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## MEASUREMENT OF FLUCTUATING FLUID PRESSURE EXERTED ON THE WALLS OF A TUBE BUNDLE

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### ABSTRACT

Flow-induced vibrations are particularly important as a problem field in reactor technology. Beyond the need to prevent fluidelastic instability phenomena which can lead to grid-to-rod fretting, it is necessary to also account for the long-time effects of the flow turbulence excitations. These features are crucial for the predictive dynamical analysis of flow-excited nuclear components, such as steam generators tubes or fuel rods.

In this perspective, in addition to conventional velocity measurements, an original instrumentation has been developed in order to measure the local fluctuating pressure on a tube. The required and obtained sensitivity is about a few Pa and the frequency range up to 300 Hz. This original measurement represents meaningful input from the more classical data usually available: the measurement is made on the tube surface where the velocity measurements are not available or less accurate, the pressure power spectra are an image of the turbulent scales, and the fluctuating pressure represent the bulk of the force applied on the tube.

Some results obtained on a 5x5 fuel rod bundle are presented, upstream and downstream of a spacer grid, at various azimuths. The power spectral density of the pressure fluctuation on the tubes is measured, showing the decrease of the pressure fluctuation downstream of the grid.

### INTRODUCTION

Flow-induced vibrations (FIV) are particularly important as a problem field in reactor technology. Beyond the need to prevent fluidelastic instability phenomena which can lead to rapid failures, it is necessary to also account for the long-time effects of the flow turbulence excitations. For instance, the grid-to-rod fretting wear is still a worldwide dominant fuel rod leaker mechanism [1] and its main root cause has been identified as fuel rod vibration induced by the turbulent flow [2].

A large effort is thus devoted to the prediction of the vibration response of a tube, from a fuel assembly or a steam generator, subjected to turbulent axial and/or transverse flow, through the advanced mechanical modelling of a multi-supported beam under a representative excitation to be fully determined. The need remains for an accurate knowledge of the spectral content and spatial distribution of the flow excitation [3], usually obtained

from experiments, where the forces are either directly measured [4] or inferred from the system responses [5].

Even if computational fluid dynamic (CFD) simulations for highly turbulent flows already produce results [6, 7, 8, 9], some innovative instrumentation is yet required to provide accurate validation data in terms of magnitude, spectral content and spatial distribution of the fluctuating pressure on the tube wall, known from the literature to represent about 90% of the force applied by the fluid.

The current paper is therefore dedicated in the first part to the presentation of the development of such a measuring device. In the second part, two experimental configurations implementing this technology are introduced and in the third part, some results are presented and discussed. Only fuel rods submitted to axial flow are considered in the following work, but the proposed methodology also applies for other flow-excited systems, such as tubes from steam generators subjected to transverse flow.

### EXPERIMENTAL PROCESS DEVELOPMENT

The following paragraphs design an effective experimental methodology for measuring the local spectral and spatial features of strongly non-uniform turbulent flow excitations in tube bundles. Literature and CFD simulations show that the fluctuating pressure represents the main part of the force applied on the tubes, the shear contribution being negligible compared to the pressure force [6, 7].

#### *Pressure sensor*

Experimental and simulation results available at CEA on reduced or full scale fuel assemblies mock-ups set the capabilities expected from the pressure measuring device: the resolution must be a few Pa, with a pressure range corresponding to the dynamic pressure of the flow, i.e. about 12 500 Pa, and a maximum frequency around 300 Hz. Tests are performed at temperatures below 60°C.

Piezoelectric and piezoresistive sensors are selected for their high sensitivity and small size, allowing them to be installed inside a tube, with their own characteristics in terms of supported pressure levels or sensitivity to structural vibrations.

