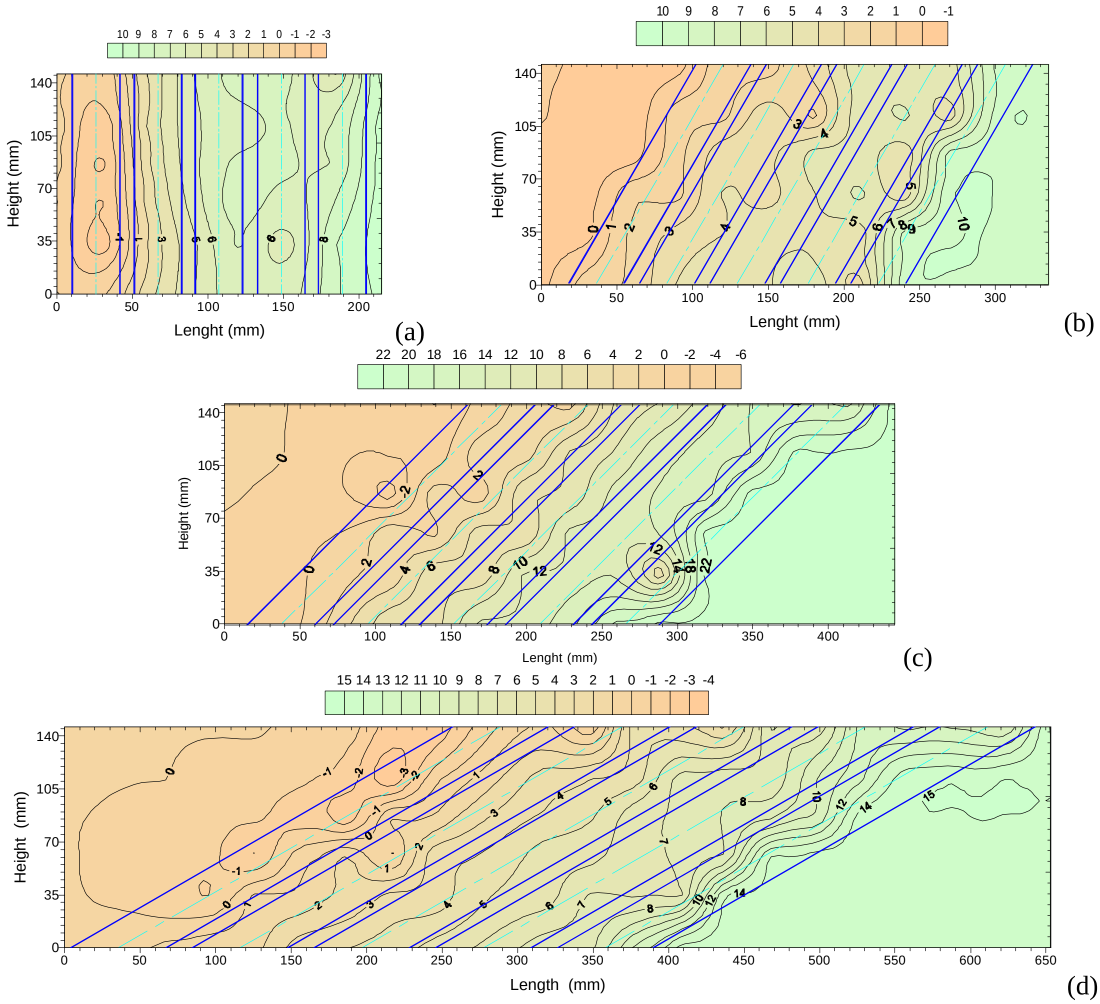

Fig 4: Channel side wall pressure distribution as contours. Flow is from right to left.

