Investigation on vortex dynamics downstream moving leaflets by means of Robust Image Velocimetry

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Abstract The interaction of a sudden flow through an orifice and moving leaflets hinged at its border was investigated experimentally in a Plexiglas vessel. This configuration is typical of many biological flows, such as in sea-animal propulsion, where the moving flaps control the flow optimizing thrust, or in heart valves, where the leaflets prevent backflows. Therefore, the comprehension of the flow structure interaction and of the features of the flow is fundamental for the design of prosthetic heart valve that minimize regurgitation. In our experiments, the flow was driven by a computer controlled piston generating a flow with Re = 2000 and St = 0.2. A rectangular slot 3.0 cm wide and 10.0 cm high was equipped with aluminum leaflets hinged at its longer border. Three leaflets configuration have been tested: two symmetrical leaflets, a leaflet twice the other and a single leaflet. A continuous laser illuminated the middle plane of the test section and an high-speed camera acquired images. Velocity fields were obtained by RIV (Falchi et al. 2006) in order to accurately resolve the small scale structure of the vorticity field. The dynamics of the opening of the leaflets, the vorticity fields, and the features of the vortices generated during their aperture was investigated and compared in the different leaflet configurations.

1. Motivation of the Present Investigation

The sudden onset of a jet-flow in calm ambient generates a vortex ring that begins to travel in the direction of the jet axis. Typically, the vortex ring grows up to a limiting value and, if the flow continues furthermore, it detaches from the trailing jet which does not contributes anymore to the increase of circulation of the vortex, producing a vorticity layer at its wake. The comprehension of such a phenomenon is of basic importance in a wide range of applications, such as the intraventricular flow and aquatic animal propulsion (Dabiri and Gharib, 2005). The link between the characteristics of the jet-flow and the features of the resulting vortex ring has been investigated extensively in the past (Shariff and Leonard, 1992, for comprehensive review). Investigations include theoretical analysis and modelling, such as that of Saffman (1970), predicting the travel velocity of a viscous vortex ring, and the one of Pullin (1979), using similarity theories to predict the main parameters of vortex rings originated both by tubes and orifices. On the basis of experimental observations, Gharib et al. (1998) suggested an analytical model predicting a parameter limiting the growth of a vortex ring and the consequent pinch-off.

In some cases, moving flaps, or leaflets, hinged at orifice border, control the flow. Typical examples of that configuration are the heart valves, where the aim of the leaflets is to prevent backflow. When the jet flow is coupled with moving leaflets, the vortex generation is driven by the developing boundary layer on the leaflet surface and it is highly influenced by the specific leaflet geometry. Almost all experimental and numerical approaches consider axial-symmetry as the basis to investigate the phenomenon and also the design of prosthetic valves preserve some symmetry for rotation (valves with two and three leaflets). Recent three-dimensional Direct Numerical Simulation (DNS) of the entire aortic root geometry with prosthetic bileaflet valves well reproduce the experimental “in vitro” results (De Tullio et al. 2008). Nevertheless, as always in nature, symmetries are ideal simplifications not verified in reality. It has been reported that the left
ventricle and aortic valves are parts of highly non-symmetric complex systems in which the
hemodynamic stresses are not distributed symmetrically (Grande et al. 1998, Cooke et al. 2004).
Grande et al. (1998) reported right sinus stresses 15% greater than in the left sinus. This asymmetry
may also influence the valvular biomechanics, the resulting tissue dilatation and bioprosthetic valve
durability; it was rarely considered in previous experimental and numerical valve models.

The non-symmetrical nature of the ventricular flow is originated by an asymmetry of the
mitral valve leaflets which in a two-dimensional sketch appear as tissue stripes of different length.
In Figure 1 such a sketch is reported as given by Bolzon et al (2003); the effect is the generation of
a jet with non symmetric vortices on the two side. The interaction with the left ventricle boundaries
seems to make more efficient the discharge into the aorta. This observation leads to two-dimen-
sional numerical simulations on the mechanism of the jet and vortex formation by
considering couples of moving leaflets having different widths (ratio of leaflet over orifice aperture
different from 0.5) (Bolzon et al. 2003, Pedrizzetti and Domenichini 2006).

