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UNSTEADY PATTERN AND OSCILLATION OF FLOW IN SUPERSONIC AXIAL COMPRESSOR STAGES

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ABSTRACT

The compressor noise is attributed to the sources connected with unsteady flow pattern that forms in compressor flow path, in particular under action of propagating upstream and downstream disturbances caused by shocked flow around rotor blades and by blade wakes as well as by generation of vortices resulting from initiation of flow separation. The experimental investigation of unsteady flow pattern in stages being models of fans having different gasdynamic and geometrical design parameters permits to analyze possible noise sources. It can be supposed that in connection with the fact that the rotor blade tip sections have maximum values of tip speed and flow velocity in relative motion, the disturbances created by these sections are the main noise source. The special methodology for processing the readings of fast-response sensors was developed. It permits: to visualize unsteady flow pattern in the tip section of rotor blade passages, in the inlet and outlet ducts by constructing pressure isobars; to determine unsteady flow parameters in the tip section of the wheel and in the inlet and outlet ducts, such as flow velocity in absolute and relative motions, blade angles, their instantaneous and averaged values within some rotor revolutions, values of tip clearances for each blade, fields of losses and pressure ratios.

The instantaneous flow patterns allow to create cartoon films visualizing the intensity, location and movement of shock in blade passages, in-time variation of disturbances propagating upstream and downstream in the form of shock waves, acoustic disturbances and blade wakes.

The investigation pursued allowed to reveal the general properties of flow connected with supersonic flow around rotor blades profiles.

Introduction

During different operating modes of compressor supersonic stages the pressure jumps appear in the flow path of these stages' rotors that is connected with the supersonic flow over the blade portion near the tip section.

The flow pattern in supersonic compressor stages depends on:

a) design values of parameters: tip speed value U, airflow G, pressure ratio π^* depending on which one or another flow pattern realizes.

b) specific operating mode of the stage: the specific value of tip speed U and speed n (tip sections spin-up), and the specific position of the operating point on the characteristic (angles of attack, effectiveness, stability), i.e. depending on airflow and pressure ratio.

The stage can operate under conditions when the flow structure corresponds to the design mode or it is close to it as well as under conditions when the flow regime significantly differs from the design one.

The goal of investigations was to observe the variations of flow non-uniformity as well as in the level of disturbances at deviation of rotors operating modes from the design or optimal ones.

RESULTS OF EXPERIMENTAL INVESTIGATION OF FLOW PATTERN

The investigations were pursued with the help of fast-response pressure transducers installed over the rotor (Fig. 1) and in the special probes. Measured were oscillations of static pressure over the rotor and radial distributions of oscillations of total and static pressure in the inlet and outlet ducts. The instantaneous and averaged flow patterns in the tip sections of rotors in each blade passage, in the inlet and outlet ducts were presented in the form of isobars of the total and static pressure. To construct these isobars there was developed a solver permitting to obtain both averaged and non-averaged flow patterns. Those determined were the fluctuation characteristics of flow such as root-mean-square deviation of pressure σ and $\varepsilon = \sigma/P_{av}$ in different modes with respect to $\overline{n}$, π^*, and G. The various stages differing in the design pressure ratio, airflow, and tip speed were studied. All the stages had the design tip speed U_{dis}>400m/s, $\pi^*\geq1.4$, $\overline{d}=D_{tip}/d_{hub}=0.32\text{-}0.7$. The studies were conducted in parallel with measuring the stages performance, and the data on flow pattern and fluctuations were compared with the averaged parameters of the stages: efficiency, pressure ratio, and their radial fields. Measured were the parameters in respect of flow at several points in the range of speeds: $\overline{n}=0.6\ldots1.0$.

The estimation of recorded by pressure sensors flow fluctuations was carried out and their variation depending on the operating mode (tip speed, flow velocity in relative motion, blade angles, and angles of attack on the leading edges) and on the sensors position in the flow path was analyzed. Obtained were statistical characteristics of pressure oscillations (amplitude and frequency spectra, fluctuation intensity) depending on the operating mode of a stage. The connection between pressure fluctuations over the rotor and the flow pattern in blade passages was studied; revealed was the increase in flow fluctuation in the shock formation area in the blade passages as well as the variation of amplitude-frequency content of fluctuations at change in the operating mode: at optimal points of characteristics and near the stability boundary. The flow pattern and flow fluctuation characteristics in the inlet and outlet ducts were obtained.

