Foreign object damage simulation of aero-engine blade

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Abstract. To study the anti-foreign object damage (FOD) ability of aero-engine compressor blades, finite element model of compressor blades was established. Blades damage was evaluated with different steel ball diameters and shock angles. Results show that the damage width and depth becomes bigger with the steel ball’s diameter increases. The damage width doesn’t change apparently with the shock angles, and the damage width nearly equals to the steel ball diameter. The damage depth mostly becomes smaller with the increase of shock angle.

1. Introduction
The seventh stage compressor blades of one type of aero-engine were found damaged and distorted in use. According to the maintenance requirements, damaged blades need to be replaced, which leads to the waste of aero-engine. When aero-engine operates near the ground, all kinds of foreign objects moving with the high speed airflow were sucked. When the foreign object is bird, it is usually called soft object shock. When the foreign object are stone, gravel, bolt and rivet, they are called hard object shock. Only the damage caused by the hard object shock is called foreign object damage (FOD) in the design specification, standards and manuals.

There is residual stress near the FOD. It is usually thought that fatigue strength of components can be enhanced by compressing residual stress and reduced by stretching residual stress. Therefore there is need to do research in residual stress near FOD. Boyce[2], Duo[3]once measured the residual stress near FOD with X-ray diffraction method. But the measuring accuracy is restricted for the small size of FOD and big residual stress gradient. Therefore FOD simulation is recommended by researchers.

FOD simulation is numerical solution of shock boundary question. Currently, nonlinear finite element method is used widely. Besides, many kinds of business software can be used, like LS-DYNA, MS/DYTRAN, ABBUS/Explicit. Lin[4], Tranter[5], Wei Xuexia[6], Luo Rongmei[7], Ji Yuhui[8], Yin Dongmei[9] et al. used one kind of business software to carry out FOD simulation, and the used material models include ideal elastic model, bilinear relevance model, Johnson-Cook model.

Johnson-Cook model was used in this paper to do research in FOD simulation for the seventh stage blade of one aero-engine.

2. Establishment of Blade FOD model

2.1. Blade finite element model
Eight-node hexahedron element was used to establish the seventh stage blade finite element model, as
shown in figure 1.

![Blade finite element model.](image)

Figure 1. Blade finite element model.

2.2. material parameters
The shock foreign object is steel ball, and its material parameters is shown in table 1.

| Material | \( \theta \) (°C) | \( \nu \) | \( E \) (GPa) | \( \sigma_s \) (GPa) | \( G \) (GPa) | \( \epsilon_y \) | \( \rho \) (kg/m³) |
|----------|----------------|--------|--------------|------------------|-------------|----------|----------------|
| GCr15    | 20             | 0.29   | 212          | 1.7              | 82.5        | 0.40     | 7810           |

The blade material is TC8, and Johnson-Cook material model is used in simulation. The material parameters are shown in table 2.

| Material parameters                      | Symbol | Value  |
|------------------------------------------|--------|--------|
| Density                                  | \( \rho \) (kg/m³) | 4436   |
| Elastic inertia                          | \( E \) (GPa)    | 125    |
| Shear modulus                            | \( G \) (GPa)    | 46.7   |
| Poisson ratio                            | \( \nu \)      | 0.3    |
| J–C yield strength                       | \( A \) (MPa)   | 880    |
| J–C hardening coefficient                | \( B \) (MPa)   | 162.39 |

2.3. Blade shock velocity
Relative parameters of blade shock velocity are shown in table 3.

| Blade stage | Shock area radius (mm) | \( V_{\text{tangential}} \) (m/s) | \( V_{\text{air}} \) (m/s) | \( V \) (m/s) |
|-------------|------------------------|-----------------------------------|-----------------------------|--------------|
| 7           | 145.2                  | 297.07                            | 137.91                      | 327.52       |

2.4. simulation parameters
Steel balls with different diameters were used in blade shock simulation in different angles. The direction of movement goes through the center of the leading edge, as shown in figure 2.
3. Blade FOD simulation

FOD simulations were carried out with steel balls of 1mm, 2mm at angles 0°, 30°, 45°, 60° and 90°, results are shown in table 4 and figure 3.

Table 4. Simulation results of blade FOD.

| Shock velocity (m/s) | Steel ball diameter (mm) | Shock angle (°) | Damage width (mm) | Damage depth (mm) | Damage appearance |
|---------------------|--------------------------|-----------------|-------------------|------------------|------------------|
| 327.52              | 1                        | 0               | 1.07519           | 0.61695          | gap              |
| 327.52              | 1                        | 30              | 1.08079           | 0.60376          | gap              |
| 327.52              | 1                        | 45              | 1.00731           | 0.59971          | gap              |
| 327.52              | 1                        | 60              | 1.15898           | 0.54724          | gap              |
| 327.52              | 1                        | 90              | 0.97835           | 0.56614          | gap              |
| 327.52              | 2                        | 0               | 2.14796           | 1.75698          | gap              |
| 327.52              | 2                        | 30              | 2.02766           | 1.37445          | gap              |
| 327.52              | 2                        | 45              | 2.02431           | 1.20014          | gap              |
| 327.52              | 2                        | 60              | 2.01644           | 1.09977          | gap              |
| 327.52              | 2                        | 90              | 2.09472           | 0.96306          | gap              |

The blade FOD appearances are shown in figure 3, it can be seen that the damage appearances are gaps, and there are no cracks and pits.

(a) Damage appearance when the diameter of steel ball is 1mm.

(b) Damage appearance when the diameter of steel ball is 2mm.

Figure 3. Blade damage appearances.
It can be seen from Table 4 and Figure 3 that the bigger the steel ball’s diameter is, the bigger the damage width and depth are. The damage width doesn’t change apparently with the shock angle. The damage width caused by shock nearly equals to the diameter of the steel ball. For the steel ball with diameter 1mm, the damage depth decreases with the shock angles and increases when the shock angle equals to 90°. For the steel ball with diameter 2mm, the damage depth decreases with the shock angles.

4. Conclusion
Finite element simulation of aero-engine’s seventh compressor blades was carried out. The changing laws of damage size and damage appearance with shock angles and steel ball diameters were studied. The conclusion is that damage width and damage depth increases with the steel ball’s diameter becoming bigger. The damage width nearly equals to the steel ball’s diameter and has a weak correlation with the steel ball’s diameter. The damage depth has a negative correlation with the shock angle.

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