Acoustic relaxation of the hydro-mechanical system under critical expiration of swirl flow

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Abstract. The mechanism of generation of acoustic oscillations associated with the formation of stable vortex structures in the moving fluid was considered for the impact swirl flow. Experimental studies were carried out to determine the relationship between large-scale vortex motion and acoustic effects in hydro-mechanical systems. It was shown that a sharp change of the amplitude-frequency characteristic of the acoustic oscillations of hydro-mechanical system corresponds to the maximal flow rate of the swirl flow. The established connection between the generation of sound waves and geometrical and regime parameters of the hydro-mechanical system formed the basis for the developed method of diagnostics of the processes of vortex formation.

1. Introduction

Formation of vortex structures in the flow is connected with presence of viscosity in any real fluid. The presence of internal friction determines the fact that any change of channel geometry, e.g., contraction, expansion, bending, etc. leads to vortex formation. A detailed analysis of these effects is given in [1]. The main objective of the proposed methodology is the early identification of conditions of vortex generation to avoid dangerous operation modes of power units.

A self-regulatory effect of acoustic oscillations was revealed in a series of experiments, conducted to substantiate the developed diagnostic technique. The effect of self-regulation is expressed in a resonant amplification of the amplitude of natural frequencies of the hydro-mechanical system due to the absorption component of the spectrum of acoustic vibrations, generated by the vortex flow structure. In elements of thermal power equipment of nuclear power systems such effect can lead to a sharp increase in vibration and, consequently, to destruction of constructions. The comparison of amplitude-frequency characteristics of acoustic oscillations with visualization of the vortex structure of flows and numerical simulations allowed identifying the topological features of the impact swirl flow [2]. The connection of the internal vortex structure of the flow with the effect of the occurrence of acoustic resonances has been identified, using the acoustic method proposed in [3] and based on the measurement of frequency characteristics of sound waves in impact swirl jet. Theoretical analysis, using the approximation of acoustic flows [3] and the theory of screw flows [1], and comparison of experimental and calculated results are a justification of the proposed physical model of the flow, predicting the occurrence of acoustic resonances, caused by the topology of the vortex flow.
2. Correlation of acoustic oscillations with vortex structure of the flow
The results of the preliminary studies, given in [3-5], allow correlating the generation process of vortex structures to the recorded acoustic oscillations with frequencies, concentrated mostly in the sound range. Detailed description of the experimental setup used in present studies was given in [2, 4].

The mechanism of the effect of self-regulation may be explained as follows: at the condition of the maximum flow rate of the working fluid, which corresponds to the condition of critical flow expiration, the flow obtains a clear vortex structure. The swirled jet, exiting the orifice of the vortex chamber in the region of twist, and the radial spread of the flow over the edge of the hole are divided into thin spiral vortices, which is confirmed by the picture of the wake vortex visualization (Figure 1g). In this case, the energy flux is sufficient to generate the vortex structure of the flow, characterized by two rotation frequencies (Figure 1): frequency $f_1 = 63.5$ Hz around the $z$ axis and frequency $f_2 = 273$ Hz around the axis $\phi$ (Figure 1d).

![Figure 1](image.png)

**Figure 1.** Sub-critical expiration regime for the obstacle with diameter $D = 70$ mm at the output hole diameter $d_0 = 5$ mm and the flow rate $G = 1.15 \cdot 10^{-3}$ m$^3$/s: a) the time scan of the acoustic wave; b) the result of summing the harmonic oscillations with frequencies $f_1 = 63.5$ Hz and $f_2 = 273$ Hz; c) the amplitude-frequency characteristics; d) picture of the wake vortex on the lower surface of the obstacles; e) a Lissajous figure with frequency $f_1 = 63.5$ Hz and $f_2 = 273$ Hz in the cylindrical coordinate system $(r, \phi, z)$. 
If the energy of individual vortex is not sufficient, then, reaching the edge of the obstacle and encountering the resistance of the atmospheric pressure of the external environment, a spiral vortex does not leave the system and returns to the center of the obstacle where it is again picked up by the effluent stream. Since the output flow is a swirled, jet, breaking into thin spiral vortices spreading in the radial direction, displaces on a certain angle with every turn of the stream.

Frequency $f_1$ is the harmonic oscillation frequency of rotation of the group of thin spiral vortices around the axis of the vortex chamber. The flow may go through several oscillatory cycles until its energy is sufficient for passing into the environment. The experimental diagram (Figure 1a) shows the corresponding smooth increase and decrease of sound pressure level. The resistance of atmospheric pressure depends on the area of the outlet section of the slit. So the number of cycles, for which energy necessary for the flow exit from under obstacle is accumulated, depends on the size of the obstacle $D$. In this case, the frequency $f_2$ must also depend on the diameter of the obstacles. The resulting vortex system tends to instability and rebuilding. Sources of additional energy are vibrations of structural elements of the vortex chamber.

The vortex chamber, from which the expiration air flow occurs, consists of a rigid metal construction with glued upper plexiglass surface with the central hole for the output of the swirl air flow. The bottom of the vortex chamber is a solid single surface, and the upper end surface of the chamber with a central hole of diameter $d_0$ is removable, that allows varying the diameter and the shape of the outlet hole edge.

