Laser diagnostics of the instability onset in the confined vortex flows

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Abstract. This paper focuses on the application of optical methods of pulsating vortex flow diagnostics on the example of swirling flow instability in a cylinder with rotating lid and aspect ratio $h = 3.3, 3.4$. To obtain a complete picture of auto-generated pulsations development, long-term LDV measurements of the tangential velocity component were carried out with a continuous method of the Reynolds number variation from 2000 to 3500 over 8 hours (30,000 seconds). In the view of the smallness of the Reynolds number increase rate $\Delta Re / \Delta t = 0.05 \text{s}^{-1}$, this process can be considered as quasi-equilibrium. A comparison with the widely used discrete method of the Reynolds number variation is made, given range of the Reynolds numbers was studied with a step $\Delta Re = 50$ for 20 minutes per point. It was found that at the same $h$, $Re$ different vortex structures are formed depending on the Reynolds number variation method. In the case of discrete the Reynolds number variation, the development of pulsations may require up to 2000 rotating lid revolutions or 500 seconds, it should be considered conducting the experiments.

1. Introduction
The effective use of closed vortex centrifugal mass- and heat exchangers enormous potential in the first place is affected by our understanding of vortex motion depending on the intensity and swirl of the flow and ability to predict it [1]. It is of immense importance to control vortex flow instability for improving mass transfer processes in closed bio- and chemical reactors. In such reactors a complex fluid flow is formed, characterized simultaneously by a vortex and circulation movement [2]. Modeling those flows, cylindrical and polygonal cross-section containers with rotating disk inscribed in the end wall are used [3-6]. The development of instability usually is investigated by optical methods (LDV and PIV) after the establishment of a given flow regime [4-8]. Such optical methods allow to avoid external flow disturbance, since instabilities development is very sensitive [9]. Both the experiment and the numerical simulation show with good agreement that significant cylinder elongations lead to the flow stability loss due to multiplets formation, inducing velocity pulsations grow [10, 11].

However, the study of particular steady-state regimes does not allow to obtain a complete picture of pulsations development with an increase in the Reynolds number. For example, in [7, 8], it was found that with swirl increase in the flow, with certain geometric parameters, the flow becomes expectedly pulsating. With a further vortex motion intensity increase, period of velocity pulsations also increases up to hundreds or even thousands of disk rotation periods, and, with an even further increase in the angular velocity of rotation of the disk, the flow stabilizes. Another interesting fact for the first time
was recorded in [12], where two possible instability development scenarios were experimentally found in an intense swirling flow: the increase or decrease of the amplitude of velocity pulsations with increasing flow swirl. Moreover, it was found that in the meridional cross-section the maximum amplitude of radial and axial velocity component pulsations expectedly grows with the Reynolds number increase, if the frequency of secondary disturbances is lower than of the primary ones, or, conversely, unexpectedly decreases, if greater. Usually, experimenters fix the aspect ratio $h$ and discretely change $Re$ during the experiment, accounting for the time necessary for the flow relaxation in the entire volume (usually 100÷200 disc revolutions). When the regime is changed, transition can influence the development of flow instability. It is possible to overcome this factor if disk rotation speed and corresponding Reynolds number are changed linearly at a rate small enough to neglect influence of transient processes.

2. Experimental setup and experimental methods

The development of instability in a well-studied swirling flow generated in a closed stationary cylinder with rotating lid is investigated in current work. The main motion of the fluid is toroidal rotation around cylinder axis with axial motion towards the lid in near-axis zone and in opposite direction near the walls. Flow structure in this simplest configuration depends on two parameters: the ratio of cylinder height to the radius $h = H/R$ and the Reynolds number $Re = R^2 \Omega/\nu$, where $\Omega$ is the angular velocity of rotation of the lid and $\nu$ is the kinematic viscosity of the fluid.

Experimental investigation of pulsations development was carried out in a vertical transparent glass cylinder of optical quality with an inner diameter of 150 mm and length 1000 mm with bottom rotating lid (figure 1(a)). Upper end wall position can be adjusted in order to change aspect ratio $h$. The rotating disk radius is $R = 74.5$ mm. The gap between disk and the cylinder wall is negligibly small - 0.5 mm, less than 0.5% of the disk diameter. The reference point of the coordinate system is set in the center of rotating lid, $r$-axis passes through bottom plane and $z$-axis coincides with the vertical container axis. Water-glycerin solution (75% glycerin) was used as a working fluid. Polymide spheres of neutral buoyancy with an average diameter of 10 microns were used as light-scattering particles for LDV measurements. To minimize optical aberrations and temperature fluctuations test section was placed inside a rectangular transparent glass container with dimensions 500x500x1000 mm filled with water.

![Figure 1](image_url)

**Figure 1.** (a) – Photo of cylindrical cavity, (b) – Example of numerical computation and LDV measuring point, $h = 3.4$, $Re = 3200$. Variance of velocity magnitude, $m^2/s^2$. 1 – rotating lead, 2 – LDV, 3 – LDV measuring point at $z = 2.6R$, $r = 0.75R$. 


