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Introduction to Turbocharger Containment Testing using Finite Element Explicit Dynamics

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Abstract—*Containment is the capability of housing to contain burst component to avoid catastrophic failure. So to save human and product life from this severe failure containment test is carried out before its consumer use. In this study basic of turbocharger, containment testing such as burst scenario, energies associated with it, Theory behind explicit dynamics solving technique, material Plasticity model for FEA simulation, force associated with the impact is explained.*

Keywords*: Containment, Explicit dynamics, Johnson Cook Model, Impact force.*

1. INTRODUCTION

In today's fast moving world everyone is strived to the more and more power of their vehicle, which lead to development of new technology to empower the engine of the vehicle which is well known as turbo charging technology. A turbocharger is turbine driven force induction device which forces extra air into the engine to improve efficiency and the power of the engine. In Figure. 1 all parts associate with turbocharger and its working is explained. Turbocharger mainly consist of Turbine housing, compressor housings, wheels and accessories for rotating system. Turbine takes exhaust from the engine radially which rotates wheel and leaves axially, Due to this rotational motion compressor wheel is coupled with the turbine wheel by means of shaft starts rotating, which takes fresh air axially and gives to the engine. Volute design of housing has major role in pressure and velocity development in turbocharger.

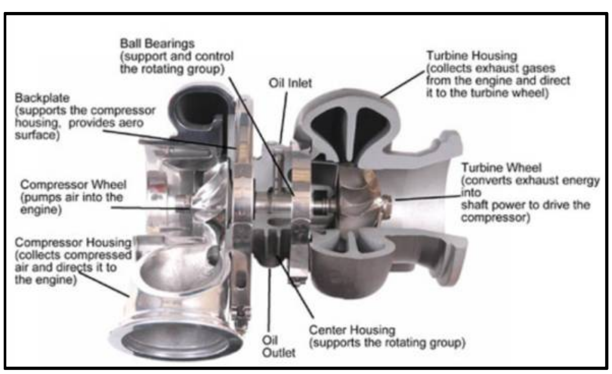

Figure 1: Assembly of turbocharger [1]

A well designed turbocharger may have no failures in the future but in case moto-sport cars safety of the turbocharger is not really considered. Today's turbos are subjected to vey higher speeds, hotter temperatures and severe duty cycles. New wheels, housings and complete turbos are constantly being developed to make its efficiency higher than the previous generations. This may lead to be great to ignore safety and go for the lightest wheels and thinnest housings possible, in order to get more and more performance from the turbo and the race vehicle. But if a turbo manufacturer focuses on performance only and does not qualify their products to contain both compressor and turbine wheel bursts, then there is no guarantee that the high-velocity wheel fragments will remain inside the housings if the turbo is intentionally or accidentally pushed past its safe operating limits. The severity of turbocharger burst is shown in figure.

Figure 2: Burst during containment testing [2]

Turbocharger containment is the capability of a turbine or compressor housing to contain a burst wheel. It is essential to ensure the product safety and to prevent catastrophic accidents.

When turbine and compressor wheel of the turbochargers fails to hold itself against centrifugal force then burst may occur. The temperature and the speed are the major contributors for the reduction of strength of these wheels.

The centrifugal force that the wheel must resist is proportional to the square of the rotational speed, and the strength of typical wheels falls off drastically at temperatures above their critical limits. Wheels are designed to resist the stresses associated with high temperatures but there is always a limit, sole effect of these two parameters leads to burst.

There are two major types of bursts occurs in general practice those are hub burst and blade detachment. These two bursts are shown in Figure. Hub burst is the more severe condition in which it gets burst in two or more large pieces while in case of blade detachment root of the blade which attached to the hub cannot resist the centrifugal force and two more blades gets detached from the hub. It is highly recommended to use high quality of oil for lubrication and heat dissipation so that its temperature will not rise and wheels will rotate at required speed without failure [2].

Figure 3: Hub burst and wheel detachment. [3]

There are several other means for burst such as foreign object damage, fatigue stress and material inability. The turbocharger rotor systems runs at very high speed ranging from 80000-200000 RPM depending upon its size and application, When foreign object such as rock, broken pieces of welds etc. Comes in contact with turbocharger in running conditions from compressor side, it may get collide on the rotating system which leads to catastrophic failure. Again in case fatigue Low cycle fatigue is the most severe for the hub burst. For example city bus driver needs to take his passenger from various stations, so it is required to accelerate and deaccele rate the bus several times. Also microscopic material defect may lead to form crack and after some certain amount of cycles this crack gets propagate to wheel burst.