In a first phase dedicated to testing and comparing various sensors, their sizes impose a geometric scale larger

than 1. It shall be followed by a second phase where extra-miniaturization occurs to retrieve the actual scale. A 2.83 scale is thus chosen for the following experimental mock-ups, with fuel rods of actual diameter 9.5 mm represented by stainless steel tubes of diameter 26.9 mm. One advantage of the larger scale is the higher Reynolds achieved with a relatively low temperature, up to 300 000, to compare to the classical 500 000 in-core Reynolds number for PWR fuel assemblies.

The design of the device is schematically shown in Figure 1. The pressure sensor is positioned axially in a mechanical assembly. The fluid pressure is measured at the wall by means of an orifice and a cavity. The drain system allows expel air trapped in the cavity. The device is cylindrical, its cross section is circular, and its outside diameter is the same as that of the rod. The volume of the cavity is defined according to the design constraints (size of pressure sensors, drain system, feasibility of machining...) and optimized during the development of the methodology.

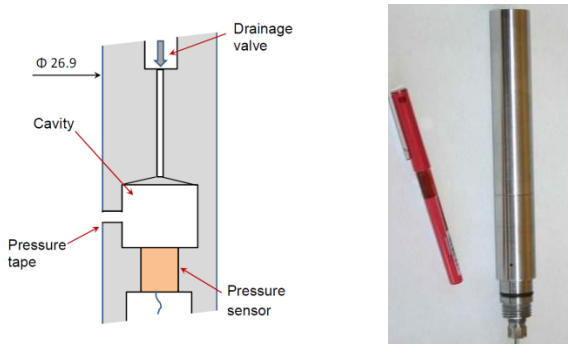
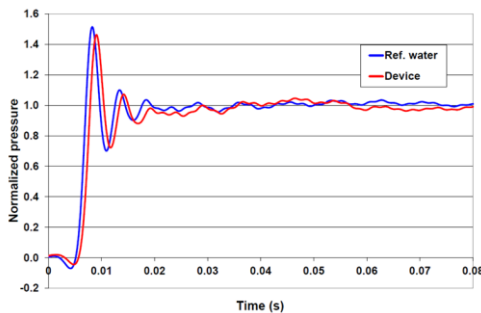


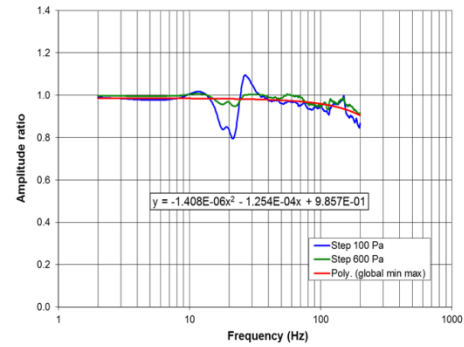
Figure 1. Sketch and photography of the pressure measuring device.

**Sensor calibration**

The calibration of the full device (external tube and integrated sensor) is performed on a specific pressure step generator with various initial pressures and amplitude of the step and a reference pressure signal measured by piezoelectric sensors with very high sensitivity (Kistler 7261A). It is verified that the transfer function is not affected by temperature or pressure, within the ranges [20°C ; 55°C] and [100 hPa ; 500 hPa] and that the expected sensitivity and accuracy are achieved, for both level and frequency (see Figure 2).



(a) Time response - Pressure gauge: 500 hPa, pressure step: 100 Pa



(b) Transfer function - Amplitude ratio

The curve for the 100 Pa step shows an oscillation at 20 Hz corresponding to the resonance of the calibration device.

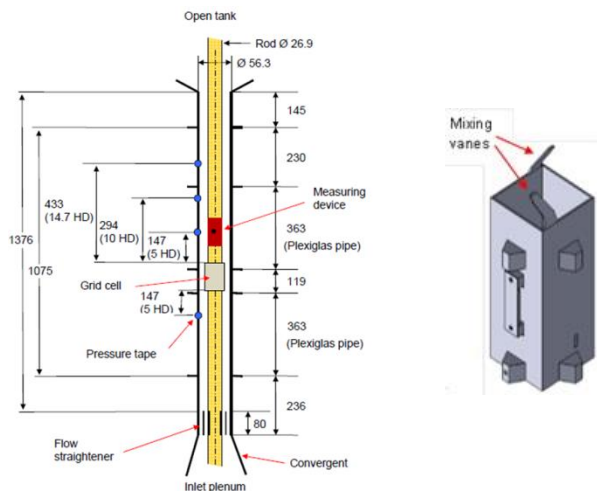
Figure 2. Calibration of the pressure measuring device

