FLUID DYNAMIC CHARACTERISATION OF MECHANICAL HEART VALVE BY LDA

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ABSTRACT

In this paper an experimental test bench for mechanical heart valve and the procedure for non-invasive optical measurement are reported. Fluidynamic behaviour of a bileafleat mechanical valve in steady state and pulsed flow conditions has been studied. Laser Doppler Anemometry (LDA) is used to access velocity and turbulence values at different distances before and after the mechanical valve. Data obtained can be related, according to the literature, to typical pathologies affecting patients who underwent surgical procedures to implant mechanical heart valves. In particular thrombosis and hemolysis can be related to high levels of shear stress affecting blood cells. Measurements of velocity, turbulence and shear stresses have been performed.

Keywords: Mechanical heart valve, laser Doppler anemometry, shear stress.

1. INTRODUCTION

The first clinical use of cardiac valve prosthesis took place in 1952, when Dr C. Hufnagel implanted the first artificial caged ball valve for aortic insufficiency. Essentially it was a tube of Plexiglas containing a ball occluder and was inserted into the descending aorta without the need for cardiopulmonary by-pass. The first implant of a replacement valve in the anatomic position took place in 1960, with the advent of cardiopulmonary bypass. Prosthetic heart valves have achieved remarkable results during the last 40 years. It must be remembered that, in this period of time, more then 50 different models of mechanical valves have been introduced on the market. Nowadays, about 175000 prosthetic heart valves are implanted each year throughout the world (of which 60000 in the U.S). Common types of prostheses are the caged-ball valve, the tilting disc valve, the bileaflet valve and the bioprostheses (or tissue valve). Unfortunately, in spite of many years of experience and success, many problems associated with artificial heart valve have not been eliminated. Among them the most serious problems and complications are: valve failure due to material fatigue or chemical change, hemolysis and thromboembolism, anticoagulant-related haemorrhage, tissue overgrowth, infection, paravalvular leaks due to healing defects. Among these, valve failure and thrombosis can concern engineering: the first from a material point of view, while the second from a fluid-dynamic point of view: indeed thrombus formation can be related to high shear stress and foreign surfaces inside the human body. These phenomena include morphologic and functional changes associated with the endothelial cell layer [1–4], the deposition and adherence of platelets [5–6], the formation of artherosclerotic plaque [7-8], and the development of intimae hyperplasia.

Elevated levels of turbulent shear stress as well as higher level of turbulence have been measured near abnormal aortic valves, especially stenotic valves [9]. Since all prosthetic valves create obstructions to the normal flow, high levels of shear stresses have been measured in aortic valves [10]. The most precise measures of shear rate have been obtained from in vitro models. Some studies have used direct shear measurement techniques, but large part of the literature is referring to an approach based on the detection of flow velocities in the vicinity of the vessel wall. Laser Doppler Anemometry (LDA)[11] ultrasound pulse Doppler [12] and photochromic dye [13] are some of the measurement techniques utilised in in-vitro models. For in vivo experiments, hot-film anemometry (HFA) [14], ultrasound pulse Doppler and electromagnetic flow-derived velocity methods, are some of the techniques employed.

Many researchers tried to evaluate the shear stresses threshold values, above which the blood cells can be damaged. There is not a unique result from all the previous works: this is due to the fact that lethal damage to blood cells depends strongly on the presence of foreign surfaces and on the duration of the applied stresses [15]. Severe damages to the different blood components (erythrocytes) can be caused by high shear stresses (in the order of 1500 – 5000 dyne/cm^2) [16], as well as for much lower shear stress (500 dyne/cm^2). In order to make the data concerning shear stress comparable with other results from literature shear stress will be expressed in dyne/cm^2 (1 dyne/cm^2 = 10^{-5} N).

Given the large and growing interest on such topic, authors intentions are to provide a measurement methodology to perform repeatable test on mechanical heart valves with the aim to study the velocity behaviour of such objects by LDA measurement technique. Results aim to assess the fluid dynamic behaviour of mechanical heart valve and to provide data useful for the evaluation of local shear stress.