The temperature dependence of working fluid viscosity was approximated by the second order polynomial. As the viscosity of the working fluid is sensitive to temperature, the fluid temperature was measured with an accuracy of 0.1 °C, thus reducing the uncertainty of viscosity determination to 0.2%. The total error of Re did not exceed ±10 in the range of investigated Reynolds numbers.

A two-component LDV system (LAD-06i) developed at the Kutateladze Institute of Thermophysics SB RAS, based on a Mitsubishi ML1013R semiconductor laser (with 70 mW power and 684 nm wavelength) and operating in a backscattering configuration, is used to measure the tangential velocity component. A two-frequency differential optical configuration is applied with a frequency shift of 80 MHz based on a Bragg cell to eliminate the directional ambiguity. Split by the Bragg cell, two laser beams are then focused by the optical head with a focal distance of 0.5 m and measurement volume of 0.05×0.05×1 mm (in air).

Rotating disk was driven by a stepper motor. Digital sinusoidal control signal was generated on PC, converted to analog form by DAC and supplied to the driver. Speed of the motor (and, accordingly, the Reynolds number of the flow) is proportional to the frequency of the signal, transmitted to the driver. Thus allowing us to programmatically set the Reynolds number schedule for the whole experiment.

Loss of stability and the development of flow pulsations lead to emergence of clear peaks on the spectrogram of velocity pulsations (figure 2), which corresponds to a change in vorticity – the formation of azimuthal wave modes or rotating vortex multiplets (figure 3) [4, 7, 11]. Since velocity pulsations are not equal in the flow volume, it is necessary to determine the area of flow where pulsations will be most pronounced. During the preliminary CFD calculations, the velocity dispersion distribution was obtained and a measuring point of \( z = 2.6R, r = 0.75R \) (figure 1 (b)) was assigned, which correlates with the area of maximum of velocity pulsations [7, 8].

![Figure 2. Velocity pulsations spectrum.](image)

![Figure 3. Iso-contours of phase averaged axial vorticity, rotating multiplet [7].](image)

To experimentally study auto-generated flow pulsations two different methods of the Reynolds number variation were used and compared.

For the continuous method of the Reynolds number variation, the Reynolds number was linearly increased from 2000 to 35000 during 30000 seconds with growth rate \( \Delta Re / \Delta t = 0.05 \text{ s}^{-1} \). During the experiment, tangential velocity component was continuously measured by LDV and recorded.

For the discrete method of the Reynolds number variation, the range of the Reynolds numbers 2000÷35000 was divided into a sequence of discrete steps with the step size \( \Delta Re = 50 \). At each step, measurements were performed at a constant disk rotation speed during the time \( T_S = 1200 \text{ s} \) (figure 4).
After that at even intervals of 10 seconds the disc was decelerated, held fixed and then accelerated to a new speed value corresponding to the next step during $T_p = 30$ sec.

Figure 4. Discrete method of the Reynolds number variation chart.

For this study aspect ratios $h = 3.3$, 3.4 and the Reynolds number range $2000 \div 3500$ were chosen due to the fact that at $h = 3.3$, according to previous works [4, 7, 8], with increasing angular velocity of disk rotation an anomalous stabilization of the vortex motion appears. Of additional interest is the fact that the dimensionless pulsation frequency $\omega_m \approx 0.3$ found in the experiments correspond to the rotation of the $m = 3$ vortex structure, while numerical calculations show that the transition to the non-stationary flow manifests itself as a vortex structure formation with wave modes $m = 3$ and 2 with frequencies $\omega_m \approx 0.3$ and 0.2 respectively.

3. Results

Time-dependent power spectral density of the tangential velocity component measured by LDV is presented on Figure 5 for aspect ratios $h = 3.3$ and 3.4 for both continuous and discrete method. Threshold was set to hide irrelevant noise. Using our Reynolds number variation schedule we can map the Reynolds number values on the time axis and normalize frequency of pulsations $f$ by the frequency of disk rotation $f_D$.

$$ f(t) \rightarrow Re(t) \rightarrow \omega_m(Re) ; \quad \omega_m = \frac{f}{f_D} ; \quad f_D = \frac{Re \cdot \nu}{2 \cdot \pi \cdot R^2} . $$

It can be noted that for both $h = 3.3$ and 3.4, the ranges of the Reynolds numbers where velocity pulsations are registered do not depend on the method of the Reynolds number variation. At $h = 3.3$, the pulsations are found at $2125 < Re < 2300$, and at $Re > 2700$. At $h = 3.4$, the pulsations arise at $Re = 2065$ and exist till the limit of investigated range $Re = 3500$. Additional wave modes are presented at $Re > 3100$. These results completely agree with previous experimental studies [7, 8]. However, there are significant differences in the values of dimensionless frequencies $\omega_m$ near the transition to instability border. In the case of continuous method, the first-appeared mode $m = 3$, has a frequency $\omega_m \approx 0.3$ and permanently exists with a further increase in the Reynolds number. The arise of secondary modes $\omega_m \approx 0.22, 0.45, 0.5$ at $Re > 3200$ does not destroy this main mode containing most of the energy.