**EXPERIMENTAL PROCESS**

*Single rod analytical setup*

According to the complexity of the expected measures for a tube bundle, a simplified analytical setup is first considered, consisting of a test section equipped with one single rod and one mixing grid cell (see Figure 3). Particular attention is paid to the hydraulic containment upstream and downstream of the test section and isolation of the test section from mechanical vibrations and hydraulic perturbations.

Various checks and tests are performed to purge the measurement device, test different flow velocities, test the effect of rod vibrations on the measurement, and examine the reproducibility of the methodology. For instance, the reproducibility of RMS pressure value is about +/- 1%. CFD simulations of this experimentation are also performed to analyze the results and develop the simulation methodology [6, 7].



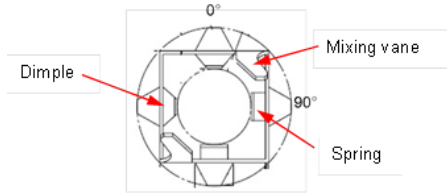
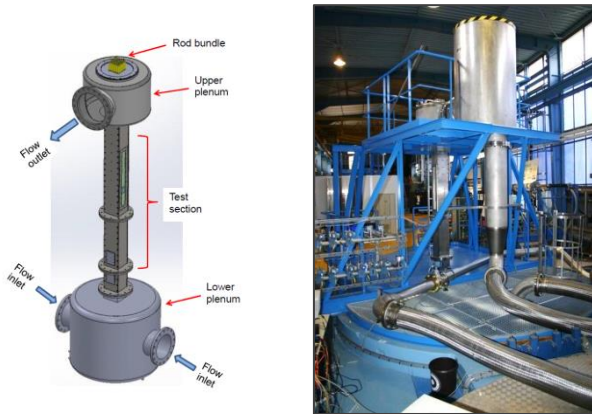


Figure 3. Single rod setup

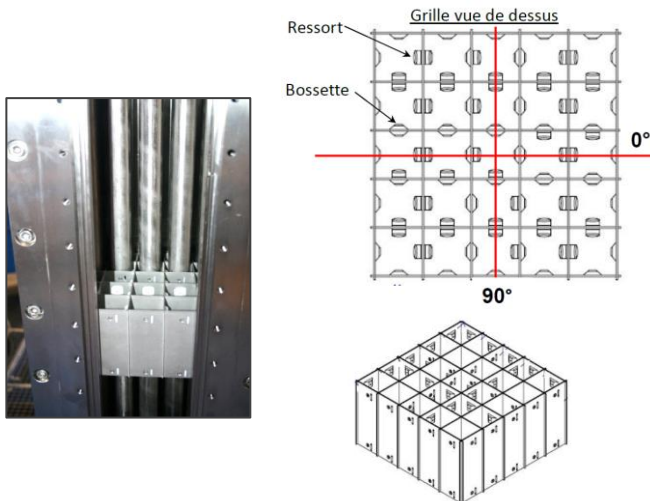
### 5x5 bundle setup

Based on this whole feedback, the experimental apparatus dedicated to a 5x5 fuel assembly bundle is designed, implementing concepts for hydraulics very similar to those validated through the first configuration (see Figure 4 for the 5x5 setup). The hydraulic diameter (HD) in the test section is 27.6 mm.

For these first measurements in tube bundle, the grids have no mixing vane (see again Figure 4). The 0° azimuth corresponds to the front face presented on Figure 4b. The flow rate required for a representative velocity range of [1 m/s ; 5 m/s] and the water temperature (18°C in the present situation) are accurately controlled during the tests.



