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STUDY OF LOCALIZED VIBRATIONS OF MISTUNED BLADES OF CENTRIFUGAL COMPRESSOR

T. Jamróz[*]

Abstract: *Presented paper deals with sensitivity analysis of a mistuning centrifugal compressor. Vibrations of blades of mistuning bladed disk generate local zoning of vibration modes as well as amplitude magnification, which primarily reduces the high cycle fatigue life of engine. The sensitivity analysis uses a criteria for determination of the level of these local mode effects depending on mistuning deviations. The analysis shows that some vibration modes of centrifugal compressor structure which are characterized by significant percentage of blades on the total bladed disk strain energy, have a significantly higher sensitivity to blade mistuning. These vibration modes are characterized with low structural coupling blades such as higher bending modes or modes with high numbers of nodal diameter lines.*

Keywords: Centrifugal compressor, mistuning, blade vibration, mode localization.

1. Introduction

Good knowledge of dynamic behaviour of bladed disk is essential during the design as well as test-phase of future aeroengine rotors. Especially in the case of integrated bladed disks (blisks) become more important aiming at more environmentally-friendly, more efficient, and more powerful aeroengines. The deletion of the heavy bladed disk connection results in reduced masses, higher maximum rotational velocities, and improved pressure ratios (increased efficiency factors). In this connection also, a number of disadvantages occur above that are mentioned in Beirow, et al. (2005) such as very low structural damping and higher sensitivity with regard to mistuning. This behaviour reduces the margin for dynamic load and consequently causes a problem that is connected to High Cycle Fatigue (HCF) as noted by Seinturier (2007) or earlier Steffens (2001).

Mistuning, which primarily results from manufacturing tolerances, but also from wear or even strain gauge instrumentation, can cause mode localizations accompanied by a severe increase of blade displacements compared to the tuned response. Almost 50 years ago a conservative limit (1) for an estimation of the maximum displacement increase of bladed disks only depending on the number of blades N by Whitehead (1966) was introduced. This formulation was more or less validated later by Petrov & Ewins (2003).

$$\gamma = \frac{\max u_{mistuned}}{\max u_{tune}} = \frac{1}{2}\left(1 + \sqrt{N}\right) \qquad (1)$$

Nevertheless, mistuning can be described by other parameters such as Mode Localization and Mode Fill factor. These characteristics were described by Klauke, et al. (2009). Thus especially the mode localization has to be kept in mind during the rig test vibration monitoring because only a few blades will be instrumented with strain gauges. Therefore suitable choice of blades is essential to avoid critical misinterpretations during assessment of results from measurement. To achieve a better understanding of these contexts, free and forced vibration behaviours of updated full FE models of the centrifugal compressor from aeroengine M601 was analysed using different evaluation factors.

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[*] Ing. Tomáš Jamróz: Aerospace Research and Test Establishment, Beranových 130 Prague 9, CZ, jamroz@vzlu.cz

2. Numerical Analysis of the Tuned Blisk

In order to get an idea about basic vibration characteristics a FE model segment is derived from the ideal design of centrifugal compressor with main blade and splitter blade (Fig. 1a). This FE model segment is rotated to make full model of the centrifugal compressor. Based on this model an eigenvalue analysis with the effect of rotational speed included is carried out, firstly to derive the nodal diameter plot (Fig. 1b) and with that to get an overview about relevant blade mode families and disk dominated modes as well.

