Development of the Technology of Vortex Diagnostics to Improve the Safety of Operation of Nuclear Reactors

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Abstract. The results of studies are aimed at developing theoretical foundations and instrumentation system to ensure a technology of vortex diagnostics of the state of flows of fluids for nuclear power installations with power water reactors and fast neutrons reactors with liquid-metal coolants. The technology of vortex diagnostics is based on the study of acoustic, magneto-hydrodynamic and resonant effects related to the formation of stable vortex structures. For creation a system of monitoring and diagnostics of the crisis phenomena due to hydrodynamics of the flow, it is proposed to use acoustic method to record the radiation of elastic waves in the fluids caused by the dynamic local rearrangement of its structure.

1. Introduction

In this work for creating a system of monitoring and diagnostics of the crisis phenomena hydrodynamics of the flow, it is proposed to use acoustic method to record the radiation environment of elastic waves caused by the dynamic local rearrangement of its structure. The restructuring of the flow of coolant may be related to effects of the generation of coherent vortex structures and phase transitions accompanying the unauthorized boiling of the coolant or cavitation effects.

The advantage of the proposed diagnostic method of acoustic resonances over existing methods of nondestructive testing is that it gives the opportunity to track the emergence and development of threat for the designs of the nuclear power vibration processes and resonance oscillations, and directly in the operation of nuclear facilities.

The complex of experimental and theoretical studies includes:
- development of methods and means for diagnosis, prognosis and study of vortex structure of turbulent flows in channels of nuclear-power installations,
- rationale for new approaches in physical-mathematical modeling of complex vortex flows, including the development of physical models and mathematical descriptions of the processes of generation and dynamics of vortex structures
- identification of control factors, leading to destabilization of the flow regimes of the fluids and the formation of large-scale vortex structures
- development of a method of acoustic resonances,
consideration of the impact of changes in the operating parameters of flow, variability of the geometry of the flow channel, as well as the influence of fluid conductivity on the process of vortex generation.

2. Method of acoustic resonances
The relevance of the proposed thermal-physics researches and development of acoustic diagnostic method due to the need for scientific justification of design decisions, providing an increased service life of the nuclear reactor of the integrated type and energy equipment for the new generation ice-breakers and nuclear power plants of low power, designed on the basis of ship technologies.

The results of carried out experimental researches on the identification of the conditions of generation of large-scale vortex structures and topological features of turbulent flows in channels of complex geometry and generalization of experimental data on revelation the mechanisms of occurrence of acoustic oscillations in such complex dynamic systems, what are the nuclear power installations of block and mono-block types, show, that the restructuring of the flow of coolant may be related to effects of the generation of coherent vortex structures and phase transitions accompanying the unauthorized boiling of the coolant or cavitation effects.

Available experimental data show that flow in channels of power installations, wrap of obstacles (fins, protrusions, rough edges, bends, etc.) are associated with the processes of vortex formation and generation of oscillations in the range of the sound spectrum. Due to the fact that the spectrum of the generated oscillations is determined by the elastic characteristics of the elements of the channels and the internal vortex structures of the flow, it carries much information about the condition of the hydro-mechanical system.

Previous researches [1, 2] showed that the danger of resonance can be diagnosed in advance, before that as the hydro-mechanical system has been achieve the state of resonant instability.

The connection of the internal vortex structure of the flow with the effect of the occurrence of acoustic resonances have been identified using the proposed in [3] an acoustic method based on measurement of frequency characteristics of sound waves in a swirled impact jet. Theoretical analysis using the approximation of acoustic flows [1] and the theory of screw flow [4] 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.

The results of preliminary studies are given in [1-3, 5,6] allow unambiguously compare of the generation process of vortex structures with recorded frequencies of acoustic oscillations are concentrated mostly in the sound range. Detailed description of the experimental setup used in these studies was given in [5].

In the present work we considered three characteristic modes of outflow for impact swirl flow: subsonic, sonic sub-resonant and resonant. Figure 1 presents a graph comparing the intensity of sound oscillations for these three modes of the flow.

As it was shown in the works [1, 2], the subsonic flow regime occurs for small values of air flow rate in the vortex chamber. Under this regime, which corresponds to line 1 in Fig.1, the rotation of unfixsed obstacle around its axis is observed and the sound effect is missing.

The sound sub-resonant mode occurs when the maximum of flow rate in the vortex chamber is reached. The concept of the maximum achievable flow rate was introduced by academician I. I. Novikov in [7] to describe such hydrodynamic flow regime, when the increase in pressure gradient at the entrance to the work area does not increase flow velocity. In this mode there is a cessation of the obstacle rotation around its axis and sound oscillations at low frequencies (line 2 in figure 1) arise. For this regime in Fig. 2 it is shown a comparison of the visualization picture of the wake vortex of the flow on the surface of the obstacles (Fig. 2 a) with the theoretical interpretation of the trajectory of vortex motion for the particle of the fluid corresponding to the Lissajous figure shown in Fig. 2 b. This flow regime is unstable, and after some time it may spontaneously switch to mode 3.
Figure 1. Dependence of the intensity of the sound wave of the frequency for obstacle of diameter $D = 70$ mm, the diameter of the outlet of the vortex chamber $d_0 = 5$ mm and air flow rate $G = 1.15 \times 10^3$ m$^3$/s for the three flow regimes: 1 – subsonic 2 - sonic sub-resonant and 3 - resonant.