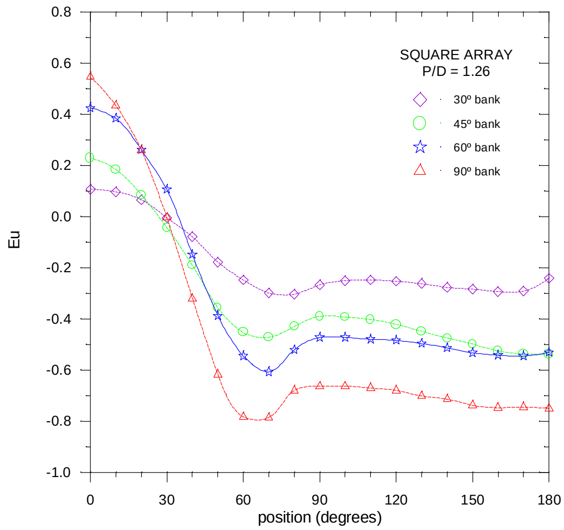

Fig. 5-a: Mean wall pressure distribution on one tube of the bank (dimensionless).

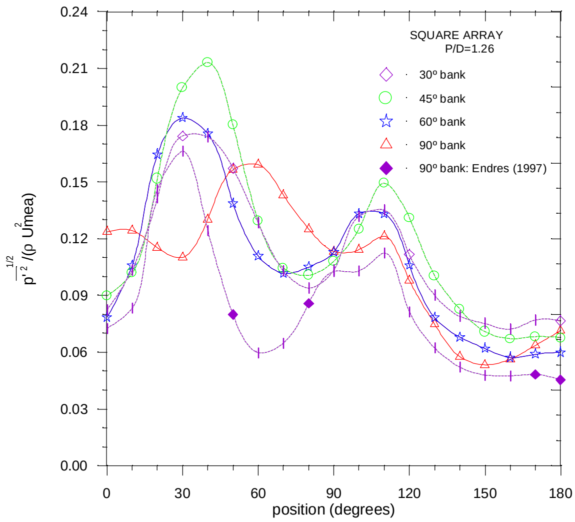

Fig. 5-b: RMS values of the wall pressure fluctuations on one tube of the bank (dimensionless).

oscillations start to appear. These oscillations are very clear at 45^o and at 30^o. The frequency of these oscillations are about 40 Hz for the 60^o bank, 60 Hz for the 45^o bank and 130 Hz for the last one, and correspond to the Strouhal numbers of the peaks in spectra, Figs. 6 and 7. Noticeable is that the highest oscillation occurs for the 45^o bank, where the spectra have the highest energy. Since these oscillations appear only in the inclined tube banks studied, it can be attributed to phenomena occurring in association with a change in the flow pattern, when compared to the 90^o bank, like a change in flow direction as it passes by the tube, generating more important three dimensional effects before and after the tubes with dominant frequencies, probably associated with recirculation effects in those regions and vortex shedding on the back side of the inclined tubes.

CONCLUDING REMARKS

This paper presents the experimental study of the velocity and wall pressure fluctuations in the turbulent flow through arrangements of yawed circular cylinders simulating inclined tube banks with square arrangement. Air was the working fluid impinging on the tube banks at several incidence angles. Experimental results of velocity fluctuations and wall pressure fluctuations were obtained by means of hot wires and a pressure transducer.

The interpretation of the phenomena studied here is directly connected to the cross correlation plots: as the tube bank angle decreases, strong three-dimensional effects appear which can be associated with vortex shedding on the back side of the inclined tubes. These effects, characterized by the oscillations in cross correlations at 45^o seem to vanish as the inclination angle is continued to be reduced. An additional interesting hydrodynamic problem arises therefore, this being the angle where cross flow characteristics stop being dominant and axial flow starts. Constitutive models using macroscopic theories [7, 8] indicate that flow resistance is a combination of the resistance of pure axial and pure cross flow. This fact must be, confirmed.