The different flow pattern can be formed in the rotor blade passages tip section depending on rotor profiling and on operating mode according to $\overline{n}$, π^* and G and correspondingly on flow velocity in the relative motion. With shock-free flow over the leading edge, the pattern with one shock can be realized in blade passages at the design point. This shock having different strength depending on flow velocity in the relative motion can locate at outlet, in the center of the passage or at inlet. At low angles of attack and appropriate relative flow velocity there forms a system of oblique shocks and a terminal normal shock. If the angle of attack achieves big values then the pattern with an expulsed shock forms in the tip section passages. The differences in the flow pattern cause different distributions of averaged parameters (such as pressure ratio and efficiency) along the height of blade passages. It also tells on unsteady processes and on propagation of disturbances inside the stage.

Fig.2, as an illustration of the above-stated, demonstrates the flow pattern in the rotor tip section ($\pi^*= 2.0$) at two fixed values of the rotor speed corresponding to the values of tip speed $U \sim U_{des}$ and $U \sim 0.85\ U_{des}$ as well as at three pressure ratios π^*_{min}, π^*_{opt} and π^*_{max}. Fig 2 visualizes the flow pattern in three rotor channels where shown in red are the areas of pressure rise in the shock corresponding to flow deceleration in the relative motion, and in blue – the areas of pressure decrease and the corresponding increase in flow velocity. It is seen that when the operating mode of a stage changes, the flow pattern in the tip section channels varies that manifests itself in movement of flow deceleration and acceleration zones along the channel and in change in their intensity. The variation of pressure fluctuations over the rotor corresponds to flow pattern change; the intensification of fluctuations can be observed in the shock formation zone in the blade passages, also observed is the change in amplitude-frequency content of fluctuations during the change in the operating mode: at the optimal points of characteristics and near the stability boundary. Fig. 3 demonstrates the variation of the root-mean-square deviation of pressure along the rotor flow path in a broad frequency band (σ) that corresponds to the flow pattern shown in Fig. 2 (a, e, f). The comparison of the total parameters and the flow pattern shows that at the optimal points of characteristics at values of n close to the design ones we can observe both shock-free flow over the leading edges (Fig. 2b) and the pattern with expulsed shocks of different intensity (Fig.2 c) that depends on the flow direction in the relative motion. The flow pattern with an expulsed shock of different intensity (Fig.2 c, d, e, f) realizes when the airflow decreases and the stability boundary is approached as well as at reduced speeds. The flow pattern change connected with the shock travel tells on subsequent movement of σ_{max} along the rotor flow path. At that, the fluctuations at exit can intensify at decreased pressure ratios, and at increased pressure ratios the fluctuations at entry can grow.

Simultaneously with variation of fluctuation intensity at shock travel the frequency content of the fluctuations changes too. Fig. 4 and 5 show the variation of pressure root-mean-square deviation along the stage flow path in a broad frequency band, at the blade passing frequency and in a $0 \ldots f_{rot}z_{rot}$ frequency band at the same speed and at two pressure ratios – π^*_{opt} and π^*_{max}. The shock expulsion near the stability boundary at π^*_{max} results in 2-3 times increase in static pressure fluctuation over the rotor blades leading edges and in the inlet duct in a broad frequency band. In this case, the main contribution to fluctuations is made by fluctuations at the blade passing frequency. It is marked that the shock expulsion is also accompanied by redistribution of the fluctuation energy into the $0 \ldots f_{rot}z_{rot}$ frequency band, and the fluctuations near the leading edge also become 2-3 times more intensive. This entails the same number of times attenuation of fluctuations at the rotor exit in all the mentioned frequency ranges.

The variation of flow fluctuations along the compressor flow path was considered at different speeds. The unsteady processes at the stage entry and exit run differently at variation of speed from low values $-\bar{n}=0.6$ up to the design speed at $\bar{n}\approx1.0$. Fig. 6 demonstrates the variation of fluctuation energy and its redistribution from a broad frequency band to an low frequency band at change of speed at the optimal points of characteristics. When shock expulsion occurs, the flow disturbances upstream of the stage at the blade passing frequency are 6-12 times more intensive than they are at shocked flow over the blades with subsonic velocity at low speed. The fluctuations at the stage exit in the mentioned frequency ranges are weaker than at its entry at all speeds except for the design mode.

At that, the variation of fluctuations near the stability boundary may differ from the fluctuations at the optimal points of characteristics. As it is shown in Fig.7, the fluctuations at the rotor entry in the mentioned stage at the blade passing frequency (mainly contributing to the flow fluctuations) are by 5-10 dB higher near the stability boundary than they are at the optimal points of characteristics.

