Modelling the Influence of Load Reduction Device on the Dynamic Characteristics of Commercial Aircraft Engine during a Fan-Blade-Off Event

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***Abstract* — Load Reduction Device (LRD) is widely used in commercial engine to reduce the Fan Blade Off, FBO, load transmitted to aircraft. A typical LRD is composed of a mechanically weakened section of the support of bearing No.1 and multiple shearing pins extending through the inner and outer race of bearing No.2. In this paper we study how LRD influences the dynamic characteristics of an engine after a FBO event is discussed based on the analysis of a full-engine finite element model. Simulations for cases with and without LRD are conducted in LS-DYNA, and the results are compared and discussed. They show that failure of LRD would change the transmitting path of the imbalance load, thus shift loads from bearing No.1 to bearing No.2. For the mount system, application of LRD would reduce the reaction loads at both the front mount and the thrust rod, but increase the reaction load at rear mount slightly, transferring some of the abnormal loads from the heavily-loaded front mount to the lightly-loaded rear mount. In addition, both the load transferred to fan frame through flanges and the maximum equivalent stress on main load-bearing frames are relatively low for the case with LRD. Thus, adopting LRD can reduce the FBO loads from the aero-engine to the aircraft.**

Keywords - LRD, influence; dynamic characteristics; aircraft engine; FBO event

I. INTRODUCTION

During routine operation, an aircraft might be hit by flying birds or other foreign objects, which may lead to an catastrophic accident. Since a hagdon was stuck in an aircraft and led the aircraft to crash into sea in 1912[1], bird strike accident emerges in endlessly, causing great economic loss [2]. Compared to other components of an airplane, engine has the highest proportion of being hit (43.13%) [3]. Birds impacting on engine may lead to one piece or more pieces of fan blade broken and separated from the remainder of the fan, namely Fan Blade Off (FBO).

Under normal operating condition, the rotor assembly of an engine, including the fan section, has an axis of rotation that passes through its centre of gravity and rotates with high speed. However, the centre of gravity would deviate from the rotation axis once a FBO event occurs. Due to the constraint of the bearings, the rotor assembly would still rotate along the axis deviated from its centre of gravity, and produce a substantial rotary imbalance load within the damaged fan. Thus serious damages to the stationary frames may occur, as well as engine mount release, fire, etc., threatening the flight safety seriously. To resolve this problem, aviation authority of each country has made relevant requirements [4-6] to ensure that FBO accidents will not disrupt the normal flight of the aircraft.

FBO accident itself is hard to avoid, and consequent actions must be taken to guarantee a safe fly-home of the aircraft. One traditional way is sizing the support components to provide additional strength for the fan rotor support system. However, this would undesirably increase an overall weight of the engine and decrease its efficiency under the normal operating condition.

To minimize the effects of potentially damaging imbalance loads without increasing the overall weight of an engine dramatically, LRD is introduced to aero engine design. The LRD usually includes two mechanically weakened sections, one of which is called primary fuse while the other is secondary fuse. And primary fuse usually refers to a special breakable element placed on the 1st fan support, while the secondary fuse is usually placed near the 2st fan support. Both the primary fuse and the secondary fuse will fail under imbalance loads due to FBO event. This would decouple the fan rotor from the fan support system, change the load path and reduce the loads transferred to the key components, thus protect the engine.

At present, research of predicting bearing and mount loads on aero-engine after a FBO event has been performed by engineers at home and abroad[7-9], mainly focusing on simulating method of the bird and simplification of the engine structure. However, few reports on influence of LRD to dynamic loads caused by FBO have been found. As LRD plays an important role in protecting aero-engine after FBO event, its influence on dynamic characteristics of an aero-engine during FBO event is analysed in the current work.

II. MECHANISM OF LRD

Usually, a Low Pressure (LP) shaft is supported by three bearings, which are bearing No.1, bearing No.2 and bearing No.5. For most situations, bearing No.1 and bearing No.5 are roller bearings, while bearing No.2 is a ball bearing. As bearing No.1 and bearing No.2 are close to the fan rotors, they are also called fan bearings.

A. Structures of LRD

During normal operation, the fan rotators are balanced, and bearing No.1 maintains aligned and passes operational loads into fan frame. Once a fan blade is released, the LP rotor is subjected to an impulsive force at the fan-disk acting radially outward due to introduction of sudden imbalance. And a substantial load created in the damaged fan would transmit to fan frame, mount systems, even components of airframe mainly through fan bearings and their supports.

