Problem 1: Blade flutter prediction in jet engine compressors

M.E. Kolotnikov[1], *P.V. Makarov*[2], *V.V. Vedeneev*[3]

The development of modern and efficient aircraft engine compressors with increased pressure ratio and reduced weight has led to flutter problem of highly loaded stages. Blade flutter is caused by interaction between the motion of the blades and the unsteady aerodynamic forces. These aerodynamic forces can either damp or excite the motion. Flutter and limit cycle oscillations could induce extensive damage to the engine with catastrophic consequences to the aircraft.

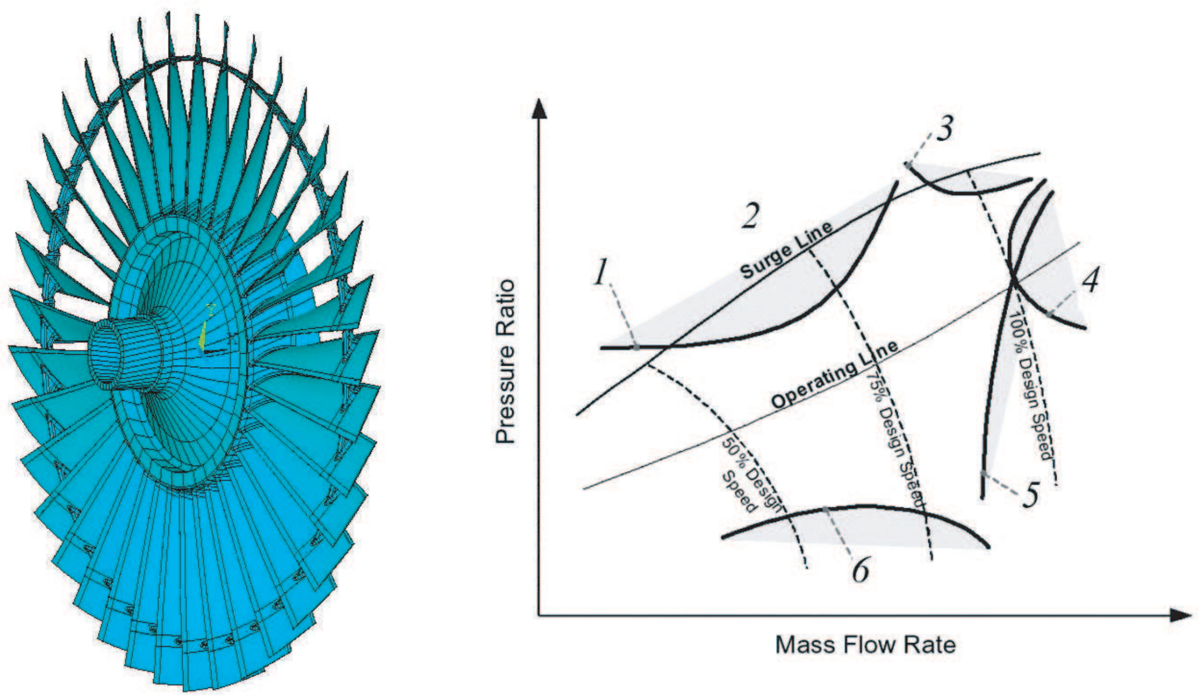

Figure 1: Compressor regime diagram. 1: subsonic stall flutter, 2: surge line, 3: supersonic stall flutter, 4 and 5: supersonic unstalled flutter, 6: choke flutter.

Due to the close interaction between performance and structural integrity, designers of jet engines must place great importance on aeroelastic effects to optimize a given design. Moreover, designers must pursue higher engine performance by reducing the blade thickness and weight, which has a negative impact on the aeroelastic behavior of the blades. In consequence of the

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[1] Chief Designer, Gas Turbine Engineering Research and Production Center "Salut", kolotnikov@salut.ru

[2] Head of Stress Department, Gas Turbine Engineering Research and Production Center "Salut", kbpr@salut.ru

[3] Associate Professor, Department of Hydromechanics, Lomonosov Moscow State University, vasily@vedeneev.ru

pursuit of high performance, the dynamic operating line during transients such as accelerations and decelerations, may intersect the flutter boundaries in the characteristic map represented in Figure 1. This figure shows the overall characteristics of a complete multi-stage compressor made up of a number of sequential stages. The flutter behavior depends on the point of operation on the characteristic compressor map. Common types of flutter have been designated as unstalled supersonic flutter, subsonic/transonic stalled flutter, supersonic stalled flutter, and choke flutter. It is necessary to note that supersonic flutter can occur on the operating line in Figure 1 on which the engine is designed to operate; the other types of flutter occur at off-design conditions despite being inside the surge line.

Prediction of compressor blade flutter in modern engines at the design stage of engine development is an extremely difficult and challenging problem. In gasturbine engine industry, typical method of blade flutter prediction is a semi-empirical method based on statistics generated using previous experimental flutter studies. Large volume of test data collected guarantees high quality prediction for the blade types used in this statistical data. However, flutter of new blade types, for example shroudless wide chord blades, steam turbine blades, and blades having new sophisticated shapes, etc, cannot be studied due to lack of appropriate experimental statistics. Therefore, new methods of flutter prediction based on numerical simulation must be developed.

One of the possible methods for aeroelastic stability analysis is energy balance method. However, so far it has not been developed and implemented in gasturbine engine industry due to great problems in airflow-blade interaction analysis. According to this approach, one considers natural blade mode

$$\vec{u}(x,y,z,t) = \vec{U}(x,y,z)\sin(\omega t), \tag{1}$$

where u is the blade surface deflection, and calculates aerodynamics damping of this mode. Conducting unsteady aerodynamic analysis in the blade passage with blades oscillating according to (1), one obtains unsteady air pressure $p(x,y,z,t)$ and calculates work during one blade oscillation period

$$A = \int\limits_{t_0}^{t_0+T} \int\limits_{S} \vec{p}(x,y,z,t) \cdot \vec{v}(x,y,z,t)\,ds\,dt \tag{2}$$

Here $T = 2\pi/\omega$ is oscillation period, S is the blade surface, $\vec{v} = \partial\vec{u}/\partial t$ is velocity of the blade surface. Sign of A is flutter criterion: the blade is stable if $A > 0$ and unstable otherwise. In terms of aerodynamic damping $\delta = -A$, flutter occurs if the damping is negative.

Unsteady flow analysis based on solution of Navier-Stokes equations, and subsequent calculation of aerodynamic damping works perfectly for unstalled flutter calculations (curves 4 and 5 in Fig. 1). However, more typical flutter types are subsonic and supersonic stall flutter (curves 1 and 3 in Fig. 1). During stall flutter vibrations, each blade motion is accompanied by flow detaching and re-attaching. Such processes are extremely difficult for simulation in commonly used CFD codes (Ansys CFX, Fluent, Star-CD, etc). First, detached flow is extremely unsteady. Second, detaching and re-attaching of the flow are bifurcation points of the flow type. Correct simulation of such a flows requires extremely small step time, and consequently extremely powerful computer resources. That is why deeper understanding and new modelling techniques of stall flutter are welcome.

Another problem is calculation of limit cycle amplitude of flutter oscillations and estimation of probability of blade fatigue failure.

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