2. NATURAL AND ARTIFICIAL HEART VALVE AND EXPERIMENTAL SET-UP.

There are four valves in the human heart, one at the exit of each chamber. In order of blood flow they are the Tricuspid (right atrium), Pulmonary (right ventricle), Mitral (left atrium), Aortic (left ventricle). Due to the higher pressure gradients, the mitral and aortic valves are usually affected most by disease. Nowadays there are two main groups of prosthetic heart valve: Mechanical Heart Valve (MHV) and Bioprosthetic Valve (BV). In this article all the tests have been conducted on a bileaflet MHV, reported in figure 2.1. This type of valve is the commercially dominating prosthetic valve.

Figure 2.1 Bi-leaflet mechanical heart valve used for the tests.

This valve has two semicircular leaflets, which divide the area available for forward flow into three regions: two lateral orifices and a central orifice. This type of valve is lifetime lasting, but patients receiving it must undergo continuous anticoagulant therapy that makes them borderline haemophiliacs. This valve can show as high shear stresses as 2000 dynes/cm^2 that according to Nevaril et al. [15] is sufficient to induce lethal damage to the blood cells and to activate the anticoagulant factors.

In figure 2.2 it has been reported the experimental set-up for the hydrodynamic test as it has been realized. A centrifugal pump has been utilised to generate the flow. A flowmeter (ITT BARTON Series 7000) is used to control the volumetric flow and a measurement chamber containing the bileaflet valve specially realised for LDA optical access. An image of the measurement chamber is reported in figure 2.3. A thin transparent pipe has been realised inside the measurement in order to solve the problem of index matching. The LDA probe is moved by a traversing gear along the X, Y and Z axis (traversing resolution: 50 μm)

The hydraulic loop was filled of water (ρ =1000Kg/dm^3 ; μ = 0.98 * 10^{-3}) and then seeded with cone pollen. Tests for steady state flow were carried on at 2 different flow rates: 5.2 and 3 l/min.

An Argon Ion Laser with a maximum power of 4W and a beam radius of 1.5 mm has been used as laser source for the LDA system. For measuring the two velocity components (axial and radial) of interest simultaneously two wavelengths are generated: λ_1 = 488 nm and λ_2 = 514.5 nm. The LDA processing system is based on couple of BSA (Burst Spectrum Analyser) 57N20/35 ENHANCED supplied by DANTEC. Each BSA system processes the information relative to one of the two velocity components. Maximum frequency operative range is 120 MHz, so they must sample the signal with a frequency of at least 300MHz. BSAs are connected to the PC by a IEEE 488 interface board for data acquisition and processing.

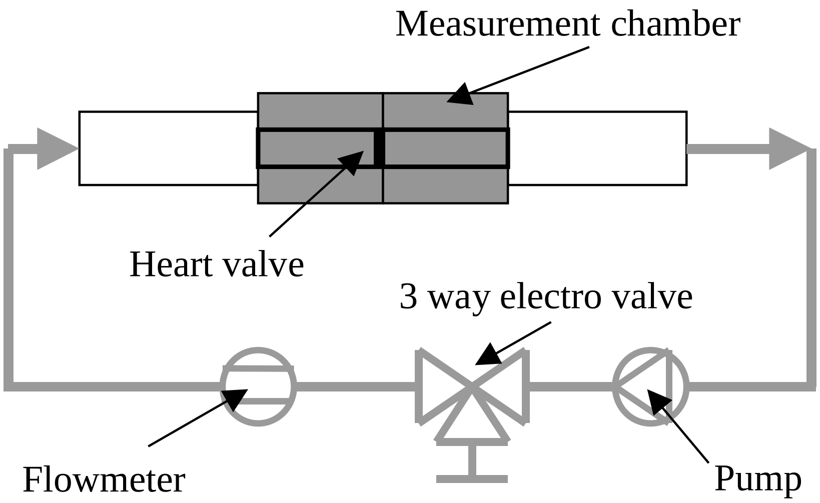


Figure 2.2 Experimental set-up used for mechanical valve testing.

