Problems with identification of vortex rings when using anemometry measurements.

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Abstract. Measurement of key vortex rings properties with the use of anemometry techniques is not so straightforward due to the angular dispersion of these structures and in consequence change of their trajectories as they move downstream. Owing to the fact that in available literature no much attention is paid to this issue, there is still a need to address this problem. In the present work we show some preliminary data which allowed to quantify the dispersion of vortex rings when these propagate over a distance up eight orifice diameters. The presented results indicate that the vortex structures generated at a certain frequency are characterized by increasing unrepeatability and angular dispersion as a function of distance from the generator. This leads to difficulties in their identification because their position in respect to the fixed position of the hot-wire probe changes.

1. Introduction
When the fluid is transiently released from the nozzle one may expect a formation of a toroidal structure at the nozzle exit which is commonly known as a vortex ring (VR). Such structures are encountered in a number of natural processes as for instance animal locomotion [1] or discharge of blood into the heart left ventricle [2]. VRs have also found an application in industry – pulsed jets [3,4], swimming devices [5–7] or cooling of electronics [8,9] may serve as examples.

Available literature offers also information on more fundamental aspects as VRs formation [10–12], evolution [13–19] or VRs collisions with different obstacles [20–24]. These, however, are mostly theoretical and numerical contributions as an experimental study of the VR behaviour is not so straightforward and only a few experimental techniques are capable for such a purpose. The most popular one is smoke visualisation [25,26], however, the results that can be obtained from this technique have the qualitative character only. A much more advanced method that provides a detailed insight into the flow is the particle image velocimetry (PIV) [27–31] which involves the
processing of consecutively capture images in the reconstruction of the velocity field in a given cross section. This approach suffers, however due to the fundamental drawback: as the capturing of high-resolution images requires a huge memory space the sampling frequency is substantially limited. In turn, the application of the method is limited to the low Reynolds member flows only. Another experimental technique, that allows to overcome the already mentioned limitation is hot-wire anemometry (HWA) technique as it offers a high temporal resolution. On the other hand HWA allows for point measurements only.

Among available works related to the HWA measurements of the VRs [32–35] one may observe that no much attention is paid to angular dispersion of such structures. For instance in the paper of Dziedzic and Leutheusser [35] authors first used the smoke visualisation technique to identify the location of the vortex core and then placed the HWA probe in that location in order to estimate the propagation velocity $U_p$ and the vortex radius $R$. Authors, on one hand, pointed out that VRs may pass over the hot-wire probe at different angles, on the other hand no further information about statistical dispersion was delivered. This problem was firstly raised in the work of Glezer and Coles [36] in which the Laser Doppler anemometry (LDA) technique was employed in the study of VRs produced with the piston generator. Since then not much attention has been devoted to that issue in the literature. No need to mention that the problem is still actual and more analysis on that issue and some possible solutions should be well welcomed by the fluid dynamics community.

In such a regard, it is interesting to perform a statistical analysis of the velocity signals collected from a multitude of VRs generated one after another in order to examine whether there is a repeatability of eddy structures from the point of view of their radial position for different distances from the outlet of the generator. Hence, herein the preliminary results are delivered regarding the evolution of VRs dispersion.

2. Experimental setup

Figure 1 illustrates the scheme of the experimental setup used in the present investigation along with a sketch of a moving VR. In the given setup the Gaussian-like signal is generated using a personal computer (1) through the Mathematica software and then is transmitted through the MOSFET amplifier Mac Audio Edition Two LtD 600W (2) to the loudspeaker Hertz Es 200.5 Subwoofer 600W (3) mounted on one side of the cylindrical tube (4). The motion of the membrane pushes the fluid towards the axial direction $x$ and in turn generates the VR (5) at the orifice (6) outlet. The motion of the VR is then detected and its velocity is recorded using the hot-wire probe (7) mounted on the precise automatic traversing system (8) that ensures traversing of the probe in $x$ and $r$ directions (when concerning the cylindrical coordinate system). The wire of the probe was 0.4 mm in length and 3 $\mu$m in diameter and it was positioned vertically to the axis of the tube. Calibration of the sensor itself was performed with the use of DANTEC DYNAMICS StreamLine Pro Automatic Calibrator. The tube length $L$ and its inner diameter $D_1 = 200$ mm and 33 mm, respectively, whereas the orifice diameter $D_2$ was equalled to 33 mm. Measurements of the velocity were performed at four different distances $x = 3D_2$, $x = 5D_2$, $x = 7D_2$ and $x = 8D_2$ (measured from the orifice outlet) and at fixed $r$ position 0.85 $D_2$ (measured from the axis of the generator).

