SIMULATION OF TURBOMACHINE BLADE BENDING-TORSION FLUTTER USING A PRETWISTED BEAM FINITE ELEMENT

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Abstract

A review of turbomachine blade flutter is given, highlighting the importance of coupled bending-torsion blade flutter. A pretwisted beam finite element blade model for coupled fluid-structure stand-alone blade dynamics assessment is introduced. Stability analysis of a typical last-stage power generation turbine blade under non-stationary gas loading is conducted and its dynamic bifurcation mechanism is investigated.

Keywords

Turbomachine, blade, flutter, Hopf bifurcation.

1 Introduction

Compressor and turbine blading vibrations are among the most topical issues that can be encountered during the design of transport and stationary gas and steam turbine engines. Foershing [Foershing, 1994] defines flutter of blades in axial turbomachines as an aerodynamic instability caused by an interaction between the vibratory motions of an assembly of blades and the fluid dynamic forces resulting from these motions. A similar definition is given by Marshall and Imregun [Marshall, Imregun, 1996]: flutter is defined as an unstable and self-excited vibration of a body in an airsteam, resulting in continuous interaction between the fluid and the structure. Despite the significant efforts, aimed at turbomachine blade flutter issues solving, these issues continue to be urgent for several decades. This is caused by constant strengthening of the requirements imposed on modern gas turbine engine components, which make them more and more vulnerable to flutter. First of all, flutter issues affect axial compressors. According to Olshtain [Olshtain, 1976], one of the methods to reduce dimensions and mass of a turbomachine is to apply high length-to-chord ratio blade designs. This leads to appearance of low-engine order excitation frequencies within the operating range and increase of flutter initiation probability [Olshtain, 1976]. According to Doi [Doi, 2002], as a result of high compressor efficiency pursuit the operational line can cross flutter boundaries at startup and shutdown. Finally, according to [Thermann, Niehuis, 2005], today due to constant tendency to reduce mass of the components and implement higher pressure ratios in compressor design, first stages of compressors continue to be highly vulnerable to flutter. Fan flutter probability growth is partly caused by promotion of wide-chord, twisted and tilted blades for noise reduction. Similar to compressors, turbine blades can also get into flutter conditions, despite the fact that turbine blade flutter was encountered relatively recently compared to compressor blade flutter. One of the first publications on this topic, known to the authors, deals with cooled high-pressure turbine blade of the Space Shuttle [Smith 1990] engine. The author of the review [Verdon 1993] predicts the possibility of aeroengine turbine blade flutter due to the increase of flow velocities. Siemens Power Generation [Montgomery et all., 2005] and ALSTOM Power [McBean et all., 2005] representatives claim that flutter threat is typical for last stages of high-power stationary turbine units.

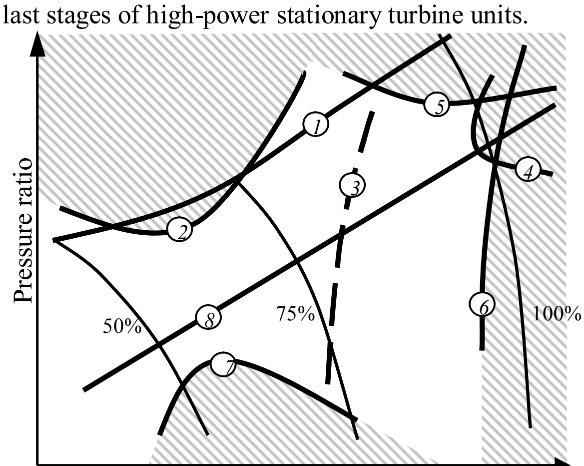

Fig.1 Compressor map [4,10,16]

Concluding, one can note that flutter issues are more or less typical for all blading of stationary and transport gas turbines. The importance of these issues increases with the growth of requirements to new hardware and modern blade designs.

