Investigation of vortex ring formation with account of generator piston motion

I V Khramtsov, VV Palchikovskiy, A A Siner, Yu V Bersenev
Perm National Research Polytechnic University, Perm, 614990, Komsomolsky prospect, 29, Russia
E-mail: igorhrs92@mail.ru

Abstract. The formation and dynamics of such an elementary object of fluid dynamics as a vortex ring was investigated. Intense turbulent vortex rings created by a piston generator were considered. For qualitative determination of vortex ring properties, the law of motion for the generator’s piston was experimentally established. This law was used in the numerical simulation, which was performed for the axisymmetric problem formulation with the use of ANSYS Fluent software. The obtained results correspond to the self-similar law of vortex ring motion and experimental results.

1. Introduction
The existing problem of aviation noise is related above all to its deleterious effect on humans. Community noise of civil aircrafts is regulated by ICAO requirements and is an important issue for aviation industry despite significant achievements in its mitigation. The possibilities of further aviation noise reduction with traditional approaches are limited by difficulties in their implementation; therefore, acoustics of modern aircrafts has a significant effect on their competitiveness. Further work in this direction requires the development of new approaches and ideas based on a deeper understanding of the physical processes responsible for the generation of noise by turbulent flows.

In subsonic turbulent jets, which are one of the main noise sources of aircraft engines, noise is generated by turbulent vortices. The central problem in a jet noise study is related to the presence in turbulent jets of vortices with different scales interacting with each other, which leads to distortion of the radiation pattern. Thus, it is extremely important to investigate the fundamental problems of sound radiation by turbulent flows for the case of an isolated vortex.

A good example of such an isolated vortex is a vortex ring. To study aeroacoustic characteristics of the given vortex, a vortex ring generator was developed in the Laboratory of Noise Generation Mechanisms and Modal Analysis at Perm National Research Polytechnic University (PNRPU). Preliminary investigations of the noise of intense vortex rings with a Reynolds number of \( \sim 10^5 \) in the anechoic chamber of PNRPU confirmed the main results observed in previous experiments: the acoustic radiation of the vortex ring is concentrated in a rather narrow frequency band, the carrier frequency of the peak in the spectrum shifts over time into the low-frequency region, etc. [1].

The major observed features of vortex ring dynamics and acoustic radiation can be explained by the developed theoretical models of vortex rings [2-4]. A model of noise radiation by an intense vortex ring[2-4]allows relating the noise with the average parameters of the vortex ring flow (dimensions, velocity and vorticity). A deeper understanding of the noise radiation mechanisms could be obtained from the knowledge of nonstationary processes in the vortex ring cores. However, experimental data on the structure of the vortex ring and, particularly, nonstationary processes in the core of the vortex, are essentially limited.
One way to study this flow is numerical simulation. The solution of the problem of motion and oscillations of a vortex ring by direct numerical simulation in a three-dimensional formulation is limited by the power of modern supercomputers and represents a formidable computational problem. One of the subproblems that must be solved at the preliminary stage is the problem of the formation of the vortex ring and its motion at the initial section of the trajectory.

This problem can be solved in an axisymmetric formulation, assuming the axisymmetric formation and motion of the vortex at the initial section of the trajectory [5]. However, the properties of this vortex essentially depend on the conditions of its formation. In this regard, for the qualitative verification of this problem, a technique was developed for the experimental determination of the conditions of the creation of a vortex and its further motion [4]. Subsequently, the results obtained with the help of this technique were used in the numerical simulation for setting the initial and boundary conditions. Validation was performed by comparing the trajectories of the vortex motion obtained numerically and during the experiment.

2. Experimental study

In the experimental study of the vortex ring noise, the most important requirement is identification of the noise of vortex ring proper against the background noise, including the structural noise of the vortex ring generator, the reflection of sound from hard surfaces, etc. To do this, the vortex ring must be sufficiently intense so that the sound radiated by it can be distinguished against a background noise, and the way to create vortex ring, on the contrary, be as quiet as possible. It can be achieved by using a special piston generator and the anechoic chamber [6].

The vortex ring generator is a polished hollow steel cylinder with a diameter of 0.16 m, to which a conical nozzle with an exit diameter of 0.04 m is fixed. Inside the cylinder, the lightweight fluoroplastic piston moves freely. Before starting the vortex, the piston is extended from generator for a fixed distance of 0.06 m. Figure 1 shows a part of the vortex ring generator and the recording system (view from the anechoic chamber).

