

Laser Velocimetry in the study of the fluid dynamics of artificial organs

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The study of cardiovascular implantable devices requires advanced techniques, owing to the importance of assuring the highest quality and continuity of functioning after implantation. It is sufficient to recall, with regard to this, that a heart valve opens up and closes approximately 40 million times per year, and that a prosthetic valve is designed to last well beyond the patient's life expectancy. One of the main concerns of the clinical usage of heart valves is the turbulence associated to them, especially at peak systolic (diastolic) flow for the aortic (mitral) valve or during the leakage phase, for both mitral and aortic implants.

Actually, turbulence in the blood stream has often been correlated with thrombogenesis [1] and hemolysis [2]. The latter problem, although relatively less frequent than the former in the current models of mechanical prosthetic heart valves (PHVs), is nevertheless something which needs an accurate study, since hemolysis cannot be controlled pharmacologically, as opposed to the case with thrombus formation (a strict regime of anticoagulants is strongly suggested for PHV recipients [2]). These clinical concerns prompted the FDA [4] to advocate the testing of PHVs at the maximum Reynolds number conditions, to investigate the worst case for turbulence production. The velocity measurements have to be very accurate and precise, in order to guarantee a reliable assessment of the blood damage associated with the use of such devices.

Laser Doppler anemometry (LDA)

In the recent past, the Laboratory of Biomedical Engineering of the ISS has been addressing the issue of turbulence measurements of cardiovascular implants mainly with LDA, which allows reliable single-point measurements. The main features of LDA are the small measurement volume,

the high temporal resolution and repeatability of measurements, especially in forward scatter mode, which is affected by a potential large decrease in data rate for a less than optimal disposition of the transmitting and receiving probes; a possible cause for this is the imperfect refractive index matching between fluid and walls of the test section. Although being a time-consuming technique, for both set-up and data acquisition, LDA is still the technique of choice for high-accuracy measurements. Actually, a single particle crossing the measurement volume (MV) provides the instantaneous velocity, whereas for PIV a certain number of particles per interrogation window is required to have reliable measurements, depending on the local velocity gradient [6], since PIV is based on a statistical approach, yielding the mean value of a small cluster of particles in the interrogation window.

Mechanical stress on the blood constituents is due to the turbulent flow downstream of a PHV is usually quantified with the Reynolds shear stress (RSS), or turbulence shear stress (TSS). In fact, as shown by Fig. 1 (a St. Jude Standard valve was tested, at a downstream distance of 7 mm), the laminar shear stress, defined as $\mu \frac{d\bar{U}}{dz}$, z and μ being the cross-stream coordinate and the kinematic viscosity, respectively, is much lower than TSS_{\max} , so that the mean value of the viscous shear stress can be neglected, as a first approximation.

PIV measurements on PHVs

Another technique often applied in the recent past, and gaining an increasing success also in the field of biomedical engineering, is the particle image velocimetry (PIV). Although the first attempts of deriving velocities from the analysis of particle images are quite old (dating back to the early years of the XX century), it is only with the recent availability of large computing power that the PIV concept has established itself as a reliable and fast measurement technique. The most popular application of PIV is nowadays the cross-correlation digital PIV, where the intensity of the first of a

pair of particle images (separated by a suitable temporal displacement) is cross-correlated with the second one. This operation is performed on digital processors, usually by means of the bidimensional fast Fourier transform (FFT). In the future, the possibility of parallelization of the FFT operation (which consists essentially of the sum of a series derived by the input sequence) will probably render the PIV analysis even more popular than it is today, owing to the rapid analysis of complex instantaneous flow fields.