In the considered case of excited self-oscillations at the swirl air outflow from the vortex chamber, its upper end surface is subjected to an asymmetric force impact that can cause bending vibration at a frequency $f_{11}$, which can be estimated by the formulas for a circular plate in accordance with the recommendations of [6]:

$$f_{11} = 2.09 \cdot f_{01},$$

$$f_{01} = 0.9342 \frac{b}{2R^2} \sqrt{\frac{E}{3\rho(1-\nu^2)}},$$

where $R$ is the radius of the plate, $b$ is the plate thickness, and $E$, $\rho$, $\nu$ are the Young's modulus, density, and Poisson's ratio of plate material, respectively.

In this case, (as it was illustrated in figure 2.1. in the work [6]), the fixed circumference is the edge of the round plate, and the nodal diameter is the line, connecting the region with occurring compensation of flow rate of inlet and outlet air flow under the obstacle. According to formulae (1, 2) frequency of bending vibration of plexiglass plate with radius $R = 45$ mm and thickness $b = 5$ mm is $f_{11} = 2824$, when values of $E = 41\cdot10^3$ Pa, $\nu = 0.394$, and $\rho = 1.18\cdot10^3$ kg/m$^3$ Hz, which well agrees with the experimental values of the frequency $f_1$ and corresponds to the resonance condition. In a series of experiments with the upper edge surface of the vortex chamber, which was made of duralumin alloy, a resonance effect was not observed, because the natural frequency of a duralumin surface was significantly higher and was outside the range of oscillations, generated by vortex structures.

Emerging from the vortex chamber, the flow of high kinetic energy excites vibrations of elastic surface, which are accompanied by fluctuations of the air volume under the obstacle. The coincidence of the frequency of one of the overtones of air vibrations with the natural frequency of the upper end surface of the camera $f_{11}$ causes a resonance. This condition is necessary to form a thin structure of longitudinal helical vortices with frequency $f_1 = 2796$ Hz and rotation around the axis $r$ (Figure 2d). The output flow leaves the space under the obstacle during the time of one cycle of rotation, not returning to the center of the obstacle. The visualization for this case is presented in Figure 2g. Figure 2a illustrates the corresponding experimental dependence of acoustic pressure on time, showing that under the resonance mode of the outflow the accumulation and discharge of energy takes place in one oscillation cycle.
3. The energy of acoustic oscillations

Three characteristic modes of impact swirl outflow were considered in the present work. These are subsonic, sonic sub-resonant and resonant modes. Figure 3 presents a graph, comparing the intensity of sound waves for these three expiration regimes of the flow.
Figure 3. Frequency dependences of the sound wave intensity for the obstacle of diameter $D = 70$ mm (for $d_0 = 5$ mm and $G = 1.15 \cdot 10^{-3}$ m$^3$/s) for three flow regimes: 1 - subsonic mode, 2 - sonic sub-resonant mode and 3 - sonic resonant mode.

Subsonic regime occurs for small values of air flow rate in the vortex chamber. Under this regime corresponding to line 1 in Figure 3, a rotation of obstacle around its axis was observed while the sound effect was missing. In the subsonic mode, the energy of the air outflow from the vortex chamber goes for rotating the obstacle, and the air outflow is distributed evenly around the perimeter of the output gap.

The sonic sub-resonant mode occurs upon reaching the maximum value of the flow rate in the vortex chamber. The concept of limit of the fluid flow rate was introduced by academician I. I. Novikov in [7] to describe the hydrodynamical regime of a swirl flow, when the increase of pressure gradient in the work area does not increase the fluid flow rate. At this mode the cessation of the obstacle rotation around its axis was observed, and sound oscillations at low frequencies (line 2 in Figure 3) were identified.

The energy balance corresponding to the energy of the flow from under the obstacle for the sub-resonant regime (line 2 in Figure 3) consists of summing the kinetic energy of air flow arising from vortex chamber and energy of the sound waves, emitted by a hydro-mechanical system. This mode was recorded at the time of stopping the rotation of obstacles and the advent of sound. Such flow regime is unstable, and after some time it may spontaneously switch to mode 3.

The resonant mode is characterized by a sharp increase of sound oscillations at natural frequency of the vortex chamber (line 3 in Figure 3). In the experiment, the first of the achieved natural frequencies of the considered hydro-mechanical system was the frequency of oscillation of the lid, glued to the upper end surface of the vortex chamber. Figure 3 clearly shows that the energy of the acoustic oscillations increases considerably at the transition of the system to a resonant outflow mode (line 3 in Figure 3). A source of additional energy in the resonant system is the energy of vibrations in the elastic lid of the vortex chamber, which are excited due to the external force action of the vortex structure of the air flow.

4. Conclusion
As a result of this study it has been established that under the condition of critical outflow the swirl flow relieves excess energy through acoustic vibrations.
The identified vortex structure generates acoustic vibrations. Their frequency at the coincidence with the natural frequency of the structural elements of the work area, in turn, is the cause of excitation of the vibrating process and the redistribution of energy due to resonance.

On the basis of realized investigations the method of acoustic resonances is proposed. This acoustic method allows diagnosing the appearance of undesirable vortex structures and identifying threats of dangerous hydro-dynamical regimes, because the main natural frequencies of nuclear power installations relate to sonic and infrasonic ranges.

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