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UNSTEADY PRESSURE FIELD ANALYSIS AT PUMP INLET EQUIPPED WITH A SYMMETRICAL SUCTION ELBOW

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Abstract. The flexible operation of the large hydraulic pumps requires to be run at variable discharges and speeds. The large pumps are equipped with a suction elbow which generates non-uniform flow at the impeller inlet leading to unsteady hydrodynamic phenomena. The experimental investigation presented in this paper is focused on unsteady pressure measurements at pump inlet. Two vortices generated by suction elbow are visualized being ingested by impeller. The equivalent amplitude and frequency associated to hydrodynamic phenomenon at pump inlet are determined at variable discharges and several speeds in order to be quantified the unsteady flow field. A discrimination procedure is applied on unsteady signals in order to be evaluated the plunging and rotating components. The experimental investigations are performed for nine discharge values from 16.75 l/s to 43.55 l/s and four impeller speed values from 2 700 rpm to 3 000 rpm.

Key words: unsteady pressure, large pump, symmetrical suction elbow, variable discharge and speed.

1. INTRODUCTION

The large pumping units are widely used in industry to store energy [1], to ensure cooling or heating in different systems [2] and to transport water [3]. The flexible operation of the large hydraulic pumps requires to be run at variable discharges and speeds. Constructively, the solutions for large pumps are different than regular ones [4]. A suction elbow with complex three-dimensional geometry is installed upstream to the impeller of large pumps or to the first impeller of the multistage pumps. This suction elbow generates circumferential non-uniformity in velocity distribution at the impeller eye due to the geometry and the flow around the shaft [5–8]. Consequently, the flow with pre-rotation is generated over roughly one half of the impeller inlet section and counter-rotation in the second half [7–12]. This non-uniform flow is ingested by the impeller [9–12] leading to the following: (i) loss in efficiency [14]; (ii) noise and vibrations are excited [15–17]; (iii) radial forces are generated [18]; (iv) cavitation erosion on the impeller blades and even its damage [19–21]; (v) lifetime of mechanical components is reduced [22].

The paper investigates the unsteady pressure field at the inlet section of a pump equipped with a symmetrical suction elbow for variable discharges and speeds. The experimental setup is described in Section 2. The pressure data analysis is presented in Section 3 while the conclusions are drawn in last section.1.

2. EXPERIMENTAL SETUP

A test rig is available at "Politehnica" University Timisoara in order to investigate the pump hydrodynamics (Fig. 1). The main components consist in two reservoirs of 1 m^3, a hydraulic pump with characteristic speed $n_q = n Q^{0.5} / H^{0.75}$ ~30 and a 37 kW electromotor. The test rig is equipped with a variable speed system control. The DTC-inverter varies the speed of the induction motor from 500 rpm up to 3000 rpm [23]. An acquisition system was implemented to acquire sensors data for overall pressure, discharge and electrical power. The acquisition system has 32 input channels (voltage/current differential inputs) and maximum 100 kb/sec acquisition frequency. The data is transferred to a computer using a RS232 interface. A remote control system was implemented, increasing the operability of the test rig [24].

The symmetrical suction elbow corresponding to a large pump is manufactured and installed on test rig. The non-uniform flow field induced by suction elbow at the impeller inlet is measured using Laser Doppler Velocimetry (LDV) system by Draghici *et al*. [8]. As a result, a hydrodynamic structure with vortices is identified such as it is schematically presented by Bolleter *et al*. [13] and numerically computed [9–12]. This flow structure is generated by three-dimensional geometry of suction elbow and two of them being visualized like cavitating vortices, (Fig. 2), when the reference pressure on test rig is dropped down.