ACKNOWLEDGEMENTS

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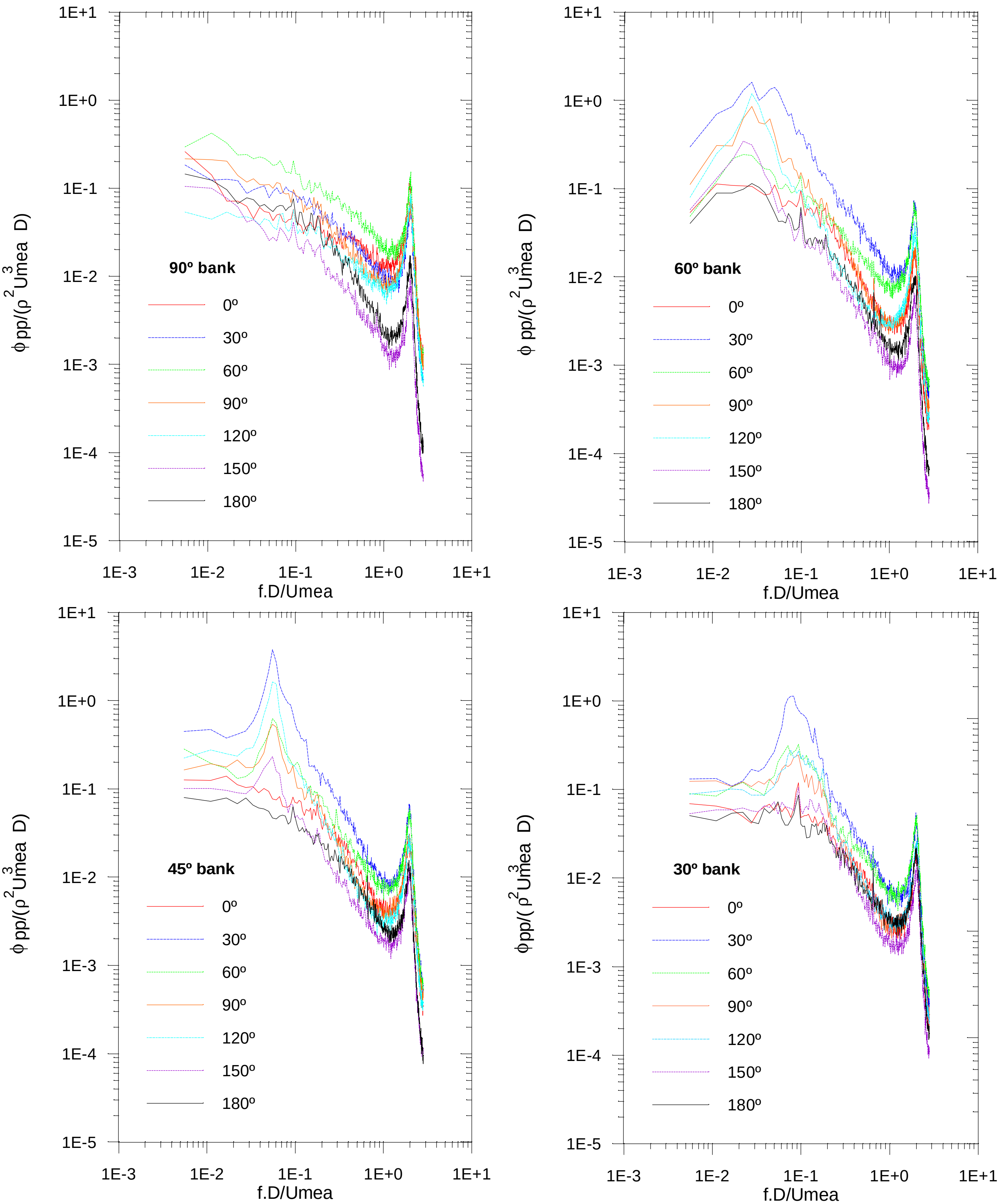

Fig. 6: Autospectral densities of wall pressure fluctuations in the narrow gap between tubes of the third row of the banks.

