Vibration Analysis of an Axial Turbine Blisk with Optimized Intentional Mistuning Pattern

Bernd Beirow, Brandenburg University of Technology, Cottbus, Germany

Felix Figaschewsky, Brandenburg University of Technology, Cottbus, Germany

Arnold Kühhorn, Brandenburg University of Technology, Cottbus, Germany

Alfons Bornhorn, MAN Turbo & Diesel SE, Augsburg, Germany

Long Abstract

Introduction

Low engine order excitations (LEO) of blade integrated disks in turbocharger applications are well known to cause forced vibrations of fundamental blade modes. Hence, LEOs have to be considered as a relevant source of fatigue. Recently, efforts have been spent to mitigate the forced response by means of employing intentional mistuning patterns. This has proved to be a promising way [1][2] if first the dedicated travelling wave mode of the tuned counterpart is weakly damped compared to most of the other travelling wave modes and second that sufficiently high differences are existing between inter blade phase angle-dependent maximum and minimum aerodynamic modal damping ratios. In this paper, genetic algorithms are applied to design an optimized intentional mistuning pattern for an axial turbine blisk namely to reduce the forced response of the fundamental flap mode clearly beneath that of the tuned counterpart without severely increasing the response of higher modes. Subset of nominal system mode (SNM) [3] models are employed for that purpose in which the aeroelastic coupling is considered by means of aerodynamic influence coefficients (AIC). Two prototypes have been manufactured to prove the suitability of the approach: A first one with the optimized intentional mistuning pattern (Fig. 1) and another one with theoretically identical blades. The necessary differences of blade alone frequencies from blade to blade in case of the intentionally mistuned blisk have been accomplished by intended geometry variations. Since additional random mistuning due to the process of manufacture is unavoidable, disparities in modal properties between design intention and really manufactured blisk are expected. That is why experimental analyses are carried out in order to identify the differences between intended designs and really manufactured blisks in terms of identifying frequency based mistuning. Finally, updated structural models are used for numerical forced response analyses in order to prove the robustness of the intentional mistuning pattern with respect to additional random mistuning.

Approach and Results

Aiming to find an optimized intentional mistuning pattern for a turbine blisk regarding the relevant EO 6 excitation of the first mode (M1) a minimization of the greatest possible forced response is formulated as objective function. In order to keep the manufacturing effort within a limit only two possible blade geometries are allowed which means that an integer optimization problem is formulated. Hence, the dimension of the design space takes a value of 2^{41} or about $2.2*10^{12}$ respectively. Due to the great number of design variables and the non-linear objective function it is hardly possible to find the global minimum. That is why genetic algorithms have been employed for this pure deterministic optimization. The results shown in Fig. 1 (blue curve) have been computed employing an in-house code. In theory the maximum forced response (EO6/M1) will be decreased down to a level of 29.4% compared to that of the tuned counterpart (100%). This is a consequence of an increase of the resulting aerodynamic damping ratio by a factor greater than 4 which in turn is explainable with the superposition of the forced response by several nodal diameter modes instead of only the 6th one as it would occur in case of a tuned blisk.

After manufacturing the optimized blisk design by milling a blade by blade frequency check applying a patented approach has been carried out for the purpose of identifying the real mistuning distribution. Figure 1 indicates deviations between theory and practice resulting from uncertainties connected to the process of manufacture such as wear of the milling tool or allowable tolerances. Nevertheless, the original design intention remains largely recognizable. Based on the experimental mistuning data another SNM-model is updated and validated by means of experimentally determined mode shape involutes (Fig. 2). These experiments have been taken applying piezoelectric excitation at the disk and laser Doppler response measurements at the blade tips inside a vacuum chamber in order to separate as many modes as possible. The good match between measurement and computation documents the suitability of the reduced order modeling to achieve a satisfying accuracy. Subsequent calculations again yield a clear reduction of a maximum forced response (EO6/M1) down to 37.6% compared to an ideally tuned blisk, which still represents a success regarding a reduction of the mode 1 response and proves the robustness of the intentional mistuning pattern as well.