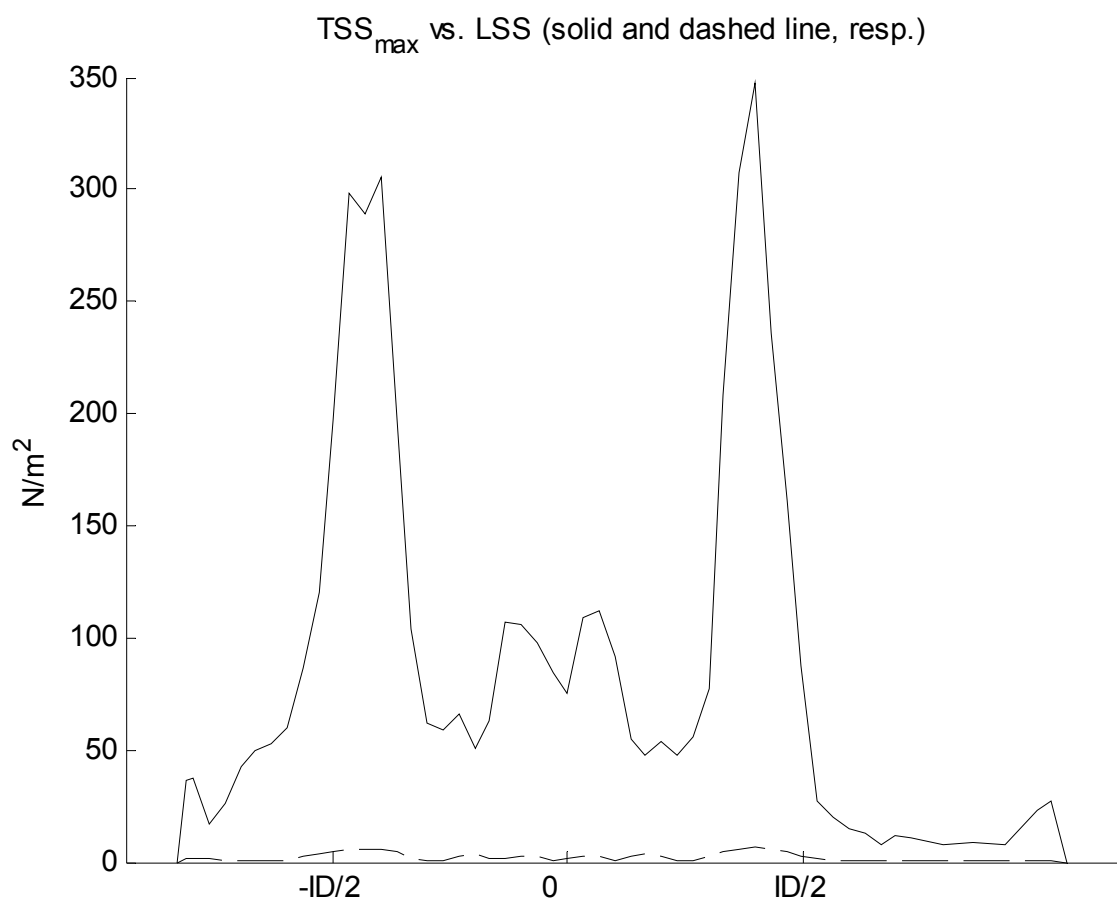


Figure 1

Although very attractive, as it exploits the increasing processing speed of off-the-shelf computers, this technique is not exempt from problems, especially as far as complex flow fields are concerned.

As an example of the pitfalls associated to the PIV analysis, in Fig. 2 the flow field is shown of a CM 19 mm. In the central zone, a much disordered vector field can be appreciated. Actually, turbulent flow often causes a remarkable loss-of-particles effect (i.e., the presence of a given particle in only one of the couple of images used to derive the velocities relative to a time instant), with unrealistic results. This can be checked by investigating the quality of the correlation between particle images. It is not surprising that in this case the peak of the cross-correlation function was not clearly superior to the other maxima, on account of the high noise level, associated to the loss of particles between the first and the second image. The central part of the flow field of this PHV was previously seen as characterized by flow instability, with the loss of the central velocity peak that is expected in a bileaflet valve [5].