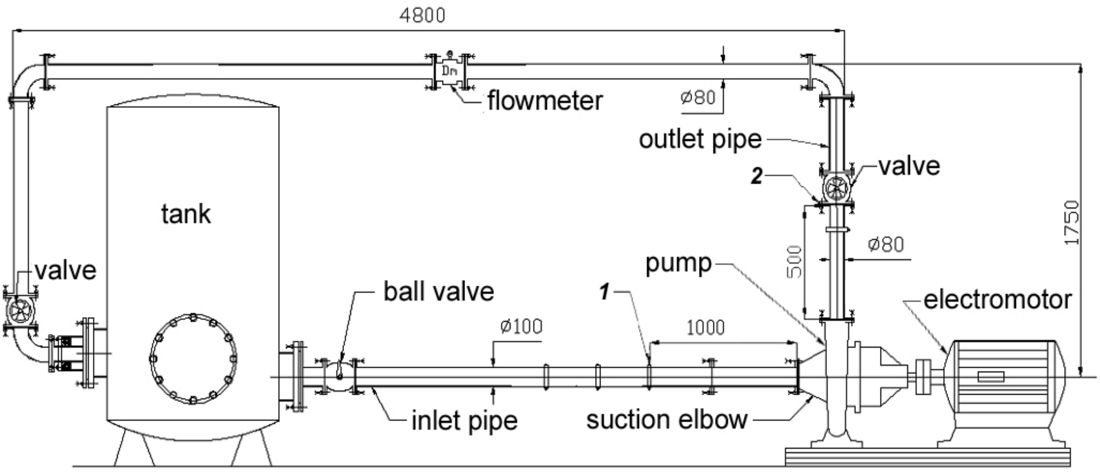


Fig. 1 – Schematic view of the test rig with actual dimensions in mm.

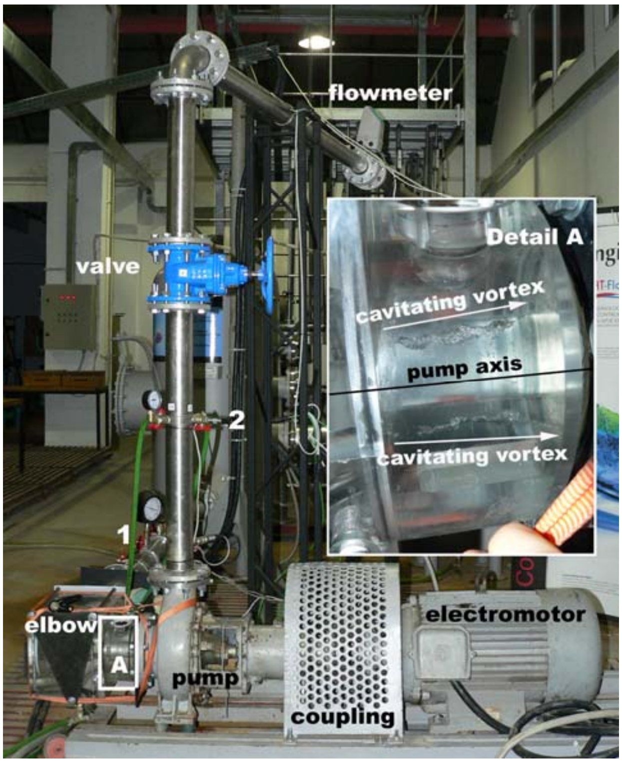
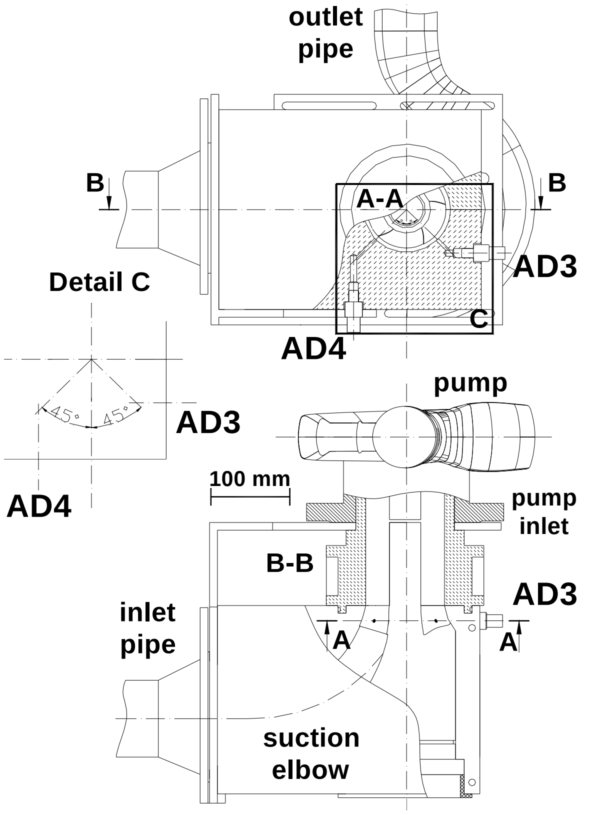


Fig. 2 – Visualization of the vortex pairs generated by the suction elbow at the pump inlet.