Typical structures of LRD [10-11] are applied as primary fuse and secondary fuse respectively, as shown in Fig.1. The primary fuse refers to a hollow cone on the support of bearing No.1 between a forward bearing seat and an aft mount flange. And the secondary fuse refers to the pins set between the inner and outer ring of bearing No.2, which would fail under the FBO induced imbalance load to release the radial and pitch rotation stiffness of bearing No.2. Thickness of the primary fuse (the hollow cone) and the diameter of the secondary fuse (the pins) are sized to fail in shear under FBO induced imbalance load.

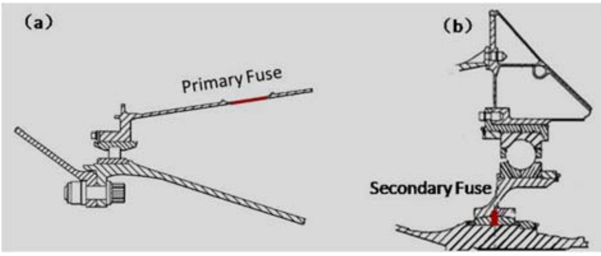

Figure 1. Scheme of the load reduction device: (a) thin section; (b)fuse pin

B. *Mechanism of load reduction*

After FBO event, primary fuse on support of bearing No.1 fails under FBO induced imbalance load, effectively decoupling the damaged fan rotor from other stationary frames of engine. Next, significant imbalance load created in the damaged fan cannot be transferred through support of bearing No.1 sequentially. In addition, failure of primary fuse releases the constraint of the fan rotor at bearing No.1. Thus, rubbing between fan blades and fan case would be severer after the utilization of LRD.

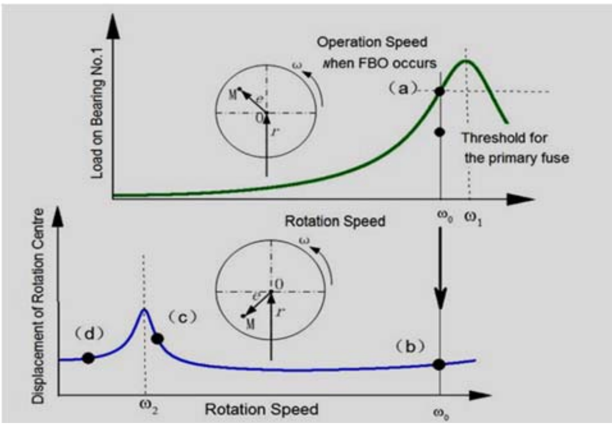

Figure 2. Scheme of the mechanisms of LRD

Main mechanism of LRD on reducing orbit of the fan disk and imbalance loads is shown in Figure 2. Normally, operating speed of the fan rotor ω_0 is below the fan critical speed ω_1. Thus, the fan of an aero-engine operates in subcritical state before the failure of LRD structures. And the centre of gravity M of the damaged fan is located beyond the line between its geometrical centre O and the rotating centre. After failure of the LRD structures, the number of supporting bearings of LP shaft is reduced from 3 to 2, losing the constraint at bearing No.1. As such the support stiffness for the LP shaft is reduced. This would make the fan critical speed reduces fromω_1 toω_2, and operating speed of the fan rotor ω_0 becomes higher than its critical speed. Then the centre of gravity M of the fan disk would locate between the geometrical centre O and the rotating centre C. During the process of shut-down after FBO event, speed of the fan is reduced and crosses its critical speed at a relatively low value with rapid deceleration, having correspondingly reduced peak loads in consequence.

III. FULL-ENGINE FINITE ELEMENT MODEL

As FBO event is a transient impact process with high nonlinearity, the currently widely-used methods for analysis of aero engine dynamic behaviour after FBO event are mainly based on full 3D finite element (FE) simulation. Thus two full-engine 3D finite element models for cases with and without LRD are considered here to conduct the analysis, using explicit dynamic calculation such as LS-DYNA. These models are relatively simple because simulations are carried out without consideration of other units, such as squeezed film dampers, friction in the bearings, air and temperature effects.

