METHOD OF PREDICTION OF DYNAMIC STABILITY OF GAS-TURBINE ENGINE BLADE ASSEMBLIES FOR SUBSONIC FLUTTER

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The analysis of defects in compressor rotor blades in the development and operation of aircraft gas-turbine engines implies the aerodynamic nature of rotor blade vibrations (in most cases). Flutter is a very dangerous phenomenon, that is why it is necessary to outline the conditions of its occurrence in engine development. This is especially true of modern engine compressor rotor blades with a high aspect ratio and integral joint connection with the blade wheel disk.

Despite many existing methods for determination of the conditions of flutter initiation, its prediction at the stage of engine design remains a topical issue.

This paper will focus on basic concepts of the express assessment of the dynamic stability limit of gas-turbine compressor blade assemblies to prevent subsonic flutter, as well as the examples of its application.

Keywords: blade assembly, subsonic flutter, dynamic stability limit, angle of attack

1. Introduction and Problem Statement

It is known that the main target in designing modern gas-turbine engines (GTE) is the assurance of vibration reliability of the blade assembly of rotor wheels. Experience in designing aircraft gas-turbine engines shows that more than half of the defects found during engine development tests have been caused by vibration. Among the most often encountered vibration-related problems are resonance vibrations of rotor blades and their flutter [1, 2].

Flutter is one of the most dangerous phenomena of aeroelasticity because it leads to a rapid increase of the amplitudes of blade vibrations, which can cause a fatigue crack propagation in the material with its eventual fracture [3]. This is especially true for currently available light-weight, largely extended blade structures, which is explained by designers’ desire to reduce both the axial dimension and specific weight of the engine.

Depending on the flow conditions of the blade assemblies of axial compressors different types of flutter are possible [4]. Subsonic (stall) flutter is the most common and dangerous one. It occurs, as a rule, under the conditions of the off-design behavior of the engine with the subsonic relative velocities of approach flow at both positive and negative attack angles [5].

What is now needed is the prediction of the critical conditions of flutter excitation. This is especially important at the design engine stage since the reliable prediction of flutter allows one to avoid significant material and time costs associated with the redesign, experimental verification, and development as a part of a full-size engine. In particular, such problems arose in the development of the F100 engine [6].
Thus, the aim of this paper is to present the basic tenets of the developed express assessment of the dynamic stability of GTE compressor blade assemblies for subsonic flutter and show its practical approval.

2. Object of Investigation and Its Modeling

An assembly of cantilever blades of GTE compressor is considered assuming their subsonic gas flow. A straight cascade of the blade airfoils is used to determine the aerodynamic loads acting on the blades and the characteristics of aerodynamic damping of their vibrations. Figure 1 illustrates the scheme of the straight cascade where \( b \) is the airfoil chord; \( i \) is the angle of attack; \( \beta \) is the stagger angle; \( t \) is the cascade spacing; \( V_1 \) is the velocity of the incident flow. The geometric characteristics of the airfoil cross section and conditions of its gas flow are in compliance with the chosen blade section.

![Figure 1: A schematic of a straight cascade of airfoils.](image)

The justification of using the straight cascade of blade airfoils as the test object is due to the following. From the analysis of numerous test data it is known that for the lower (i.e., the first flexural and torsional) vibration modes of blades, as the most dangerous in terms of their flutter occurrence, practically 80% of the work done by the flow falls at the blade tip section representing about 20% of its height, which, for the most part, predetermines the stability of the whole blade assembly [7]. Therefore, the critical parameters of the airfoil vibration corresponding to the selected blade tip section and defining the subsonic flutter stability of the airfoil cascade will also determine, with a great degree of probability, the blade assembly stability for the above modes of blade vibration.

3. Basic Tenets of the Express Assessment of Dynamic Stability of the Blade Assemblies for Subsonic Flutter

This method is based on the test results obtained at the G. S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine using the straight cascades of blade airfoils. The experimental investigations were aimed at the study of aerodynamic damping of vibrations of AGTE compressor blades and conditions of initiation of subsonic flutter within the wide range of variations of the determining characteristics: the phase shift angle of flexural, torsional and flexural-torsional vibrations of the adjacent airfoils; the attack angle \( i \); the reduced frequency of vibrations \( K = \omega b / V_1 \) (\( \omega \) is the angular vibration frequency); geometric parameters of the airfoil and cascade; law of motion of blade airfoils [8].

The dynamic stability limit of blade assemblies for subsonic flutter is the zero-equation of the aerodynamic decrement of vibrations, and it is characterized by the critical value \( K_{cr} \) of the reduced vibration frequency.
\( K_{cr} \) is determined from the calculation using the energy method [9] and eigenvalue method [10] by the results of the experimental determination of unsteady loads acting on the blade airfoils vibrating in a flow on the test rig [11].

The obtained results of experimental and calculation investigations made it possible to create a database of \( K_{cr} \) values of the reduced frequency of vibrations for different values of the relative blade spacing \( \overline{t} = t/b \), stagger angle \( \beta \), attack angle \( \alpha \), flexural-torsional coupling factor \( \psi = (a_1 - a_2) / (a_1 + a_2) \), where \( a_1 \) and \( a_2 \) are the amplitudes of the airfoil leading edge and trailing edge displacements, respectively.

