Interest in the problem of the instability of compressor blade oscillations generated by a gaseous medium arose in the mid-1970s. Since that time, there have been many publications describing the instability of high-pressure compressors if the rotational speed of the compressor grows. The majority of investigations have been devoted to the aerodynamic aspects of this problem, and only some have studied the compressor as an interdependent mechanical–aerodynamic system [1]. Thus in work [2], using the records of blades oscillations, and in work [3], using the records of blade oscillations and synchronous records of pressure pulsation in the countercurrent air flow, the problem of blade flutter (unstable collective oscillation) evolution if the rotational speed of turbojet engine’s compressor increases, is studied. The engine consists of a single-stage compressor, a combustion chamber and a turbine.

In the present work, the investigations started in [3] are continued. The records of blade oscillations and synchronous records of pressure pulsation in the air flow are used in order to identify the process of blade flutter occurring in the three-stage low-pressure compressor of a turbo-fan engine. This engine consists of a fan and axial low-pressure compressor (the cold part of the engine), an axial high-pressure compressor, a combustion chamber, and axial pressure turbine (the hot part of the engine). This engine is a version of a bypass engine with bypass ratio of \( m = 4.43 \). The form of the blades of the coaxial low-pressure compressor is similar to the form of the fan blades. This three-stage, low-pressure compressor (the fan) was tested independently under a constant value of engine rotational speed. The pressure was controlled with the help of the throttle. The records of the blade’s vibrations if compressor’s axial velocity drops are provided by CIAM (Baranov Central Institute of Aviation Motorbuilding).

Unstable oscillations of axial compressor blades and pressure pulsations in the air flow in the flutter evolution process. Figure 1a depicts (as an example) the strain gage record \( w = w(t) \) of oscillation for the blade of the third stage of the axial compressor, and Figure 1b depicts the synchronous record of pressure pulsations in the countercurrent air flow near the third stage of this compressor. The form of the records of blade vibration and pressure pulsations for the first and second stages of compressor are similar. But low-pressure stages and high-pressure stages of the compressor play different roles in the process of blades’ collective unstable oscillation generation. The evolution of the blades’ collective unstable oscillations is most appreciable in the third stage of the compressor (Fig. 1a). These processes relate to the blades’ eigenmodes instability. Primarily, the blades’ oscillations (Fig. 1a) are forced random oscillations caused by the aeroelastic forces of the air flow. The spectra of such forced blades’ oscillations are different and the blades’ fundamental frequency (bending frequency or torsion frequency) are apparent in it [4]. The random blade oscillations caused by aeroelastic forces can organize themselves into the blades’ collective mode, that is, the initial stage of flutter. In this case, the blades’ fundamental frequency is determined with a sufficiently high degree of accuracy in all records of blade oscillations. Similarly, several predominant fundamental frequencies of acoustic diametrical modes appear in the spectra of pressure pulsations in the air flow; this fact indirectly verifies that collective modes of blade oscillations arise [3].
In order to understand clearly how the oscillation process transforms into flutter, and due to the fact that frequency spectrum of the blades’ unstable oscillation is not informative, we suggest to use the changes in value and sign of damping at these frequencies. The spectral parameters of the blades’ oscillation records are determined by Prony Fast Transformation [5]. Let us give the brief formulation of spectral analysis according to the Prony method. The time series is written as follows

$$w[k] = w((k - 1)\Delta t), \quad k = [1:N],$$  \hspace{1cm} (1)

where $\Delta t$ is the time sampling interval, represents the time dependence of oscillation amplitude $w = w(t)$ for $t \in [1, t_N], t_N = N\Delta t$. Then, for short we select $\Delta t = 1$

Spectral Prony expansion of time series (1) has the following form

$$w[k] = \sum_{l=1}^{p} r_l(z_l)^{k-1} + n(k), \quad k = [1:N],$$  \hspace{1cm} (2)

where $p$ is the number of poles of the time series; $z_l = \exp(\delta_l + j2\pi f_l)$, $l = [1 : p]$ are the poles being determined on the basis of the time series (1); $\delta_l, f_l$ are damping and frequency, respectively; $r_l = A_l \exp(j\phi_l)$, $l = [1 : p]$ are the residues in these poles; $A_l$ and $\phi_l$ are the amplitude and phase, respectively; $n(k)$ is an additive noise caused by measurement inaccuracy and internal impact. After determination of the poles $z_l, l = [1 : p]$, the residues in these poles $r_l, l = [1 : p]$ can be determined by the least-squares method. The main advantages of Prony Fast Transformation are the possibilities of extraction of the main energetic components of oscillations, the reconstruction of the oscillation record according to its poles and residues by (2), and on this base the estimation of the accuracy of the spectral analysis. The estimation of the time dependence of discrete spectra of the decrements and frequencies $\{\delta_l, f_l, l = [1 : p]\}$, and the corresponding discrete spectra of amplitudes and phases $\{A_l, \phi_l, l = [1 : p]\}$ is done according to the total record of oscillation by sequential shifting of the time window with fixed length. We also present the basic results of the spectral analysis of transient oscillations of the blades' cascade and pressure pulsations in the air flow for the axial low-pressure compressor when flutter arises. The estimation of damping and frequency spectra, and the corresponding spectra of amplitudes and phases (all of them depend on time) for the total record of oscillation is calculated by sequential shifting of the time window with a fixed length $N\Delta t$. Under $t = 30$ s, the oscillation amplitude (Fig. 1) increases greatly. It makes it possible to determine the blade bending frequency $f_B = 532$ Hz. As in the liner model of compressor blade flutter [6, 7], the instability of oscillation of axial compressor blades is found according to a sudden change in the value and sign of damping corresponding to bending frequency $f_B$. The narrow band filtration at blade bending frequency $f_B = 532$ Hz precedes the procedure of the spectral analysis of oscillation record (Fig. 1a). With the help of Prony Fast Transformation, it is shown that the predominant frequencies of collective blade oscillation of the three-stage axial compressor reduce exactly to this frequency.

**The results of spectral analysis of unstable oscillations during blade flutter.** Spectral analysis of the transient process in the strain gage record of blade oscillation (Fig. 1a) shows how the unstable collective bending oscillations of the blades (bending flutter) arise. In spite of sufficient constructive differences between the single-stage compressor studied in works [2, 3], the examination of the axial low-pressure com-