BLADED DISKS: MISTUNING

Robert E. Kielb
USA

1. Introduction

Although the blades of a bladed disk are designed to be identical, manufacturing variations and field damage cause the blades to be slightly different. These differences can have a significant effect on stability and forced response. The airfoils in blisks and bladed disk assemblies are coupled structurally (through the disk, blisk, and/or shrouds) and coupled aerodynamically. Although it is well known that both coupling mechanisms can play a significant role in determining stability and maximum airfoil resonant response of a frequency mistuned bladed disk (e.g. Ewins 1969; Bendiksen, 1984; Griffin & Hoosac, 1984; Wei & Pierre, 1988; Afolabi, 1985; Crawley & Hall, 1985; Dugundji & Bundas, 1983; Kaza & Kielb, 1982; Srinivasan & Tavares, 1994, and Lin & Mignolet, 1997), the vast majority of research efforts have concentrated on frequency mistuned forced response with models only accounting for the structural coupling. These studies have shown that the forced response can display "mode localization" behavior and increase the response amplitude by more than a factor of 2 over that of a bladed disk with identical blades. However, it has been found that frequency mistuning has a suppression effect on flutter. Recently, more attention has been paid to aerodynamic coupling effects. Some examples are Seinturier, E. et al., 2000, Kielb R., et al. 2004b, and Kielb, R. et al. 2005, Sladojević, I., et al., 2005, He, Z. et al. 2006, and Sladojević, I., 2006.

The subject of aerodynamic asymmetries has received some attention in the literature. Fleeter and Hoyniak (1989) studied the effect of variation of circumferential blade spacing. Alternating blade spacing was found to stabilize a system that was unstable with equal spacing. Sladojević (2006) studied the effect of alternating stagger angle on stability. Small deviations in stagger angle (0.5 degrees) did not significantly affect the stability. However, larger variations (2.0 degrees) were found to be significantly destabilizing.

This lecture presents the controlling equations for mistuned bladed disks with both structural and aerodynamic coupling using a high fidelity, reduced order model (ROM) structural coupling model, and an aerodynamic coupling model based on the results of unsteady CFD codes. The model is applied to a representative front stage compressor rotor and its flutter stability and forced response are investigated. First, examples of frequency mistuning are presented for both flutter and forced response. This is followed by examples with aerodynamic asymmetries.

2. Controlling Equations

This section summarizes the equations of motion for a mistuned bladed disk with both aerodynamic and structural coupling between the blades. The computational method used herein is based on the "single family of modes" approach (Feiner & Griffin, 2003a, Corral, et al. 2004, and Kielb, et al., 2004). The modal equations of motion for a mistuned bladed disk or blisk can be written in traveling wave coordinates as

$$\left[\left(\Lambda^0 + \Delta K\right) - \omega^2\left(I + \Delta M\right)\right]\{Y\} = \{F^m\} + \{\mathrm{W}\} \quad (1)$$

ΔK and ΔM are the perturbations in the modal stiffness and mass matrices due to frequency mistuning. F^m is the modal force vector due to blade motion. W is the modal force vector due to external excitations. Λ_0 is a diagonal matrix containing the squares of the tuned system mode frequencies due to structural coupling only. Structural damping can be added to the problem by expressing the diagonal terms of the Λ_0 matrix as a complex stiffness.

When the blades are aerodynamically identical (represented by a 0 superscript) the aerodynamic forces due to blade motion can be expressed as

$$\{F^{m0}\} = \left[A^{m0}\right]\{Y\} \qquad (2)$$

The A^{m0} matrix is a diagonal matrix containing the traveling wave unsteady aerodynamic coefficients that are usually determined from unsteady CFD analysis assuming that the blades are aerodynamically identical. For each traveling wave the physical forces on each blade are identical except for a constant interblade phase shift. When the blades are aerodynamically asymmetric (also referred to as aerodynamically mistuned), the aerodynamic forces due to blade motion can be expressed as

$$\{F^m\} = \left[A^m\right]\{Y\} = \left[\left[A^{m0}\right] + \left[\hat{A}^m\right]\right]\{Y\} \quad (3)$$

In general the A^m matrix is full. The equation of motion with both frequency mistuning and aerodynamic asymmetries then becomes

$$\left[\left[\left[\Lambda^0\right] + \left[\hat{A}\right] - \left[A^{m0}\right] - \left[\hat{A}^m\right]\right] - \omega^2[I]\right]\{Y\} = \{W\} \quad (4)$$

The frequency mistuning matrix, $\hat{A}$, can be related to the frequency variation in each individual blade/disk sector (e.g. see Feiner & Griffin, 2003a). These sector frequency deviations characterize mistuning in both the blade and its corresponding wedge of the disk. However, if the mistuning is confined to the blades, then the sector frequencies relate to the individual blade frequencies through a simple scaling factor (Feiner & Griffin, 2003b). It is assumed that the modes are part of an isolated family (e.g. the 1st bending family). That is, the frequencies are well separated from those of other families. It is also assumed that the strain