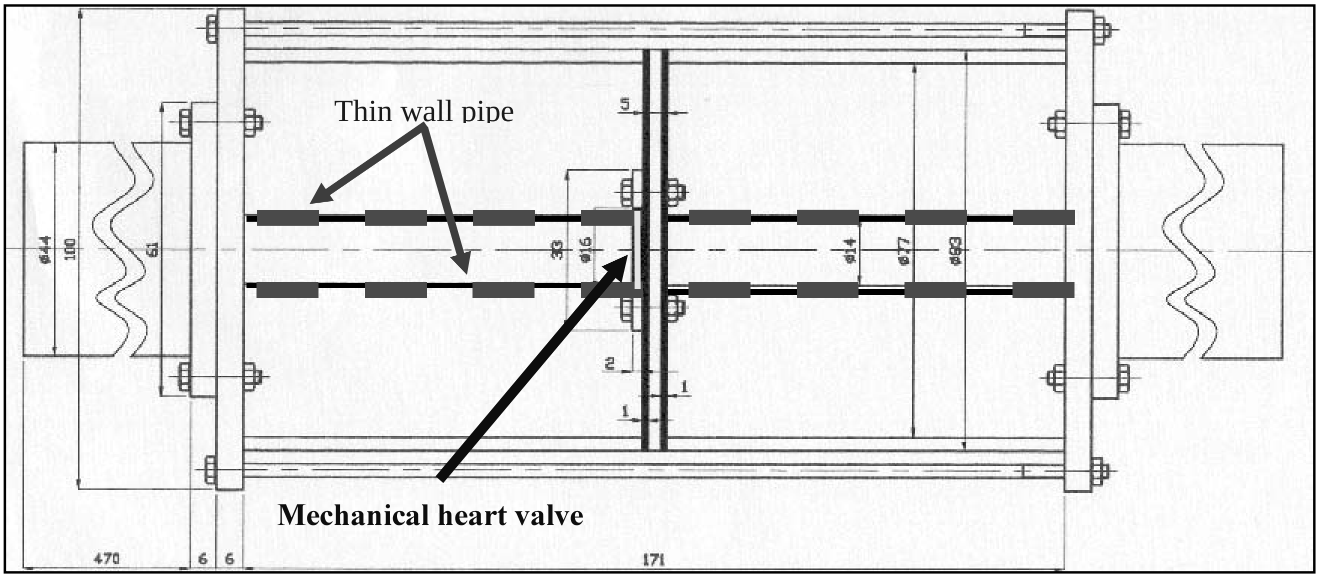


Figure 2.3 Measurement chamber employed for the valve test.

The measurements are taken along the diameter orthogonal to the three regions. Where not indicated, in this paper are reported the measurements performed in the central point of the pipe.

3. RESULTS AND DISCUSSION

Velocity time history for pulsed flow at 6 L/min at a distance of 18 mm after the valve position is reported in figure 3.1. Figure 3.2 reports the velocity direction time history in the same test conditions.