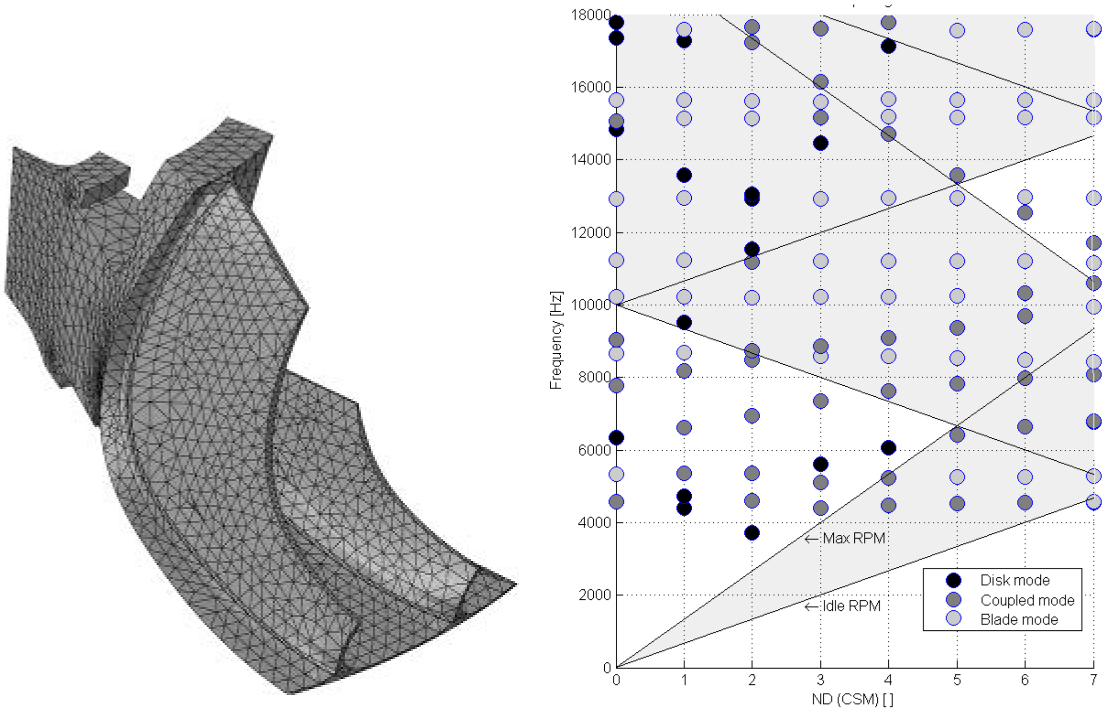

Fig. 1: a) FE model segment of centrifugal compressor and b) Nodal map diagram for tune blisk.

In the nodal diameter map (Fig. 1b), all eigenfrequencies of the tuned system are showed against nodal diameter also known as their CSM (Cyclic Symmetry Mode). Additionally, the modes can be distinguished using the blade percentage of the total blisk strain energy as a reliable indicator (Table 1). Hence, several blade-modes mode families can be easily identified. These mode families occur as nearly horizontal lines. In contrast to this, disk-modes and coupled modes show more rising frequencies with an increasing number of nodal diameters caused by increasing disk stiffness, as mentioned above can be found in Strehlau & Kühhorn (2010).

Tab. 1 Distinguish of blisk modes.

	Disk mode	Coupled mode	Blade mode
Blade percentage of total blisk strain energy	*<50%*	*50%÷75%*	*>75%*

3. Numerical Analysis of Mistuned Blisk

3.1. Modeling of Blade Mistuning

Modeling of mistuning of full model was realized by changing the material properties. This realization due to the decrease and increase in the individual blade's Young modulus E_i, the blade eigenfrequencies were modified without changing the blade geometry. The change in blade eigenfrequencies is proportional to the change in the square root of the blade's Young moduli.

Modeling of blade mistuning was performed by different artificial sinusoidal blade mistuning deviations in contrast to the measured mistuning distributions, which differ from blade mode to blade mode and can be characterized by a Weibull-distribution.

The number of full sine waves around the blisk circumference was chosen to be 1 and 4 with standard deviations of 0.33%, 0.98%, 2.62%. Generally, the mistuning of a bladed disk assembly results in several fundamental effects such as splitting of double mode and mode localization, according Srinivasan (1997).

3.2. Evaluation of Mistuning Blisk

The variation of the vibration mistuning modes of the blisk was based on a discrete Fourier transform (DFT) such as those done before by Castanier & Pierre (2002). The mistuned mode is represented as a superposition of tuned modes, where the coefficients of the single tuned modes in the modal summation characterize the level of mode distortion.