In this study flutter types classification is considered in relation to the compressor map, which is a diagram in coordinates “mass flow” – “pressure ratio”. Each point on such a diagram defines a unique compressor operation regime, defined by flow velocity and blade stagger angles. Flutter boundary separates the domain of stable operation from the domain characterized by vibration growth. Different types of compressor flutter are shown on fig.1; where 1 is the surge line; 2 – subsonic stalled flutter boundary; 3 – bending-torsion flutter boundary; 4 – supersonic unstalled shock wave flutter boundary; 5 – supersonic stalled flutter boundary; 6 – supersonic unstalled flutter boundary; 7 – choke flutter boundary; 8 – operating line. Detailed description of flutter types and compressor map characteristics can be found in [Doi 2002], [Bendiksen and Freidmann, 1980]. Unfortunately, the authors of the present paper are not aware of the existence of similar maps for turbines except the maps delivered by RPMTurbo [Petrie-Repar et all., 2006]. One must note, that among all the different flutter events, shown on fig.1, only two types of flutter may initiate if the engine runs along the operational line. During supersonic unstalled flutter, blades receive energy from the unsteady flow and vibrate in their natural bending or torsion modes, almost unchanged compared to steady loading conditions. The second type of flutter that initiates at design conditions is coupled bending-torsion flutter [Bendiksen and Freidmann, 1980, Bendiksen, 1988, Khorikov, 1974, 1976]. The other flutter types are referred to off-design conditions and are out of scope of this study. Supersonic unstalled flutter today is the most-investigated aerodynamic instability; its assessment, based on either empirical of analytical tools is a part of standard blade design process [Montgomery, et all. 2006, Shrinivasan, 1997], so it is beyond the scope of this study as well.

The possibility of coupled bending-torsion flutter initiation is shown independently by [Bendiksen et all, 1980, 1988] and [Khorikov, 1974, 1976]. This type of self-excited aeroelastic vibrations differs from the other types, because it is mainly influenced by the proximity of natural frequencies and mode shapes of the vibrating blade. In a certain conditions, coupled bending-torsion flutter can initiate at almost every stage of a gas turbine engine; its mechanism is very close to “classic” bending-torsion flutter of airplane wing, which is characterized by closure and interaction of bending and torsion vibration frequencies, which leads to instability [Den Hartog, 1956].

Some experts believe that there exist significant hurdles, preventing the initiation of bending-torsion flutter of blades.

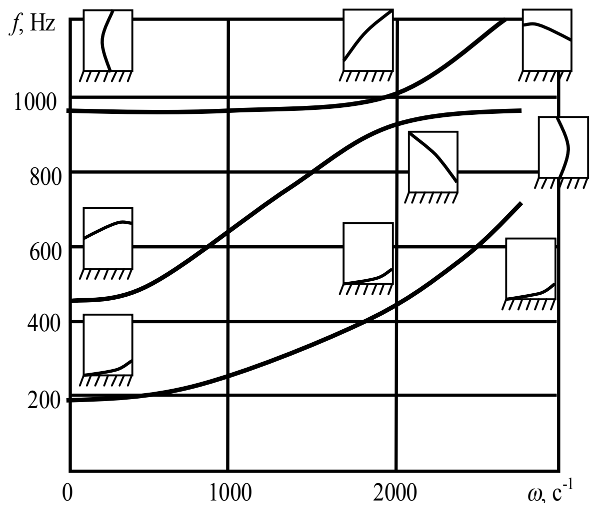

Fig.2 Changing of blade vibration mode shapes and frequencies under centrifugal load [14].

According to [Forsching, 1994], the issue of turbomachine blade flutter is different from wing flutter, because the mass ratio (ratio of the blade mass and the mass of the attached gas) for solid titanium or steel turbomachine blade is generally much higher than that of a lightweight aircraft wing and both blade vibration frequency and the corresponding mode shape remain almost independent of gas loads. The author of [Forsching, 1994] concludes that aeroelatic bending-torsion coalescence flutter coupling between two modes, typical for classical aircraft wing flutter, is less important in turbomachine blades.

Despite these obviously correct reasons, “classic” bending-torsion flutter of turbomachine blades can initiate. First of all, the reasoning regarding high blade mass ratio is incorrect if applied to composite and hollow blades of modern fans. Moreover, there exists one more mechanism besides gas loading that can bring blade frequencies together. Fig.2, taken from [Khorikov, 1974], shows the change of spectrum and mode shapes of a blade with rotation speed change (Campbell diagram). Along with rotation speed dependence of blade’s frequencies it shows schematic mode shapes of blade airfoil (rectangles with nodal lines) at different rotation speeds. It is widely known, that under centrifugal loading bending frequencies increase, while torsion modes remain almost unaffected; this behavior continues until bending and torsion frequencies coalesce [Khorikov, 1974]. Interaction of the 2nd bending and the 1st torsion frequencies is shown on fig.2. This example shows that under some conditions bending and torsion frequencies of the blade, separated without loading, may come together and interact.