(a) Sketch and photograph of the 5x5 setup



(b) 5x5 grid with no mixing vane

Figure 4. 5x5 configuration setup

## MAIN RESULTS FOR THE SINGLE ROD CONFIGURATION

Tests are performed for different values of the flow velocity (2, 3, 4 and 5 m/s) at a temperature of 20°C.

For each flow velocity, azimuthal pressure fluctuations profiles are given at 4 levels downstream from the grid (1, 2, 3 and 5 HD above the grid, as well as 1 one level at 5 HD below the grid (HD equals 29.4 mm in this configuration). Azimuthal profiles are performed with an angular step of 10° and results are presented in Figure 5.

To characterize the pressure fluctuations, the Power Spectral Density (PSD) over a frequency range up to 300 Hz is computed. The graphs presented in Figure 5 show the angular distribution of standard deviations resulting from the integration of the spectrums.

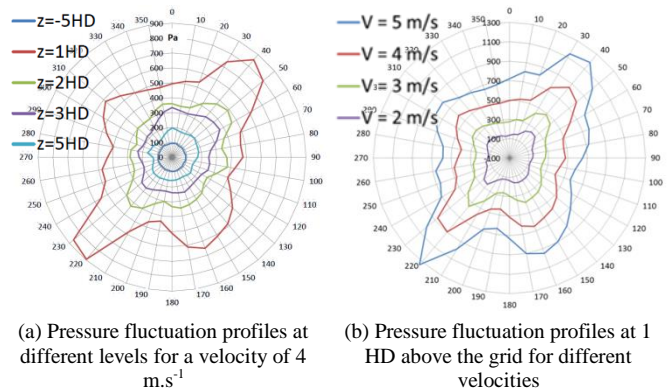


Figure 5. Pressure fluctuation profiles for the single rod setup

For all flow velocities, extrema representative of the turbulence of the mixing vanes wake can be observed at the azimuths 40° and 220° 1 HD downstream from the grid. They persist at 2 and 3 HD and decrease further from the grid. Secondary extremums also appear at about 160° and 310°, resulting from the acceleration of the flow through the free spaces between springs and dimples. Upstream from the grid, the pressure fluctuations are very uniform over the periphery of the rod.

The reduced PSD of the pressure is provided in Figure 6 for various velocities and angular positions at the level 1 HD downstream the grid. Reduction is achieved through the following expressions:

$$PSD_r(P) = \frac{PSD(P)}{\rho_0^2 V_0^3 D} \quad (1)$$

$$f_r = \frac{f \times D}{V_0} \quad (\text{reduced frequency}) \quad (2)$$

where  $f$  is the frequency (Hz),  
 $D$  the rod external diameter (m),  
 $V_0$  the average axial flow velocity (m.s<sup>-1</sup>),  
 $\rho_0$  (kg/m<sup>3</sup>) the fluid density,  
 $PSD(P)$  is the power spectral density of the measured pressure  $P$  (Pa<sup>2</sup>/Hz).

The PSD of the pressure is presented on a log-log plot, with the reduced frequency  $f_r$  on the horizontal axis.