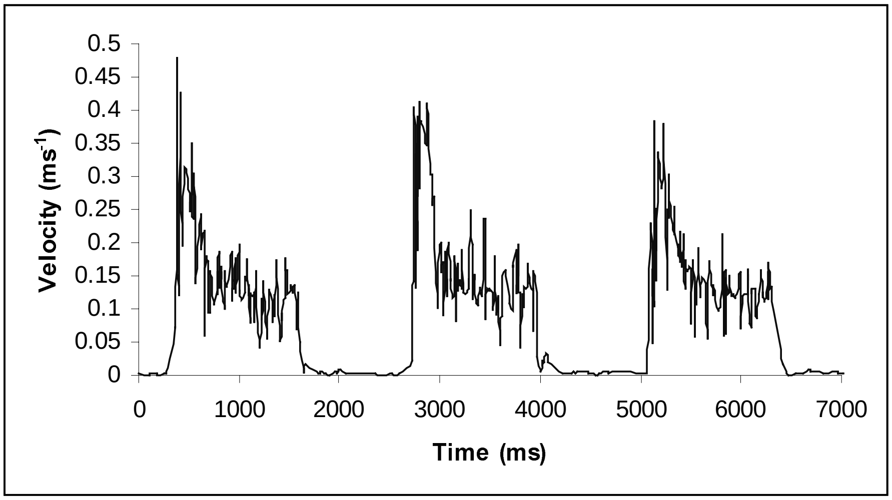


Figure 3.1. Velocity time history at 18 mm after the valve.

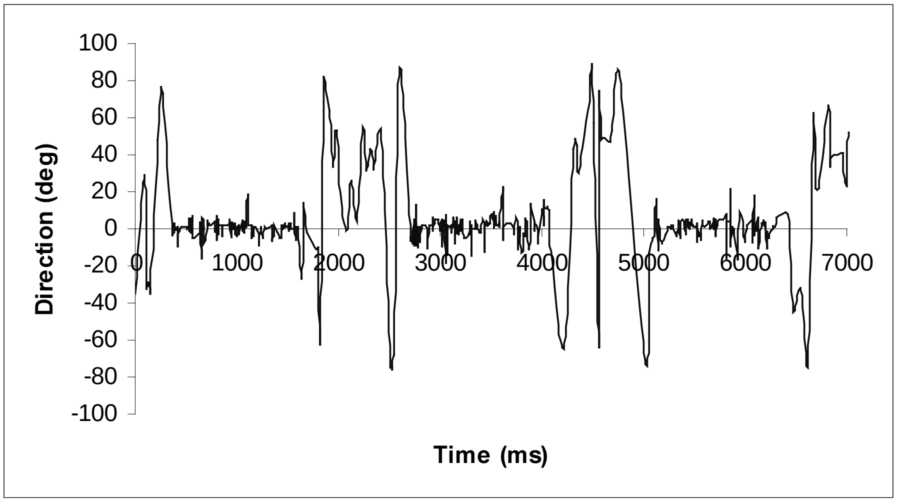


Figure 3.2. Velocity direction time history at 18 mm after the valve.

It is possible to observe the typical shape of the square wave imposed by the pneumatic valve action. The effects at the aperture of the valve are evident such as the overshooting in the velocity amplitude due to the Venturi effect and inertia of the fluid or the direction changes induced by the leaflet aperture and turbulence generation. When the valves are open the laminarisation effect, due to the velocity increase, guides the flow and reduces the fluid perturbation.

With data collected it is possible to measure with precision the behaviour of the fluid and to follow the velocity variation with a very high accuracy and an adequate “sampling rate”. As well known, LDA is not able to measure velocity variation with a fixed sampling rate. In fact for this technique samples are constituted by the bursts observed by the photodiode and produced by the particles passing on the probe volume, and these bursts are produced at non-constant frequencies, being the particles randomly distributed and being not possible to control the corresponding sampling rate. The only control available on the test bench is the seeding concentration; high concentration causes an increase in the average data rate.

In order to calculate the power spectrum of the signal is therefore necessary to re-sample the signal interpolating it at a constant rate. In Figure 3.3 the spectrum of the particles velocity is shown in point at 18 mm after the valve. It is possible to note the typical spectral distribution of the square wave with odd harmonics higher than the even one.

