Laboratory modeling of hydrodynamic instability and sound generation processes in the ship NPS

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Abstract. This work is devoted to investigations of the self-oscillation regimes in the model of emergency stop valve chamber in the ductline of the systems of heat exchange in the ship nuclear power setup (NPS). Experiments were carried out on special aeroacoustical setup with simultaneous use of PIV methods for measuring velocity fields and measurements of sound generation characteristics. Dependency of parameters of self-oscillation regimes on the parameter of the length of the gap between the inlet and outlet ducts in the chamber was investigated. An explanation of the observed regimes was proposed.

1. Introduction
Occurrence of self-oscillation regimes in technical systems usually leads to negative effects due to cyclic and inhomogeneous influence on structural elements, complicates diagnostics and control of flow patterns, etc. These modes can be a source of narrow-band acoustic signals, which can also be considered as a negative factor. Typical flows in technical system for which such regimes arise, and properties of use Particle Image Velocimetry (PIV) method to carry out measurements are described in the work [1]. Investigations of turbulent boundary layer over the obstacle, cavities, protrusions and other inhomogeneous elements on the flat surface described in review [2, 3] can be for applications associated with flows in ductlines of different configuration. Flow-through elements such as splitters (twins, tees, etc.), duct joints of various transverse sizes and cross-section types, bends can be sources self-oscillatory modes (see [4]). Such elements are typical for heat exchange systems in power plants including nuclear ones.

The main aim of this work is investigation of self-oscillation regimes within the task of modeling the flow in the elements of heat exchange ducts nuclear power setups including destined for ship operating. The configuration of chamber of the valve in the duct line was simulated. The dependence of the characteristics of the hydrodynamic and acoustic regimes of the flow on the length of the gap between the ducts inside the model chamber was studied. An explanation of the physical mechanism of the process was proposed.

2. Experiment and measurements
2.1. Description of aeroacoustic experimental setup
A special aeroacoustic setup was developed for modeling hydrodynamic instability and sound generation processes in the valve chamber model of the heat transfer ductline of ship NPS. It includes: the valve chamber model, inlet and outlet ducts, air exhauster, and absorption device situated between...
the exhauster and the model to prevent transmitting vibrations caused by exhauster operation (see Figure 1). Exhauster and absorption device were situated separately from the other devices in the anechoic room.

Figure 1. Principal scheme of experimental setup, side view: 1 – laptop 2-inlet duct with conical nozzle, 3 - valve chamber model, 4 – high speed camera , 5 – microphone, 6 – laser sheet device 7 – outlet duct, 8- device for absorbing vibrations, 9 - exhauster,

The model of valve chamber was a parallelepiped volume with inside volume dimensions 60×80×140 mm, and was made of plexiglas 8 mm. Inlet and outlet ducts (length 0.9 m and 1.4 m correspondingly) were the round polypropylene pipes 1.5 mm thick and outer diameter - 50 millimeters. The model and ducts were mounted on the special optical table which is equipped with special vibration mounts preventing the transmission of parasitic vibrations from floor of laboratory room. All components forming a single system together with the model of the chamber. Installation of a conical nozzle on inlet of the supply duct allows us to reduce airflow resistance. Acoustic parameters were monitored using a microphone which could be installed in various places, outside the model chamber and inside it both. The frequency of sound pressure signal was measured in the range of 50 ... 8000 Hz.

2.2 PIV-measurements scheme and properties of the image processing

The scheme of PIV-measurements was close to what was performed in [3]. For PIV-measurements air flow was seeded with droplet size of 5 micron particles by using of smoke spray generator, which was located in front of the entrance nozzle at a distance of about 1 m and operated in a pulsed mode synchronously with laser-optical system. The typical time of continuous operating of the generator was about one second.

Laser sheet was formed from the beam of a 6W (450 nm) blue LED continuous laser with defocusing cylindrical optics and crossed the chamber model from above in the middle along the direction the air flow. View from a side on visualized flow with smoke droplets in the laser sheet was filmed with a high-speed digital camera Memrecam NAC HX-3. The filmrate was 12220 frames/second with size of image 768 ×960 in pixels, and 66×83 in mm. The scheme of PIV-measurement is shown in Figure 2 a.
A dynamic background subtraction from the each frame was used to reduce static noise and parasitic flare on the images. Also, it should be taking in to account that seeding density varies significantly within operating time interval caused to the irregular character of the smoke generator operation.

A cross-correlation image processing in accordance to PIV-method was performed after subtracting the background. The velocity field on the regular rectangular grid was obtained baising on cross-correlation processing of successive frames. Typical two-pass scheme was used (see [3]). At the first stage, the displacement field was roughly calculated with a comparison window of 128×128 px with overlapping 50%. The resulting field was filtered and interpolated to the grid with twice less space. On this grid the main calculation of the displacement were carried out: for interrogation window 64 x 64 px with overlap 50%, and preliminary symmetric shift of the interrogation windows. The gaussian approximation of the peak of the cross-correlation function taking in to account three nearest points was used to avoid peak locking effect.

