Mechanical Systems and Signal Processing 106 (2018) 158–175

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Dynamic modeling and vibration characteristics analysis of the aero-engine dual-rotor system with Fan blade out

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ARTICLE INFO

Article history:
Received 14 December 2016
Received in revised form 6 December 2017
Accepted 9 December 2017

Keywords:
Fan blade out
Sudden unbalance
Rub-impact
Inertia asymmetry
Transient response
Steady-state response

ABSTRACT

Fan Blade Out (FBO) from a running rotor of the turbofan engine will not only introduce the sudden unbalance and inertia asymmetry into the rotor, but also apply large impact load and induce rotor-to-stator rubbing on the rotor, which makes the mass, gyroscopic and stiffness matrixes of the dynamic equation become time-varying and highly nonlinear, consequently leads to the system's complicated vibration. The dynamic analysis of the aero-engine rotor system is one essential requirement of the authorities and is vital to the aero-engine's safety. The paper aims at studying the dynamic responses of the complicated dual-rotor systems at instantaneous and windmilling statuses when FBO event occurs. The physical process and mechanical characteristics of the FBO event are described qualitatively, based on which the dynamic modeling for an aero-engine dual-rotor system is carried out considering several excitations caused by FBO. Meanwhile the transient response during the instantaneous status and steady-state response at the windmilling status are obtained. The results reveal that the sudden unbalance can induce impact load to the rotor, and lead to the sharp increase of the vibration amplitude and reaction force. The rub-impact will apply constraint effects on the rotor and restrict the transient vibration amplitude, while the inertia asymmetry has little influence on the transient response. When the rotor with huge unbalance operates at windmilling status, the rub-impact turns to be the main factor determining the rotor's dynamic behavior, and several potential motion states, such as instable dry whip, intermittent rubbing and synchronous full annular rubbing would happen on certain conditions.

1. Introduction

Blade losing is an actual possibility for an aero-engine operating in complex conditions. It may be caused by the heavy strikes from birds, stones and other foreign objects, as well as the fatigues related to the airfoil or the dovetail. Many literatures name this mechanics problem and engineering phenomenon [1,2,15] as Fan Blade Out (FBO). FBO can not only induce large unbalance and asymmetry of blade-disk, but also apply large impact load and rotor-stator rubbing to the rotor system and containment casing, which will further lead to the complicated vibration response of the whole aero-engine. Due to the severe damage of FBO event, the authorities request the manufactures to pass FBO test to demonstrate the strength and integrity of the engine and aircraft [1], but the test is extremely expensive and needs a considerable period. Therefore, ana-

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https://doi.org/10.1016/j.ymssp.2017.12.012
0888-3270/

lytical modeling and numerical simulation to predict the vibration response of the aero-engine are practically employed to reduce the test cost and to guide the structural safety design [2].

During the past decades, a significant amount of researches have been done on the topics of FBO event. Those works can be mainly classified into two categories, one is to study the strength of containment system and the integrity of mount suffering a very large impact load caused by the released blade [3,4], the other is to research the rotor dynamics problems such as the influence of the sudden unbalance load generated on the rotor [5,6], the asymmetry of inertia [7,8], the rub-impact between blade and casing [9–11], and the mechanical behavior of the damaged rotor during deceleration [12], etc.

Among these, the rotor dynamical response excited by the sudden unbalance is the main interest of this article. Many literatures have focused on the transient response generated by FBO, and the influence of different parameters such as damping, gyroscopic moment and support stiffness, etc. are analyzed. Genta [5], Kailinowski [13] and Wang [14] respectively established the dynamic model of a Jeffcott rotor with sudden unbalance and investigated the effects of rotation speed, excitation amplitude and other parameters on the vibration displacements and orbits of the rotor. Dzenan [6], Liang [15] and Wang [16] respectively simulated the vibration response of an overhung rotor to consider effects of gyroscopic moment under the excitation of sudden unbalance. Meanwhile, corresponding experiments were carried out to verify the simulation results. Above works demonstrated that the sudden unbalance produced impact load on the rotor, the impact effects are closely related to the operating status, and low order natural frequencies can be observed in the frequency domain.

