Research by the Hilbert optics methods of the vortical structures arising at diffraction of pressure front on an aperture

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Abstract

The methods of Hilbert optics are widely used in tasks of visualization and measurement of phase optical density in fluids. In this work the problem of vortex rings generation upon sudden opening of a cylindrical chamber containing a gas at elevated pressure is considered. At diffraction of pressure front on an aperture in a wall the vortical rings propagated in the opposite directions from the wall have been detected by optical Hilbert methods.

Keywords: Optical flow diagnostics, Hilbert optics, vortex ring

1. Introduction

Visualization of optical density fields is commonly applied for measuring structure characteristics of fluid and gas flows [1]. Optical inhomogeneities are most frequently investigated by schlieren methods based on finding the light wave deflection in the medium and the refractive index gradient distribution. Development of the linear system theory in optics enables to study the problem of density field visualization by optical filtering methods and develop new trends in flow diagnostics, which are concerned with applying Fourier optics and optical Hilbert transform [2].

Ring vortices have always attracted much attention of researchers, which is related to the importance of understanding vortex formation processes in various basic and applied problems of gas dynamics [3, 4]. This paper reports on the first observation of a phenomenon, whereby rings vortices moving in the opposite directions are formed during the diffraction of a pressure front on a hole in a flat wall [5].

The task of an experimental research of evolution and structure of these whirlwinds is considered. The main difficulty of the experiment was related to a weak perturbation of the optical density at low pressure drops. In order to detect such perturbations, we have used the method of optical Hilbert filtration of the light fields [3]. The Hilbert diagnostics was performed with a commercial schlieren instrument of the IAB-463M type, which was equipped with a modified system of optical filtration in combination with point or slit light sources. The field of vision of the IAB-463M optical system has a diameter of 400 mm. The images were recorded with a CCD camera. Visualization of the vortical structures was carried out with application the biquadrent Hilbert-filtration and a slot-hole light source that provided one-dimensional the Hilbert-transformation of an optical signal.

The experimental vortex ring generator had a chamber with dimensions 0.19 × 0.19 × 0.38 m. The front edge wall was 5 mm thick and had a central hole with a diameter of 20 mm. The rear edge wall represented the membrane of an electrodynamic loudspeaker head. The side walls were provided with high-quality optical windows for observation of the vortex structures moving inside the chamber. The electrodynamic loudspeaker was driven by
rectangular electric pulses with variable polarity, amplitude and on/off ratio. A pulsed control signal was generated by a computer sound board, amplified, and fed to the input of the electrodynamic oscillator. The CCD camera recorded the Hilbert schlieren patterns of vortex structures formed inside and outside the generator chamber.

On Fig. 1 examples of the Hilbert schlieren patterns illustrating evolution of the vortical structures arising at positive pressure jump are brought.

We have also obtained the Hilbert schlieren patterns reflecting the formation and propagation of vortex ring structures moving in the opposite direction upon a negative pressure drop in the chamber. In this case, regimes were observed in which the velocity of vortices inside the chamber was higher than that outside. Figure 2 shows evolution of pair the vortical rings arising at negative pressure jump.
On the whole, the experimental data confirmed the results of numerical simulations of toroidal vortex generation upon sudden opening of a cylindrical chamber containing a gas at elevated pressure. The calculations were based on the Navier–Stokes equations for a laminar confined axisymmetric flow. The results of numerical simulations showed that toroidal vortices were formed under these conditions upon opening of a hole, which moved along the hole axis in the opposite directions away from the partition. Figure 3 shows the patterns of (a) flow lines and (b) gas density in the vortices moving in the forward and reverse directions at a pressure drop of 101 Pa.

The received results are important for understanding of mechanisms of vortex formation in fundamental and applied tasks of hydro- and gas dynamics, developments optical diffraction analogies of interaction of front of pressure to an obstacle and a substantiation of ways of management of structure and evolution of vortical rings.
On Fig. 4 the distribution of density of gas received as a result of numerical modelling in a vicinity of an aperture in the increased scale for the whirlwinds moving both in direct and return directions is shown. It is visible, that the vortex in the opposite direction is late in the development, than at lower pressure difference more. On Fig. 5 it is brought corresponding Hilbert – pattern recorded in the experiment.

The formation of vortex structures in the system under consideration can be considered as the diffraction of a shock wave on a hole in a wall [4]. As a result, diffracted fields of pressure are formed outside and inside the chamber, the structure of which can be described by a function of the type $-pJ_1(aw)/aw$, where $J_1(aw)$ is the Bessel function, $a$ is the hole radius, $p$ is the pressure drop amplitude, and $w$ is the spatial frequency in the Fourier plane perpendicular to the axis of the cylindrical coordinate system. The signs of the main and side diffraction maxima of this function are alternating. As a result, the diffracted pressure field induces vortex structures of a toroidal type, which propagate in the opposite direction away from the wall with the hole.

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References