Two fast response piezoresistive pressure transducers are installed at pump inlet in order to measure unsteady field, (Fig. 3). The transducers with absolute pressure range of 0 … 200 kPa and a maximum acquisition frequency of 100 kHz are used. The pressure transducers are labelled AD3 and AD4 like in Fig 4. Pressure taps are installed at 90° to each other on same level (see Detail C in Fig. 3). In this way, the same average static pressure is measured when the pumped is stopped checking the deviation. The pressure pulsation types at pump inlet are discriminated with two sensors located on same level. There are two types of pulsations according to Jacob and Prenat [25]. The rotation type (asynchronous) is acting in cross section being given by unsteady vortices and plunging type (synchronous) is travelling in all hydraulic system. Each pressure sensor is connected with an amplifier. The accuracy for sensor-amplifier is ± 0.3%. The output signal from the amplifier is collected by acquisition system. This acquisition system is linked with LDV system which was installed for velocity measurements on annular section at the pump inlet [8]. Accordingly, the LDV system simultaneously measures two velocity components (axial and circumferential) and two pressure signals (AD3 and AD4). Each set corresponds to an acquisition time interval of 20 seconds and a sampling rate of minimum 1000 samples/second (1 kHz sampling frequency). The measurements are performed with good accuracy taking into account that phenomenon investigated at the impeller inlet has less than 50 Hz while the acquisition frequency is at least 20 times larger.



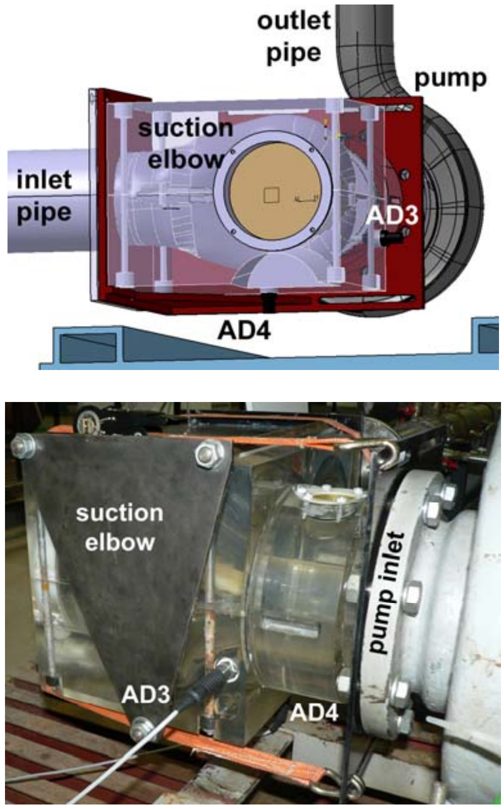


Fig. 3 – Side view (up) and upper view (down) of suction elbow together with centrifugal pump.

Fig. 4 – Axonometric view of the pressure sensors locations on the suction elbow (up) and the test rig view (down).