![Figure 1](image.png)

Figure 1. Photo of the recording system. 1 – nozzle of the vortex ring generator; 2 – microphones recording the motion of the vortex ring (A, B).

The vortex ring is created by pulsed ejection of a portion of gas through the nozzle by the piston. Then, the formed vortex structure separates from the nozzle edge and moves in space along the axis coinciding with the piston axis. The piston is driven by the impact of a heavy hammer on the piston rod. To avoid the reverse motion of the piston, the vortex ring generator is equipped with a special brake assembly, which fixes the rod when the piston reaches its extreme position.

In this work, a joint registration of the generator piston motion and the vortex ring motion was carried out. The piston motion was realized with an accelerometer mounted on the outer wall of the piston. To determine the vortex ring motion, the method was utilized [4] based on microphones installed at a small distance from the generator axis, fixing the peak of the pressure at the time of passage of the vortex near the corresponding
microphone. These microphones were located only at the initial section of the trajectory, where the motion of the vortex ring can be assumed axisymmetric. The scheme of the experiment is shown in figure 2.

To record the deviation of the vortex flight trajectory from the generator axis, a rectangular screen from a thin wire with silk streamers with dimensions of 2×1 m was used. This screen was set at a distance of 6.5 m from the nozzle exit section so that the center of the screen was on the axis of the generator. During the passage of the vortex ring through the screen, the silk streamers deflected, making the position of the ring visible. It made it possible to select for the further investigation only the correctly flying vortex rings passing through the center of the screen.

![Figure 2. Scheme of the experiment.](image)

Since each created vortex ring has individual properties (velocity, deviation from the expected trajectory, dimensions) due to the percussive method of starting the piston, a series of experiments was conducted. Then, an analysis of the time realizations of the signals of the accelerometer and microphones A and B (figure 2) was carried out. The signals from the accelerometer were integrated to obtain the velocity and displacement of the piston. This allowed us to use in the numerical simulation the real law of motion of the piston, whereas in some studies, theoretical laws are used, which could be poorly consistent with the actual movement of the piston [7]. The obtained dependences of acceleration, velocity and displacement of the generator piston are shown in figure 3.
Figure 3. Dependences of acceleration, velocity and displacement of the generator piston for one realization.

Analysis of the signals of microphones A and B determined the time of flight of the vortex ring near the corresponding microphone. The signals received from these microphones are shown in figure 4.

Figure 4. Dependence of pressure on microphones A and B on time for one realization of the vortex ring flight.
Thus, for further analysis, one characteristic realization of the experiment was selected, in which the ring arrived at the center of the screen and parameters of the piston and ring motion were close to the average ones.

3. Numerical simulation of the vortex ring formation

The numerical simulation of the vortex ring formation at the initial section of its trajectory was carried out in the ANSYS Fluent software. The process of the vortex ring formation is performed directly, by analogy with the experiment in which the air flow is ejected from the nozzle by a movable piston. In numerical simulation, this process is realized by generation of computational grid in the region of the piston wall displacement. Regeneration of the grid is carried out in accordance with the experimentally determined dependence of the piston displacement.

Formation and dynamics of the vortex ring is characterized by complex nonstationary turbulent flows. The numerical solution of the problem was based on the direct numerical solution of the nonstationary Navier-Stokes equations for compressible fluid:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \tau
\]  

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{v}) \cdot \nabla E = \nabla \cdot \left( \chi \nabla T + \tau \cdot \vec{v} \right)
\]

(1)

The viscous stress tensor \( \tau \) is defined as

\[
\tau = \eta \left[ (\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right]
\]

(2)

and total energy \( E \) is

\[
E = h - \frac{p}{\rho} + \frac{\vec{v}^2}{2}
\]

(3)

Here \( \rho \) is density; \( \vec{v} \) is velocity vector; \( p \) is pressure; \( T \) is temperature; \( h \) is enthalpy; \( \eta \) is molecular viscosity; \( \chi \) is conductivity; \( I \) is unit tensor. To complete the system (1) - (3), the state equation of the perfect gas is used.

The geometric model used in computations is internal region of the generator and the region behind the nozzle exit section wherein the vortex ring forms and moves. The size of this region is 21 nozzle-exit diameters, since in this section of trajectory the flow could be assumed axisymmetric. The geometric model is shown in figure 5.