Obtained velocity fields were filtered in time sequence for each point of the spatial grid. The values of velocity for which at least one of the two calculated components by more than three standard deviations differs from the average value over the entire record (for a given point) were filtered out through two passes. About of 5% of the points were discarded usually.

2.3 Conditions and procedure of carrying out measurements

Experiments were carried out under the conditions of constant flow rate (centerline wind speed was set close to the 30 m/s).

The main aim of experiment was investigation of the influence of the length of gap between the ducts inside the chamber on the aeroacoustic properties of the flow. Initially the ducts were installed without protruding edges, flush with the inner walls (for \( L = 60 \) mm). In this configuration a sound was clearly heard, that confirmed by measurements with microphone: peak frequency of 340 Hz. Also measurements recorded a weak noise at the second harmonic of 680 Hz. Then the gap was slowly decreased by pushing the inlet duct into the model of chamber. Reducing \( L \) to 48 mm led to instability of the sound generation, and sharp decreasing of the sound amplitude to the level of external interference. Discrete sound spectra didn’t recover till \( L \) didn’t reach 38 mm. Further reduction of the gap between the ducts led to the resumption of the tonal sound of the system at a higher frequency of 680 Hz which was maintained up to the \( L=28 \) mm. Diagram of frequency spectra and time of observation (corresponds length of the gap between the ducts) was reconstructed (see Figure 3).
Figure 3. Diagram showing spectra frequency of sound pressure from microphone for different time of experiment corresponding different length of the gap $L$ between ducts.

Then, to carry out PIV-measurements three different cases of gaps between the ducts were chosen: 55 mm, 42 mm, 35 mm, corresponding observed character of acoustic diagram. Comparison of averages, and instantaneous velocity fields are shown on the Figure 4. There is no significant difference between mean velocity fields, but the instantaneous random ones demonstrate the presence of distinguishable vortices at the boundary of the jet for the cases when discrete sound generation was observed (see Figure 4d and f).

Average spectra of velocity fluctuations were calculated as follows: in each point in the coordinate grid of the velocity field spectra of horizontal and vertical component were calculated and then averaged over the whole field. Analysis of flow velocity spectra, presented on the Figure 5, confirmed the occurrence of the self-oscillatory regime in the flow. The fluctuation spectra of the vertical and horizontal velocity components confirmed the presence of hydrodynamic perturbations with frequencies equivalent to observed acoustic signals (compare Figure 5 and Figure 3).
3. Interpretation of the mechanism of self-oscillating regime.

For detail investigation of the mechanism of hydrodynamic self-oscillation mode and acoustic signal generation, sequence of images obtained with a long (compared to PIV-measurements) exposure 1 ms was analyzed (see Figure 6). The conditions of the most intensive generation (340 Hz frequency of flow velocity fluctuations and sound) at $L=55$ mm was taken. This sequence clearly represented four stages of periodic process: the first is an increase of the intensity of vorticity near the edge of the inlet duct (Figure 6a); the second indicate that vortex sheet loses stability and folds into a discrete ring vortex (Figure 6b); on the third the movement of the vortex downstream can be seen (Figure 6c); and the final fourth stage is the blow of the vortex against the edge of the outlet duct and its resorption on its walls (Figure 6d).
Basing on the image analysis we can suggest following screenplay of the mechanism of vortices and sound generation. Vortex sheet (thin surface with nonzero vorticity) forms at the boundaries of the air jet penetrating from one duct to another which separates the main flow air from the air in the stagnant zone of the model of the chamber. It corresponds to shear in the longitudinal (horizontal in our case) component of velocity from the value in the main part of the flow to values close to zero in the stagnant zone of the chamber. The vortex sheet is an unstable structure which with the slightest inhomogeneities tends to “collapse” into a system of large discrete vortices, as well known from hydrodynamics. The most important thing in this process is that the indicated periodical motion of the vortices leads to a periodical change of the air flow rate through the inlet and outlet sections of the chamber. Accordingly, observed vortex can be identified with an equivalent dipole source, oriented longitudinally, exciting acoustic waves.

This mechanism of the acoustic signal generation process explicitly reveals the reason for the influence of the gap between ducts on it. $L$ and the flow velocity $U$ determine the time interval during which a vortex forms and reaches the edge of the outlet duct and hence the frequency of hydrodynamic instability. Obviously hydrodynamic instability with this frequency in some cases is synchronized with other resonances of the system which generates self-oscillations and the accompanying sound generation.

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