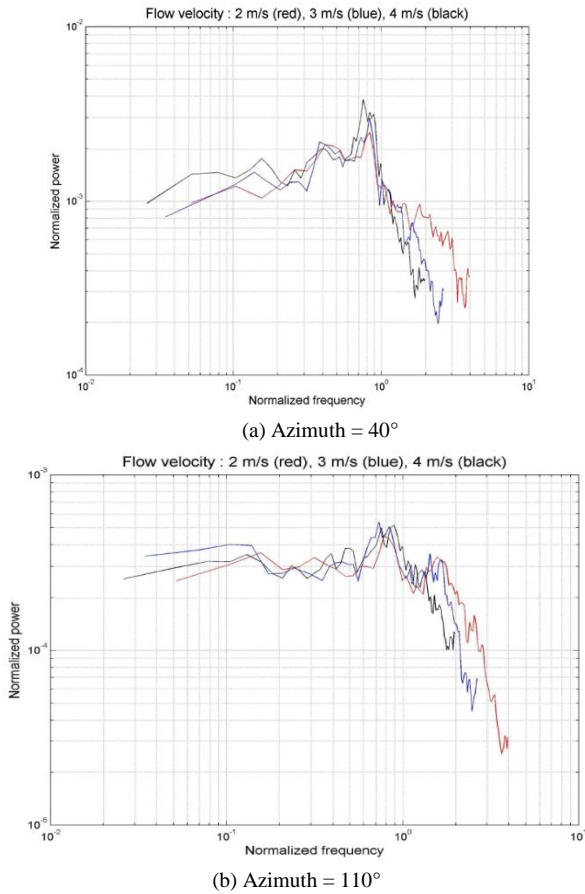


Figure 6. Reduced PSD of the pressure at level 1HD downstream the grid

PSDs are representative of the turbulence induced by singular pressure loss: these are broadband spectrums, level increases with flow velocity and decreases with the frequency and with distance to the grid. On the reduced PSD, the low frequency area, where  $f < f_c$  ( $f_c$ : cutoff frequency), corresponds to that of the large swirls. Above the cutoff frequency, the proposed spectra do not exhibit the classical transition between inertial and dissipative ranges, due the presence of the geometric singularity preventing the turbulence to fully establish [10].

Comparing reduced PSDs in Figure 6 shows variations of both levels and slopes of the curves according to angular position and flow velocity. This can be explained by the presence of a strong three-dimensional flow downstream of the grid: the swirls generated by the vanes are certainly different in size and velocity from those present in less turbulent areas. Choosing between the mean flow velocity or the local velocity to compute the dimensionless PSD is thus not obvious.

On the reduced PSD, the cutoff normalized frequency varies between 0.4 and 0.8.

## RESULTS FOR THE 5X5 CONFIGURATION

The tests are carried out for different flow velocities in the range [1 m/s, 5 m/s]. The water temperature is 18°C +/- 1°C. In the test section, the static pressure is always below 1 bar. Fluctuating pressure is measured on the central rod, at various levels along the tube bundle, in the range - 5 HD

upstream the bottom of the structural grid and 20 HD downstream the top of the structural grid. For each level, azimuthal profiles are performed again with an angular step of 10°.

### Root Mean Square of Pressure

The RMS presented in Figures are measured with a flow mean velocity of 2.4 m/s, corresponding to a flow rate of 221 m<sup>3</sup>/h. The Reynolds number is thus 66 000.

First, the reproducibility of the pressure measurement is tested. A result is presented in Figure 7, with two fluctuations profiles measured at 4 HD downstream the grid. Between the two measurements, the instrumented rod has been dismantled. The reproducibility is satisfactory, the difference is a few percent, the local maximum difference is less than 10%.

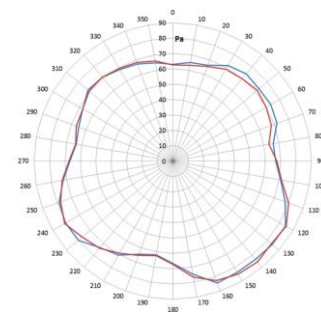


Figure 7. Reproducibility of pressure fluctuations profiles at 4 HD downstream the grid.

A large increase of the pressure fluctuation induced by the grid can be observed in Figures 8 and 9. At 5 HD upstream of the grid, the RMS value is very homogeneous, corresponding to a circular profile, with a mean value of 44 Pa. On the contrary, downstream of the grid, the RMS reaches a maximum value of about 700 Pa at 0.5 HD and 240° (716 Pa). This increase is mainly due to the spring and dimples generating strong fluid deviation and acceleration in the grid, and so turbulence downstream in the sub-channels of the bundle. The value in the wake of the springs (90° and 180° azimuths) is two times the value reached in the wake of the dimples (0° and 270° azimuths). Therefore, the fluid forces due to each path flow are not balanced around the rod. The RMS pressure fluctuation increases, which means that the turbulent intensity increases, and so the fluctuating pressure force. Grid without mixing vanes generates much lower turbulence compared to the grid with mixing vane, but the effect is still significant.