3. ANALAYSIS OF UNSTEADY PRESSURE FIELD AT PUMP INLET

The unsteady pressure field at the pump inlet is measured in order to be quantified the hydrodynamic phenomena generated by three dimensional complex geometry of the suction elbow. The measurements are performed for nine discharge values (from 16.75 to 43.55 l/s) and four variable speeds (from 2700 to 3000 rpm). As a result, the unsteady pressure signal *p(t)* is acquired for each transducer. The unsteady pressure signal *p(t)* can be written as follow $p(t) = \overline{p} + \Delta p$ where $\overline{p}$ is the average value and Δp the pressure pulsation, respectively. The pressure pulsation might be represented in different forms [24]: peak-to-peak amplitude $\Delta p_p - p$, amplitude $\Delta p_a = \dfrac{\Delta p_p - p}{2}$ and RMS amplitude $\Delta p_{RMS} = \dfrac{\Delta p_a}{\sqrt{2}} = \dfrac{\Delta p_p - p}{2\sqrt{2}}$, respectively. The pressure pulsation acquired for each transducer at speed value $n = 3\,000$ rpm, average pressure at suction (AD3: $\overline{p} = 76.284$ kPa and AD4: $\overline{p} = 70.331$ kPa) and discharge Q=33.5 l/s is plotted on left side in Fig. 5 while the Fourier spectra can be found in the middle. Once can be observed on Fourier spectra the rotational frequency $f_n = 50$ Hz. This frequency is associated to the impeller speed of $n = 3\,000$ rpm being followed by its harmonics. The spectra show as distinct peak the blade passing frequency of 250 Hz ($5 \times f_n$). One significant amplitude of harmonic in the range of 0 … f_n is identified being associated to the suction recirculation according to Nelson and Dufour [26]. A detailed view between 0 Hz and fundamental frequency 50 Hz (corresponding to 3000 rpm) is plotted in Fig. 5 on right side. It is clearly indentified the low frequency of $f_v = 19.7 \pm 0.1$ Hz. As a result, this low frequency is the first parameter used to quantify the unsteady pressure field at the pump inlet. A general view of detailed spectra in range of 0 … 50 Hz for all discharge values are plotted in Fig. 6. The low frequency is marked with red line on each plot in Fig. 6 from smallest to largest discharge value for each transducer.

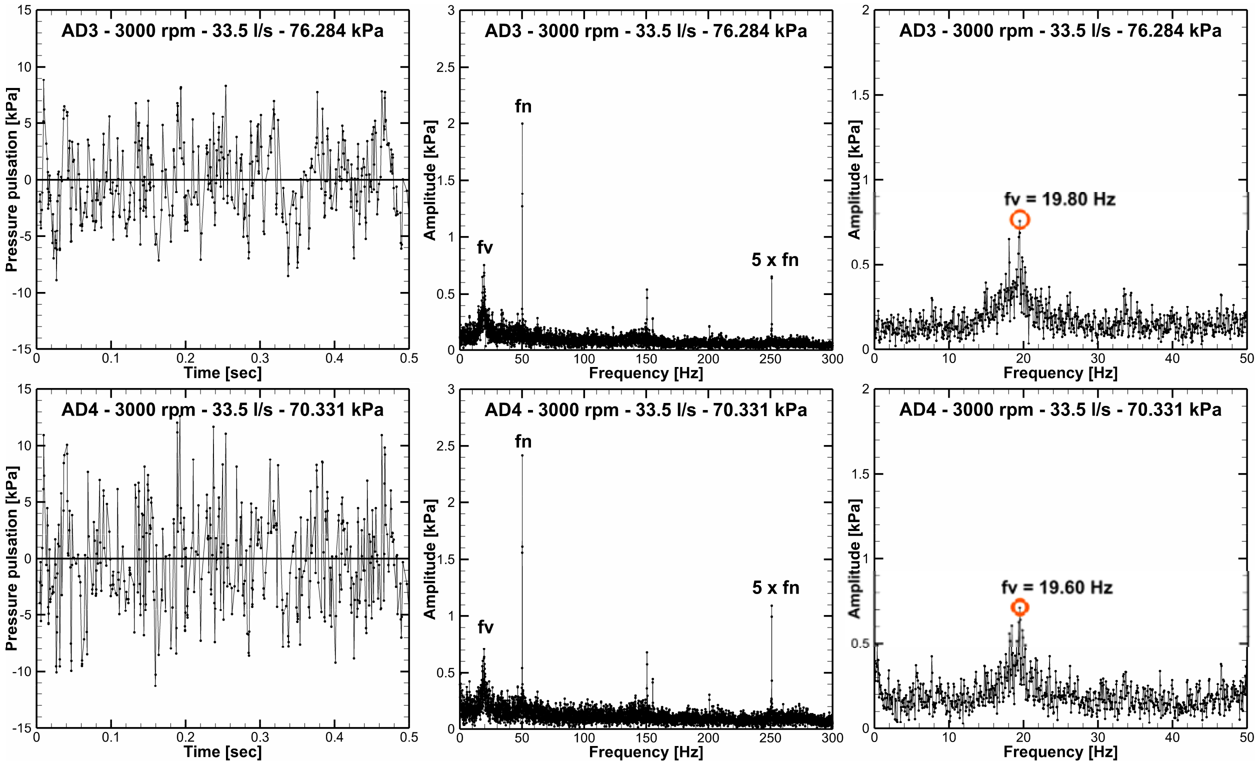


Fig. 5 – Pressure pulsations at suction elbow outlet (left), Fourier spectra of signals (middle) and detailed Fourier spectra (right) for AD3 (up) and AD4 (down) at reference discharge of 33.5 l/s and speed value of 3000 rpm.