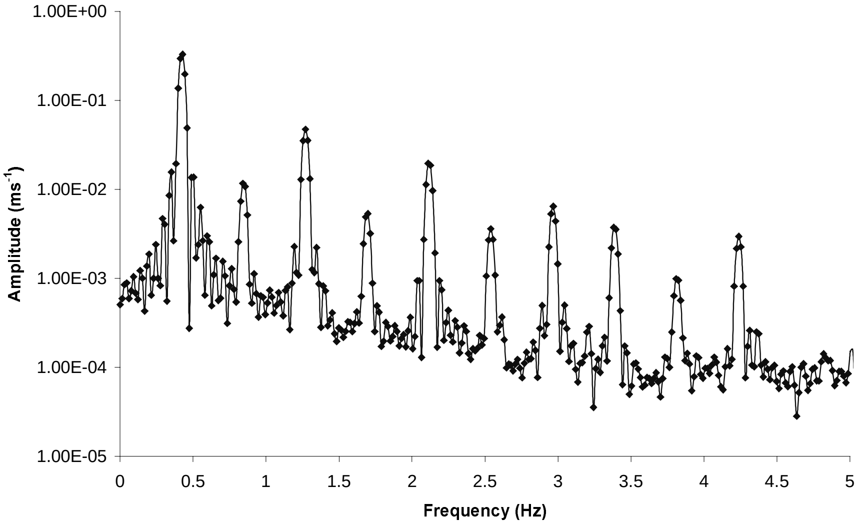


Figure 3.3. Power spectrum of the particle velocity at 18 mm after the valve.

The frequency bandwidth acquired was 50 Hz, with a frequency resolution of 15 mHz. These values have been obtained extending the measurement time and enlarging the amount of data processed.

In Figure 3.4 some profile of the flow field are shown. Flow pattern before the mechanical valve (see figure 3.7) appear to be regular and is not affected by the circuit turbulence. After the valve the two wakes of the leaflets are evident. They dominate the flow section and exhibit important velocity gradients. The energy dissipation is large, the wakes vanishing rapidly, causing high shear stress rates in the fluid.

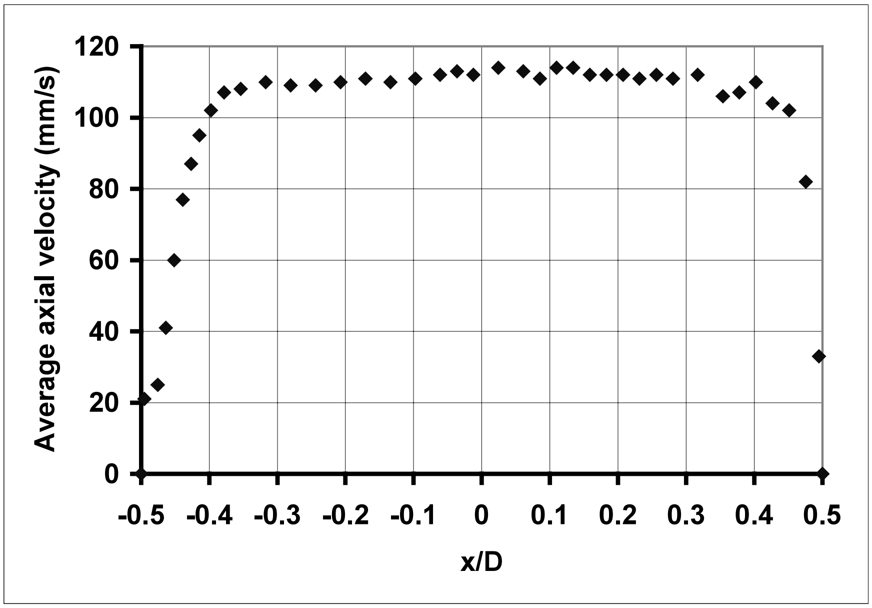


Figure 3.4. Particle velocity profile at 37 mm before the valve, flow rate 3 L/m.

