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A NEW METHOD OF CONTROL OF COHERENT STRUCTURES IN VORTEX APPARATUSES

Abstract. *A new method for direct control of energy-intensive coherent vortex structures (ECVS) in a vortex chamber is provided with stable vortex wires, which are descended from the lateral edges of a small elongated wing which is mounted in the inlet nozzle of the chamber. The main task is to determine the reaction of the ECVS in the dead-end ("passive") and the flow ("active") parts of the chamber to the control actions of the nozzle exciter is solved. The efficiency of the principle of mutual susceptibility of vortex structures on the processes of controlling coherent structures for bounded flows in the fields of centrifugal forces is experimentally proved. The observed phenomenon of "pumping" energy of pulsations from small vortices to larger ones allows it to be used to control aerodynamic and hydrodynamic processes of mixing and thermal processes in vortex process and energy devices.*
Key words: *coherent vortex structures, control of the flow structure, vortex chamber, wing type vortex generator, mutual susceptibility of vortices.*

Introduction

Furnace units for power and industrial boilers, combustion chambers of gas turbine units, cyclones, separators and similar vortex devices have the same feature in common: they all take advantage of the action of centrifugal forces. Although the opposite manifestations of the latter factor may be used in different types of devices, they exhibit the same peculiarities of the bulk force field effect on the streamlined flows near curvilinear walls. Thus, the well-known phenomenon of centrifugal instability leads to the formation of coherent vortex structures (CVS) of the Götorler-Taylor, Ludwig, and other types in the near-wall regions [1, 2].

This induces the flow structure heterogeneity in averaged and pulsating motions, significantly changing the local and integral characteristics of the mass transfer, impulse, and heat transfer in the operation area of vortex-based devices. The consequences are: either reduction of completeness of combustion, the exhaust of combustion products, increase of harmful emissions of nitrogen and carbon oxides, deterioration of efficiency and reliability of energy machines and installations, or

quality reduction of purification and separation of fractions of multicomponent media in cyclones and separators [3–6]. At present, there is a lack of comprehensive and consistent data on vortex components of different scales in limited and semi-circular swirled flows. Therefore, traditional methods of controlling impacts on transfer processes are primarily focused on changing the flow general pattern [3, 4].

Given this, the conventional approach fails to represent the adequate physical features of the fine vortex structure of the flow in apparatuses, which make them energy-efficient. This necessitates the elaboration of more effective methods for controlling the CVS that determine the mixing processes, or vice versa, separating components of working fluids. It is known that the maximum contribution to the transfer process is rendered by the most powerful CVSs. In vortex chambers with an elongated dead-end part, stable spiral-shaped vortices of "whiskers"-type exhibit the maximum power [7, 8]. They start to form in the near-wall area of the chamber near the inlet nozzle device with a concentrated gas supply and diverge from the nozzle to the sides of the flow and dead-end zone of the chamber.

Therefore, it is expedient to focus the control actions on these particular structures, in accordance with the principle of mutual susceptibility of vortex structures [9], which attempt is made in this study.

Problem formulation

The new method of target control of energy-intensive spiral-shaped CVSs in a vortex chamber is provided by stable vortex hollow tubes, which descend from the lateral edges of a motionless low-aspect wing that is installed into the inlet nozzle of a chamber.

The respective increase in the induced drag of the wing may be compensated by the profile drag reduction, which is accomplished by usage of a smooth streamlined profile surface, which also has quite a wide range of stall angles of attack, i.e. with no flow separation. Installation of a wing with a relatively small profile thickness in the inlet nozzle of a chamber will not significantly increase the aerodynamic drag of the chamber. Under these conditions, it is also possible to provide the maximum value of the lift force coefficient $c_{y,\max}$ within a sufficiently wide range of Reynolds numbers, which is critical for improving the efficiency of the wing application as a vortex generator [10]. A certain growth of $c_{y,\max}$ is also enhanced by the ground effect from the wall of a nozzle at non-zero angles of attack. The objective is to determine the response of energy-intensive spiral-shaped CVSs in the dead-end ("passive") and the flow ("active") parts of the chamber to the control actions of the nozzle vortex generator (VG).