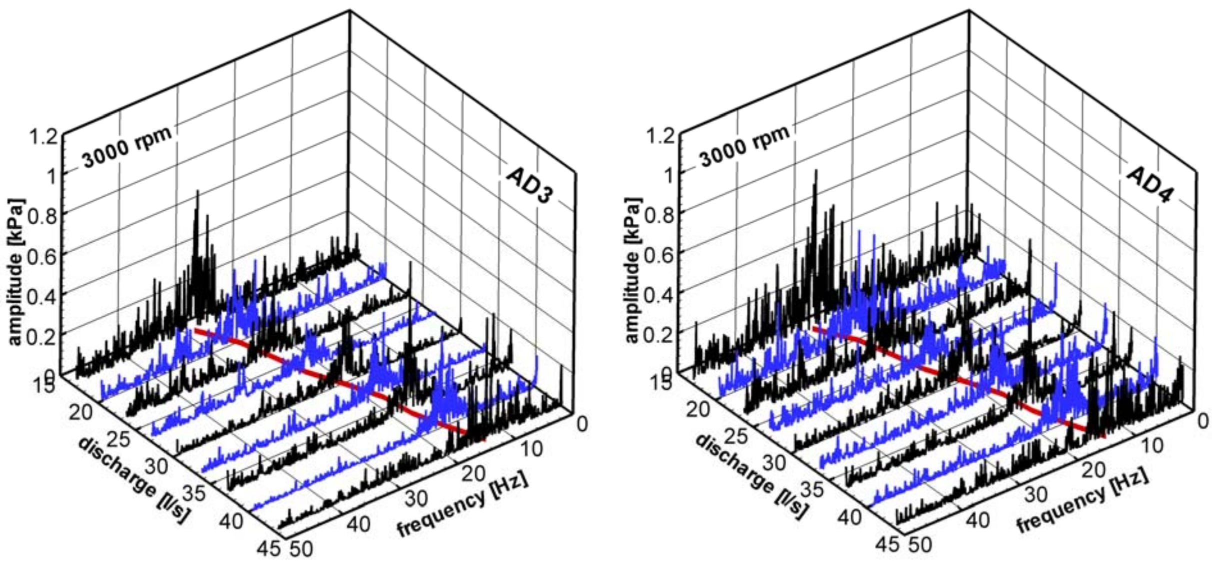


Fig. 6 – Fourier spectra in range of 0 … 50 Hz for AD3 (left) and AD4 (right) transducers at pump inlet and speed of 3000 rpm.

Several sets of data were acquired to each transducer in order to be quantified the evolution of the low frequency associated to the unsteady phenomena at pump inlet. As a result, the low frequency in terms of the average absolute static pressure is plotted in Fig. 7 for both transducers (AD3 (○) and AD4 (■)) at impeller speed of 3 000 rpm and discharge value of 33.5 l/s. A linear function is fitted on each set of data yielding the following functions: AD3 $f_v\left(\overline{p}\right) = 0.47887\overline{p} - 15$ and AD4: $f_v\left(\overline{p}\right) = 0.49992\overline{p} - 14$, respectively. Also, the cavitation coefficient σ is defined according to [27, 28] using the following equation

$$\sigma = \left[0.5\left(\overline{p}_{AD3} + \overline{p}_{AD4}\right) - p_v\right] / (\rho g H), \quad (1)$$

where $\overline{p}$ is the average absolute static pressure acquired by transducer, $p_v = 2\,300$ Pa vapour pressure of water at 20°C, $\rho = 998.2$ kg/m^3 water density, $g = 9.80665$ m/s^2 gravity and $H = 42.85$ m pumping head at 3 000 rpm and discharge of 33.5 l/s, respectively. The low frequency is directly correlated with the average absolute static pressure at pump inlet or the cavitation coefficient according to Fig. 7.