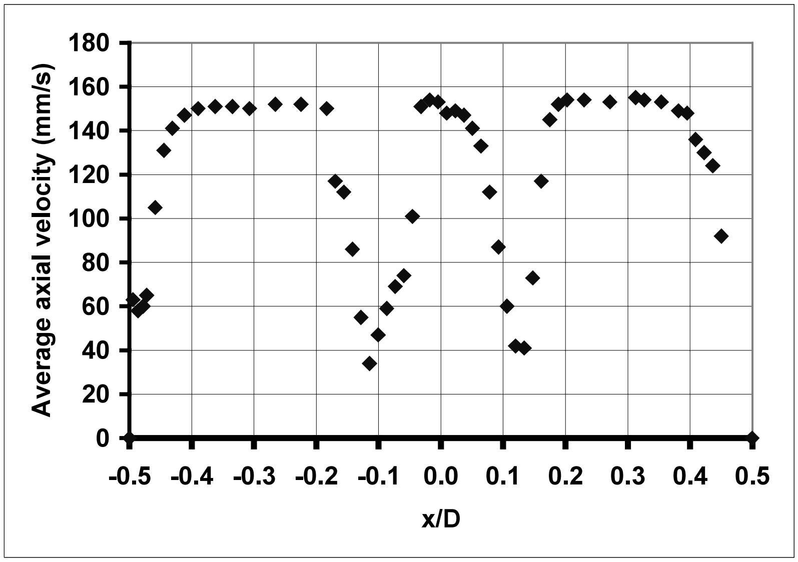


Figure 3.5. Particle velocity profile (at 8 mm after the valve, flow rate 3 L/m).

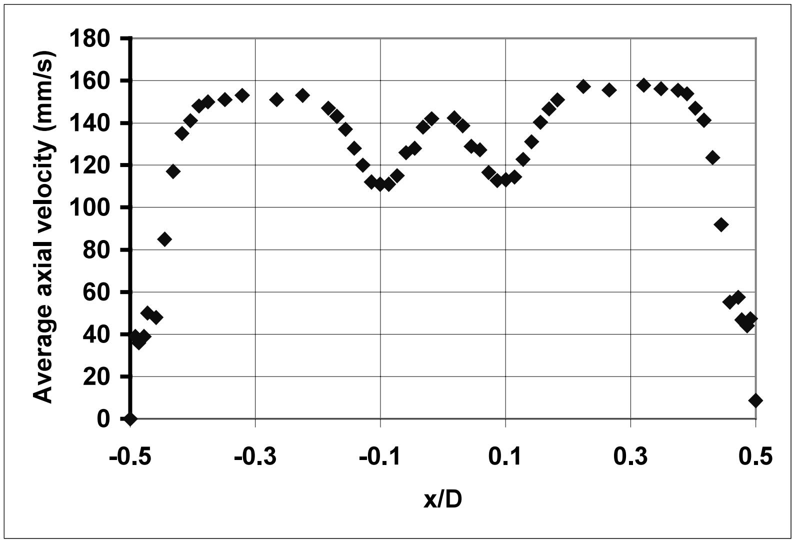


Figure 3.6. Particle velocity profile (at 18 mm after the valve, flow rate 3 L/m).