Papers [Khorikov, 1974, 1976] prove, that taking into account interaction of modes due to blade rotation the work of aerodynamic forces over the blade can become positive, passing the energy to the blade. Based on [Khorikov, 1974, 1976] the review paper [Olshtain, 1976] concludes, that frequency separation should be used as a rule during blade design process. Independently, [Bendiksen, 1980] concludes, that the effect of bending-torsion interaction significantly changes the boundary of dynamic stability of a cascade. [Bendiksen, 1988] also states, that there exist experimental evidences of flutter for fans, which had close bending and torsion modes.

Therefore, coupled bending-torsion flutter is also a topical issue despite the relatively insufficient coverage in literature, and will be studied in detail in this paper.

2 Blade model

In the present work, pretwisted beam finite elements are used to build the model of the blade. Today three-dimensional solid or shell finite element models are most widely used for the assessment of dynamics of gas turbine blades and vanes. Taking into account the contemporary level of computational means, time expenses for a single calculation using these models are comparable to the time required for pre-processing, and, therefore, these expenses are admissible. However, if large series of similar calculations are conducted (e.g. dynamics tuning of a newly designed turbomachime blades), the situation is quite different. In this case to consider a variety of design cases, high-speed but accurate computational methods are required.

These demands are met by pretwisted beam blade model. The fullest review of beam theory development for turbomachine applications is given in the study [Vorobiev, Shorr, 1983], the pretwisted blade FE model development - in [Temis et. all, 2001, 2007]. FE model, developed in [Temis et. all, 2001, 2007], forms the basis for this analysis. It is a nonlinear model, that takes into account nonlinear elastic deformation of the blade under applied loads and change of centrifugal load value with elongation of the blade.

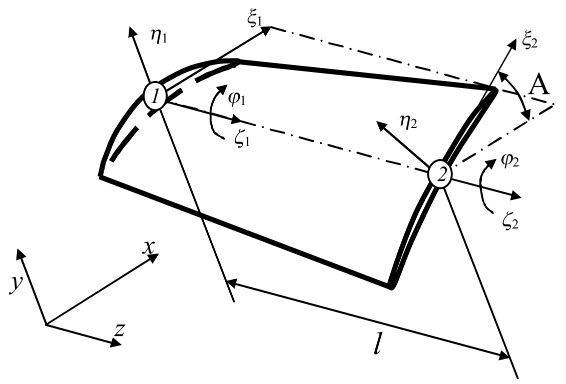

Fig.3 Pretwisted beam finite element

Pretwisted beam finite element, having 2 nodes is shown on fig.3. Its main characteristics are length l, cross-section area S, pretwist per unit length $\alpha = \mathrm{A}/l$, central axial moments of inertia J_ξ, J_η, centrifugal moment of inertia $J_{\xi\eta}$, polar moment of inertia J_p, polar-axial moments $J_{p\xi}$, $J_{p\eta}$, second polar moment of inertia J_r and a characteristic of a torsional stiffness J_k etc. [Temis et all, 2001, 2007] The center of gravity and shear center in this paper, unlike [Temis and Karaban, 2001] are not assumed to coincide [Montoya 1966, Avramov et. all, 2008]. In the present work, the usage of pretwisted beam finite element, besides swiftness of the assessment, also allows to use the analogy between dynamic analysis of a beam model of pretwisted blade and a beam under follower force loading [Bolotin, 1963].

The equation of small vibrations of the rotating blade about the equilibrium in finite element form [Bathe, 1996] can be expressed as

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F_{aero}(x, \dot{x})\,. \qquad (1)$$

Here $[M]$ is the mass matrix; $[C]$ is damping matrix. $[K]$ is the blade's stiffness matrix that includes prestress effects from centrifugal loads and constant gas loading. These prestress effects are calculated as a result of nonlinear elastic analysis of rotating blade [Temis et. all, 2001, 2007].

$$F_{aero}(x,\dot{x}) = \begin{bmatrix} F_\xi(x,\dot{x}) \\ F_\eta(x,\dot{x}) \\ F_\varphi(x,\dot{x}) \end{bmatrix} \qquad (2)$$

is vector of nonstationary aerodynamic loads caused by blade vibration, depending on both displacements and velocities of the solid body; $x(t)$ - vector of nodal displacement, which has 6 components in case of pretwisted beam.