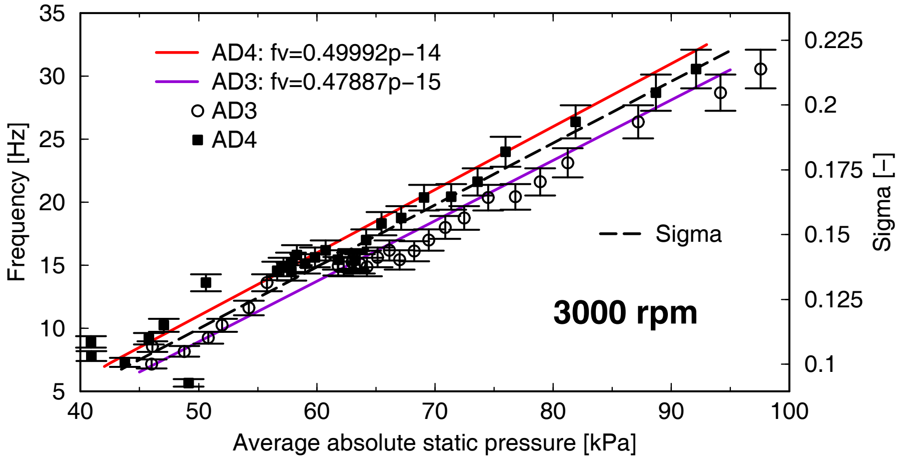


Fig. 7 – Low frequency (f_v) and cavitation coefficient (σ) *versus* average absolute static pressure at pump inlet at impeller speed of 3000 rpm and discharge value of 33.5 l/s.

Therefore, the low frequency associated to the unsteady phenomenon at pump inlet for each discharge is adjusted using the linear function for each impeller speed and each transducer. These values for all regimes are plotted in Fig. 8 for each transducer. A unique linear correlation between low frequency and discharge is obtained for each transducer. Consequently, the unsteady phenomenon generated by the suction elbow and impeller is directly connected with the discharge value. One can be observed that the frequency slows down once the discharge is increased.

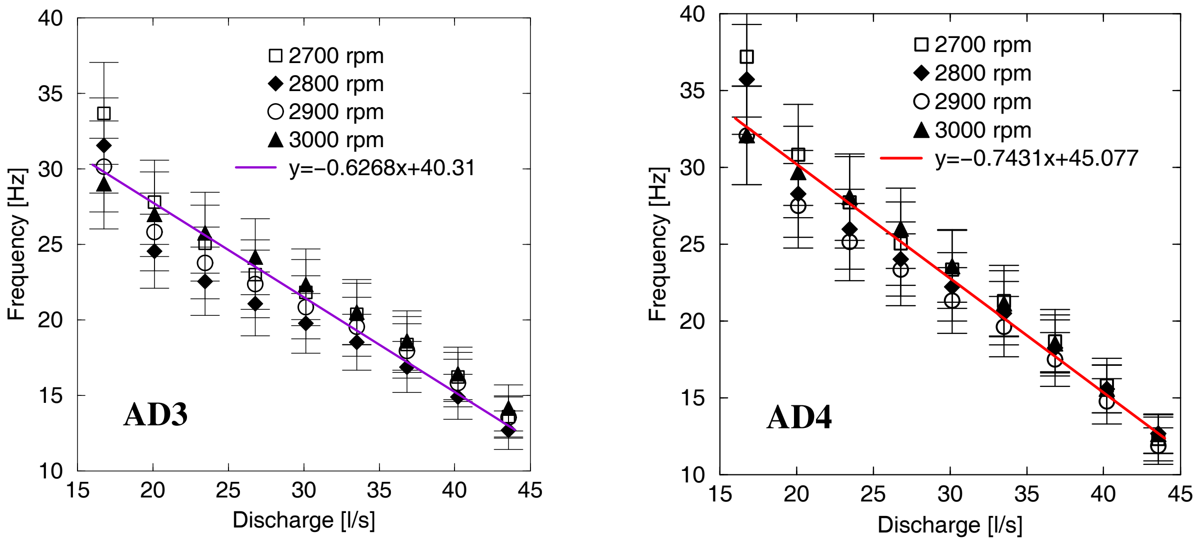


Fig. 8 – Low frequency versus discharge for all impeller speed values (from 2 700 to 3 000 rpm) at AD3 (left) and AD4 (right).