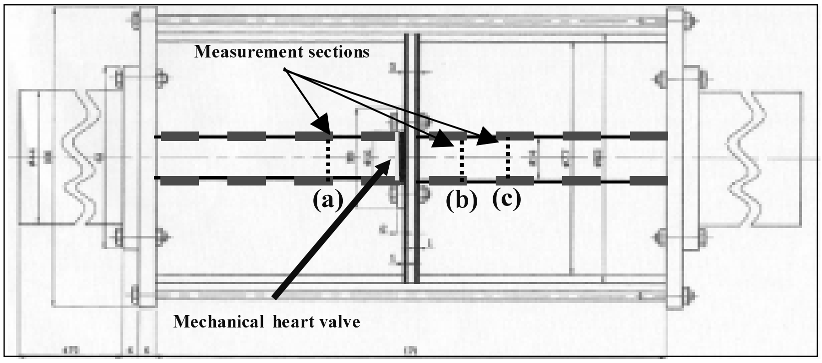
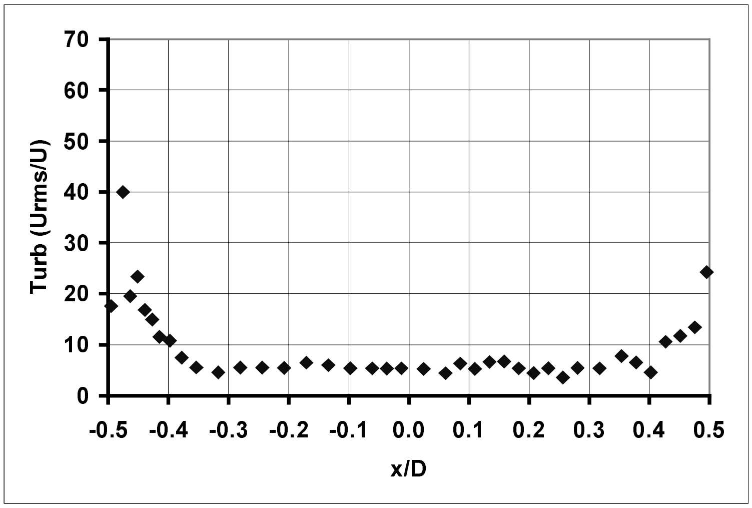
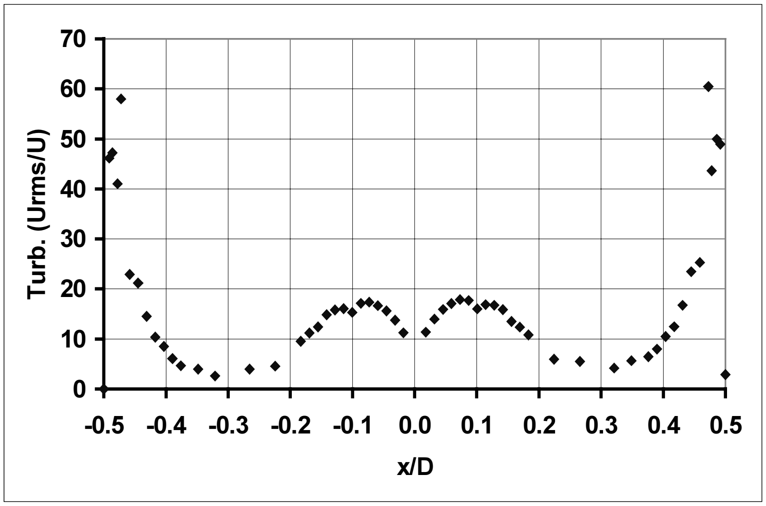


Figure 3.7. Measurement sections a, b and c at respectively: 37 mm before, 8 after and 18 after the valve.

In Figure 3.7 the turbulence profiles at 8 mm (a) and 18 mm(b) are shown. Such profiles confirm that the fluid field is good before the valve being the turbulence level low and uniform in the section. After the valve the turbulence level increase, in particular in correspondence to the leaflets and the valve support.



(a)



(b)

Figure 3.7. Turbulence profiles at 8 mm (a) and 18 mm(b), after the valve (Flow rate: 3 L/min).

4. CONCLUSIONS

In the present paper an experimental test bench for the measurement of fluid dynamic behaviour of mechanical heart valve is reported. Results obtained from LDA measurements on a bi-leaflet prosthetic valve are presented in terms of velocity amplitude and direction time histories.

The experimental test bench and the optical access solution proposed allow to perform precise measurements fluid-dynamic parameters. Pulsate flow can be analysed observing the turbulence values and the local velocity in his evolution and also a spectral analysis can be performed.

Examples of velocity profiles along valve diameter are reported for 3 L/m stable flow at 37 mm before the valve and at 8 and 18 mm after the valve, as well as turbulence profiles are reported at 8 and 18 mm after the valve.

Data obtained can be can be used to perform the calculation of fluid-dynamic parameters, such as shear stress, that can affect blood cells state. In our tests, maximum shear stresses levels of 450 dyne/cm^2 at 6.5 L/m flow and 650 dyne/cm^2 at 14 L/m have been measured.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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