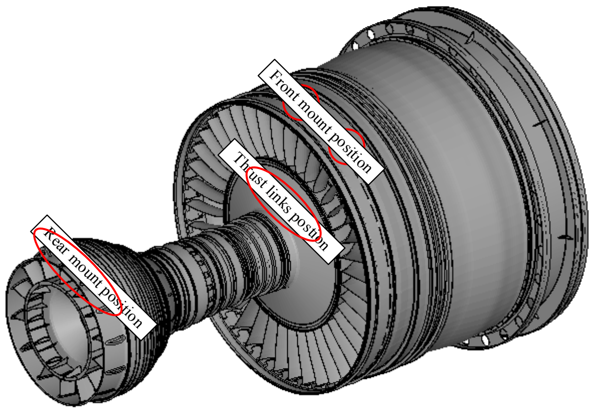

Figure 3. Full-engine model

A full-engine using LS-DYNA is shown in Figure 3, of which X axis is in horizontal direction, Y axis is in axial direction, and Z axis is in vertical direction of the engine. The finite element model is mainly made of eight-noded reduced integration constant stress brick elements, while shell elements are used as coating elements between blades and disks. Tied contacts are used to join flanges of stationary cases. For the case without LRD, relative sliding between the inner and outer ring of bearing No.2 would never occur. The interface between the inner and outer ring of bearing No.2 is simulated by tied contact in this model. For the case with LRD, the inner and outer ring of bearing No.2 are restrained by pins and relative sliding between the inner and outer ring

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is not allowed in normal operation. After FBO event, these pins would fail under imbalance load, and relative sliding between the inner and outer ring of bearing No.2 is permitted. Therefore, interface between inner and outer ring of bearing No.2 is simulated with surface-to-surface contact for the case with LRD.

Both the fan blades and the fan case are made of composite materials for the engine analyzed. As full dynamic interaction between the fan and the containment case must be captured precisely to predict the dynamic loads correctly, it's important to mesh the fan blades in great detail. Thus a fully-bladed fan-rotor model is adopted, as shown in Figure 2, including three finely- meshed blades and all other blades with relatively coarse mesh. These three finely-meshed blades are the primary released blade (RB), the first tailing blade (TB1) and the second tailing blade (TB2).

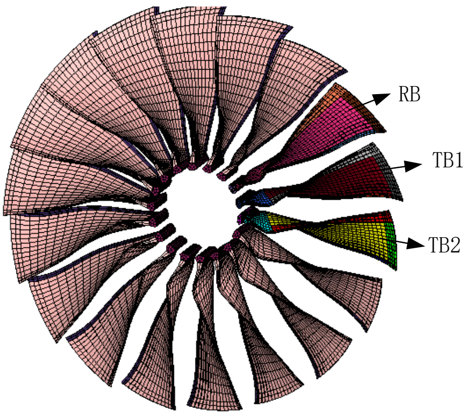

Figure 4. Finite Element Model of the Fan Blades

The full-engine model is attached to the aircraft wing through the mount systems and the pylon at three positions. To simulate this boundary condition, following constraints are applied. Node groups have been established in the finite element model corresponding to locations of the front mount, the rear mount, as well as the thrust rod on the engine, shown as white nodes in Figure 3. Degrees of freedom of these node groups corresponding to the front mount and the rear mount are restrained in X-direction and Z-direction respectively, while degree of freedom of the node group corresponding to thrust rod is restrained in Y-direction.

IV. DISCUSSION OF SIMULATION RESULTS

A FBO event on a full-engine finite element model is simulated using LS-DYNA. The LP rotor operates at its red line speed at the beginning, one of fan blades (RB) breaks from its root. Both cases with and without LRD are calculated. Comparison of their results are carried out and analyzed to demonstrate the influence of LRD on the engine's dynamic characteristics.

A. Damage of fan blades

A released blade (RB) is set free from its root as the initial condition of the simulation. Progressive damage of fan blades can be found in Figure5 for the case with LRD. Velocity vector of RB is tangential to the fan case initially, with its center of gravity moving in a direction perpendicular to its instantaneous radial direction rotating about its center of gravity to keep conservation of angular momentum. Once the released blade is in contact with the fan case, direction of its velocity vector begins to change. As a result of interaction with the inner of the fan case, the released blade will be bent and broken. Later, TB1 will hit RB and be damaged into fragments at almost 3.3ms, whose fragments might hit TB2. Meanwhile, other coarse meshed fan blades would rub against the fan case along with the orbit of the LP rotor, causing damage to the other fan blade tips.