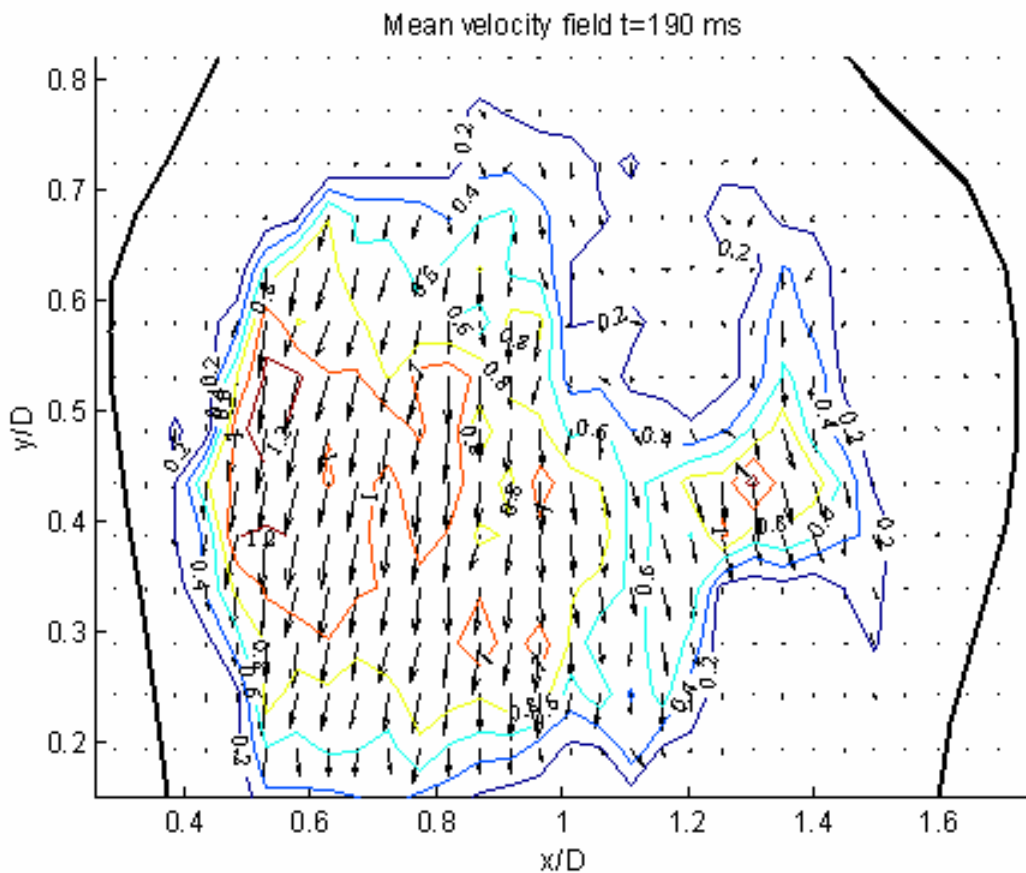


Figure 2

In contrast, here LDA would not have suffered a loss of data quality, since only one particle is needed in the MV to derive (in appropriate SNR conditions) a velocity measurement.

Other critical points of the PIV technique are the necessity of having good seeding conditions anywhere in the flow, whereas for LDA this is not an absolute requirement because, whenever the seeding density is not optimal, fewer particles cross the MV per unit of time, but the effect is just that the data rate worsens, not the quality of the single velocity recording. In PIV analyses, instead, the depletion of particles which often affects parts of the flow field is detrimental for the quality of the single velocity calculation in the considered zones.

As for the accuracy of velocity measurements, also LDA is not entirely free from problems, since the signal produced by the scattered light is a modulated sinusoid, with a gaussian as the modulating function.

Therefore, the spectral content of the received signal is not a pure spectral line, whose frequency is ideally proportional to the particle's velocity (according to the Doppler principle), but is instead a gaussian centered about the expected frequency f_0 : if $g(t) = \exp(-t^2/T^2)$ is the pulse envelope, the received signal can be expressed as $s(t) = g(t) \times \sin(2\pi f_0 t)$, whose Fourier transform yields (considering only positive frequencies, for simplicity of notation) $S(f) = G(f) * \delta(f - f_0) = G(f - f_0)$, $\delta(f)$ being the Dirac impulse in the frequency domain.