One of the fundamental parameters that is evaluated is called Mode Fill Factor (*MFF*) which has been published by Klauke, et al. (2009). This parameter is used for comparison of the magnitudes of mode filling of different blade modes with each other. This factor specifies the number of harmonics that are included in each the vibration mode. In other words, how strong is the deviation of modification of mistuning mode with regard to tune vibration mode and how many *EOs* are able to excite this *(M) CSM.*

$$MFF_i = \frac{100}{CSM_{max}}(\xi_i - 1)\ [\%], \qquad where \quad \xi_i = \left(\frac{\sum_{i=0}^{CSM_{max}} DFT_i}{DFT_{max}}\right) \tag{2}$$

Another important parameter is the Localization Factor (LF). The amplification factor alone gives no information about the number of high displacement blades during forced response analysis of a mistuned blisk. Hence, it is possible that a lot of blades reach high magnification factors or only one single blade reaches a higher displacement level. This knowledge is helpful in terms of an optimum blade selection for strain gauge instrumentation of rotor stages and vibration results analysis.

$$LF_i = \frac{100}{\sqrt{N} - x}(\varsigma_i - x)\ [\%], \qquad where \quad \varsigma_i = \frac{U_{i,max}}{RMS_i} \tag{3}$$

Where $x=1$ if $CSM=0$ or $CSM=CSM_{max}$ and $x=\sqrt{2}$ if $1 \le CSM \le CSM_{max}$ (odd N) or $1 \le CSM < CSM_{max}$ (even N)

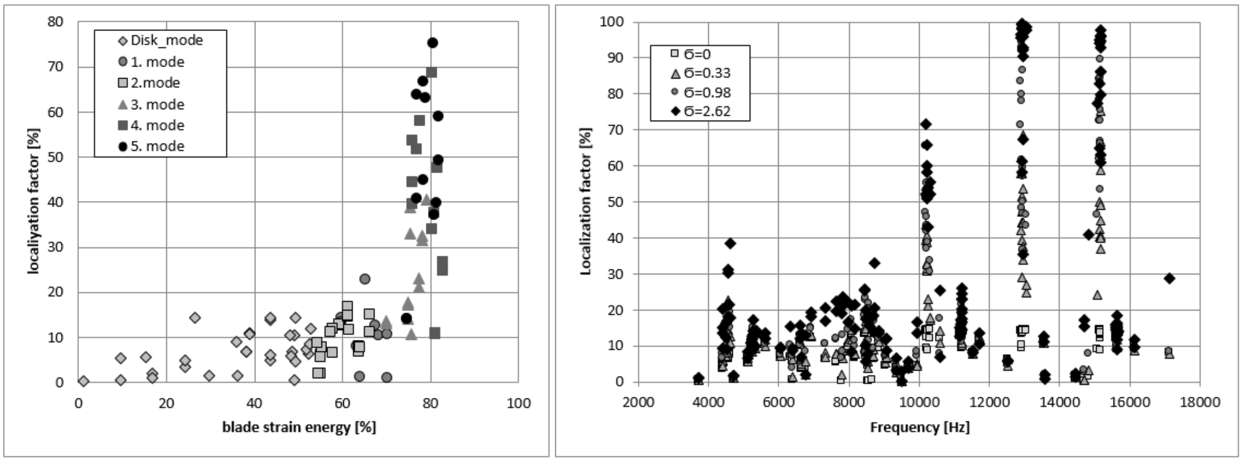

Fig. 2: Localization factor versus percentage of blades of total blisk strain energy, σ=0.33% and Localization factor of natural vibrations depending on the blade mistuning deviation.

4. Conclusions

The results of sensitivity analysis of mistuning centrifugal compressor have shown similar conclusions as those for axisal compressor according Klauke, et al. (2009). The vibration modes of blade integrated disks are very sensitive to individual blade mistuning. The reason for this behaviour is very low structural damping. The mistuning effect leads to the formation of local zoning of the vibration modes (mode localization). The determined localization factors show that in general higher bending modes have a more pronounced local zoning of the vibration modes than lower bending modes as well as modes with lower numbers of nodal diameter lines. These higher bending modes have a low structural coupling between blades and disk, which can be characterized by significant percentage of blades on the total blisk strain energy.

Other general effect of mistuning bladed disk and local zoning is the double modes splitting. These modes are split into two adjacent eigenvalues, by the symmetry loss. By increasing the mistuning of the system, the distance between the adjacent eigenfrequencies increases.

Force response analysis shows that high amplitude increases of forced vibrations appear at moderate mistuning levels for low damped systems, while the localization of blade modes constantly increases with higher blade mistuning.

An understanding of these correlations will lead in future to better preparation and analysis results from strain gauge measurement during operational condition of aeroengine that will be performed for centrifugal compressor and gas turbine.

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