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A parametric study of Limit Cycle Oscillation of a bladed disk caused by flutter and friction at the blade root joints

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ABSTRACT

The purpose of this paper is the parametric study of the non-linear aero-elastic phenomena of a bladed disk for aeronautical applications in the presence of friction contacts using a one-way coupled method. The calculation is performed using a method based on the Harmonic Balance Method (HBM) and the balance between the energy introduced by the unsteady aerodynamics on the blade airfoil and the dissipative energy. The HBM method is preferred with respect to the Direct Time Integration (DTI) for the strong reduction of the computation time that HBM technique allows in spite of an acceptable level of approximation when nonlinearities are introduced and the response is periodic.

The nonlinearity is introduced by purposely developed contact elements, placed at the blade root-joints, that produce additional stiffening and damping in the system due the introduction of contact stiffness and friction forces based on Coulomb's law. The aero-elastic equilibrium will be investigated through a sensitivity analysis of the Limit Cycle Oscillations (LCO) of the system. The effect of such variations will be highlighted in order to demonstrate what are the parameters that influence most the blade amplitude, both for the CFD and the mechanical simulation. In particular, the uncertainty in the definition of the contact parameters at the blade root will be taken into account by varying the friction coefficient and the normal force distribution on the blade joint. Finally, the results of the analysis will be compared with the experimental data produced with a cold-flow test rig to verify if the sensitivity study associated to the simplifications introduced in the method are compatible with the measured response.

1. Introduction

The existence of reducing fuel consumption and pollution produced by air traffic has led to the need to improve the design of the aircraft systems, including the propulsion system. Therefore, the general issues of a reduction of the weight and an increase of the efficiency are also applied to the aircraft engine. High Aspect Ratio (HAR) airfoils have been developed to reduce the number of rotor stages by increasing the mass flow rate, in spite of slender and thinner blades. The problem linked to this new blade design is a reduction of the natural frequency of the blade and an increase of the amplitude of the vibrations with a consequent reduction of the fatigue strength and reliability of the component in the engine. Major attention will be put on the behavior of the Low Pressure Turbine (LPT) for aeronautical applications.

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The vibrations of a turbine bladed disk are mainly caused by two factors:

1. the excitation by time-varying forces caused by the considerable non-uniformity of the flow of the hot gases that pass through the turbine blades. This type of excitation is linked to the turbomachinery architecture, in particular the number of vanes preceding and following the turbine stage and the shaft angular frequency;
2. the self-excitation that can occur in the absence of the previous excitation forces when the unsteady work performed by the fluid exceeds the energy dissipated from the damping in the system.

Self-excited excitation is one of the most important problems that has been studied by aircraft structural engineers in the last decades as soon as the weight reduction and flight performance had to be maximized. In the turbomachinery area, turbine blade cascades underwent the same optimization process in order to meet requirements of larger turbine disks and higher rotation speed that means high aspect ratio of the airfoil and higher aerodynamic loads. Aero-elasticity is a topic addressed by different authors, see for example Marshall and Imregun (1996); Srinivasan (1997); Hall et al. (2005). The most effort to predict and avoid the occurrence of this problem was given in the fluid-dynamic physics by means of CFD calculations through the solution of the Reynolds-Averaged Navier–Stokes equations (RANS) with different level of complexity (linearized form or more complex degree of coupling between blade motion and unsteady pressure distribution around the airfoil). Based on the vibrations of a structural mode shape (Sayma et al., 1998; Nowinski and Panovsky, 2000; Vahdati et al., 2009; Rice et al., 2009), it is possible to calculate the value of the aerodynamic damping factor and stiffness for that blade mode shape as the Inter-Blade Phase Angle (IBPA) varies.