Figure 2. Sonic sub-resonant regime. The comparison of calculation results with visualization of the flow pattern:  a) - picture of the wake vortex on the lower surface of the obstacle; b) - the Lissajous figure in the cylindrical coordinate system $(r, \varphi, z)$ with the frequencies $f_1 = 2796$ Hz and $f_2 = 273$ Hz.

The resonant mode is characterized by a sharp increase of the sound oscillations at the natural frequency of the vortex chamber (line 3 in figure 1). This phenomenon may be explained as the amplification of acoustic oscillations generated by vortex structure of the flow, due to the absorption of energy of vibrations of hydro-mechanical system. Calculations carried out for the considered
example of the impact jet outflow of the swirl flow showed that in the sonic sub-resonant mode, the total intensity of the entire spectrum of acoustic oscillations generated by a deterministic vortex structure of the flow, made up 0.164 W, while in the resonant mode, the intensity of the acoustic oscillations has increased to 6.34 W due to a sharp increase in the amplitude of natural oscillations of hydro-mechanical systems. In elements of thermal power equipment, nuclear power systems this phenomenon can lead to a strong increase in vibrations and, consequently, to destruction.

Corresponding to this regime, the comparison of the visualization of the vortex structure of the flow represented by a fixed system of thin helical vortices, and the Lissajous figures corresponding to the closed phase trajectories characterizing periodic motion with multiple frequency ratio of harmonic oscillations in two mutually perpendicular directions, is shown in Fig. 3.

![Image](image_url)

**Figure 3.** Resonant regime. The comparison of calculation results with visualization of the flow pattern: a) - picture of the wake vortex on the lower surface of the obstacle; b) - the Lissajous figure in the cylindrical coordinate system (r, φ, z) with the frequencies \( f_1 = 2794 \text{ Hz} \) and \( f_2 = 63.5 \text{ Hz} \).

It was established experimentally that when the maximum velocity rate of swirl flow [7] there is a spontaneous restructuring of amplitude-frequency characteristic of the acoustic oscillations of hydro-mechanical systems. This so-called self-regulatory phenomenon of acoustic oscillations, manifesting itself in a resonant enhancement of the amplitude of the natural frequencies of the hydro-mechanical system due to the absorption component of the spectrum of acoustic vibrations generated by vortex flow pattern may be detected as the critical transition between the two acoustic modes, preceding the phenomenon of self-regulation. The theoretical approach used to determine the correlation between recorded parameters of acoustic emission (coefficient of electro-acoustic conversion, the unevenness of amplitude-frequency characteristics, dynamic range amplitude measurement signals, etc.) and reproducible images of deterministic vortex structures, based on the thermodynamic theory of crisis stability in condensed matter and the results of physical and mathematical simulation.

The advantage of the proposed diagnostic method of acoustic resonances over existing methods of nondestructive testing (ultrasonic, radiation, magnetic) is that it gives you the opportunity to track the emergence and development of threat for the designs of the nuclear power vibration processes and
resonance oscillations, and directly in the operation of nuclear facilities. Additionally, the minimized weight and size characteristics diagnostic equipment, as for its technical implementation technology of vortex diagnostics using the method of acoustic resonances does not require bulky measurement systems such as source-receiver or the imposition of an external magnetic field.

The amplitude-frequency characteristics of acoustic waves, carrying the information about changes in the local pressure field, the vortex structure of the flow and the heterogeneities of fluid medium are fixed in the time of measurements.

3. Conclusion
For the impact swirl flow it is shown that in the region of the critical transition corresponding to the frequency range of acoustic oscillations generated by the formation of a stable coherent spiral vortex structures, the intensity of the sound oscillations, recorded with the help of the frequency response increases by 2-3 orders of magnitude.

The conducted research allowed to reveal the basic regularities and physical features of complex vortex and swirling flows, and to identify the main factors influencing the fluid flow and heat transfer in elements of equipment of nuclear power installations. This gives the opportunity to propose in this project a number of concrete ways to improve the vibration resistance and the optimization of geometrical and operational parameters of marine nuclear power plants from the point of view of increasing the safety and efficiency of their work.

The results of the present study are intended to provide monitoring and condition diagnostics for stationary and transport nuclear power units, as well as to formulate recommendations to improve the design of new generations of nuclear power installations.

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