The second parameter selected to quantify the unsteady pressure field at the pump inlet is the equivalent amplitude $\Delta p_{RMS}\left(0 - f_n\right)$ of the pressure pulsation in range of 0 … f_n being defined as follow

$$\Delta p_{RMS}\left(0-f_n\right)=\sqrt{\sum_n\left(\Delta p_{RMS}\right)^2}=\sqrt{\sum_N\left(\frac{\Delta p_a}{\sqrt{2}}\right)^2}=\sqrt{\sum_n\left(\frac{\Delta_p-p}{2\sqrt{2}}\right)^2}\ \ [\text{Pa}], \tag{2}$$

where n is number of narrow bands contained within 0 … f_n. The equivalent amplitude is proportional with the root mean square (RMS) collecting all spectrum contributions in selected range [29]. Therefore, the second parameter is directly correlated with the energy content in a selected frequency range [30]. The equivalent amplitude $\Delta p_{RMS}\left(0-f_n\right)$ computed for signals acquired by AD3 and AD4 transducers at discharge value of 33.5 l/s and impeller speed of 3 000 rpm are plotted in Fig. 8. The equivalent amplitude $\Delta p_{RMS}\left(0-f_n\right)$ on each pressure transducer in terms of discharge for all impeller speeds is drawn in Fig. 9. The distributions in Fig. 9 show a typical evolution for data available on pumps [9, 29]. One can observe that higher values of equivalent amplitude are determined at largest impeller speed of 3 000 rpm. The maximum value of equivalent amplitude is obtained at minimum discharge value of 16.5 l/s while the minim one is located around discharge value of 25 l/s. Also, the equivalent amplitude values computed at AD4 seem to be quite larger than the values at AD3.

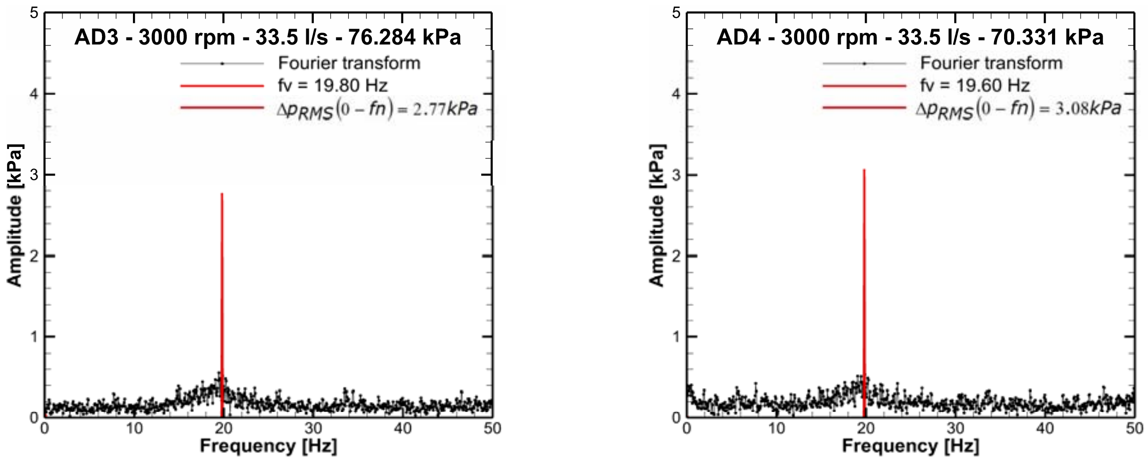


Fig. 9 – Equivalent amplitude for signals acquired on AD3 (left) and AD4 (right) at discharge value of 33.5 l/s, average pressure at suction (AD3: $\overline{p} =$ 76.284 kPa and AD4: $\overline{p} =$ 70.331 kPa) and impeller speed value of 3 000 rpm.