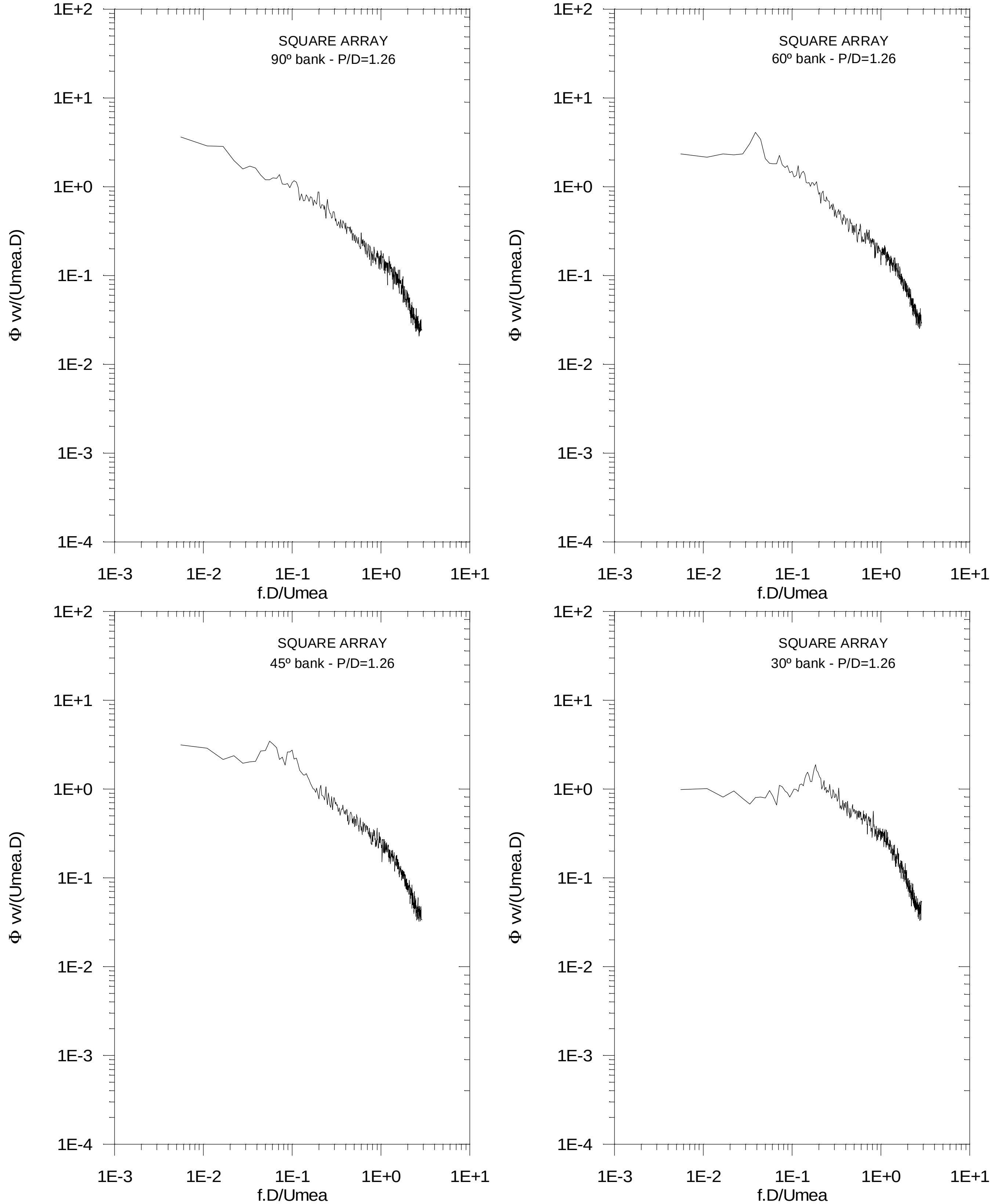

Fig. 7: Autospectral densities of velocity fluctuations in the narrow gap between two tubes in the third row of the banks.