Experimental technique

The description of the experimental unit and the general part of the methodology for carrying out experiment are given in [2, 7, 8]. The working area is made in the form of a transparent vortex chamber (VC) with internal radius $r_0 = 0.051$ m and the total length $L_0 = 0.635$ м.

The single inlet nozzle has a tangential angle to the cavity of the chamber, a flow path of a rectangular section of $0.02 \times 0.04\ m^2$ with rounded corners.

To ensure the above-mentioned conditions for the inlet nozzle vortex-generator, MB253515-type wing was chosen [11]. The measuring complex of the experimental unit includes hot-wire equipment by "DISA Elektronik" with a single-wire sensor with a diameter of a sensitive element $5 \ \mu m$ and standard devices for controlling of flow and pressure with a set of pneumometric nozzles to determine the directions and the local velocities measuring.

The hot-wire equipment is connected to the analog-digital converter L-264 by "L-Card", installed in the form of expansion board to the IBM-compatible computer. Visualization experiments were accompanied by video and photography with special lighting and subsequent computer processing. The elongated dead-end zone of the chamber serves as an additional vortex generator due to the presence of four stable coaxial vortex structures with the pairwise opposite axial motion [2, 7–10].

The analysis of data in these works shows that concentrated tangential gas admission to the chamber, more than 70% of the input flow flows towards the blind end, and from there – to the active part of the chamber. Resulting strong shear layers in the dead-end zone of the flow should affect the flow characteristics at the exit of the vortex chamber. Therefore, hot-wire measurements of the current actual velocity at 12 points along the dead-end zone of the chamber near the wall at the upper generating ray of its cylindrical part, as well as in the exit cross-section of the chamber are planed. It is expedient to measure axial and circumferential components of flow velocities, which prevail in the dead-end zone of the flow.

Obtained data made it possible to carry out spectral analysis of pulsation motion in the current dead-end zone and dispersion analysis for the flow part of the chamber for evaluation of the whiskers-type CVS response to the control action from the nozzle device.
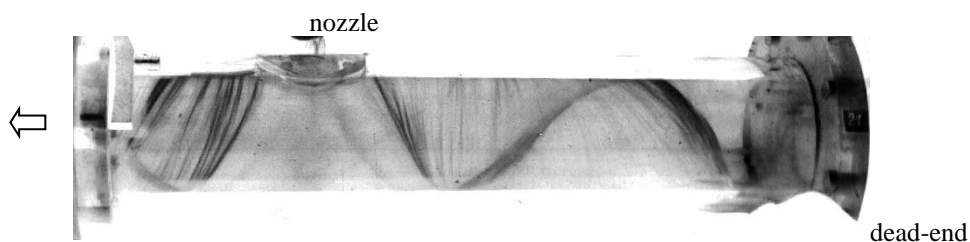
nozzle

dead-end

Fig. 1 – The vortex chamber and visualization of the most energy-intensive spiral-shaped coherent vortex structure

Results and discussion

The algorithm for processing the experimental data obtained by hot-wire anemometry for a chamber with and without VG (with the same Reynolds number $Re = 95000$) was as follows.

First, it is taken into account that the field of instantaneous velocities reflects both deterministic and the stochastic essence of the turbulent flow. But random variables do not have a complete description than the probability distribution density curve [12]. To determine the shape and comparison of distribution curves for each of studied points of the field, in the flow of ordering samples is not enough. They were presented in the form of histograms, that is, graphs in which the ordinate axis postponed the number of values of the function that fall into the given intervals, and

the abscissa axis is the limit of these intervals (intervals of grouping every 0.5 m / s). The number of intervals of grouping s of experimental data was selected within the range of $0.55n^{0.4} < s < 1.25n^{0.4}$, where n is the number of elements in the sample (unit measurements in realization period), $n = 50000$. This is correct for all unimodal distributions. The verification for stationarity was carried out by dividing each implementation (100 s) into a series of intervals (10 s), calculating for each interval main statistical parameters (mean and dispersion) and analyzing the change of these parameters using statistical criteria (hypotheses). This verification was performed with the use of Microsoft Excel datasheets.