The comparison of the flow fluctuation characteristics with the speed-depending variation of the stage operation efficiency have shown that with rise in fluctuations at exit the stage efficiency decreases by 4-5%. The stage efficiency can be influenced by change in the rotor profiling while keeping the specified design parameters: $\bar{n}$, π^*, and G.

The change in blade profiling while maintaining the design values of pressure ratio and tip speed results in change in the flow dynamics at entry and exit. As Fig.8 demonstrates, the redistribution of the fluctuation energy from the entry to the exit takes place according to the change in flow pattern in the tip section. At that, the fluctuations at entry at decreased speeds can become by 10-12 dB higher than at the design speed. Simultaneously, the fluctuations at exit can increase by 10 dB at intermediate speeds in comparison with those at low speed, and they can decrease by 5-6 dB at increase in speed. This occurs because of the shock travel from the blade passages to the exit (Fig.2a). When the shock is located inside the passage (Fig. 2b) the fluctuations at entry and exit have the approximately equal minimum intensity ($\bar{n}=0.92$) (Fig. 8) that is accompanied by decrease in the total pressure loss at entry and exit as well as by improvement in the stage efficiency.

CONCLUSIONS

Thus, varying the flow pattern in the blade passages by changing the rotor blade profiling we can minimize the fluctuations at the operating point at entry and exit. And the decrease in fluctuations can reach 10 dB at the same speed.

It is also possible to reduce by 5-7 dB the intensity of disturbances propagating from the rotor by shifting the operating line by means of changing the throttle position.

The optimization of the process in rotors also results in decrease in the fluctuation intensity in the inlet and outlet ducts.

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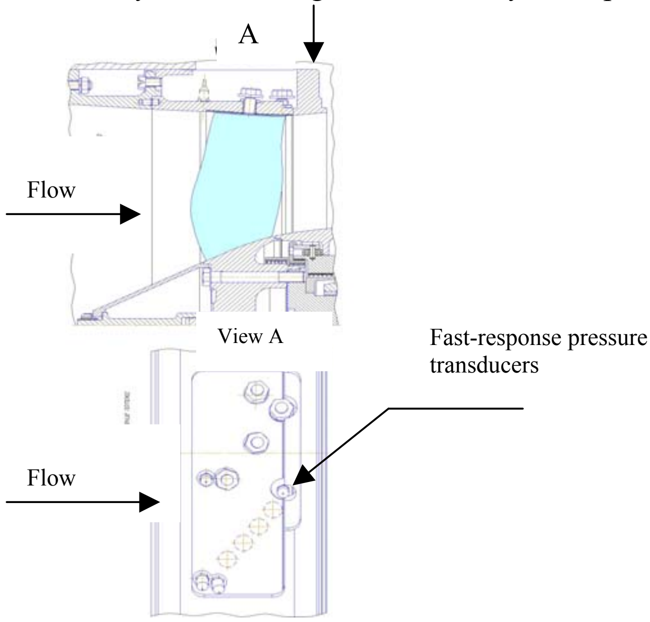

Figure 1 - Instrumentation of model axial supersonic stage with fast-response pressure transducers.

