BLADED DISKS: FLUTTER

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1. Introduction

Flutter is a serious design concern for turbomachinery blades, especially those in fans, the front stages of a compressor, and low pressure turbines. Both preliminary and detailed design methods are currently used in industry. Preliminary design methods typically consist of empirical approaches or empirical approaches augmented with CFD results (usually 2D). Traditional aeroelastic parameters such as reduced frequency, Mach number, and incidence are used Three dimensional CFD approaches are almost always used for detailed design. This lecture begins with an examination of the equations controlling flutter and a discussion of the types of flutter. This is followed with descriptions of flutter design methods for fans and compressor blades. Finally, flutter methods for low pressure turbine blades are presented.

2. Controlling Equations

Consider the single DOF torsional oscillator (e.g. an airfoil) excited by an aerodynamic moment (Figure 1).

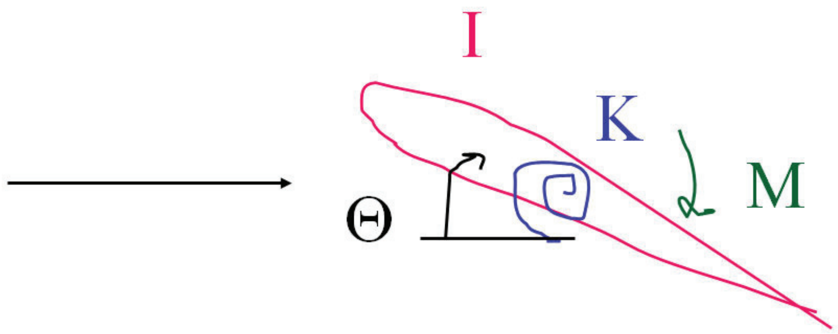

Figure 1, Single Degree of Freedom Airfoil

The well known equations controlling the motion are:

$$I\ddot{\Theta} + K\Theta = M$$
$$M = -A_I\ddot{\Theta} - A_D\dot{\Theta} - A_K\Theta + A_G\sin(\omega_f t)$$
$$(I + A_I)\ddot{\Theta} + A_D\dot{\Theta} + (K + A_K)\Theta = A_G\sin(\omega_f t)$$

The “structural” properties are defined by the torsional stiffness, K, and the rotational inertia, I.

In this case the structural damping is assumed to be zero. The aerodynamic moment contains motion dependent terms and terms which are independent of motion, which are commonly called the "gust" terms. In many aeroelastic problems, especially for turbomachinery blading, the aerodynamic inertia is much smaller than the structural inertia and the aerodynamic stiffness is much smaller than the structural stiffness. The result is that the aerodynamic forces have very little effect on the natural frequency (also the mode shape for multi-DOF systems). On the contrary the structural damping is commonly very small (in this example 0) and the aerodynamic damping term, A_D, can be dominant. The simple solution to this equation contains the homogeneous solution (flutter problem) and the particular solution (forced response problem).

$$\Theta = R_H e^{-Dt} \sin(\omega_D t + \phi_H) + R_P \sin(\omega_f t + \phi_P)$$

$$D = \frac{A_D}{(I + A_I)}$$

$$R_P = \frac{A_G}{\sqrt{\left[K + A_K - (I + A_I)\omega_f^2\right]^2 + \left(A_D \omega_f\right)^2}}$$

Of course, the homogeneous solution must have a decaying behavior (stable) for the particular solution to have a practical meaning. For the homogeneous solution to be stable the aerodynamic damping, A_D, must be positive. Thus, the primary goal in a flutter analysis is to determine the sign of the aerodynamic damping. If this system is stable, one can then proceed to calculate the forced response.

Next consider the flutter solution for the case of harmonic motion.

$$\Theta = x e^{-i\omega t}$$

$$\mathrm{M} = x\left[\left(A_I \omega^2 - A_K\right) + A_D \omega i\right]$$

$$-\omega^2 I x + K x = x\left[\left(A_I \omega^2 - A_K\right) + A_D \omega i\right]$$

$$a(\omega) = \frac{1}{I}\left(A_I \omega^2 - A_K\right) + A_D \omega i$$

$$\omega_n^{\ 2} = \frac{K}{I}$$

$$\omega^2 = \omega_n^{\ 2} - a(\omega)$$

Typically, the aerodynamic term, $a(\omega)$, is calculated by a CFD code with a prescribed frequency, typically ω_n. The aeroelastic (complex) frequency can then be determined from the last equation above. The physical aeroelastic frequency is real part of this complex frequency and the critical