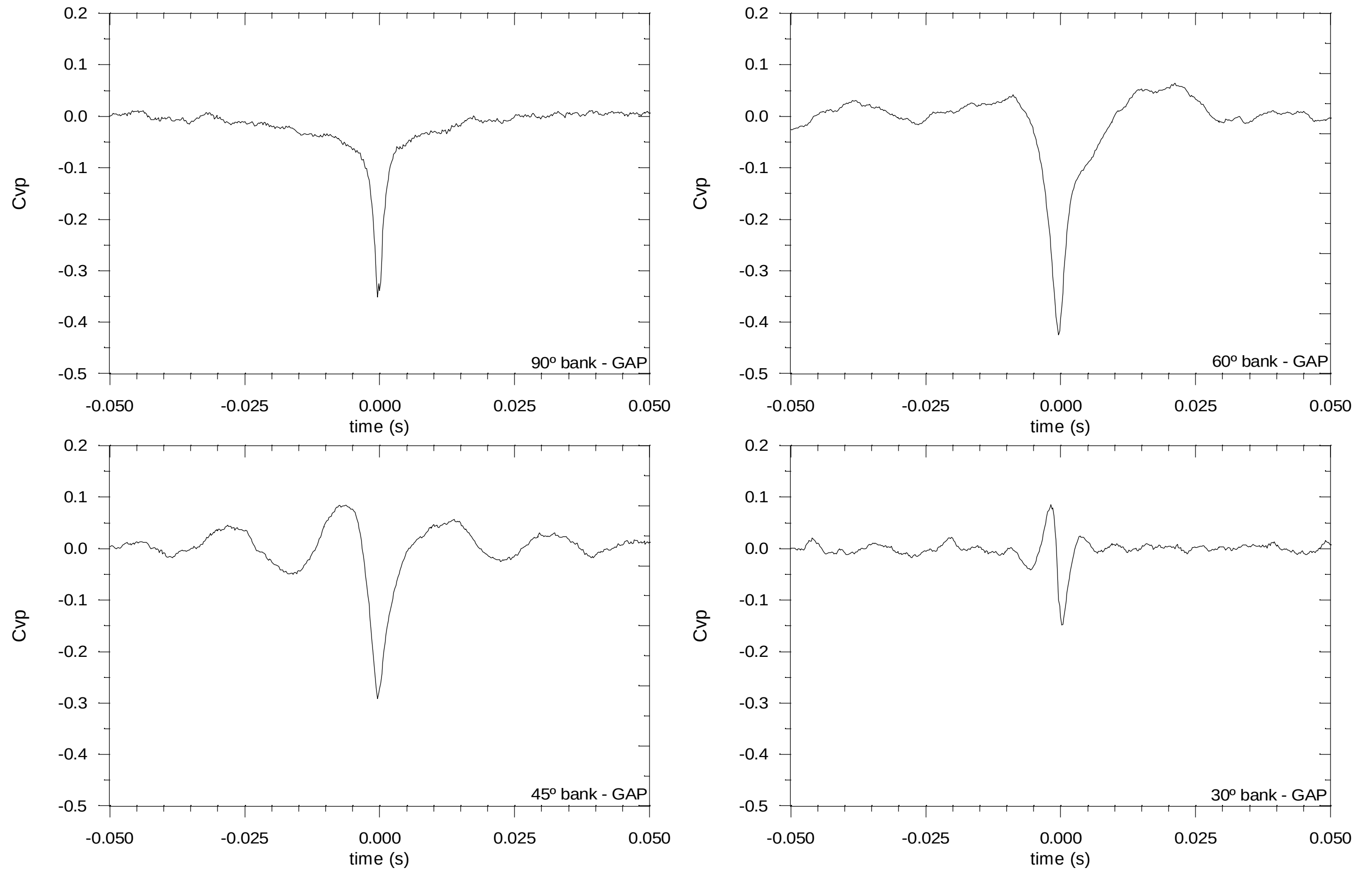

Fig. 8: Cross correlations between velocity and pressure fluctuations in the narrow gap between tubes of the third row.

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