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Determination of Impact Force for Turbine Housing Containment

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***Abstract*— In the Turbo-chargers, it is well known that the rotary parts may sometimes be subjected to extremely high centrifugal forces which could cause the bursting of turbine wheels at their most highly stressed regions or in portions where some material flaw exits. Wheel fragments can cause catastrophic failures, which can lead to Fire accidents. Extensive testing is essential to design the Turbine housings to contain the wheel fragments, which eventually meets the Safety norms. Finite Element Analysis or Mathematical models are alternate to minimize the testing, but they are not granted as a substitution. Simulations need to be conducted to study the impact forces and energy generated by fragments during the wheel burst. This paper presents the Finite Element Analysis of wheel burst for determination of impact eenergy and related fragment characteristics, in which the wheel burst is achieved within a predetermined rotating speed range. The fragments size of the turbine wheel varied significantly with the weakening method. The objective of this study is to capture the fragment characteristics and accurately represent the practical phenomena in simulations. Good agreement was found between the results of the simulations and testing.**

This paper presents the wheel burst analysis of the light duty application turbine wheels, for which speeds vary between 1,50,000 rpm to 2,00,000 rpm. An Explicit ANSYS AUTODYN technique is used to simulate the wheel burst. In this study, strain rate dependent strength model and plastic strain failure models are used model the wheel material behavior

Keywords—Turbine wheel; wheel burst; numerical simulation; impact energy

I. INTRODUCTION

Turbocharger wheel operates under high temperature exhaust gasses and subjected to high rotational velocity, engineers should design wheels to with stand all the extreme operating conditions. But at any point of time, a certain combination of operating conditions may always lead to failure. Smaller turbochargers can see speeds up to 200000 rpm from 150000 rpm, and can experience a temperature of 700°C approximately. Material strength reduces drastically at higher temperatures. [6] Weak links in design, material defects and stress raisers are potential locations for failure, they also dictates the failure modes. Wheels primarily have blade detachment and hub burst as failure modes. Even though burst accidents happen infrequently nowadays, they are not completely avoidable. Fig. 1 shows a CF6-80A2 engine high pressure turbine disk burst accident that happened at Los Angeles International Airport in June 2006 (Aviation Safety Network, 2006). In 2010, another serious turbine disk burst accident (Fig. 2) was reported in a Qantas A380 engine (Hradecky, 2010). [1] Therefore, it is significant and necessary to study the impact by turbine wheel burst fragments.

Fig. 1 A CF6-80A2 high pressure turbine disk burst accident which occurred at Los Angeles International Airport (Aviation Safety Network, 2006).

Turbocharger turbine blades basically have three critical regions on which attention should be focused: the weakening slot, the blade root and the hub zone. The hub root area usually represents the most critical area from the point of view of the static and fatigue approaches. The loads associated with this region are mainly the centrifugal forces and thermal stresses.

In this study, the focus is given to analysis of the damage mechanisms of the turbine blades subjected to both operational and over speed conditions and also to indicate critical areas, from the point of view of the stress analysis. The additional goal of this analysis is to improve the safety and reliability of the turbocharger.

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Fig. 2 A Rolls Royce Trent 972 intermediate pressure turbine disk burst accident which occurred near Singapore (Hradecky, 2010)

II. COMPUTATIONAL SCHEME

The Lagrangian processor expresses the partial differential equations of conservation of mass, momentum and energy in Lagrangian coordinates. Together with the material model and a set of initial and boundary conditions, the complete solution of a problem is defined. The Lagrangian grid is deformed with the associated material, thus the conservation of mass is automatically satisfied. The density is calculated from current volume of grid element and the initial mass by Eq.1

$$\rho = \frac{\rho_0 V_0}{V} = \frac{m}{V} \quad (1)$$

Acceleration is related to the stress tensor σ_{ij} by the partial differential equations of conservation of momentum (see Eq. 2)

$$\rho\ddot{x} = b_x + \frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{xy}}{\partial y} + \frac{\partial\sigma_{xz}}{\partial z}$$

$$\rho\ddot{y} = b_y + \frac{\partial\sigma_{yx}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{yz}}{\partial z} \quad (2)$$

$$\rho\ddot{z} = b_z + \frac{\partial\sigma_{zx}}{\partial x} + \frac{\partial\sigma_{zy}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}$$

Conservation of energy is expressed via Eq.3

$$\dot{e} = \frac{1}{\rho}\left(\sigma_{xx}\dot{\varepsilon}_{xx} + \sigma_{yy}\dot{\varepsilon}_{yy} + \sigma_{zz}\dot{\varepsilon}_{zz} + 2\sigma_{xy}\dot{\varepsilon}_{xy} + \sigma_{yz}\dot{\varepsilon}_{yz} + \sigma_{zx}\dot{\varepsilon}_{zx}\right) \quad (3)$$

These equations are solved explicitly for each element in the model, based on input values at the end of the previous time step. Small time increments are used to ensure stability and accuracy of the solution. In Explicit Dynamics there is no any form of equilibrium; simply results are taking from the previous time point to predict results at the next time point. There is no requirement for iteration.

