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Containment ability and groove depth design of U type protection ring

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Abstract High-energy rotor uncontained failure can cause catastrophic damage effects to aircraft systems if not addressed in design. In this paper, numerical simulations of three high-energy rotor disk fragments impacting on U type protection rings are carried out using LS-DYNA. Protection rings with the same mass and different groove depths are designed to study the influence of the groove depth. Simulation results including kinetic energy and impact force variation of single fragment are presented. It shows that the groove depth infects both the axial containment ability of the protection ring and the transfer process of energy. The depth of groove ought to be controlled to an appropriate value to meet both the requirement of axial containment and higher safety factor. Verification test on high-speed spin tester has been conducted and shows that protection ring with appropriate U structure can resist the impact of the disk burst fragments. The ring is inflated from a circular to an oval-triangle shape. The corresponding simulation shows good agreement with the test.

1. Introduction

In turbine cooler of environment control system (ECS), auxiliary power unit (APU) and air turbine starter in aircraft, failed high speed rotor can be released as high-energy fragments, affecting flying performance in a number of direct and indirect ways and even leading to the loss of airplane.[1] With a more stringent working condition of higher temperature and rotational velocity, degradation and burst failure are more likely to occur, especially on the critical disks. Even though disk burst accidents happen infrequently nowadays, they are not completely avoidable.[2] Due to the catastrophic results, specific provisions are established for containment ability in both civil and military airplane specifications. Federal Aviation Administration (FAA) Federal Aviation Regulations (FARs) set requirements for equipment containing high-energy rotors of

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transport category airplane in Part 25.[3] Corresponding technical standards for APU are also put forward in TSO-C77b, gas turbine auxiliary power units by FAA.[4]

An available practice for studying the containing process is the combination of experimental tests and numerical simulations. With the advent of computer non-linear finite element codes, numerical simulations have become an important means for researchers to conduct their studies. A number of investigations have included experiments and numerical simulations of high-energy disk fragments containment. Hagg and Sankey[5] carried out tests which showed that containment of missile-like disk quarter fragments by a steel cylindrical shell is a continuous two-stage process. In Stage 1, the main objects to be considered are the loss in kinetic energy of system and the energy dissipated in plastic compression and shear strain. For non-perforation, the process enters Stage 2, which mainly involves dissipation of energy in plastic tension strain. The effects of mesh refinement on numerical simulations of uncontained engine debris impact on thin plates were studied by Norman Jr.[6] and Ambur[7] et al. In their studies, it was concluded that very fine mesh should be used to predict damage similar to that obtained from experimental results. Eric and Steven[8] proposed a simulation method of using ANSYS/LS-DYNA to develop an analysis method that could provide more accurate predictions of containment failure limits for a wider range of disk and containment geometries. Li et al.[9] carried out aeroengine turbine blade and disk containment tests respectively and analyzed them using numerical simulations with ANSYS/LS-DYNA. He et al.[10] conducted numerical study of an aeroengine fan blade/casing impact process and the effects of stress initialization on simulation are assessed. Liu et al.[11] studied compressor disk containment of aircraft cooling turbine used in aircraft environment control system. The disk burst into 3 pieces and containment process was investigated in combination of experimental results and numerical results. In this paper, numerical models are established first to predict the containment ability and loads. Then, simulation results are validated through test data. Detailed data obtained from numerical results are used to analyze the variation of the energy, the force, etc.

For protection rings, U structure seems to be an optimal design for disk bursting containment of high-energy rotor. In order to meet the requirement of containment, the protection rings must have enough thickness and U groove depth to resist the high-energy fragments. But excessive thickness results in excessive weight. To achieve a minimum weight of the casing which can offer enough containment strength, reasonable structural designs for the casing are expected. In this paper, containment ability and groove depth design of U type protection ring are studied.

This paper consists of five sections. Following this introduction, numerical simulations of fan impeller fragments in air turbine cooler impacting on the U type protection rings appears in Section 2. The containment ability of rings with different U-groove depths is studied using ANSYS/LS-DYNA. Section 3 shows a verification containment test on high-speed spin tester with the optimal protection ring chosen from the simulations. Section 4 describes the simulation of containment process under the test condition. Comparisons between the test and the simulation results are discussed. The last section presents the conclusions.

2. Containment ability of different U geometries

With the aim of saving costs and improving efficiency of research, a series of numerical simulations is carried out to study the effect of U geometry to the containment ability using ANSYS/LS-DYNA.

2.1. Design objective

Containment ability is studied through the simulation of fan impeller disk fragments in air turbine cooler impacting on the protection casing. In practical situation, fan protection casing consists of three components, among which the pipe and the protection ring play a major role of protection. Thus, the model in simulation is built without the outer shell (see Fig. 1). The installation position of the protection ring is designed (see Fig. 2).

Referring to SAE Aerospae-ARP-85F[12], the containment speed is defined 125% of the maximum speed resulting from normal operating condition. According to the design parameter of the air turbine cooler, the fan disk is supposed to burst with the speed of 70,069 r/min. The main design parameters are listed in Table 1. It should be noted that 2Cr13, the material of the protection ring, is a common material used in aerospace for its good corrosion resistance to the atmosphere. Available material parameters for simulation and fine machinability lead the choice.

2.2. Failure mode

According to FARs, it must be shown by test that high-energy rotor equipment can contain any failure of a high energy rotor that occurs at the highest speed obtainable with the normal speed control devices inoperative. TSO-C77b also puts forward provision that containment must be substantiated in accordance with the condition of hub containment in APU.[4] In advisory circular (AC) 20-128A of FAA, engine and APU failure model include single one-third disc fragment, intermediate fragment, fan blade fragment, etc.[13] Before the test, the most dangerous bursting mode must be determined. In order to simplify the question, the impeller is assumed to be a disk with a radius of r. Therefore, the rotational kinetic energy (E_c) of the disk can be calculated as

$$E_c = \frac{1}{2}J\omega^2 = \frac{1}{2}\left(\frac{1}{2}mr^2\right)\omega^2 \tag{1}$$

where m is the total mass of the impeller and ω the disk rotating/burst speed.

During the process of impacting, translational kinetic energy (E_t) plays a leading role among all the types of the energy of fragment. Assume the disk bursts into n equal parts. Thus, the centroid radius (r_m) and E_t of a fragment can be defined as

$$r_m = \frac{2r\sin(\pi/n)}{3(\pi/n)} \tag{2}$$

$$E_t = \frac{1}{2}\cdot\frac{m}{n}v_m^2 = \frac{1}{2}\cdot\frac{m}{n}(\omega r_m)^2 \tag{3}$$

The ratio of E_t to E_c is presented as