Secondly, the algorithm foresees the determination of spectral bands of the signal, removing of energy-intensive frequency bands from the general signal using band-pass filters, a construction of the amplitude-frequency characteristics of instantaneous velocities for each of 12 points along the boundary zone of the dead-end part of the chamber.

The analysis of histogram shows that the use of the wing-type vortex generator in the inlet nozzle leads to changes in the histogram, and therefore, the distribution laws at the considered points in comparison with the case without control, indicating a certain influence of control actions on the powerful spiral-shaped CVS as the main component of gas flow in the dead-end zone of VC.

Comparing the histograms of different samples, the method of checking statistical hypotheses using Pearson's criterion [12] was used as a measure of the difference in observed probability density in the control actions and the probability density with respect to the conditional analytic model of the distribution law without control actions in the input nozzle.

$$\chi^2 = \sum_{i=1}^{k} \frac{\left(f_i - F_i\right)^2}{F_i}$$

where f_i, F_i is the observed (nozzle with the wing) and the expected (nozzle without a wing) frequency in i-th speed interval of the same histogram columns, Hz; k is the number of speed intervals.

Calculated values of χ^2 criterion for axial and circumferential velocity components are shown in Fig. 2 for analyzed points at dimensionless distances from the middle of the inlet nozzle L^* (with relation to the total depth of $0.446\ m$ of the dead-end part of the VC) with a maximum non-stalling positive angle of attack of the wing in the inlet nozzle $\alpha = + 14°$ and at $Re = 95000$ (calculated by hydraulic diameter of the nozzle).

The dash-dotted line corresponds to the critical value of the consent criterion, which according to the Wilson-Hilferty formula [12] for the number of measurements $n > 30$ equals

$$\chi^2_{\text{кр}} \approx n\left(1 - \frac{2}{9n} + u_p\sqrt{\frac{2}{9n}}\right)^3 \approx 50404,$$

where $u_p = 1,2815$ (with a confidence of probability $P = 0.9$) – the upper p-quantile of the standard normal distribution.
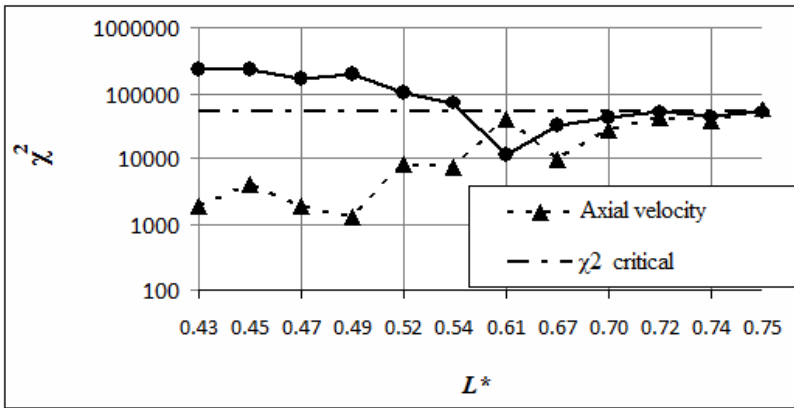
Fig. 2 – Distribution of Pearson's criterion along the dead-end zone of the VC with control actions in the chamber's input nozzle comparing to the case without control action

As can be seen from Fig. 2, along most of the dead-end zone, the distributions χ^2 for the circumferential and axial velocity components are different. When $\chi^2 > \chi^2_{\kappa p}$, the histograms are statistically scattered with a confidence of probability P = 0.9, which indicates the explicit influence of control actions on the circumferential component of instantaneous velocity. When $\chi^2 < \chi^2_{\kappa p}$, the histograms are statistically indistinguishable, which does not directly indicate the presence of such response, but not excludes the possibility of the energy redistribution between vortices of different scales. In the vicinity of blind end at L* = 0.75, the distribution curves χ^2 for both components of the speed practically coincide with the straight line $\chi^2_{\kappa p}$.