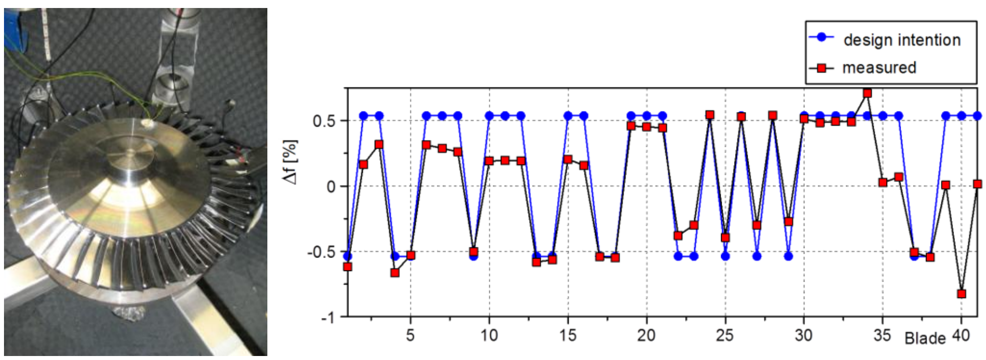

Figure 1. Blisk prototype (left) and frequency mistuning of fundamental flap mode (right)

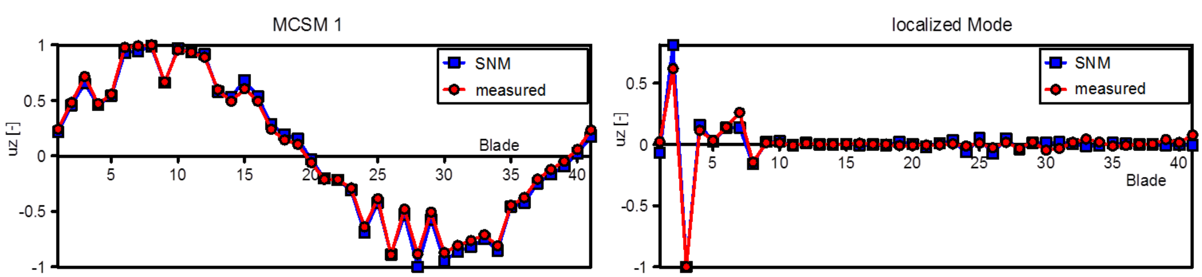

Figure 2. Measured and computed mode shape involutes (M1/leading edge tip)

Further investigations are addressing higher modes, in particular those which are prone to resonances resulting from excitation orders corresponding to the number of NGV blades. These modes (e.g. mode 5) have been already considered within probabilistic studies after finishing the optimization and it has been found that no relevant increase of the forced response will occur for these modes. However, this applies to the optimized theoretical mistuning pattern so that evidences are required with respect to the robustness of real mistuning distributions. The experimental determination of letter ones partly reveals stronger deviations from the expected patterns so that additional SNM updates have to be accomplished and validated as well. Complementary forced response analyses will follow to indicate the differences between expectation and reality. If necessary more efforts have to be spent in improving the optimization process, e.g. by taking into account the random character of additional mistuning already in the optimization process. That would mean that the objective function used before has to be enhanced by considering the variance of the greatest forced response. In this case a probabilistic study has to be performed after each deterministic evaluation. Such a strategy could be of interest in particular for those cases for which the pure deterministic approach employed before fails to identify mistuning patterns yielding a maximum forced response less than that of the tuned reference.

The investigations described before are repeated for the second prototype hardware with identical blades in theory. Again mistuning induced by manufacture becomes apparent which commonly will increase the maximum forced response. In conclusion a comprehensive comparison will be provided addressing the potential and the robustness of intentional mistuning.

References

[1] E. P. Petrov. Reduction of Forced Response Levels for Bladed Discs by Mistuning: Overview of the Phenomenon. Proceedings of the ASME Turbo Expo 2010: Paper GT2010-23299, Glasgow, June 14-18, 2010.

[2] B. Beirow, A. Kühhorn, T. Giersch, J. Nipkau. Optimization-Aided Forced Response Analysis of a Mistuned Compressor Blisk. *J Eng Gas Turb Power*, 137(1): 012504/1-10, 2015.

[3] M．T．Yang, J. H. Griffin. A Reduced-Order Model of Mistuning Using a Subset of Nominal System Modes. *J Eng Gas Turb Power*, 123: 893-900, 2001.