Beyond 0.5 HD, the expected decrease of the pressure fluctuation along the span is observed. At 1 HD, the profile is still very asymmetrical; the maximum values are again in the sub-channels at 0° and 270°. At 2, 3, 4 and 5 HD, the profile is more symmetrical but non homogeneous. Finally, at 10 HD and beyond, the profile is almost circular, values are comparable to values at -5 HD. Zooming in Figure 9 on the profiles at 10, 15 and 20 HD between 35 and 51 Pa (see Figure 9b), some relative square shapes are observed, with

maximum values corresponding to the directions of the centers of the sub-channels around the rod, at 45°, 135°, 225° and 315° azimuths. Such a measurement is representative of the sensitivity of the proposed pressure measurement device.

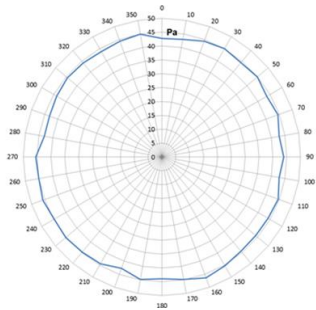
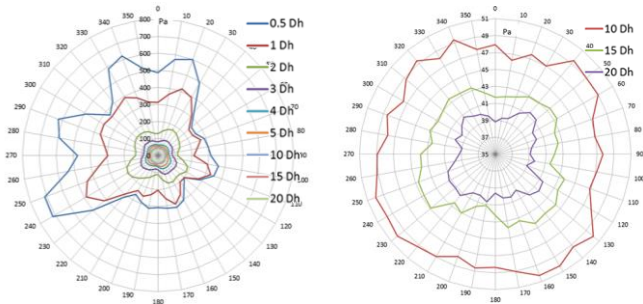


Figure 8. Pressure fluctuation profile 5 HD upstream of the grid.



(a) Profiles for all HD (b) Zoom on profiles at 10, 15 and 20 HD

Figure 9. Pressure fluctuation profile downstream of the grid

Figure 10 presents the mean RMS of the pressure downstream the grid. Each level value corresponds to the mean value of the 36 azimuthal RMS. The values rapidly decrease after the grid. Between 0.5 and 5 HD, we have lost about 85% of the RMS value. After 5 HD, the strong turbulence generated by the grid tends towards an established turbulence. At 10, 15 and 20 HD, the pressure fluctuation is similar to upstream the grid at -5 HD.

The RMS pressure fluctuation decreases downstream of the grid, meaning the turbulent intensity also decreases and so the pressure excitation force. This result is already observed experimentally [4, 10] and by CFD simulation [6, 7, 8, 9]. This decrease being a consequence of the average rate of dissipation of turbulent kinetic energy in the fluid, its measurement proves very useful for the qualification of CFD simulation software.

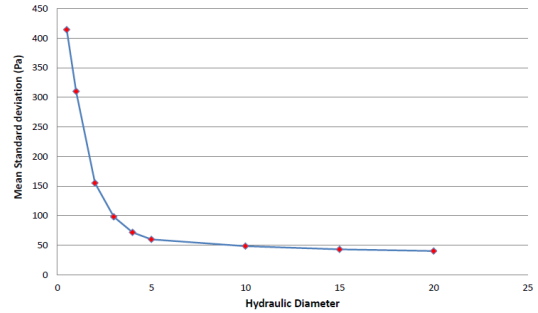


Figure 10. Mean RMS of the pressure downstream of the grid.

### Power Spectral Density of Pressure

The reduced PSD of the pressure, at various distances upstream and downstream of the grid, and for 0° azimuth (gap between two adjacent rods) and 310° azimuth (in front of the center of a sub-channel), is presented in Figures 11 and 12.