This characteristic point requires more detailed analysis of the histograms for the components of velocities (Fig. 3) and for the amplitude-frequency characteristics (Fig. 4), especially at their comparison. Designation "MB" in the charts refers to the control effects of the MB253515 wing.
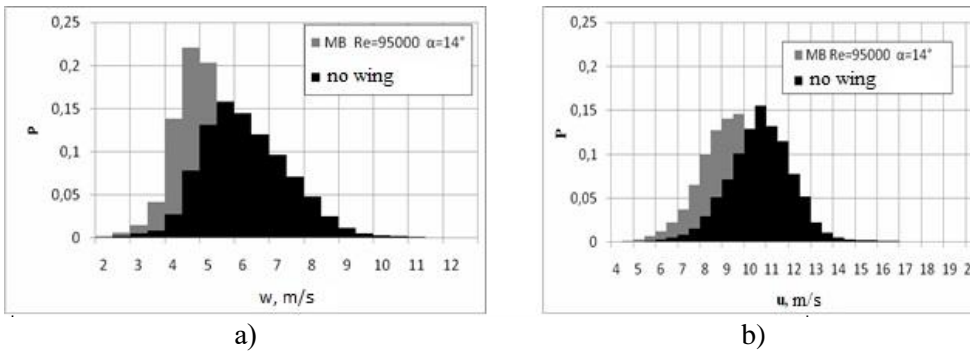

a)

b)

Fig. 3 – Histograms of axial (a) and circumferential (b) components of the instantaneous velocity at point *L* = 0.75*
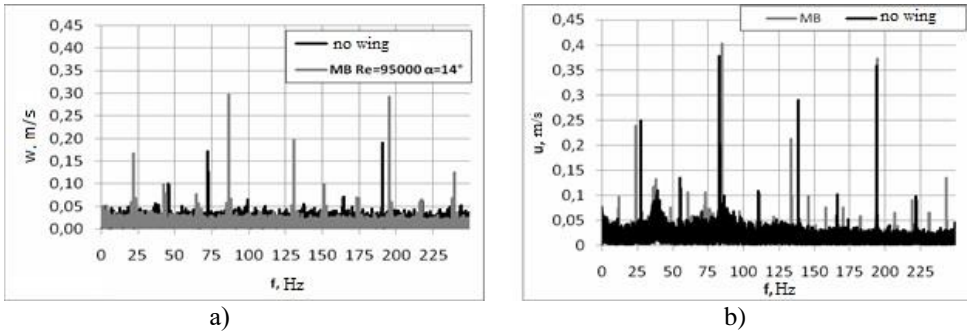
Fig. 4 – Amplitude-frequency characteristics of instantaneous axial (a) and circumferential (b) flow velocities

As seen from Fig. 3, the action of vortex filaments formed by the vortex generator wing puts to evident reduction of the average flow velocity. On the other hand, the analysis of amplitude-frequency characteristics shows the same increase of the pulsation motion amplitudes, which is accompanied with the emergence of a number of new energy-intensive frequencies, as a response to control actions. This can be attributed to the average motion energy redistribution in favour of pulsation energy as a result of the mutual susceptibility of the controlling vortices generated by the wing and the controlled CVS in the dead-end zone of the chamber.