In a well-posed Explicit Dynamics simulation, mass, momentum, and energy should be conserved. Only mass and momentum conservation is enforced. Energy is accumulated over time and conservation is monitored during the solution.

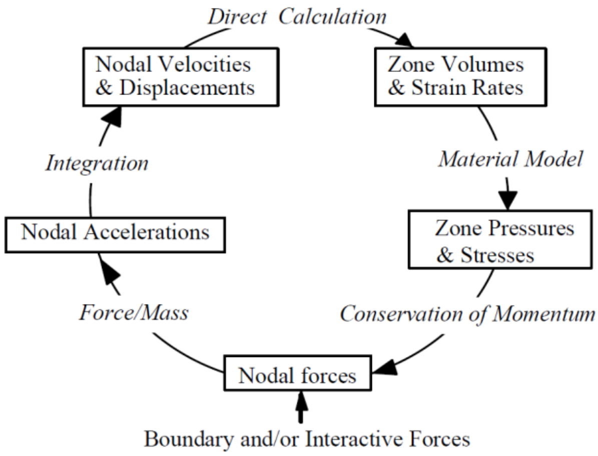

Fig.3 Solution Strategy for explicit dynamics

III. EXPLICIT TIME INTEGRATION

Explicit methods calculate the state of a system at a later time from the state of the system at the current time. If $Y(t)$ is the current system state and the Y (t+Δt) is the later state then, Y (t+Δt) =F(Y (t)).[10]

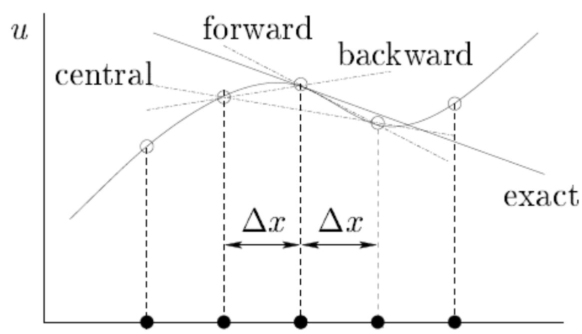

Fig.4 Central difference integration method

The central difference formula is, $\left(\frac{\partial u}{\partial x}\right)_i = \frac{u_{i+1} - u_{i-1}}{2\Delta x}$

After forces have been computed at the nodes of the mesh (resulting from internal stress, contact, or boundary conditions), the nodal accelerations are derived by equating acceleration to force divided by mass.

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Therefore the accelerations are,

$$\ddot{x}_i = \frac{F_i}{m} + b_i$$

Where,

$\ddot{x}_i$ = Component of nodal acceleration.

F_i = Forces acting at the nodal points.

b_i = Components of the body acceleration.

m = Mass of the node.

The velocity at time n+$\frac{1}{2}$ are determined as,

$$\dot{x}_i^{n+1/2} = \dot{x}_i^{n-1/2} + \ddot{x}_i^n \Delta t^n$$

The displacements at time n+1 are calculated as,

$$x_i^{n+1} = x_i^n + \dot{x}_i^{n+1/2} \Delta t^{n+1/2}$$

The advantages of using this method for time integration for nonlinear problems are:

- The equations become uncoupled and can be solved directly (explicitly). There is no requirement for iteration during time integration.
- No convergence checks are needed because the equations are uncoupled.
- No inversion of the stiffness matrix is required. All nonlinearities (including contact) are included in the internal force vector.