Therefore, the present experimental investigation reproduces in laboratory some of the
above-mentioned asymmetries in order to compare to improve the knowledge about non symmetric
vortex features (in comparison to the quite well known symmetric vortex ring). To this aim, the
flow generated by a piston (driven by a gradually varying velocity program) downstream a thin
edged rectangular orifice was investigated (to compare with numerical simulations, the orifice
graphy is selected to obtain an almost two-dimensional flow field). The orifice is equipped with
rectangular moving leaflets of the same height but having different widths. In particular, the
following configurations have been examined:

(a) two leaflets with the same aperture (ratio of leaflet over orifice aperture equal to 0.5);
(b) two leaflets with different apertures (ratios respectively equal to 0.33 and 0.66);
(c) a single leaflet over the entire aperture (ratio equal to 1).

The velocity and vorticity fields resulting from configurations (a), (b) and (c) have been measured
in time over different piston cycles by means of Robust Image Velocimetry (RIV), which is an
image velocimetry technique based on the robust evaluation of the dissimilarity between
interrogation windows (Falchi et al. 2006).

2. Experimental Set-up and Procedures
The set-up includes a piston driven by a linear motor which forces the water flow to generate a jet through a thin edge rectangular orifice (height equal to 40 cm and width, D, equal to 3.0 cm) in which rectangular moving leaflets of the same height are placed (Figure 2). As a consequence of the forward motion of the piston, the water jet forces the leaflet to open and flows through the orifice, thus generating a couple of counter rotating vortices. The position of each of the two leaflets is described by the aperture angle \( \theta \), i.e. the angle to the direction of the wall.

Honeycombs in the upstream chamber avoided the formation of large vortical structures due to the piston motion before the flow enters into the second chamber through the orifice. As the piston reaches the maximum velocity and starts to decelerate, the leaflets get the maximum aperture angle and then start the closure phase. The details of this process are dependent on the specific forcing curve assigned to the piston and feedback controlled by a computer. For the present measurements, the forcing is always the same and it is given by two sinusoidal parts (one ascending and one descending) ensuring continuity of the function and of the first two derivatives (displacement, velocity and acceleration of the piston). This selection allows a slow back-motion of the piston, thus ensuring almost complete calm fluid in the test section before starting the subsequent cycle. Forcing piston stroke and frequency (period \( T \) equal to 5 s, leaflet aperture time equal to 0.56 s) are selected so that the Reynolds and Strouhal numbers (based on peak velocity, orifice width and piston frequency) are equal to 2000 and 0.2, respectively.

The horizontal plane is illuminated by a continuous laser and images are taken from the top using a high-speed Photron camera (1024 x 1024 x 8 bit images and up to 2000 frames per second at the maximum resolution). The laser and camera are triggered with the piston motion so that phase-measurements can be performed. More than 70 phases per cycle have been considered averaging each one over sixty cycles to compute averages. The water in the whole apparatus shown in Figure 2 is seeded with non-buoyant hollow-glass spherical particles (10 \( \mu \)m in diameter).

Images are processed using Robust Image Velocimetry (RIV) algorithm, in which the particle displacements between subsequent images are found by minimizing the dissimilarity
between interrogation windows. The RIV algorithm uses pyramidal filtering to optimize the results as well as Gaussian sub-pixel interpolation. This technique was chosen due to its better accuracy in resolving the small scale structure of the vorticity field. Further details and comparison to PIV are given in Falchi et al. (2006). An example of the acquired images for each one of the leaflet configuration is shown in Figure 3. In all three conditions the generated vortex structure is clearly visible as well as the leaflet positions (although painted in black).

Figure 3. Image acquisition in different leaflet configurations: two symmetrical leaflets on the left (case a), two non symmetrical leaflet at the centre (case b) and a single leaflet on the right (case c).

Figure 4. Piston position and velocity in time (arbitrary vertical units) with leaflet angular positions (degrees) in the different configurations. Left leaflets are indicated in red and right leaflets in blue.