To determine the effect of controlling the flow structure in the cavity of VC on its initial characteristics, an analysis of the energy balance of the pulsation velocities, depending on the bandwidth of the low pass filter at the point $r* = 0.823$ of the output section of the VC in the frequency range 0–100 Hz, was performed. The energy of the pulsating velocities is determined by the equation $E' = 0.5D$, where D is the dispersion of the actual velocity. The bandwidth of the digital filter of the lower frequencies increased from 0–5 Hz, 0–10 Hz and then to 0–100 Hz. For example, Figure 5 shows the graphs of pulsation energy variation of the flow circumferential velocity in the outlet cross-section of VC obtained with and without vortex generator depending on the filter bandwidth.
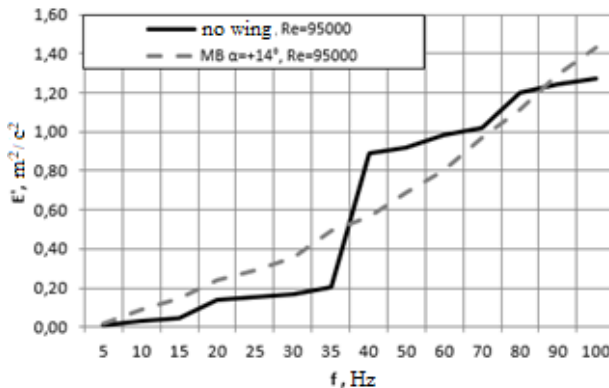

Fig. 5 – The pulsation energy of the flow circumferential velocities at point $r* = 0.823$ of the VC outlet cross-section

The analysis of Figure 5 implies that the presence of the vortex generator increases the energy of velocity pulsations approximately by 1.5-2 times in the

frequency band of 0–35 Hz, and reduces it by 20–30% in the frequency band of 35–85 Hz. Thus, there is a "pumping" of pulsation energy from relatively small vortices to the larger scale ones, which have a strong effect on the processes of mass, impulse, and energy transfer in flows. It was also found that in the frequency range of 0–250 Hz, the vortex generator increases the energy of velocity fluctuation more than of 70% at the same point $r^* = 0.823$ of the vortex chamber outlet cross-section.

Conclusions

1. The efficiency of the mutual susceptibility principle of vortex structures to the processes of controlling coherent structures of bounded flows in the fields of centrifugal forces was experimentally verified.
2. A relatively feeble effect of the control action on the inlet flow in the vortex chamber by the vortex generator significantly intensify the exchange processes at the exit from the chamber with the minimal energy loss.
3. The revealed phenomenon of pulsation energy "pumping" from small vortices to larger ones can be effectively applied to controlling the aerodynamic and hydrodynamic processes of mixing in the working substances, as well as heat transfer processes occurring in technological and energy apparatuses.

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НОВИЙ СПОСІБ КЕРУВАННЯ КОГЕРЕНТНИМИ СТРУКТУРАМИ У ВИХРОВИХ КАМЕРАХ

Анотація. Пропонується новий спосіб спрямованого керування енергоємними когерентними вихровими структурами (ЕКВС) у вихровій камері стійкими вихровими джгутами, що сходять з бічних крайок нерухомого крила малого видовження, вмонтованого у впускному соплі камери. Вирішується задача визначення реакції ЕКВС в тупиковій («пасивній») та проточній («активній») частинах камери на керувальні дії соплового вихорогенератора. Експериментально доведена дієвість принципу взаємної сприйнятливості вихрових структур щодо процесів керування когерентними структурами обмежених потоків у полях відцентрових сил. Виявлене явище «перекачування» енергії пульсацій від дрібних вихорів до більш крупних дозволяє використовувати його для керування аеро- і гідродинамічними процесами змішування середовищ та тепловими процесами у вихрових технологічних і енергетичних апаратах.

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Пропонується новий спосіб спрямованого керування енергоємними когерентними вихровими структурами (ЕКВС) у вихровій камері стійкими вихровими джгутами. Виявлене явище «перекачування» енергії пульсацій від дрібних вихорів до більш крупних дозволяє використовувати його для керування аеро- і гідродинамічними процесами змішування середовищ та тепловими процесами у вихрових технологічних і енергетичних апаратах.

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A new method for direct control of energy-consuming coherent vortex structures (ECVS) in a vortex chamber is provided with stable vortex wires. The observed phenomenon of "pumping" energy of pulsations from small vortices to larger ones allows it to be used to control aerodynamic and hydrodynamic processes of mixing and thermal processes in vortex process and energy devices.

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