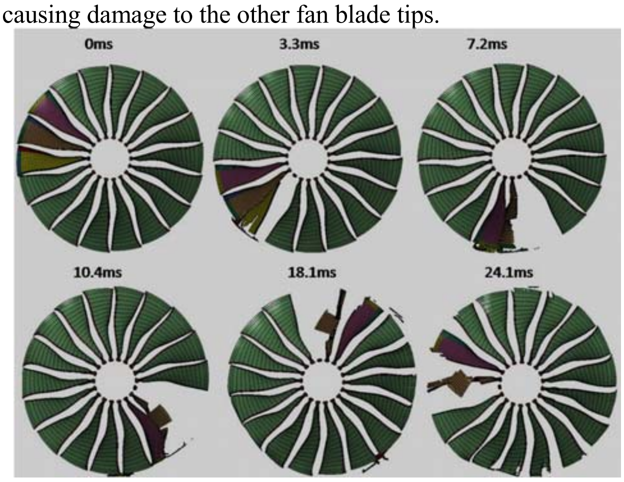

Figure 5. Progressive damage of fan blades for case with LRD

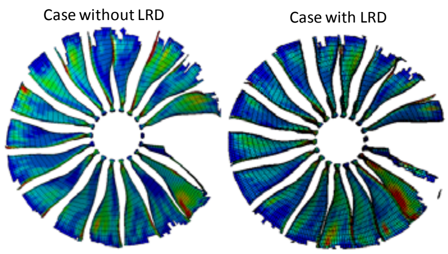

Figure 6. Damages of fan blades after 60ms

It can be seen from Figure5 that the damaged fan has rotated about 1/3 round at 7.2ms, 1/2 round at 10.4ms, 3/4 round at18.1ms and one whole round at 24.1ms. After 60ms of a FBO event, damaged fan blades for cases with and without LRD are shown in Figure 6. It can be seen that for the engine analyzed here, the damages to the fan blades caused by FBO are similar for these two cases. It is mainly because two factors affecting the damages of the fan blades most, which are skating of RB on the inner of the fan case and hitting of RB with TB1 and TB2, both occur before the failure of primary fuse. Orbiting trace of the fan rotors, which is closely related to failure of primary fuse, mainly affects the rubbing of other coarsely-meshed blades against the fan case. However, loss of blade tips for the coarsely-meshed blades is very small compared to the blade loss caused by the two factors mentioned above. Thus, losses of

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fan blades for these two cases with and without LRD are close to each other.

B. Failure of LRD structures

For the case with LRD, time-history animation of the results in LS-DYNA PrePost clearly demonstrates that secondary fuse fails earlier than primary fuse, so failure of the secondary fuse will be discussed prior to that of the primary fuse.

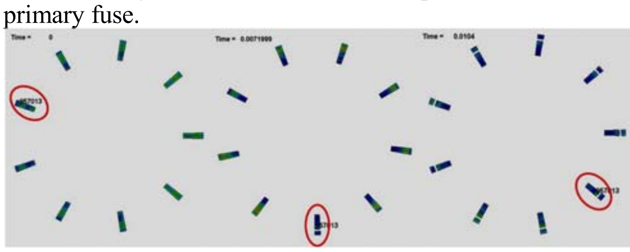

Figure 7. Failure of the pins

In this study, secondary fuse refers to several shear pin set between the inner and outer ring of bearing No.2. Failure of these pins is shown in Figure 7. It disclosed that the first broken pin is found at 7.2ms, corresponding to 1/3 revolution of the fan rotor from the moment of FBO. Its position is next to RB in circumferential direction. And other pins are broken in succession. All shearing pins have been cracked at 10.4ms after the occurring of a FBO event, corresponding to almost 1/2 revolution of the fan rotor. Failure of these pins results in relative sliding between the inner and outer ring of bearing No.2. This is helpful to avoid local stress concentrating of the fan shaft near bearing No.2.

