The influence of design parameters on the blade flutter boundaries

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Abstract. Blade flutter is one of the major problems that designers of modern gas-turbine engines face. In this paper, a study of the influence of the design parameters on prediction of blade flutter in compressors of gas-turbine engines is presented. As a rule, the flutter of compressor blades is predicted using simplified criteria based on the experience of designing and refining engines. These empirical and probabilistic criteria are not applicable to evaluation of the flutter since the parameters in question are not among the decisive parameters for simplified criteria. In this work, the energy method is used. It is shown that the inter-blade tension value has a significant influence on the blade flutter prediction, while the effect of other design parameters under investigation on the blade flutter prediction is insignificant.

1. Introduction
Blade flutter can be defined as an unstable and self-excited vibration of blade in airstream [1]. The danger of flutter lies in the rapid increase in stresses in the blades, which can lead to their breakdown and further damage to the entire engine. Thus, the blade flutter prediction at the design stage is one of the main issues for engine designers.

Basically, there are four methods for flutter prediction [1, 2]. When designing engines, engineers and designers use, as a rule, empirical [2, 3] and statistical methods [4], based on the experience gained from design organizations in designing and refining engines and processing of a great number of tests and the prediction of the blade flutter of new compressors. Another method for prediction of the blade flutter is the frequency-response method [5–9] based on calculation of natural frequencies of a coupled flow–blade system. Under this approach, the positivity of the imaginary components of the natural frequency is a criterion of the flutter onset. However, the associated problem of finding complex eigenvalues of nonsymmetric matrices requires great computational resources. The essence of the direct method [10, 11] is the modelling of the movement over time of a coupled blade–flow system. The numerical calculations, however, require considerable computational resources. In [12, 13], an energy method is used; the method is based on calculation of the work performed by aerodynamic forces on the surface of a blade that oscillates harmonically in its natural mode over an oscillation period.

In this article, the effect of the design parameters, viz., the radial clearance, the closing and opening angles of the inlet guide vanes, the radial flow nonuniformity, and the magnitude of the inter-blade tension in shrouds, on the results of the blade flutter prediction is studied numerically. Simplified criteria are not applicable to evaluation of the effect of the above factors on flutter prediction since the design
parameters do not play a decisive role in such criteria. In this work, the energy method [14] is used. The method is applicable if the oscillation modes in vacuum are close to the corresponding modes in a flow.

2. Method for blade flutter prediction

We assume that the influence of the airflow on the blades’ natural oscillations is insignificant. Then, the airflow may cause only additional damping (stability) or strengthen in (flutter) without changing the natural modes and frequencies compared with oscillations in a vacuum. The change in the total energy over one oscillation period has the form

$$ W = \int_{t_0}^{t_0+T} \int_S p(x,y,z,t)n(x,y,z,t)v(x,y,z,t)dSdt $$

where $T$ is the oscillation period of the blade, $S$ is the blade surface, $p$ is the pressure, $n$ is the normal to the blade surface, and $v$ is the velocity of the blade points. We neglect the viscous stresses in the air, as they do not usually influence the flutter boundaries.

If the work $W$ is positive, in each period of oscillation, the energy is boosted from the flow to the blade and its amplitude is increased. If the work is negative, in each period of oscillation, part of the energy of the blade is dissipated in the flow. As a consequence, the sign of $W$ is the flutter criterion.

3. Results

The influence of the design parameters (radial clearance magnitude, the closing and opening angles of the inlet guide vanes, the radial flow nonuniformity and magnitude of inter-blade tension) on the prediction of flutter was investigated for the first-stage wheel of a low-pressure compressor. An wheel with shrouded blades was considered. Calculations were made under two design conditions when, during the tests of the engine, flutter was diagnosed (flow regime 1) or its absence was recorded (flow regime 2).

3.1. Natural mode shapes and frequencies

The natural oscillation frequencies and modes of the disk–blades–shroud system were calculated in two simulation series. In first, Flow regime 1 and flow regime 2 were considered. The calculations accounted
for the overlapping of the shrouds of unstrained blades by 0.54 mm. The second and third families of the oscillation modes of the disk–blades–shroud system induced by the interference of the modes and the proneness of the latter to flutter were considered. In second, the natural oscillation frequencies and modes were calculated at different inter-blade tension values.

The interference diagram (Fig. 2) one can see that for the second and third modes, a decrease in the natural frequencies is observed with increasing inter-blade tension. We should note that the frequencies of the second oscillation mode family are practically indiscernible in the absence of tension and at an inter-blade tension caused by the overlapping of the blades by 0.27 mm.

![Figure 2. Interference diagram at different inter-blade tension values under regime 1: (curve 1, solid line) 0 (no tension); (curve 2, dashed line) 0.27 mm; (curve 3, dash-dotted line) 0.54 mm; and (curve 4, dotted line) 0.8 mm. (a) The second family oscillation modes and (b) the third-family oscillation modes.](image)

### 3.2. Flutter results

The work of the pressure forces was calculated for various design parameters. For every natural oscillation mode family the full range of the number of the nodal diameters was considered. A series of computational models, representing the change of one of the design parameters, was considered. The following configurations were studied:

1. Increased radial clearance by 0.5 mm
2. Increased radial clearance by 0.5 mm and shut by 1.5° inlet guide vane
3. Increased radial clearance by 0.5 mm and opened by 2° inlet guide vane
4. Increased radial clearance by 1 mm
5. Specified radial non-uniformity of the flow at the inlet

Calculation results for flow regime 1 that flutter is observed in all cases at the second-family oscillation modes at m = 5. At other values of the nodal diameters at the second-family oscillation modes, the work of the pressure forces is negative. At the third-family oscillation modes, the work is negative with all nodal diameters. At flow regime 2, the work of the pressure proved to be negative at the second- and third-family modes in all configurations. The data provided show that the calculated results differ insignificantly at different design and aerodynamic parameters.

![Figure 3. Work done by unsteady pressure vs nodal diameter. Mode 2 (a), 3 (b).](image)
A special series of calculations was conducted to establish the influence of the inter-blade tension. As a result, it was obtained that the work value at each nodal diameter differs greatly at different inter-blade tension value.

4. Conclusion
Investigation of blade flutter at various design and aerodynamic parameters of the stage were conducted with using energy method.

Comparison of calculation results with flutter test data shows a good agreement for both flow regimes. It was shown that the inter-blade tension had a considerable effect on the flutter boundaries owing to the change in the oscillation modes of the blades. And results for over parameters in question, viz., the radial clearance magnitude, the closing and opening angles of the inlet guide vanes, and the radial flow nonuniformity differed insignificantly within the range of changes under investigation. The above parameters almost did not affect the flutter boundaries.

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