![Figure 5. Geometric model of the computational domain. 1 – movable piston wall; 2 – piston stopping; 3 – internal region of the generator; 4 – internal nozzle wall; 5 – external nozzle wall; 6 – region of vortex ring motion.](image-url)
The numerical solution of the problems of vortex gas dynamics requires a sufficiently fine computational grid. At the same time, typical size of the vortex for the normal resolution requires 40-50 computational cells. The radius of the vortex ring core is taken as the typical size, which according to experimental data for similar vortex rings is 8-9 mm. For this reason, the average size of the computational cell in the region of vortex motion is accepted equal to 0.2 mm. At the wall of the nozzle, the computational grid is finer so that the dimensionless parameter satisfies the condition $y^* < 1$. The grid contains 540,000 computational cells and it is shown in figure 6.

![Figure 6. Computational grid in the region of the nozzle exit section.](image)

The computations are carried out under normal environmental conditions (pressure 101325 Pa and temperature 295K). The flow is considered single-phase, viscous and compressible. The working medium is air, whose properties are described by the law of ideal gas.

At the boundary of the outer region of the vortex motion the “Outlet” boundary condition with zero overpressure is used. Internal and external walls of the generator and movable wall of the generator piston are simulated by boundary conditions “Wall”. It is assumed that the walls are perfectly smooth. The boundary conditions are shown in figure 7.

![Figure 7. Boundary conditions. 1 – axis; 2 – movable wall; 3 – wall; 4 – outlet.](image)

The mathematical formulation of boundary conditions based on the following equations:

- on axis
  \[ v_n \big|_b = 0 ; \quad \frac{\partial v_r}{\partial n} \big|_b = 0 ; \quad \frac{\partial T}{\partial n} \big|_b = 0 ; \quad v_r \big|_b = 0 \]

- on movable wall
  \[ v_n \big|_b = 0 ; \quad \frac{\partial v_r}{\partial n} \big|_b = 0 ; \quad \frac{\partial T}{\partial n} \big|_b = 0 ; \quad v_r \big|_b = 0 \]
\[ v_n|_b = \left\{ \mu_p \left( \frac{t}{1} \right), \text{[m/s]} \right\}; \quad \frac{\partial v_T}{\partial n}|_b = \frac{v_T}{\kappa} \ln \left( \frac{\rho v_T y}{\mu} \right); \quad \frac{\partial T}{\partial n}|_b = 0 \]  
(5)

- on wall

\[ v_n|_b = 0; \quad \frac{\partial v_T}{\partial n}|_b = \frac{v_T}{\kappa} \ln \left( \frac{\rho v_T y}{\mu} \right); \quad \frac{\partial T}{\partial n}|_b = 0 \]  
(6)

- on outlet

\[ p|_b = p|_{t=0}; \quad \frac{\partial T}{\partial n}|_b = 0 \]  
(7)

if \( v|_b \leq 0 \), then \( \frac{\partial v}{\partial n}|_b = 0 \); if \( v|_b > 0 \), then \( \frac{\partial v}{\partial n}|_b = v_T|_b \)

Here \( u \) is piston velocity; \( \varepsilon \) is rate of turbulent energy dissipation; \( n \) is a normal. Lower indexes \( n, \tau \) are a normal and a tangential component respectively; \( b \) is a boundary component; \( t=0 \) is the initial value.

Solution of the problem (1) - (7) in Fluent is executed by the finite volume method. The computational domain is divided into finite volumes and equations are written in integrated form for each cell. For time integration the second-order implicit scheme is used. Time step is equal to \( 1/65536 \) s. The computations are conducted during 1900 time steps. The details on the scheme of solution of nonstationary Navier-Stokes equations in Fluent are presented in [8].