Similar to the case of wing flutter [Den Hartog, 1956, Bolotin, 1963], the expression to the right can be linearized with respect to both arguments:

$$[M]\ddot{x} + ([C] + [C_A])\dot{x} + ([K] + [K_A])x = 0\,, \qquad (3)$$

$[C_A]$ and $[K_A]$ are matrices of aerodynamic damping and stiffness. Since we are interested in vibratory motions,

$$x = Xe^{-i\omega t}\,, \qquad (4)$$

where ω is vibration frequency. Substituting the expression into the dynamics equation, we come to generalized eigenvalue problem:

$$\{\omega^2[M] + \omega([C] + [C_A]) + ([K] + [K_A])\}X = 0\,. \qquad (5)$$

If

$$\omega = a + ib\,. \qquad (6)$$

where a,b are real numbers, and b>0, then the vibrations are unstable and flutter initiates. While the generalized eigenvalue system can be solved directly, the authors of [Bendiksen 1980, Khorikov 1974] make further simplification, neglecting the dependence of the nonstationary gas loads on the speed of solid body vibratory motion. In (3) the dependence of gas loads on blade's speeds is described by term $[C_A]$. This simplification comes from the difference in such speeds for airplane wing and aeroengine blades. For example, in the simplest case of airplane wing gas loads are expressed as

$$L = \pi\rho V^2 c\left(\theta - \frac{\dot{x}}{V}\right), \quad (7)$$

where V is the flow speed, ρ is gas density, c is airfoil chord length, θ - angle of attack of the airfoil, $\dot{x}$ - speed of the airfoil motion in direction, transverse to the flow speed. For typical turbomachine blades rotation angles (θ) significantly surpass the ratio of blade linear speed and the flow velocity, and from this point of view the second component, representing the aerodynamic damping, can be omitted. However, the possibility of blade destabilization by small damping cannot be excluded [Bolotin, 1963] and will be checked in further studies.

In this study mechanical damping component $[C]$ is neglected as well; outer damping, such as damping of the gas flow and damping in blade fixation usually [Bolotin, 1963] provides stabilizing effect on vibrations of the blade, therefore the stability assessment results, obtained in absence of outer damping are conservative. Inner damping, such as blade material damping, can cause destabilization (Ziegler's pendulum paradox, [Bolotin, 1963]), but in this case destabilization is a prolonged dynamic process, while immediate stability loss load can be determined without taking into account inner damping [Ryu, Sugiyama, 2003]. Denoting $\omega^2 = \lambda$, we get standard eigenvalue problem, the solution of which gives us the natural frequencies and mode shapes of blade vibrations in presence of gas flow:

$$\{\lambda[M] + ([K] + [K_A])\}X = 0. \quad (8)$$

In a local coordinate system, attached to each blade section, the aerodynamic stiffness matrix has the form

$$\begin{bmatrix} K_{\xi\xi} & K_{\xi\eta} & K_{\xi\varphi} \\ K_{\eta\xi} & K_{\eta\eta} & K_{\eta\varphi} \\ K_{\varphi\xi} & K_{\varphi\eta} & K_{\varphi\varphi} \end{bmatrix}, \text{ where} \quad (9)$$

$$K_{\xi\xi} = \frac{F_\xi(\Delta\xi,0,0) - F_\xi(0,0,0)}{\Delta\xi}, \quad (10)$$

$$K_{\xi\eta} = \frac{F_\xi(0,\Delta\eta,0) - F_g(0,0,0)}{\Delta\eta} \text{ etc.} \quad (11)$$

$$\Delta\xi, \Delta\eta, \Delta\varphi \to 0.$$

In the present study the values of aerodynamic load were obtained on the basis of the following approach: for 5 sections of the blade, a 2D fluid dynamics analysis was performed using the CFD tool FLUENT 6.2.16, Navier-Stokes, standard k-ω turbulence model. A steady-state response was obtained for both nominal blade position and small (~1% of chord length) blade deflection in each principal direction $\Delta\xi, \Delta\eta, \Delta\varphi$. Then the aerodynamic stiffness matrix coefficients were calculated and used as constants in eigenvalue analysis. This approach is valid if blade vibration reduced frequency is small (quasi-static process, $k = c\omega/V \ll 1$). One must also mention, that aerodynamic stiffness matrix, determined in a manner described above, implicitly depends on flow parameters, such as flow speed V. This allows to find the dependence of aerodynamic load matrix on flow parameters.