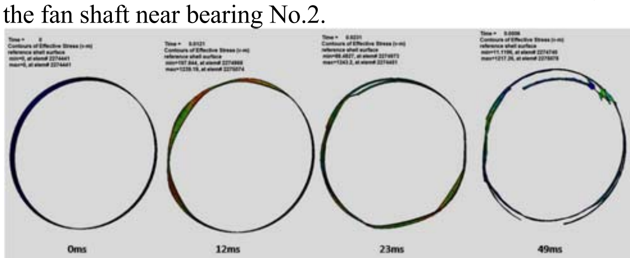

Figure 8. Progressive failure of the hollow cone for the case with LRD

Primary fuse is a hollow cone on the support of bearing No.1, which is between the forward bearing seat and the aft mounting flange. For the case without LRD, support of bearing No.1 keeps integrated after FBO event. For the case with LRD, equivalent stress of the hollow cone at different time after occurrence of FBO event is shown in Figure 8. It can be seen that the hollow cone displays obvious buckling at 12ms, which is just after 1/2 revolution of the fan rotor from the moment RB gets released. And serious damage of the primary fuse can be found at about 23ms. This demonstrates that bearing No.1 support has failed and lost the capacity to transfer load from the forward bearing seat to the aft mounting flange. This increases the flexibility of the shaft and in turn, the fundamental natural frequency of the rotor would drop.

C. Dynamic loads on main structures

(1) Bearings.

LP rotor is affected by FBO event directly. Its shaft and supporting bearings undertake most of the imbalance loads and are in main load paths. Influences of LRD on radial forces of each bearing are analyzed here. Time-history curves of radial forces on each bearing are shown in Figure 9, Figure10 and Figure11 respectively.

Time-history curves of radial force of bearing No.1 are shown in Figure 9. For the case without LRD, radial force of bearing No.1 remains at a relatively high level with a large peak load after a FBO event, and fluctuates periodically with time, due to rotation of the damaged fan. For the case with LRD, radial force of bearing No.1 increases at first, then stays stable and later decrease slightly within 23ms, and decreases sharply to almost zero as primary fuse on its support fails. Thus, its bearing capacity loses after 23ms of the FBO event.

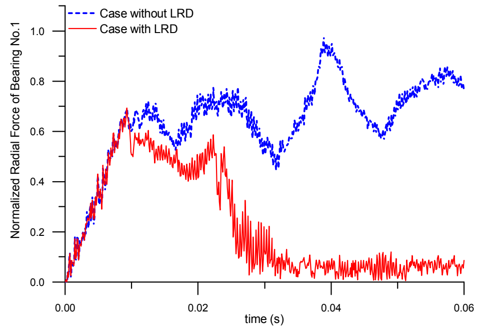

Figure 9. Radial force of bearing No.1

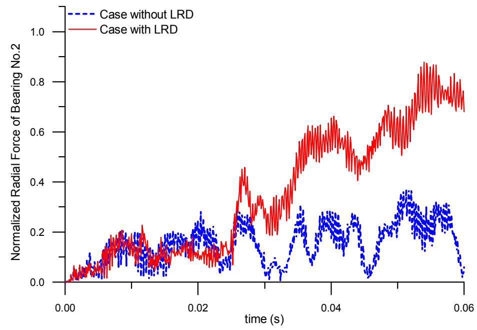

Figure 10. Radial force of bearing No.2

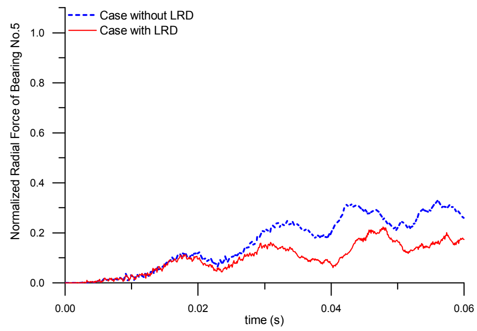

Figure 11. Radial force of bearing No.5

Time-history curves of radial force of bearing No.2 for cases with and without LRD are shown in Figure 10. It can be found that: radial force of bearing No.2 has not been influenced by LRD significantly during the first 23ms after the FBO event. However, it increases dramatically after 23ms for the case with LRD, and is much higher than that of the case without LRD. For the case without LRD, the FBO load is mainly undertaken by bearing No.1, thus load on bearing No.2 keeps relatively low. After introduction of LRD, support of bearing No.1 fails after 23ms, leaving the imbalance load shift to bearing No.2.

Time-history curves of radial force of bearing No.5 for cases with and without LRD are shown in Figure 11. It can be found that, after a FBO event, the radial force of bearing No.5 increases gradually for both cases. Besides, radial load of bearing No.5 for the case with LRD is relatively smaller than that of the case without LRD.