To understand the phenomenon of vortex generation and propagation, it is very important to describe in detail the leaflet positions in time in comparison to the forcing piston position and velocity, as shown in Figure 4. When the piston starts to move and the velocity becomes significant
the leaflets start to open very similarly in the different configurations (left leaflet means the one which generates a vortex with positive vorticity, usually in red, whereas right leaflet indicates the one generating negative vorticity, usually in blue). There is some significant difference in the starting position of the leaflets which sometimes is negative (towards the upstream chamber) or positive (downstream) but never greater than ± 5°. Moreover, a significant delay in the aperture times of the single leaflet is noticed. However, this initial delay does not cause large differences on the time at which the maximum aperture angle is reached, i.e. at \( t/T \approx 0.07 \), immediately after the maximum piston velocity is reached \( (t/T \approx 0.06) \). The maximum aperture angle is also quite similar between the different configurations \( (\theta_{\text{max}} \approx 50^\circ - 65^\circ) \) except for the right leaflet in the non symmetrical case (b). It opens up to 25° and then starts to oscillate around this position and also during the closure phase (which started when the velocity decreases), especially when the piston stops \( (t/T \approx 1, \text{ corresponding to the end of ejection}) \). Except for the right leaflet in case (b), the closure phase has also similar angles for all leaflets, ending at small positive or negative angle depending on the mechanical assembly that determines the stop angle for the leaflet.

![Figure 5. Vorticity fields with overlapped leaflet positions for the symmetric leaflet configuration. The time interval between images is about 0.11 s (0.02 of the total piston period).](image)

3. Results: Overall Flow Development

The four plots of Figure 5 illustrate a general description of the flow development in the case of symmetric leaflets (case a). They are selected among those after the accelerating phase
described in Figure 4 ($t/T > 0.05$). Two almost symmetrical vortices are generated as soon as the leaflets reach the maximum angular position (the leaflet position is derived automatically from the image sequence and is reported in the plots). They start to travel downstream showing an almost two-dimensional behaviour. It is interesting to notice that small Kelvin-Helmholtz instabilities develop in both vortices along the tangential direction (third figure of the sequence) leading to vortex breakdown and transition to three-dimensional behaviour. In the last plot, the vortex is still connected to the leaflets by vorticity layers, which means that pinch-off has not been reached. This behaviour is different from that observed in pulsed jet flows without leaflets (Gharib et al., 1998).

Figure 6. Vorticity fields with overlapped leaflet positions for the asymmetric leaflet configuration. The time interval between images is about 0.11 s (0.02 of the total piston period).

The behaviour of the vorticity field in the configuration with two non symmetrical leaflets (case b, with relative lengths equal to 0.67 and 0.33) is shown in Figure 6. In comparison to the symmetric configuration, the two vortices start to grow at different times: at first ($t/T \approx 0.04$) the one developing from the smallest leaflet and later ($t/T \approx 0.06$) the other from the longest. This is in agreement with the behaviour of the aperture angles for the two leaflets given in Figure 4. As a consequence of this delay in the generation, also the trajectory, vorticity and size show differences
between the two vortices and in comparison with the symmetric condition. On the other hand, as for the symmetric phase, the vortices are never detached from the leaflet showing an intense vorticity layer persistent during the closure phase.

Similarly, for the single leaflet configuration (case c) given in Figure 7, the two vortices grow at different times (the one on the right having negative vorticity, starts just at the beginning of the aperture phase). However, there are significant differences either in comparison to the symmetric configuration or to the previous two leaflet non-symmetrical condition. Indeed, the vortices have lower vorticity levels and presumably lower values of circulation. These points are considered in greater detail in the next section where trajectories of the vortices are derived and physical and geometrical quantities are measured along them.

Figure 7. Vorticity fields with overlapped leaflet positions for the single leaflet configuration. The time interval between images is about 0.11 s (0.02 of the total piston period).