4. Results

The evaluation of the results was carried out using a comparison of the trajectory of the vortex ring motion obtained in experiment and numerical simulation, as well as with the self-similar law of the vortex ring displacement [9]. The self-similar law of motion is a semi-empirical theory of vortex ring motion and is well correlated with empirical models proposed by other authors [10, 11]. The displacement of the vortex ring and its radius obtained in numerical simulation were evaluated in the point at which the pressure, temperature and density were minimal, and the vorticity maximum was observed in the same region. Equations (8) represent the law of vortex ring motion

\[ L(t) = \frac{R_0}{\alpha} \left[ \left( 1 + \frac{4\alpha U_0}{R_0} \cdot \frac{\Delta t}{t} \right)^{\frac{1}{4}} - 1 \right] \quad R(t) = R_0 + \alpha L(t) \]  
(8)

Here \( R_0, U_0 \) are initial radius and initial velocity of the vortex ring, respectively; \( \alpha \) is a factor of the vortex ring expansion rate. To determine the displacement of the vortex ring in accordance with the equation (8) the initial radius and the velocity determined in the numerical simulation were substituted into this system. The initial velocity of the vortex ring was determined from equation (9) as the difference in the positions of the ring in sections with coordinates \( x_1 = 0.1 \text{ m} \) and \( x_2 = 0.15 \text{ m} \) (where microphones have been set) divided by time

\[ U_0 = \frac{\Delta x}{\Delta t} \]  
(9)

The initial radius was determined at the time of the passage of the ring through the section at \( x_1 = 0.1 \text{ m} \). The factor \( \alpha \) was determined graphically according to figure 8, so that the dependence of the radius on time would well describe the results of numerical simulation. It leads to the following values of parameters, used in the self-similar motion law: \( R_0 = 0.033 \text{ m}, U_0 = 24.8 \text{ m/s}, \alpha = 0.005 \).

Figure 8 shows a comparison of the results of numerical simulation, experiment, and self-similar law. For convenient presentation of results, the origin is shifted to the point corresponding to the position of the first microphone A (figure 2), and the time is measured from this point. As can be seen,
the results of numerical simulation, experiment, and the self-similar theory of vortex ring dynamics are well matched.

Figure 8. Comparison of results of numerical simulation, experiment and self-similar law.

Figure 9 shows the distribution of the density gradient module at time point of 0.015 s. It can be seen that in addition to the main vortex, secondary vortices of lower intensity are also observed. The process of disintegration of the secondary vortices differs significantly from the axisymmetric one, which leads to an increase in the discrepancy between the computational results and the experiment on the study of the vortex ring motion.

Figure 9. The distribution of the density gradient at time point of 0.015 s.

5. Conclusion
1. An experimental technique for simultaneous determination of the motion of a vortex ring and a piston of a vortex ring generator is developed.
2. The law of the piston motion obtained in experiment was used for numerical simulation of the vortex ring dynamics. The carried out validation of the numerical model showed that the results of simulation are in good agreement with the results of the experiment and the self-similar theory of motion of the vortex ring.

Acknowledgments
The authors are grateful to Prof. V.F. Kopiev for the problem statements and further fruitful discussions.

The results have been obtained in the framework of the government task “Researchers working in scientific laboratories created by the government program “Megagrant”, contract No.9.7942.2017/P220.

Experiments were carried out on unique scientific installation “Acoustic anechoic chamber with
aerodynamic noise sources”.

References
[1] Kopiev V F, Zaytsev M Yu, Palchikovskiy V V, Khramtsov I V and Bersenev Yu VPNRPU Aerospace Engineering Bulletin. 2016 45 133-151
[2] Zaytsev M Yu and Kopiev V F Akusticheskiy zhurnal. 1993 39 1068-1075
[3] Zaitsev M Yu and Kopiev V F TsAGI Science Journal. 1998 29 83-91
[4] Zaitsev M Yu, Kopiev V F and Kotova A N Acoustical Physics. 2000 47 699-706
[5] Khramtsov I V, Pisarev P V, Palchikovskiy V V, Bulbovich R V and Pavlogradskiy V V Applied Mechanics and Materials. 2015 770 483-48
[6] Kopiev V F, Palchikovskiy V V, Belyaev I V, Bersenev Yu V, Makashov S Yu, Khramtsov I V, Korin I A and Sorokin E V Acoustical Physics. 2017 63 114-126
[7] Rosenfeld M, Rambod E and Gharib M Journal of Fluid Mechanics. 1998 376 297-318
[8] Fluent 12.0 User’s Guide, February 2008
[9] Lavrentev M A and Shabat B V The problems of hydrodynamics and their mathematical models (Moscow, Nauka) 1973 p 416
[10] Johnson GM AIAA Journal. 1971 9 763-764
[11] Maxworthy T. Journal of Fluid Mechanics. 1974 64 227-239