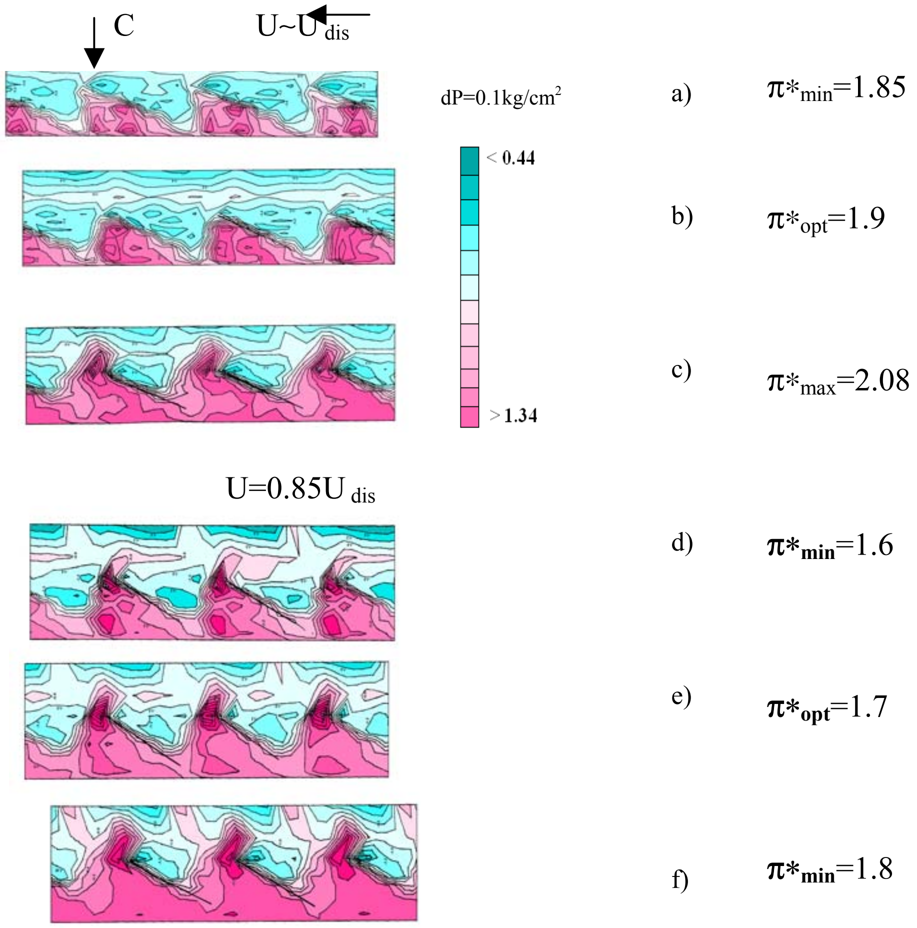

Figure 2 - Flow pattern in tree blade passages of rotor at π^*_{min} π^*_{opt} π^*_{max} and at two vlues $U \sim U_{dis}$, $U \sim 0.85U_{dis}$.

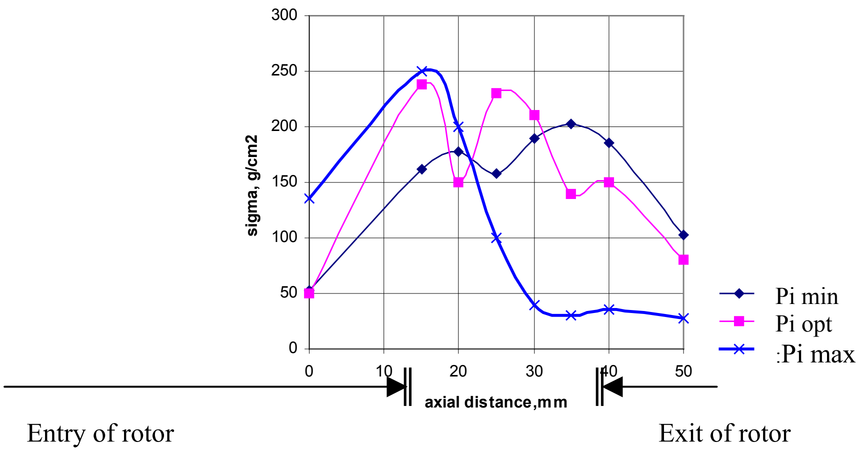

Figure 3 - Variation of pressure RMS deviation in a broad frequency *band at n=0.9 and different pressure ratios.*

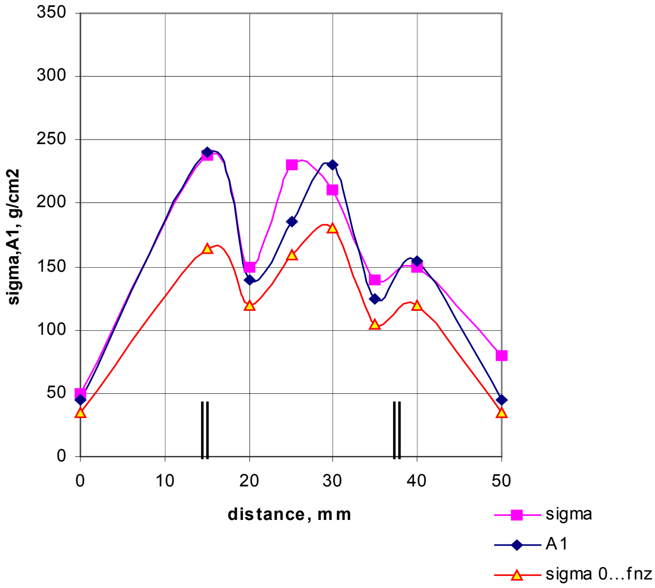

Figure 4 - Variation of pressure RMS deviation along compressor flow path at optimal regime in full frequency rang, at blade passing frequency, and in 0…fnz frequency band.

