Power density spectra of the velocity waveforms in Artificial heart valves

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Abstract — To find the possible frequencies induced by the vibration of the flexible membrane of the Jellyfish valve, power density spectra of the valvular velocity waveforms were carried out.

Most of the spectral energy was contained in frequencies lower than 11 Hz and all spectra exhibited pronounced peaks which implied wave motions in the preferred frequency range.

Two distinct peak frequencies, 1.2 and 2.4 Hz, were observed downstream of the Jellyfish valve which qualified as the frequencies of fundamental harmony of the waveform velocity and one of its sub harmonics.

Effect of oscillation on elevating turbulent shear stresses through the jellyfish and St.Vincent valves has also been investigated. Laser Doppler Anemometry (LDA) was employed to determine the velocity and shear stress distributions at various locations downstream of the valves. Comparison between two valves revealed that at 0.5D downstream of the valves the magnitude of shear stresses in the Jellyfish valve were much higher than those of the St. Vincent valve at cardiac outputs of 4, 5.5 and 7 l/min.

The cause of high shear stresses in close proximity to the Jellyfish valve could be attributed to the oscillation of the membrane which in turn generated a wake downstream of the valve (in the core of valve chamber) and produced a wide region of disturbance further downstream. This resulted in further pressure drag and consequently, higher pressure drops across the valve and higher shear stresses downstream of the valve.

Keywords — Power density spectra, Heart valves, shear stresses, oscillation, LDA technique

I. INTRODUCTION

Prosthetic heart valves are commonly used for replacement of natural valves, in ventricular assist devices (VADs) and total artificial hearts (TAHs). In artificial heart valves, the problems of haemolysis, platelet destruction, thrombus formation, perivalvular leakage, tissue overgrowth and endothelial damages are directly related to the fluid dynamic characteristics of flow past artificial heart valves ([1], [2], [3]). The presence of the prosthetic valve as a stenosis disturbs the blood flow and produces regions of high turbulent shear stresses, jetting and flow stagnation which, in turn cause pathological problems such as haemolysis and thrombosis. Blood cells in the region of high shear stresses are exposed to a distribution of shear stresses over their entire membrane which causes the blood-cell membrane to be stretched and cause harmful changes to its essential function and eventually rupture the cells. Therefore, haematologically, it is highly desirable that a valve design shouldn’t produce excessive turbulence, which may cause haemolysis ([2], [3], [4], [5]). In this study power density spectra of the valvular velocity waveforms were carried out and the effect of oscillation on elevating turbulent shear stresses and pressure drops through the jellyfish and St.Vincent valves has been investigated. Laser Doppler Anemometry (LDA) was employed to determine the velocity and shear stress distributions at various locations downstream of the valves.

II. METHOD

Power density spectra of the valvular velocity waveforms were carried out. The fast Fourier transform (FFT) was implemented by FLOware to calculate spectral estimate of the valvular velocity waveforms over the entire cycle to produce the power spectra density.

Mean spectral or power spectral density can be estimated as:

\[ S_T(f)_{\text{FFT}} = \frac{T}{N^2} \left\{ \left| \sum_{i=1}^{N} u_i e^{i2\pi f_i} \right|^2 \right\} \]
\[ \bar{S}_T = \frac{1}{M} \sum_{m=1}^{M} S_{Tm} \]

where \( S_T(f) \) is spectral estimate, \( \bar{S}_T(f) \) is mean spectral estimate or power spectral density, \( S_{Tm} \) is the spectral estimate calculated from the mth blocks of data, M is the total number of blocks, T is duration of block during which N spherical samples occur and \( u_i \) is axial velocity component of \( i^{th} \) particle.

Two valves namely Jellyfish and St.Vincent valves were selected. Jellyfish valve consist of a thin flexible membranous occluder made of Polyurethane and attached centrally to a rigid frame which have several spokes to protect against prolapse of the membrane.

A blood analogue fluid of water-saline solution was contained inside the ventricle chamber and was separated from the piston pump by the polymeric flexible ventricle. Blood analogue fluid provided a transparent and easy
handling situation for velocity measurements with Laser Doppler Anemometry. In the inlet of the flexible ventricle chamber (mitral position) a Björk-Shiley tilting disc valve was installed.

An electromagnetic square-wave flowmeter, which was calibrated before measurement, was installed 8D downstream of the valve so that the instantaneous flow rates could be determined.

The pressure pulses were measured by three disposable and physiological blood pressure transducers in the left ventricle, downstream of the aortic valve and in the compliance chamber. Flow measurements were done at cardiac outputs of 4, 5.5 and 7 l/min.

A Dantec (Skovlunde, Denmark) two-component LDA system was used to determine the flow field at various locations downstream of the valve.

Data was collected in continuous mode over 100 to 200 cycles, depending on the collected data rate to ensure that at least 1000 samples would be collected during every 5 ms of the forward flow phase. After collecting data over complete cycles, data from each cycle is divided into 168 sample windows, each 5 ms duration. Then data belong to nth sample window of each cycle was compiled into nth bin and averaged to yield fluctuating and mean components. Mean components over 100 to 200 cycles (depending on data rate collection) can be manipulated into one representative cycle as follows:

$$S_n = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} S_{ij}}{nm}$$

where $S_n$ is the mean component of nth sample window, $S_{ij}$ are the instantaneous components contained within a sample window, n is the number of data points in a sample window and m is the number of cycles measured.

All possible sources of error were carefully examined and having ensured that all recommendations concerning optical component alignment, seeding, filtering, signal processing, and calibration were carried out, the estimated measurement error of the mean velocity is $\pm 3\%$ and that in the rms is $\pm 7\%$.

Diagram of mock circulatory system is shown in Figure 1 and more details of it and LDA technique are given somewhere else ([6] and [7]).

III. RESULTS AND DISCUSSION

A Spectrum analysis

To find the possible frequencies induced by the vibrations of the flexible membrane of the Jellyfish valve, power density spectra of the valvular velocity waveforms were carried out. The random nature of the LDA prohibits sampling at regular and equi-spaced intervals which presents additional variability of the spectral estimator. In order to reduce this variability, spectral analysis of data was performed according to the method of direct Fourier transform of short blocks of data by FLOware by implementing the re-sampling of the signals for data that were not collected in the dead time mode.

Important and useful information about dominant frequency peaks and preferred mode which exists in the flow can be derived from the spectral information. Figures 2 and 3 show typical energy spectra measured at downstream locations of the Jellyfish and St. Vincent valves in the regions of stagnation and jetting at cardiac output of 6.5 l/min.