4. Results: Vortex Trajectories and Features

From the previous vorticity plots in time (as mentioned before, each plot is obtained as the average of about 60 measurements at the same phase), the vortex trajectories are computed by considering the sequence of vortex positions deriving from the maxima of the vortex indicator introduced by Jeong and Hussein (1995). In Figure 8, such trajectories are reported using the same origin for all the conditions (when the vortex is not completely formed, its position is more or less at the leaflet tip). Apart from the symmetry of trajectories of the two vortices in case (a) and the inclination of those for the cases (b) and (c), it is possible to notice that in the case of a single leaflet
the distance between the two vortices is larger due to the longer leaflet in comparison to the others. This reveals a substantial difference in the vortex dynamics. In Figure 9, the distance between the two vortices (non dimensionalized by the orifice width) is presented for the three configurations.

Figure 8. Left (red symbols) and right (blue symbols) vortex trajectories in space for the different leaflet configurations (the origin is reported in the same point).

Figure 9. Time behaviour (along vortex trajectories) of the distance between vortices in the different leaflet configurations (piston velocity is overlapped at the top in arbitrary vertical units as a solid line).

The growing rate of the separation distance between the two vortices is more or less the same for all conditions (this phase takes place during the leaflet aperture and that the piston velocity in time is also reported on the figure). On the other hand, while the symmetrical and non-symmetrical leaflet configurations proceed with the same behaviour, the single leaflet reaches earlier a limiting value almost equal to the orifice width (when the closure is already on). This means that the single leaflet configuration is much effective in separating rapidly the two vortices. In Figures
10 and 11 the diameters of left and right vortex cores are plotted (they are evaluated starting from the center up to a distance where a limiting vorticity value is obtained, tipically 1/10 of the value at the centre). The right vortex core diameter shown in Figure 11 (which develop at first), more or less show the same increase in all conditions for $t/T < 0.15$. On the other hand, the left ones (Figure 10) increase with a significant delay between the symmetric and non symmetric conditions.

![Figure 10](image1.png)

**Figure 10.** Time behaviour (along vortex trajectories) of the diameter of the left vortex core in the different leaflet configurations (piston velocity is overlapped at the top in arbitrary vertical units as a solid line).

![Figure 11](image2.png)

**Figure 11.** Time behaviour (along vortex trajectories) of the diameter of the right vortex core in the different leaflet configurations (piston velocity is overlapped at the top in arbitrary vertical units as a solid line).
Figure 12. Time behaviour (along vortex trajectories) of averaged positive (red symbols) and negative (blue symbols) vorticity in the different leaflet configurations (piston velocity is overlapped at the top in arbitrary vertical units as a solid line).

Figure 13. Time behaviour (along vortex trajectories) of positive (red symbols) and negative (blue symbols) circulation in the different leaflet configurations (piston velocity is overlapped at the top in arbitrary vertical units as a solid line).

At the same phase, the diameter of the left vortex core generated in symmetric condition is usually larger than those in non symmetric configurations and of the same order of the right one. On the other hand, the diameters of left vortices in non symmetric conditions are only $1/3 \div 1/2$ of the right ones. In any case, the limiting values of the vortex core diameter are similar and of the same order of the orifice width.

Vorticity and circulation of left and right vortices along their trajectories are reported in
Figures 12 and 13. The former shows well balanced values between the two vortices in symmetric conditions, whereas there are higher values in the case (b) of two non symmetric leaflets (especially for the negative branch, i.e. the vortex on the right) and lower values for the single leaflet case (c). The increase of the vorticity value in time started similarly for all conditions (t/T ≈ 0.02) and the maxima are reached more or less when the piston velocity has also a maximum (t/T ≈ 0.06), except for the vortex on the left in case (b). Decrease to zero appears to be delayed for the vortices on the left in the non symmetrical cases (b) and (c) (by about 0.04 t/T).

The circulation around vortices is evaluated using Stokes theorem and plotted in Figure 13. It is almost zero (due to the very small vortex core diameter as in Figures 10 and 11) up to the middle of the leaflet aperture phase and starts to increase at first for the symmetric case (a) (t/T ≈ 0.05) and later on for the non symmetric case (b) (t/T ≈ 0.08) and single leaflet case (c) (t/T ≈ 0.1). From there on, the increase rate and the limiting values are more or less the same for all conditions (slight asymmetries are observed for the cases (b) and (c) indicating larger and delayed circulation for the vortices on the right (negative values) in comparison to those on the left (positive values).

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References
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