This spectral broadening can increase the uncertainty of the velocity estimates. As an order of magnitude for the latter, from the uncertainty relationship

$$\Delta t \Delta \omega \geq 1,$$

we have that $\Delta f \geq \frac{1}{2\pi \Delta t}$, Δt being the time spent by the particle in the MV, or $\Delta t = l/v$, where l is the size of the MV. Δt is also the extent of the envelope in the temporal domain, and correspondingly Δf is the extent of the spectral width in the frequency domain.

Considering, e.g., a value of $v = 1$ m/s and $l = 100$ μm , $\Delta f \geq \frac{10^4}{2\pi} = 1591$ Hz. This finite spectral width, even though not introducing any systematic bias in the velocity determination, can decrease the precision of the measurements.

Turbulence shear stress: measured value vs. maximum value

Independently from the way in which the Reynolds stress tensor (or some components thereof) is measured, it is necessary to perform a principal stress analysis (PSA) on it before the evaluation of the mechanical load related to device-induced turbulence [7-8].

Being the Reynolds stress tensor a real-valued symmetrical tensor, it is well known that a suitable coordinate system exists such as the Reynolds tensor can be expressed in the form

$$T = \overline{\rho u_i u_k} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

with σ_1 , σ_2 and σ_3 representing the principal normal stresses (Malvern, 1977), ordered usually as follows: $\sigma_1 \geq \sigma_2 \geq \sigma_3$. This coordinate system is composed of the Reynolds tensor's eigenvectors directions, and is termed *principal coordinate system*. Accordingly, σ_1 , σ_2 and σ_3 are the tensor's eigenvalues. It can be demonstrated (Malvern, 1977) that the maximum shear stress acting on a surface element characterized by the normal unit vector \mathbf{n} can be expressed simply as $TSS_{\max} = \frac{\sigma_1 - \sigma_3}{2}$.

If only 2D measurements are available, the same approach can be followed, considering of course a two-dimensional space: thus, the Reynolds stress tensor can now be written as

$$T = \overline{\rho u_i u_k} = \rho \begin{bmatrix} \overline{u^2} & \overline{uv} \\ \overline{uv} & \overline{v^2} \end{bmatrix}$$

whence the two PNSs are the solutions of the equation

$$\sigma \mathbf{I} - T = 0, \quad (1)$$

which can be expressed as

$$(\rho \bar{u}^2 - \sigma)(\rho \bar{v}^2 - \sigma) - \rho^2 (\bar{uv})^2 = 0,$$

or

$$\sigma^2 - (\rho \bar{u}^2 + \rho \bar{v}^2) \sigma - \rho^2 (\bar{uv})^2 = 0.$$

Starting from the solutions of the eigenvalue equation (1)

$$\sigma = \frac{1}{2}(\rho \bar{u}^2 + \rho \bar{v}^2) \pm \frac{1}{2} \sqrt{(\rho \bar{u}^2 + \rho \bar{v}^2)^2 - 4\rho^2 (\bar{uv})^2},$$

the semidifference of the latter two values yields a two-dimensional TSS_{\max} of

$$TSS_{\max, 2D} = \rho \sqrt{\frac{1}{4}(\bar{u}^2 + \bar{v}^2)^2 - (\bar{uv})^2},$$

in accordance with the result, obtained in an alternative way, in [8].

The determination of the maximum Reynolds shear stress, either in a two-dimensional or in the full three-dimensional frame, is required to have a reliable assessment of the maximum load, with possible blood trauma, on the hematic components [9, 10].

This type of measurements, obtained in realistic functionment conditions, is necessary to guarantee an operational life of the implanted device as free as possible from clinical complications. It can be realistically expected, moreover, that this fine-scale characterization will help designers in improving the biocompatibility and hemodynamical performance of such devices.

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