The dynamic stability of the blade assembly against subsonic flutter is provided upon the fulfillment of the equation:

\[
K^b \geq K_{cr}.
\] (1)

The right-hand side of the equation can be determined using the obtained database of critical values \( K_{cr} \) of the reduced frequency of vibrations [12]. For this purpose, the standard equation is made:

\[
[K_{cr}] = [O][S],
\] (2)

where \([O] = \begin{bmatrix} o_{01} & o_{11} & \cdots & o_{G1} \\ o_{02} & o_{12} & \cdots & o_{G2} \\ \vdots & \vdots & \ddots & \vdots \\ o_{0g} & o_{1g} & \cdots & o_{Gg} \end{bmatrix} \); \([S] = \begin{bmatrix} s_0 \\ s_1 \\ \vdots \\ s_g \end{bmatrix} \); \([K_{cr}] = \begin{bmatrix} K_{cr1} \\ K_{cr2} \\ \vdots \\ K_{cr\sigma} \end{bmatrix} \),

here \([O]\) is the regression matrix; \( o_{g,\vartheta} \ (g = 0...G; \ \vartheta = 1...\sigma) \) are the regressors, \([S]\) is the column-vector \( G \) of the unknown regression factors \( s_{g} \); \([K_{cr}]\) is the column-vector plotted from the database \( \sigma \) of \( K_{cr} \) of the reduced frequency of blade vibrations.

From Eq. (2) the matrix equation is obtained to determine the column-vector \( G \) of the unknown regression factors:

\[
[S] = ([O^T][O])^{-1}[O^T][K_{cr}],
\] (3)

where \([O^T]\) is the transposed regression matrix.

Determination of the regression factors \( s_{g} \) allows one to derive the functional representing the influence of the angle of attack \( \alpha \) and geometric parameters of the cascade (stagger angle \( \beta \) and relative spacing \( t \)) at flexural and torsional vibrations of blades. More detailed information on the functional is presented in [8], while the equation of multiple regression is presented as:

\[
K_{cr} = s_0 + s_1^{(1)} o_1^{(1)} (\hat{x}_1) + s_1^{(2)} o_1^{(2)} (\hat{x}_1) + s_1^{(3)} o_1^{(3)} (\hat{x}_1) + s_1^{(4)} o_1^{(4)} (\hat{x}_1) + \cdots + s_\varphi^{(A_\varphi-1)} o_\varphi^{(A_\varphi-1)} (\hat{x}_\varphi) + P,
\] (4)

where \( s_1^{(1)} o_1^{(1)} (\hat{x}_1) + \cdots + s_1^{(4)} o_1^{(4)} (\hat{x}_1) \) are the polynomials of the first order in the variation of the cascade parameters and conditions of flow \( \hat{x}_\varphi \), \( s_\varphi^{(A_\varphi-1)} o_\varphi^{(A_\varphi-1)} (\hat{x}_\varphi) \) are the polynomials of the order \( (A_\varphi - 1) \); \( P \) is the notation of multiplication of functions \( o_{\hat{w}} \) by \( o_{\nu} \) where \( \hat{\nu} = 1, \ldots, \varphi, \ v = 1, \ldots, \zeta \), \( \hat{\nu} \neq \nu \).

4. Results of Method Verification

Let us consider the use case of the obtained equation of multiple regression. This equation lies at the heart of the developed method to assess the dynamic stability of the compressor blade assemblies for subsonic flutter using two GTE types.
Figure 2 illustrates the results of assessment of the dynamic stability of the first flexural mode of vibrations of the first stage of low-pressure axial compressor for various engine modes, which were obtained from the tests on straight cascades with the following values \(0.75 (\tilde{T} = 1.044; \beta = 48.1^\circ)\) and \(0.95 (\tilde{T} = 1.123; \beta = 52.7^\circ)\) of the height of the blade airfoil portion at \(\psi = 0.255\). Markers denote the values of the reduced frequency of vibrations of blades corresponding to the operation engine modes.

From the presented results it is evident that some operation engine modes, in particular case, those ones that correspond to ▲ and ■ are within the stability limit, or within the flutter zone. Here, in the process of bench testing of the considered compressor, the subsonic flutter of the given blade assembly was observed.

Later, the dynamic stability for the subsonic flutter of the blade assemblies of the stages of low- and high-pressure compressors was assessed. As in the previous case, tests were made on the straight cascades of the blade airfoils.

The results of the calculation, which are illustrated in Fig. 3, imply that the reduced frequencies of vibrations of the blade assemblies \(K_{B_{0.75}}\) and \(K_{B_{0.95}}\) of GTE for the considered modes of its operation exceed their corresponding critical values \(K_{cr_{0.75}}\) and \(K_{cr_{0.95}}\), which were determined by the developed method.

It is seen that, firstly, the values of \(K_{B}\) for the selected sections of the blade airfoil coincide practically, which allows one to assess the stability of blade assemblies by the gas-dynamic flow parameters for arbitrary blade tip sections of blades in the range 0.75 – 0.95 of the height of the blade airfoil portion. Secondly, the selected blade assemblies are stable for subsonic flutter for the considered modes of GTE operation.

![Figure 2: Dependencies of critical values \(K_{cr}\) of the reduced frequency of the airfoil vibrations, which correspond to the section 0.75 (solid line) and 0.95 (dashed line) of the height of the blade airfoil portion, on the attack angle for the first flexural mode of their vibrations of the first stage of the low-pressure compressor. Markers are the values of the reduced frequency of vibrations \(K_{B}\) for the operation engine modes.](image-url)
5. Conclusions

1. The method for prediction of the dynamic stability for subsonic flutter of GTE compressor blade assemblies was developed. It makes it possible to select the values of reduced frequency of vibrations and attack angle of the approach flow for the specified geometry of blade tip sections at the design stage.

2. The proposed method for prediction of the dynamic stability to prevent subsonic flutter was validated using the analysis of two types of GTE blades as an example.

REFERENCES