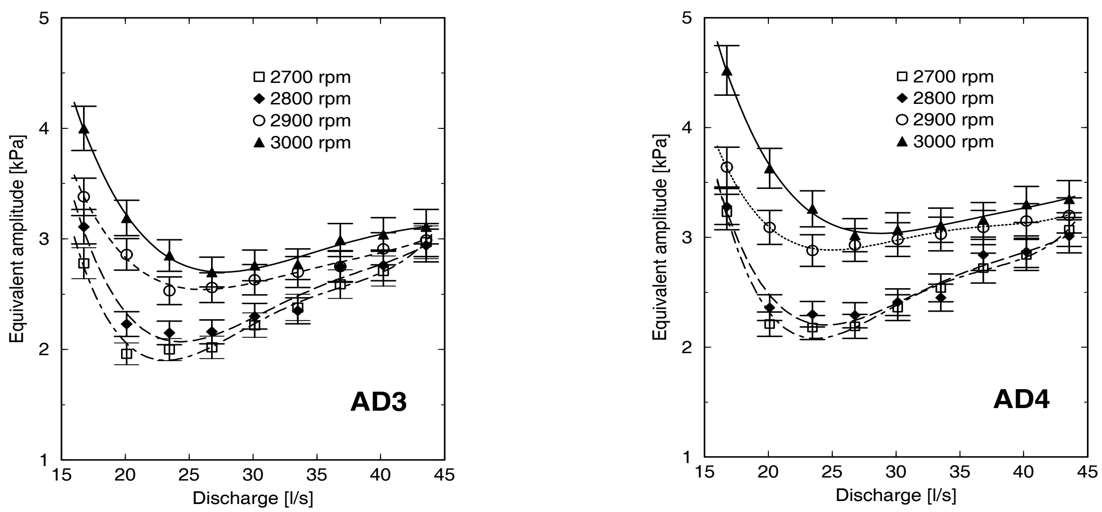


Fig. 10. – Equivalent amplitude $\Delta p_{RMS}\left(0-f_n\right)$ *versus* discharge on AD3 (left) and AD4 (right) transducers for four impeller speed values (from 2 700 to 3 000 rpm).

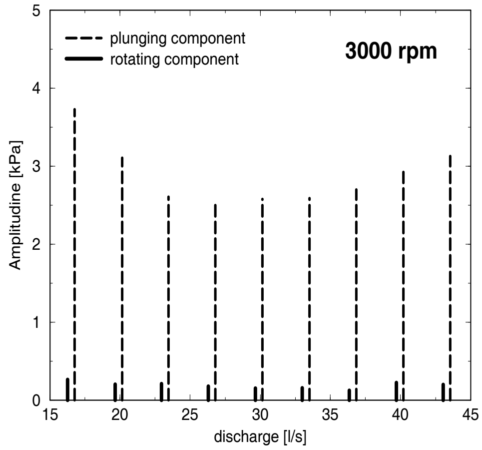


Fig. 10. – Rotating and plunging components associated to the unsteady phenomenon at pump inlet *versus* discharge at impeller speed of 3 000 rpm.

The unsteady pressure signal is decomposed into rotating (asynchronous) and plunging (synchronous) components for impeller speed of 3 000 rpm in Fig. 10 using the procedure introduced by Bosioc *et al*. [29]. A minimum of two sensors located on the same section are required in order to discriminate between two pulsation types. The rotating component of pressure pulsation is acting in the cross section being associated to vortices visualized in Fig 2. The plunging component is produced by flow within elbow and impeller (e.g. suction recirculation). This plunging component propagates in the hydraulic passage. One can observe that the plunging component is one order of magnitude larger than rotating one.

4. CONCLUSIONS

The unsteady pressure field at the inlet section of a pump equipped with a symmetrical suction elbow is experimentally investigated for variable discharge values and several speeds. The model of symmetrical suction elbow corresponding to a large pump is manufactured and installed on test rig. The measurements were performed for nine discharge values (from 16.75 to 43.55 l/s with increment of 3.35 l/s) and four variable speed values (from 2 700 to 3 000 rpm with augmentation of 100 rpm) in order to quantify the unsteady field at pump inlet induced by suction elbow. Two vortices were visualized at the pump inlet. Both frequency and equivalent amplitude associated to the unsteady signals are obtained for both transducers installed at the pump inlet. A unique linear correlation between low frequency and discharge is obtained for each transducer. The low frequency associated to hydrodynamic field at pump inlet is slow down once the discharge is increased. The equivalent amplitude values at largest impeller speed of 3 000 rpm. The maximum value of equivalent amplitude is obtained at minimum discharge while the minim one is located around discharge value of 25 l/s. The plunging component embedded within the unsteady signal is one order of magnitude larger than rotating one. This plunging component propagates in the hydraulic passage. Conclusively, the flow non-uniformity and associated unsteady phenomena generated by suction elbow are ingested by the pump impeller leading to cavitation damage of impeller [19–21] and limited lifetime of the mechanical components [22, 31].

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