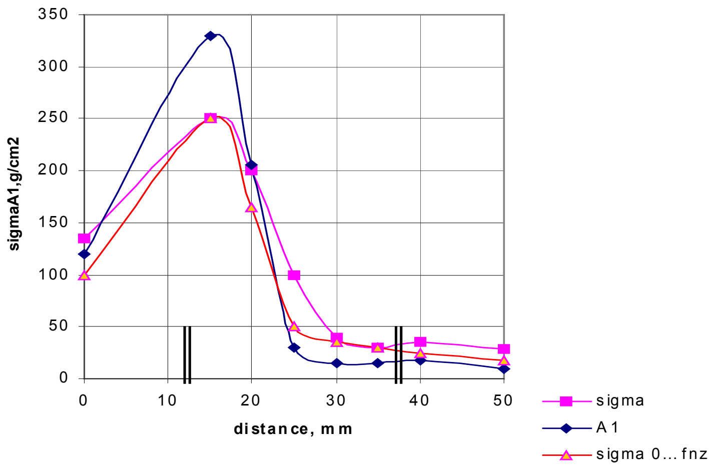

Figure 5 Variation of pressure RMS deviation along compressor flow path near stall in full frequency rang, at blade passing and in 0…fnz frequency band.

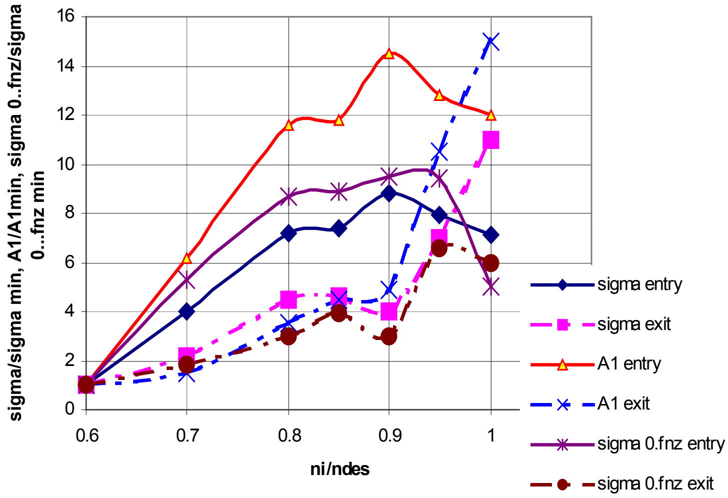

Figure 6 - Variation of flow pulsation at compressor entry and exit at optimal regimes at different rotation frequency

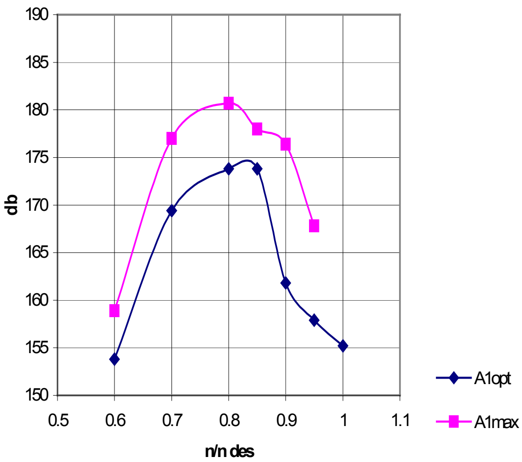

Figure 7 - Variation of rotor blade passing frequency harmonic at different rotation frequency at optimal points and near stall

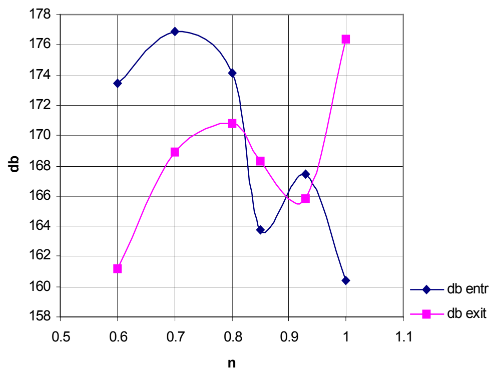

Figure 8 - Variation of pulsation intensity upstream and downstream of compressor at optimal range at different rotation frequency.