After burst of the wheel Hugh amount of energy in the form rotational kinetic energy gets released which gets incident on the housing in terms of impact force. This rotational kinetic energy can be expressed in below equation 1.

$$E = \frac{1}{2} I\omega^2 \quad (1)$$

Where E =Rotational kinetic energy of rotating object

I=moment of inertia of rotating object

ω=Angular velocity of the rotating object

In order to contain this rotating object after burst housing should overcome this much amount of energy. For designing a turbine or compressor housing from scratch, it is required to balance

High flow capacity, high aerodynamic efficiency, low weight, very tight clearances and tolerances to the wheel, dimensional stability at high temperature, and of course the capacity to contain bursts and other wheel failures. The ability of a particular housing to contain a burst is a function of overall shape, material wall thickness, strength, elongation and ductility.[2]

L. Wang *et.al. have* developed the finite element explicit dynamics approach to simulate containment testing of the turbocharger. In his analysis he has considered plasticity and fracture properties of material, by using response surface analysis he determined optimum groove depth and diameter for bursting of wheel at specified target speed.[4]

J M Ramamurthy *et.al.* have developed methodology for containment testing in his analysis he have used Area weighted mean hoop stress to determine margin of burst speed. Then simulation results are compared with several rig tests and validated. In both compressor & turbine side the wheel burst speed Simulation and rig test results towards the Burst speeds is seen to be less than 2%. [5]

Thomas Winter *et.al.* have developed methodology for turbocharger containment using linear piecewise plasticity material model and got very good correlation with experimental results.[6]

Xuan Hai-jun *et.al. have* analysed containment test using FEA and did actual test of aero-engine housing using series of double edged notched blades which are released at certain rotating speed to have an impact on inner wall of housing. Also he gave attention to the failure of the containment rings caused by the second impact. [7]

Yang Bin did blade containment evaluation of civil aircraft engine. He introduces margin of safety analysis which explains that the most critical compressor, turbine or fan blade at its maximum permissible rotating speed must be contained by the casings while the engine should operate continuously for at least 15 s. Engine fire and failure of mounting attachments during the tests are unaccepted, unless the resulting damage from blade failure induces an engine's self-shutdown. In addition, the blade release must occur at the outermost retention groove or at least 80% blade height. [8]

K. A. Dulaney *et.al.* have used multiple liners for the containment of high speed rotors, Using an analogous mass-spring-damper system, a model was developed with bond graph techniques to estimate containment loads and response. Then bond graphs, state equations, and simulation results are compared with experimental results. The model is able to predict the general trends observed in experimental data and is used as a design tool for containment

Systems. He also gave important observation that intensity of second impact gets reduces due to friction.[9]

Conger Bai *et. al.* have investigated the centrifugal compressor disk containment of auxiliary power unit (APU) in gas turbine, he showed that the fragments interact with the outer cover and the back shroud both in rotating plane and axial direction. He did verification tests on high-speed spin tester revealing both contained and uncontained cases and showed that the outer cover, the back shroud and the connecting bolts between them all play a significant role to containment. Adequate strength of these components is essential. Otherwise the outer cover will detach away and the back shroud will be damaged. [10]

Pranita Kesare et. al. studied wheel burst phenomenon, computational scheme and material model for FEA analysis of turbocharger containment testing.[11]

2. METHODOLOGY

Finite Element Explicit dynamics

FEA methods are generally resolved into the implicit method and the explicit method. Governing equation for both of these is general dynamic equation [2].

$$M\ddot{u} + C\dot{u} + Ku = F \quad (2)$$

Where M is mass matrix, C is damping matrix, K is stiffness matrix and F is the external force applied in the system.

The implicit FEA method iterates till static equilibrium condition is achieved at end of each load step. Increments are controlled by convergence criterion throughout the simulation. When the problem is highly non-linear, a large number of iterations are required to find equilibrium. This leads to invert global stiffness matrix multiple times till solution is obtained. Therefore it not only increase computational time but also memory to store the problem. Thus for to analyse problems under static and simple loading conditions Implicit method is mostly preferred.

The explicit method determines a solution by advancing the kinematic state from one time increment to the next, without iteration. It uses a diagonal mass matrix to solve for the accelerations, so there are no convergence checks. Therefore it is more robust and efficient for complicated problems, such as nonlinear behaviours, dynamic events, and nonlinear contact conditions such as multiple frictional contacts. But to obtain accurate results, the time increment has to be extremely small, which ensures that the acceleration through the time increment is nearly constant. Therefore it typically requires many thousands of increments. For this reason there is option of mass scaling to improve size of step. At the beginning of the time increment (t), based on the dynamic equilibrium equation:

$$P - I = M\ddot{u} \quad (3)$$

The nodal accelerations ($\ddot{u}$) are calculated as:

$$\ddot{u}|_{(t)} = (M)^{-1}(P - I)|_{(t)} \quad (4)$$

Where$M$ is the nodal mass matrix, P is the vector of externally applied force and I is the vector of internally induced element force. The acceleration of any node is completely determined by the mass and the net force acting on it. Through time the accelerations are integrated using the central difference rule, by which the change of the velocity is calculated from equation (4), assuming that the acceleration is constant:

$$\dot{u}|_{(t+\Delta t)} = \dot{u}|_{(t-\Delta t/2)} + \frac{\Delta t|_{(t+\Delta t)} + \Delta t|_{(\Delta t)}}{2}\ddot{u}|_{(t)} \quad (5)$$