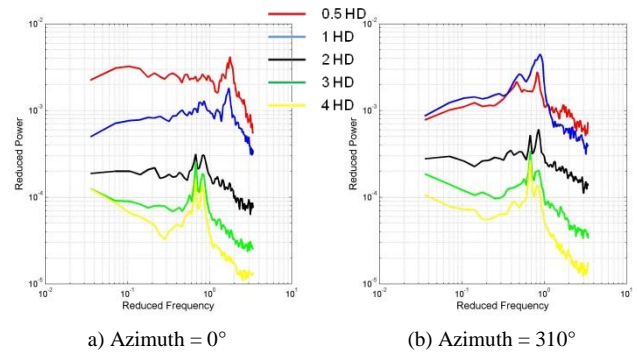


Figure 11. Reduced Power Spectral Density of the pressure downstream of the grid

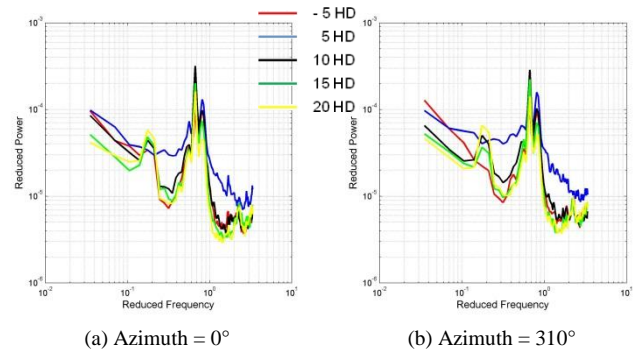


Figure 12. Reduced Power Spectral Density of the pressure at levels further downstream and upstream of the grid

Just downstream of the grid (Figure 11), up to 3 HD, a difference between the measurements at 0° and 310° can be observed. If the RMS value is quite similar, as seen on Figure 9, the spectral content is different with a maximum spectra amplitude at  $f_r \approx 1.3$  at 0°, and a maximum at  $f_r \approx 0.7$  (about 70 Hz) at 310°. After 3 HD, the pressure spectra are quite similar, the peak at  $f_r \approx 1.3$  disappears and the peak at  $f_r \approx 0.6-0.7$  endures at 310° and “appears” at 0°.

As above the single rod case, two slopes are observed in the spectra. The first is a low slope up to  $f_r \approx 1$ , the second slope is steeper for higher frequencies, which is characteristic of turbulent flows.

Further downstream of the grid (5 to 20 HD, see Figure 12) and upstream the grid (-5 HD, see also Figure 12), the pressure spectra are quite similar (with the 5 HD spectrum still slightly higher than the others). No significant difference between  $0^\circ$  and  $310^\circ$  azimuths is observed. The maximum spectra amplitude around  $f_r \cong 0.5-0.6$  is still visible. Additional investigations on the test setup attribute this peak to the vibration of the instrumented rod. It disappears if the piezoelectric pressure sensor is replaced by a piezoresistive sensor, eliminating the sensitivity of the measures to the structural acceleration.

## CONCLUSION

Pressure fluctuation measurements are performed with specific sensors placed at the wall of a tube in a bundle. The required and obtained sensitivity is about a few Pa and the frequency range up to 300 Hz. This original measurement represents meaningful input from the more classical data usually available: the measurement is made on the surface of the tube where the velocity measurements are not available or less accurate, the pressure power spectra are an image of the turbulent scales, and the pressure represents the main part of the fluid force applied on the tube.

We measure the drastically increase of the pressure fluctuation induced by the structural grid, and its decrease downstream the grid. About 10 HD downstream the grid, the turbulence level is comparable to the turbulence upstream the grid. This decrease is a consequence of the average rate of dissipation of the turbulence kinetic energy in the fluid.

## ACKNOWLEDGEMENTS

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