As the time-history curves of radial force of each bearings for cases with and without LRD shown in Figure 9, Figure 10 and Figure 11, it can be found that, for the case without LRD, radial force of bearing No.1 is the largest, while that at bearing No.2 and No.5 are relatively small. Little difference can be found for radial forces at bearing No.1, bearing No.2 and bearing No.5 between cases with and without LRD before primary fuse fails. While after failure of primary fuse on support of bearing No.1, radial force of bearing No.1 reduces to almost zero. The radial force of bearing No.2 increases sharply and that of bearing No.5 is still relatively small.

(2) Fan frame.

Fan frame is the major load-bearing case in aeroengine. Its forward flange is connected to the fan case and the aft flange connected to the high-pressure (HP) compressor case. Time history curves of dynamic loads on the forward and aft flanges of fan frame are shown below.

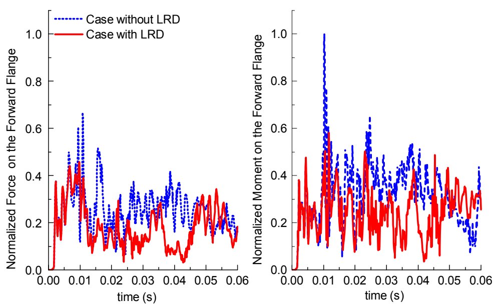

Figure 12. Load on the forward flange of the fan frame

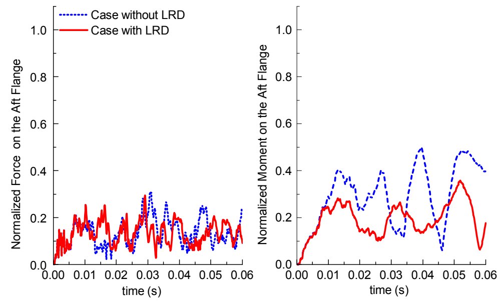

Figure 13. Load on the aft flange of the fan frame

Figure 12 and Figure 13 show the normalized time-history curves of both resultant force and moment at the forward flange and the aft flange respectively. It can be seen from curves in Figure12 that application of LRD will not only significantly decrease the force but also the moment, which are imposed to fan frame on the forward flange connected to the fan case. In addition, Figure13 also demonstrates that application of LRD helps to decrease the moment at the aft flange, thus LRD has negligible effect on the load at the aft flange. As the forward and aft flanges are the two main joints for fan frame, it can be concluded that the total loads transmitted to frame are decreased dramatically after application of LRD.

(3) Mount system.

Boundary condition of the full-engine finite element model analyzed here is shown in Figure 2. The engine's radial (X-axial and Z- axial direction) degree of freedom is constrained with the front/rear mounts, while its axial degree of freedom is constrained by the thrust rod.

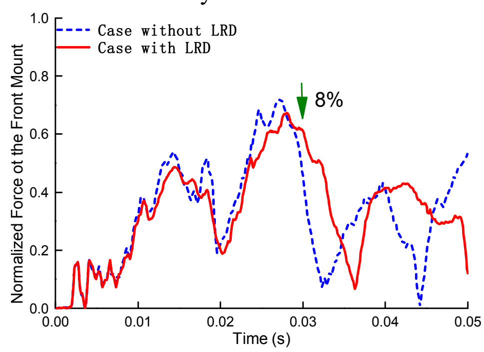

Figure 14. Radial reaction force of the front mount

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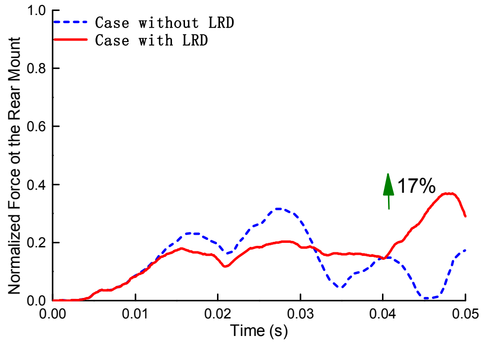