Other author (Kielb and Kaza, 1984; Hoyniak and Fleeter, 1986; Martel et al., 2008) have more recently studied the suppression of the flutter-induced vibrations by means of mistuning, both natural (due to small differences between the blades with respect to the nominal geometry, material properties and contact interfaces of joints) and purposely introduced (alternate mistuning where a blade cascade is made of two sets of blades assembled in a 01010…pattern). The effectiveness of the blade mistuning is due to the break of the cyclic symmetry that nominally characterizes the turbo-machinery dynamics and allows for the flutter onset. In fact, a significant perturbation of the blade array response in terms of amplitude uniformity in the blade cascade and phase shift between a blade and its neighbors can produce a change of the gas flow effect on the airfoil and, as a consequence, on the value of the aerodynamic damping.

These studies consider that the dynamics of the bladed disk is linear and the fluid–structure interaction is directly linked to the natural frequencies and normal mode shapes of the system. However, structural designers of aircraft engines have introduced nonlinearities in the bladed disk structure in terms of damping systems to reduce peak stress values during the vibratory phenomenon caused by the external excitation forces. These damping systems are usually friction dampers or joints geometrically optimized that use the friction forces to dissipate energy increasing the fatigue life of the blade. The major sources of friction damping in the bladed disk turbine are attributable to the blade-disc interfaces (blade root joint) (Petrov and Ewins, 2006; Zucca et al., 2012), the contact between adjacent blades connected by interference at the tip (shrouds) or mid-span airfoil (snubber, Petrov and Ewins, 2003) and the presence of underplatform dampers (Firrone et al., 2011; Firrone, 2009).

As these friction contacts limit the vibrations of excitation forces, they can be used to suppress the unstable flutter vibrations to form a periodic motion called Limit Cycle Oscillations (LCO). In this condition, the amplitude and the frequency of the LCO is determined by the equilibrium between the energy introduced in the system by the flow and the energy dissipated by the friction contacts.

This equilibrium problem is qualitatively illustrated in Fig. 1 where the aerodynamic energy is plotted with the blue dashed curve, while the dissipative energy is plotted with the red solid curve, both for one cycle of oscillation.

The balance between the aerodynamic and dissipated energies provides in this example three solutions: the solution 1 is the trivial solution where there is no exchange of energy because there is no vibration; besides, this is an unstable solution because any small perturbations of the system move the system away from 1 towards solution 2. The solution 2 is the stable solution of the system and represents the LCO; in fact, any perturbation from 2 limited between the solution 1 and the solution 3 does not change the final equilibrium. The solution 3 is an unstable solution and represents the stable limit of the system because any perturbation bigger than this limit produces ineffective damped, self-excited vibrations.

Only few authors have studied the LCO of the bladed disk structure in the presence of non-linearities as the friction contacts. The first were Griffin J. and Sinha A. in Sinha and Griffin (1983, 1985). In their works, the authors have used a lumped parameters model based on one degree of freedom with a friction contact and the obtained results are useful to understand the LCO phenomenon in terms of stable and unstable solutions. Other authors (Corral and Gallardo, 2006) have studied the LCO through the use of a lumped parameter model for the whole bladed disk sector with a blade root joint determining the amplitude of the blade from the balance of the energy dissipated at the blade root and the energy supplied by the gas flow. More recently, Petrov (2011) has developed a general method, based on the mathematical properties of the Harmonic Balance Method (HBM) and the mathematical homogeneity of the linearized equations of motion in the presence of friction contacts and flutter-induced external forces that can be applied to model generated with FEM. More recently, Krack et al. (2016) used a lumped parameter dynamic system to calculate the LCO of a cyclic symmetric structure when multiple unstable modes with different values of Nodal Diameters (ND) are considered. Great attention is paid for the calculation of the contact forces when more unstable mode shapes exist since the ND associated to the unstable modes are not commensurable. For this reason simple HBM method cannot be used to solve the equilibrium equations in the frequency domain. In fact, bi-dimensional FFT is used in Krack et al. (2016) to consider the presence of two unstable mode shapes having two different nodal diameter.