IV. IMPACT PHENOMENA

For a linear elastic isotropic solid, equilibrium conditions and stress-strain relations lead to the following equations

$$\begin{aligned} \sigma_{ij,j} + \rho f_i &= \rho \ddot{u} \\ \sigma_{ij} &= \lambda \varepsilon_{kk} \delta_{ij} + 2\mu\varepsilon_{ij} \\ \varepsilon_{ij} &= \frac{1}{2}(u_{i,j} + u_{j,i}) \end{aligned} \quad (4)$$

where σ_{ij}, ε_{ij} and u_i stand for stress, strain and displacement, respectively, ρ is the mass density, fi are body forces, and λ, μ are Lamé constants. Combining Equations, taking into account that body forces fi are negligible, and eliminating σ_{ij} and u_i, the following wave equation is obtained

$$\rho \frac{\partial^2 \Delta}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 \Delta}{\partial x_i \partial x_i} \quad (5)$$

where Δ represents the first invariant of the stress tensor. The speeds of the elastic stress waves,

$$c_1^2 = \frac{(\lambda + 2\mu)}{\rho} = \frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)} \quad (6)$$

$$c_s^2 = \frac{\mu}{\rho} = \frac{E}{2\rho(1+\upsilon)}$$

where E and υ are the Young modulus and the Poisson ratio, respectively, c_1 and c_s denote respectively the longitudinal and transversal wave speed.[4]

V. LOADS, BOUNDARY CONDITIONS AND MATERIAL PROPERTIES OF FE MODEL

Turbine wheel in a turbocharger is subjected to a combination of aerodynamic loads, thermal and mechanical loads. The mechanical loads are Centrifugal forces generated due to the product of wheel mass, radius and angular velocity squared. Turbine wheels are tested and simulated/tested at approximately 50% higher than their design speeds. Turbine housings are designed to absorb this high Kinetic Energy. By applying angular velocity, rotational phenomenon of turbine wheel is replicated in numerical simulation. [5]

Hub burst is a rare phenomenon, it is primarily driven by material defects in casting. On the other hand, blade detachment is often seen due to fatigue failures (High cycle fatigue and Low Cycle Fatigue). The current study is to determine the impact force generated due to the blade detachment failure mode. In order to achieve blade detachment, turbine wheel is artificially weakened. The weakening slots with a certain depth causes stress concentration which was sufficient to induce crack at the desired speed.

Material used for the turbine wheel is INCONEL. The similar material properties are used for turbine wheel as per [3]

Linear tetrahedral element is used for meshing as it can capture geometry more accurately. For meshing the Patch independent algorithm is used. Critical areas are finely mesh considering the mesh sensitivity study. Angular velocity will be given as initial condition for simulation.

Explicit Dynamic Finite Element Analysis is incorporated to perform the wheel burst analysis, since it is the best technique to capture the high velocity phenomenon. The number of elements and nodes for the wheel model are approximately one lakh and two lakh respectively.

VI. MATERIAL MODEL

For ductile material of the turbine wheel, the Johnson-Cook (J-C) strength model was used. The J-C model takes into account of high strain rate sensitivity, large deformation, and material softening due to adiabatic heating and damage, so it is quite well suited to problems of metal impact and penetration. Johnson and Cook (1983) expressed the von Mises flow stress as,

$$Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\log \varepsilon_p^*\right]\left[1 - T_H^m\right] \quad (7)$$

Where,
ε_p = effective plastic strain
ε_p^* = normalized effective plastic strain rate
T_H = Homologous temperature
$= (T - T_{room})/(T_{melt} - T_{room})$

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The five material constants are A, B, C, n and m. The first set of brackets in Eq. gives the stress as a function of strain, which can be found by quasi-static tensile testing ($\dot{\varepsilon}_p$= 1.0sec−1 and T_H= 0). A is the basic yield stress at low strains whereas B and n define strain hardening. The second and third set of brackets represent the effects of strain rate hardening and temperature softening. With the thermal softening, the yield strength drops to zero at the melting temperature T_{melt}. The material constants can be obtained empirically from J-C material model as shown in table 1. [6]

The effective plastic strain failure criteria is used in this study for prediction of damage [8].

VII. WHEEL BURST SIMULATION

The Purpose of wheel burst simulation is to capture the fragments characteristics. In this study, impact of weakening locations on impact force is carried out. Since the impact force is dependent on fragments mass and fragment velocity, they can vary with respect to weakening location. Assuming higher impact force can lead to overdesign of turbine housing which increases the cost. On the other hand lower impact force may lead to weak housing design, it can lead to catastrophic failure during wheel burst.

VIII. CONCLUSIONS

Form this study it is concluded that the fragment mass should be minimum 50% of the single blade mass. While designing the new wheel, this study gives the guidelines for impact force calculation. It is anticipated that the current study could provide a useful guideline to the industry community to enhance the containment capability at design stage.

IX. FUTURE WORK

Identify the minimum wall thickness for turbine housing to absorb impact force generated during wheel burst.

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