Mechanical Systems and Signal Processing 85 (2017) 662–679

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Modelling the nonlinear behaviour of an underplatform damper test rig for turbine applications

L. Pesaresi [a,*], L. Salles [a], A. Jones [b], J.S. Green [b], C.W. Schwingshackl [a]

[a] *Imperial College London, London SW7 2AZ, UK*
[b] *Rolls-Royce plc, Derby DE2 48J, UK*

A R T I C L E   I N F O

Article history:
Received 21 March 2016
Received in revised form
26 August 2016
Accepted 3 September 2016

Keywords:
Damper model
Friction damping
Turbine blade vibrations
Nonlinear dynamics
Bladed discs
Passive control

A B S T R A C T

Underplatform dampers (UPD) are commonly used in aircraft engines to mitigate the risk of high-cycle fatigue failure of turbine blades. The energy dissipated at the friction contact interface of the damper reduces the vibration amplitude significantly, and the couplings of the blades can also lead to significant shifts of the resonance frequencies of the bladed disk. The highly nonlinear behaviour of bladed discs constrained by UPDs requires an advanced modelling approach to ensure that the correct damper geometry is selected during the design of the turbine, and that no unexpected resonance frequencies and amplitudes will occur in operation. Approaches based on an explicit model of the damper in combination with multi-harmonic balance solvers have emerged as a promising way to predict the nonlinear behaviour of UPDs correctly, however rigorous experimental validations are required before approaches of this type can be used with confidence.

In this study, a nonlinear analysis based on an updated explicit damper model having different levels of detail is performed, and the results are evaluated against a newly-developed UPD test rig. Detailed linear finite element models are used as input for the nonlinear analysis, allowing the inclusion of damper flexibility and inertia effects. The nonlinear friction interface between the blades and the damper is described with a dense grid of 3D friction contact elements which allow accurate capturing of the underlying nonlinear mechanism that drives the global nonlinear behaviour. The introduced explicit damper model showed a great dependence on the correct contact pressure distribution. The use of an accurate, measurement based, distribution, better matched the nonlinear dynamic behaviour of the test rig. Good agreement with the measured frequency response data could only be reached when the zero harmonic term (constant term) was included in the multi-harmonic expansion of the nonlinear problem, highlighting its importance when the contact interface experiences large normal load variation. The resulting numerical damper kinematics with strong translational and rotational motion, and the global blades frequency response were fully validated experimentally, showing the accuracy of the suggested high detailed explicit UPD modelling approach.

* Corresponding author.
E-mail address: luca.pesaresi12@imperial.ac.uk (L. Pesaresi).

http://dx.doi.org/10.1016/j.ymssp.2016.09.007

1. Introduction

Continuous demand in the aerospace industries for lighter and more efficient gas turbine engines has driven the design of many components to their structural limits. This applies to the case of turbine blades, which are highly loaded components, carrying high thermal and centrifugal stresses as well as stresses caused by the blade vibrations [1]. These latter are high frequency alternating resonance stresses, and can lead to high-cycle fatigue (HCF) [2] and eventual failure of the blades. However, the wide operating speed range of aero-engines together with the high modal density of bladed discs makes it impossible to avoid all critical resonances during operation. Reducing the vibration amplitude at those resonances is therefore crucial, and passive systems, based on friction damping [3,4], have been the most widely used approach over the years [5].

Dry friction can provide damping in various locations on a blade, such as the shrouds, roots and blade tips, and the most effective way to exploit it relies on underplatform dampers (UPD) [5]. Underplatform dampers consist of a metal device which sits in a groove on the underside of the platform between adjacent blades, and it is kept in place and loaded by the centrifugal force. When the blades vibrate, the relative motion between the adjacent platforms and the damper leads to friction at the contact interface, which in turn provides energy dissipation and damping to the system [6,7]. The dynamics of a bladed disk assembly constrained by UPDs is governed by nonlinear differential equations, due to the nonlinear nature of the forces occurring at the interface [1]. The main sources of this nonlinearity are the localised transition from stick to slip and a unilateral normal force which can lead to gaps at the contact interface.

Many studies on damper modelling have been conducted [8–12], all leading to a better understanding of the damper behaviour, but despite all the research efforts, there is still not a well established approach available today. Initially [8,13], the blade damper system was reduced to a single degree of freedom oscillator with a spring element combined to a Coulomb friction element (Jenkins element [3]) and a semi-analytical solution was derived. In [14] an attempt to improve this model was carried out, by extending it to a two-degrees of freedom system. A higher fidelity was achieved by full FE models of the blades in conjunction with kinematic hypotheses about the relative motion between the damper and platform, in which the damper and platform faces are always parallel [9,15,6,10]. Difficulties encountered during the validation of the latter models suggested that the required hypotheses were not always realistic [6]. In more advanced models [16–20], these hypotheses were removed and the damper motion is calculated purely as the result of its interaction with the blades by means of the nonlinear contact forces. To reproduce damper motions, advanced 3D friction contact elements were employed; these account for normal load variation with separation effects and 2D tangential in plane motion [21]. To further improve the accuracy of the contact force calculation, local deformation effects were also taken into account using an explicit FE damper model [22]. These improvements have led to the emergence of tools that permit an accurate representation of the contact interface, leading to a potentially very large number of nonlinear equations to solve.

A possible approach to solving the nonlinear equations of motion of the dynamic systems is time integration, but it is computationally expensive and highly inefficient when the interest is only the steady-state response to harmonic excitation. For this reason, a combination of the harmonic balance method (HBM) [18,23–25] which is based on a fundamental harmonic or multi-harmonic approximation of the nonlinear forces, together with model reduction techniques [26–28] has emerged as a widely used approach to solve vibration problems.

Significant advances in the damper models over the last years have not always been accompanied by the rigorous validation process needed for reliable predictions. Higher fidelity models [16–19,22] comprise several parameters describing the contact interface but their impact in capturing the physics of the phenomena needs to be fully understood before those models can be used with confidence. The aim of the present work is to improve the fidelity of the current explicit damper modelling approach [22], to better capture the strong nonlinear dynamics often observed in real environments [29]. A dedicated UPD test rig was designed for this scope, based on a double beam configuration [6,11,30–32]. Unlike similar set-ups tested, particular care was taken to define a geometry able to mimic the dynamics of a real high-pressure turbine (HPT) blade. A high fidelity 3D nonlinear model was created and its results are compared to the measured data. Detailed model updating and a parameter study of the main model parameters led to a more accurate understanding of the nonlinear mechanisms at the contact interface and a significantly improved representation of the highly nonlinear response of the system.

2. UPD rig design

The validation of a nonlinear dynamic analysis of UPDs requires reliable test data from a well-controlled environment to ensure that all the required parameters can be identified and incorporated in the analysis. A dedicated UPD test rig was developed and used for the validation in the subsequent analysis.

2.1. Rig concept and Non-dimensional parameters

The underplatform damper test rig developed for this study is an experimental set up that allows the effect of UPDs on blade-like structures to be evaluated [33]. Following a review of similar test rigs [6,11,31,32], a static rig design was chosen in order to minimise the effect of mistuning on the response, as well as allow better control of the experimental set up, and simplify the testing procedure. In recent developments [34,35], a specific test rig was designed to measure the forces transmitted between the damper and the platform, as well as the relative displacements, allowing a fine tuning of the contact