Using a discrete method, there are certain regimes where pulsation frequencies differ from continuous method. These differences are presented in table 1. In these regimes at the same $h$ and $Re$, depending on the Reynolds number variation method, different wave modes may arise.
With continuous method the first first-appeared mode \( m = 3 \), \( \omega_m \approx 0.3 \), becomes dominant and, holding the energy in itself, suppresses the appearance of other modes with a further increase in \( Re \). In the case of a discrete method the rotating disk is stopped after each step, viscous friction leads to energy dissipation with flow relaxation and subsequent vortex structure collapse. Thus, setting new regime at next step, there is not a trace of vortex structure in the flow at the previous step. The “new” flow develops from the rest, and at the same time, another wave mode with \( \omega_m \approx 0.2 \) may become dominant. It is possible that acceleration of the disk affects energy transferring to one or another azimuthal wave mode during transition process when the disk is accelerated to a given speed. This fact requires additional experiments with variation of the time taken by the disk to accelerate to a given speed.

**Table 1.** Velocity pulsation frequencies.

| \( h \) | \( Re \) | 2100 | 2150 | 2200 | 2250 | 2300 | 2400 | 2500 | 2600 | 2700 | 2800 | 3000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.3 | \( \omega_m \) Cont. | 0.31 | 0.31 | 0.3 | 0.3 | - | - | - | - | 0.29 | 0.29 | 0.29 |
| | \( \omega_m \) Discr. | 0.31 | 0.31 | **0.19** | **0.19** | - | - | - | - | 0.29 | 0.29 | 0.29 |
| 3.4 | \( \omega_m \) Cont. | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.29 | 0.29 | 0.28 | 0.28 |
| | \( \omega_m \) Discr. | 0.31 | 0.3 | 0.3 | **0.19** | **0.19** | **0.19** | 0.29 | 0.29 | 0.28 | 0.28 | 0.28 |

**Figure 5.** Spectrograms of LDV velocity measurements.
One can notice small gaps in the spectrograms for the discrete method in the range of $Re$ 2100÷2300 for $h = 3.3$ and 2100÷3000 for $h = 3.4$, looking like a dashed line with varying steps. To explain their origin power spectral density of velocity pulsations with and schedule of disk rotation frequency $f_D$ are presented in figure 6 for $h = 3.4$ and 2600 < $Re$ < 2850. It can be seen that after setting disk rotation to a constant rate there is some delay $T$ in pulsation development with order of $10^2$ seconds. The dependence of delay $T$ normalized on the disk rotation period $T_D = 1 / f_D$ over the Reynolds number for $h = 3.4$ is presented on figure 7. It can be noted that near the region of bifurcations associated with instability onset, $T_D$ reaches a value up to 2000. Corresponding time interval required for complete flow development in the entire volume reaches up to 500 seconds. Thereby there exist regimes requiring significantly more time for the flow to develop than widely used interval of 60-100 seconds.

It can be assumed that slow vortex structure development speed is determined by regimes proximity to the border between steady and unsteady flow on the $h$, $Re$ plane. This is evidenced by the large value of the delay at $Re = 2050$, and also in the range 2500÷2800, which is close to the range
where at $h = 3.3$ there are no pulsations at all. With a further increase of the Reynolds number there is a slow decrease of delay, approaching to the usually used value of 100-200 revolutions of the disk. Additionally, it can be noted that the change of dominant modes at $Re = 2300$, $2500$ does not affect this delay. Extended study of flow transition to unsteadiness over wider range of aspect ratios $h$ is required.

4. Conclusion

To study the development of vortex flow instability during a long-term experiment we applied two different methods for the Reynolds number variation over $2000÷3500$ range: continuous with linear change of the Reynolds number and discrete. Regimes to study were chosen due to the specific features of instability development in a cylinder of high elongation. It was found that using continuous method, to obtain a complete picture of auto-generated velocity pulsations development, LDV measurements during 30000 seconds, requiring the minimum involvement of an experimenter are valid. Due to the small rate of change of the Reynolds number $\Delta Re / \Delta t = 0.05 \text{ s}^{-1}$, such a process can be considered as quasi-equilibrium. The obtained results are compared with the common used discrete method of the Reynolds number variation, where a given range of the Reynolds numbers was studied with a step $\Delta Re = 50$, for 20 minutes per step. Variation of rotating disk velocity by discrete steps was automated by use of programmatically set schedule.

Regimes were found where various vortex structures are formed and dominate, depending on the used method. It was found that in the case of discrete method, the development of vortex flow close to instability border may require up to 2000 disk revolutions or 500 seconds. This fact should be accounted studying instability onset region borders.

Acknowledgments

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