In addition to the sudden unbalance, FBO can also introduce the asymmetry of inertia to the rotor system. Grandall [7] performed a quantitative instability analysis on a rotor with inertia asymmetry for the first time. Based on his remarkable work, Yamamoto [17] studied the unstable vibrations of a rotating shaft with an asymmetrical rotor theoretically and experimentally. Ikeda [18] and Ganesan [8] analyzed the stability of the rotor which operates at the vicinity of the critical speed. The expressions of vibration amplitude and phase with the rotation speeds are derived, and the stability region of the rotor system are determined. Recently, some researchers also studied the multi-disk rotors with multiple inertia asymmetries. Han [19] built the parametric model for one rotor with multiple asymmetrical disks, and discussed the interaction of the parametric excitations between the two disks. The emphasis of above investigations is the parametric stability of the asymmetrical rotor, which indicates that few attempts have been done on the transient response characteristics and the influence laws of mechanical parameters, although these are more important for the safety design of aero-engine rotor system.

Rub-impact between the blade and casing could be induced by the high vibration amplitude of the rotor, which will further lead to more complicated vibration. In fact, the rub-impact problem has already attracted a lot of attention in the past decades, Muszynaka [20] has presented an excellent review on the rotor-to-stator rubbing problem. She pointed out that the rub-impact involves several physical phenomena, including the most notably impact, friction and an stiffness increase, etc. As a result, the rotor turns to be highly non-linear and will exhibit extremely rich dynamic behaviors, such as partial rubbing, backward whirl, quasi-periodic and even chaotic motions [9,21]. The early studies usually used the modified Jeffcott rotor to obtain the response mechanism of the rub-impact analytically or numerically [20,21]. Recently, the researchers begun to consider the influence of different rubbing forms and the structure features of the rotor and stator. Sinha [10] performed a comprehensive analysis for an rubbing turbofan rotor with consideration of the flexibility of the blade-disk assembly. Ma studied the rubbing-induced vibration response based on contact dynamics theory considering different rubbing types such as single-point rubbing [11], multiple-point rubbing [22] and full annular rubbing [23]. In his studies, different motions for rubbing rotor, such as period-one motion (P1), P2 and P3, were observed with the increasing rotation speeds. Thiery [24] simulated the global dynamics of a misaligned Kaplan turbine with blade-to-stator contacts, and the detailed parametric influence was obtained by analyzing rotor response in terms of Poincare sections, bifurcation diagrams and maximum displacements at steady state.

It can be noted that previous researches paid more attention on the theoretical studies of the nonlinearities produced by FBO than the dynamical response of the real rotating machinery. Researchers usually used very simple rotor models (e.g. the Jeffcott rotor) with little degrees of freedom, and focused on the dynamics with one kind of load related to FBO events. In fact, the rotor systems in aero-engines usually operate above several critical speeds and have rich dynamical characteristics. Meanwhile, the complicated load features and the combined effects of these loads should be taken into account. Above all, most current works cannot reveal the behaviors of the actual rotor system and cannot provide appropriate results for the aero-engine safety design. Therefore, this article aims at studying the dynamic response of the complicated dual-rotor system in aero-engines when FBO event occurs. A more comprehensive model is proposed, which considers not only the interaction between the high pressure(HP) rotor and low pressure(LP) rotor, the structural and mechanical characteristics of the rotors, but also the coupled influence of the sudden unbalance, asymmetrical inertia and blades-casing interaction. Meanwhile, both the instantaneous and windmilling statuses after FBO event are taken into account. The vibration responses and the support reaction forces are also discussed in detail.

2. Dynamic model for the aero-engine dual-rotor system with FBO

2.1. Physical process of FBO event

When FBO occurs, the centroid of the bladed disk altered suddenly which induces the unbalance load on the rotor system. The sudden unbalance will significantly increase the rotor vibration and the reaction force, which may cause the damage of