3 Flutter analysis

Bending-torsion flutter initiation assessment was conducted a prototype of a last stage turbine blade, designed for a heavy-duty power generation gas turbine. Fig.4 presents a Campbell diagram of this blade, obtained by FE analysis without taking into account nonstationary gas loads caused by blade vibrations. The essential feature is that this analysis was conducted using the developed pretwisted beam finite element. One can see that in the speed range 90-105% of nominal speed interaction and mutual change of the 2nd bending (2B) and 1st torsion (1T) modes takes place. At 97% speed the separation of the modes does not exceed 5%, making the blade vulnerable to bending-torsion flutter.

To obtain the response of the structure to flow speed V aerodynamic stiffness matrix was linearized with respect to V^2 in the vicinity of 0.97 of nominal flow speed. Then, eigenvalue response (8) to the flow speed increase (linear amplification of $[K_A]/V^2$) was calculated up to 140% of nominal flow speed V_{nom}^2 (fig.5). The other matrices in (8) were kept unchanged.

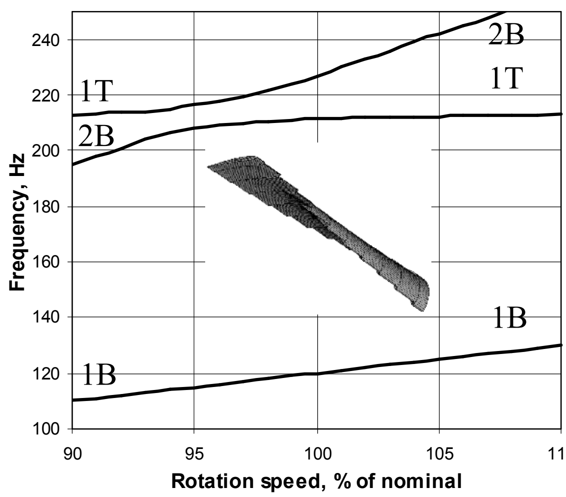

Fig. 4 Turbine blade beam model and frequencies under stationary load

As it follows from fig.5, at approximately $1.3V_{nom}^2$ the branches of the 2nd and 3rd eigenvalues come together, producing a pair of complex-conjugate eigenvalues (typically as shown, e.g., by [Ryu, Sugiyama, 2003])

$$\lambda = \gamma \pm i\delta ; \gamma, \delta > 0. \qquad (12)$$

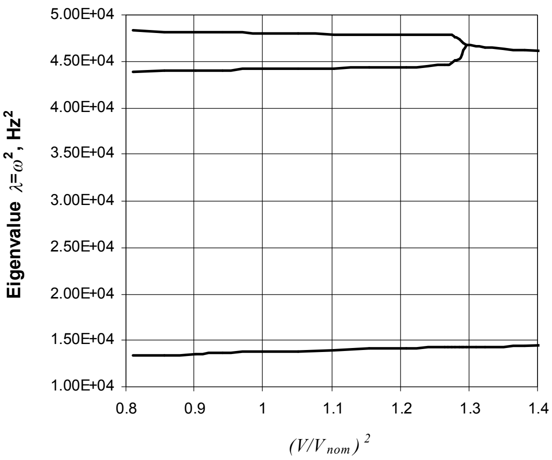

Fig.5 Bending-torsion flutter initiation

This means, that at $1.3V_{nom}^2$ there exists a natural frequency of the blade that has the form (6) with b>0, unstable mode of vibration. This type of stability loss is similar to dynamic instability of a clamped beam under follower force loading [Bolotin, 1963, Ryu, Sugiyama, 2003]

We have shown that coupled bending-torsion flutter can initiate for a blade with coalescing 2nd bending and 1st torsion modes, and the mechanism of flutter in absence of mechanical and aerodynamic damping is the dynamic bifurcation similar to follower-force loaded beam [Bolotin, 1963] or brake squeal [Flint, 2002].

4 Conclusions

A review of turbomachine blade flutter assessment was given, the actuality of this issue was highlighted and it was shown that coupled bending-torsion flutter is also topical despite the relatively insufficient coverage in literature. A pretwisted beam finite element blade model for coupled fluid-structure stand-alone blade dynamics assessment was successfully introduced. Stability analysis of a typical last-stage turbine blade under gas loading was conducted and its stability boundaries were defined. It was shown, that stability loss, similar to dynamic instability of a beam under follower force loading, is also possible for a turbine blade with coalescing torsional and bending frequencies.

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