Figure 15. Radial reaction force of the rear mount

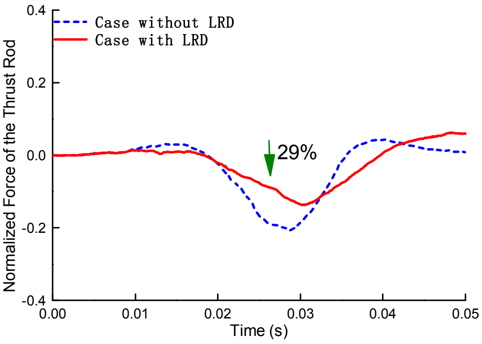

Figure 16. Axial reaction force of the thrust rod

Plots shown in Figure 14, Figure15 and Figure16 are obtained by analyzing the constraint reaction force of front and rear mounts in radial direction, and the constraint reaction force of thrust rod in axial direction. Comparisons of the results for cases with and without LRD are carried out based on the currently adopted structure parameters. Figure14 demonstrates the peak value of time-history radial reaction force on the front mount decreases by 8%, Figure15 shows the peak value of the rear mount increases by 17%, and Figure16 shows that of the thrust rod decreases significantly by 29%. Thus, loads of both the front mount and the thrust rod have decreased while that of the rear mount has increased after the application of LRD. However, increasing of the load on the rear mount shall not put the aeroengine in danger as load of the front mount is far greater than that of rear mount for the case with LRD. Without application of LRD, ratio of loads on the rear mount and the front mount is 0.44, while this has increased to 0.56 after application of LRD. Thus, LRD helps to shift some of the abnormal loads from the front mount to the rear mount, which is helpful for the safety of the front mount.

D. Maximum equivalent stress of main stationary frames

To further determine the load-reducing effect of LRD, maximum equivalent stresses on the main load-bearing frames of the engine, including fan frame, turbine connection frame (TCF) and turbine rear frame(TRF), are analyzed and compared for cases with and without LRD after a FBO event. This is carried out by imposing the peak values of time-history curves of loads on corresponding flanges of these frames using finite element software ANSYS. Checking the results in ANSYS, the bar graph in Figure 17 can be obtained.

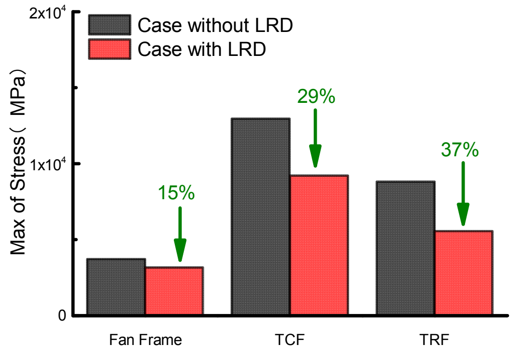

Figure 17. Maximum equivalent stress of main load-bearing frames

Figure 17 shows that maximum equivalent stress on fan frame is the smallest while that of the TCF is the largest. Application of LRD is useful to reduce the equivalent stresses of all these load-bearing frames. And the reduction amount of maximum equivalent stress of TCF is the highest (by 29%), while that of fan frame is the lowest (by 15%). Therefore, reduction amount for the frame with the largest equivalent stress is highest. And this is not only effective to keep the engine safe after a FBO event, but also helpful to design the engine in a relatively light weight for normal operation.

V. CONCLUSIONS

Influences of LRD on dynamic loads of commercial aero engine induced by FBO event are examined based on a full-engine finite element model for cases both with and without LRD using LS-DYNA, and comparisons of the results related to damage of fan blades, failure of LRD structures, dynamic loads on bearings, flanges and mount systems, as well as maximum equivalent stress of stationary frames are performed. The following conclusions can be made based on these analyses.

1) For the case with LRD, secondary fuse fails earlier than primary fuse. And all of them would fail within one revolution of the fan rotor after the release of RB.

2) Failures of LRD would change the imbalance load path, shifting loads from bearing No.1 to bearing No.2, but with minimal effect for the load on bearing No.5.

3) Application of LRD would reduce the reaction loads on the front mount and the thrust rod, while increase the reaction load at rear mount slightly, which is useful to shift some of the loads from the heavily-loaded front mount to the lightly-loaded rear mount.

4) Both the load transferred to fan frame through flanges and the maximum equivalent stress on main load-bearing frames are reduced after application of LRD.

5) Adopting LRD can reduce the FBO loads of an aeroengine without increasing its weight significantly, thus it is helpful for aeroengine design.

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