The experimental procedure was as follows. First, the hot-wire probe was positioned at a certain distance $x$ and $r$. Next, one hundred VRs were generated with an interval between consecutive excitations equalled to 1 s. Such a number of VRs generated one after another was found to be statistically sufficient to acquire reproducible results and the interval between shots used was high enough to ensure VRs not to interfere with each other. Sampling frequency during the velocity measurements was set to 2 kHz and it was enough to accurately capture all the characteristic features of the signal such as local extrema (see Fig.3b described further within the paper). At this point it is worth mentioning, that the hot-wire sensor register the magnitude of the velocity. In this regard, when the VR approaches the sensor’s wire we first observe an increase in the velocity up to the local maximum at the vortex boundary, then the velocity starts decreasing until it reaches local minimum when the vortex core and the wire are in the same position. When the vortex core passes over the
wire the observed velocity starts increasing again until it reaches the second maximum at the core boundary. Such a distribution of the velocity results from the cumulative effect of the VR propagation velocity and the velocity component resulting from the rotating nature of the vortex (which reaches zero at the vortex core). So the local minimum in the velocity, that can be observed when the probe is located exactly in the vortex core, corresponds to the propagation velocity of this structure. One should also note that the amplitude of two velocity peaks may not be the same because the centre of the vortex does not pass exactly over the probe and additionally the VRs elongates as it propagates downstream [35]. During the measurements the Reynolds number \( Re = U D_2/\nu \) (here \( U \) is the averaged air velocity and \( \nu \) is the kinematic viscosity) was kept constant at the level of \( Re = 9600 \pm 3\% \) at the orifice position.

3. Experimental results

Presentation of the results is started from illustrating sample velocity signal from HWA probe (first 30 generated VRs) collected at four different axial distances from the orifice outlet, \( x/D_2 = 3, x/D_2 = 5, x/D_2 = 7, x/D_2 = 8 \) in Figs 2a, b, c, and, respectively. The peaks visible in each figure corresponds to the VRs velocity maxima. This qualitative comparison shows, that with the increase in \( x/D_2 \) the overall velocity \( U \) drops fairly quickly. This is due to combined effect of slight vortex expansion (as is shown further) at the cost of its velocity as it is traveling, but more importantly, because of vortex decay caused by the friction with the bulk air. Another noticeable effect is, that the spread of local maxima seems to grow with increasing probe distance. This spread is seen as increased difference between lowest and highest recorded maxima within one measurement series. Such an effect may be assigned to the angular dispersion of generated VRs what and hence more attention is put further on this phenomenon.

![Figure 1. Scheme of the experimental setup](image)

![Figure 2. Sample velocity signals of 30 VRs captured with HWA probe at different axial positions: \( x/D_2 = 3 \) (a), \( x/D_2 = 5 \) (b), \( x/D_2 = 7 \) (c), \( x/D_2 = 8 \) (d) and at fixed radial position \( r = 0.85D_2 \)](image)
Figure 3. Axial evolution of averaged maximum velocity from 100 consecutively generated VRs (a), and related evolution of VRs velocity traces; the radial position was fixed at \( r/D_2 = 0.85 \).

Figure 3 illustrates the averaged maxima of the VRs velocities as a function of normalized axial direction \( x/D_2 \). Each maximum of the velocity was calculated based on 100 consecutively generated VRs, i.e. using the signal from Fig. 2. One may observe a notable decrease of the averaged maximum velocity over the relatively short distance from \( x/D_2 = 3 \) to \( x/D_2 = 8 \). Note that bars at each point represent the standard deviations, which seem not to change significantly towards higher axial distances, however, their values rising from 5% for \( x/D_2 = 3 \) to 10.4% for \( x/D_2 = 8 \). In this regard with increasing axial direction, there is a growing difficulty in acquiring the representative signal samples caused by increased vortex dispersion. Figure 3b presents velocity traces of VRs for probe distances corresponding to the ones from Fig. 3a. Note that the profiles shown here and further within the paper were superimposed in order to ensure a direct comparison between them. When increasing \( x/D_2 \) not only decrease in signal amplitude can be observed but also a notable peak broadening, which means that the diameter of the vortex core increases. Also the local minimum of velocity traces decreases with increasing distance \( x/D_2 \) which means that the vortex propagation-velocity decreases as well.

Figure 4. Three consecutive velocity traces collected at two different axial distances: \( x/D_2 = 3 \) (a) and \( x/D_2 = 8 \) (a).
As a supplement to the already presented results Fig. 4 presents three consecutive velocity traces for two different axial distances studied in the present work, i.e. for $x/D_2 = 3$ and $x/D_2 = 8$ (Fig. 4a and Fig. 4b). As can be seen much smaller discrepancies between traces can be observed when the probe is located closer to the orifice. Worthy to note is also that for a larger distance $x/D_2 = 8$ the velocity traces are much more disturbed (smoothness of the signal is lost) what is caused by development of the turbulence within the structure azimuthal waviness and breaks of vortex structure into turbulent motion.

4. Conclusions
As the results showed, measurement of vortex rings in the air atmosphere is not so straightforward due to dispersion of VRs affecting vortex position in respect to the hot-wire probe. In turn, velocity traces heterogeneity, resulting from VRs angle dispersion, is enhanced when the vortex dismisses from the orifice what leads to increased measurements uncertainty. It was quantitatively shown, that variability of the maximum velocity, indicating the boundaries of the vortex structure, does not change notably when it departs from the orifice. However, its relative change is significant as the maximum vortex velocity decreases almost by half over the distance equaled to five orifice diameters.

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