The velocities are integrated through time and added to the displacement (u) at the beginning of the increment to calculate the displacement at the end of the increment.

$$u|_{(t+\Delta t)} = u|_{(t)} + \Delta t|_{(t+\Delta t)}\dot{u}|_{(t+\Delta t/2)} \quad (6)$$

The element strain increment $d\varepsilon$ is calculated from the strain rate, and then the stresses are obtained from constitutive equations: $\sigma|_{(t+\Delta t)} = f(\sigma|_{(t)}, d\varepsilon)$(7)

3. CENTRAL DIFFERENCE METHOD

Explicit methods calculate the state of a system at a later time from the state of the system at the current time. If $Y(t)$ the current system state and the $Y(t + \Delta t)$is the later state then,

$Y(t + \Delta t) = f(Y(t))$.

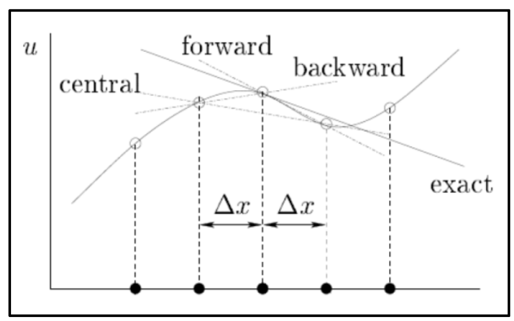

Figure 4: Central difference method solution scheme

The central difference formula is,

$$\left(\frac{\partial u}{\partial x}\right)_i = \frac{u_{i+1} - u_{i-1}}{2\Delta x} \quad (8)$$

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.[9] Central difference formula is used to find velocity and then integration gives displacement.

4. MASS SCALING

As mesh element size reduced, solver may take more time to solve. This may lead to solution un-stability [12].

According wave equation,

$$c = \sqrt{\frac{E}{\rho}} \quad (9)$$

Where, c = sound speed in that material,

E= Modulus of Elasticity

ρ=Density of material

To ensure stability, the time step size is limited by the CFL (Courant-Friedrichs-Lewy) condition:

$$\Delta t \leq f \times \left[\frac{h}{c}\right]_{min} \quad (10)$$

Where, f =Safety factor

h=Element size

Time step must be limited so that a stress wave cannot travel further than the smallest element characteristic length in a single time step.

Extreme care should be taken to ensure that results obtained remain physical.

5. MATERIAL MODEL:

Generally turbine wheel is made up of nickel super-alloy Inconel 713C due to its high nickel content it can resist the failure caused due to high temperature and speed of turbine wheel. Compressor wheel is generally made up of Aluminium or titanium alloy. Turbine housing is made up of SiMo based ductile iron due to the fact that its young's modulus does not decrease drastically with respect to increasing temperature, while compressor housing is made up of Aluminium alloy. For the development of material model it should consider its physical properties (density, thermal conductivity and specific heat), elastic properties (young's modulus, poisons ratio), plastic properties (Johnson cook model, Bilinear/Multilinear plasticity model etc.) and failure model (plastic failure strain, principal failure stress) are expressed in below stress strain graph shown in Figure.6 for general material.

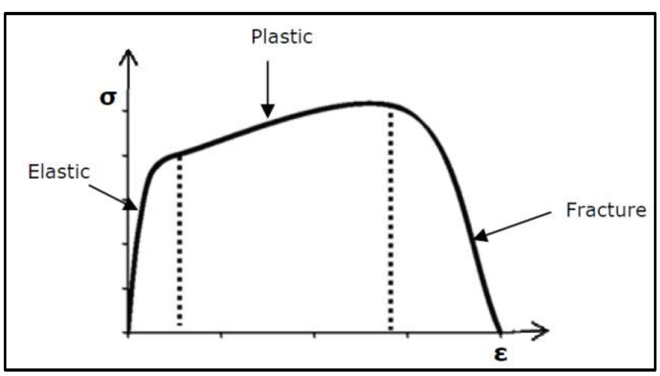

Figure 6: General stress strain curve [3]

There are several models available to define plasticity of the material. But mostly Johnson cook material model is used in the analysis due to its easy availability. To determine its constant split Hopkinson's test bar is used. The Johnson Cook strength model is used to model the plasticity behavior of the ductile iron housing, which is subjected to large strain, high strain rate and high temperature. The yield stress is defined as:

$$Y = [A + B(\varepsilon_P)^n][1 + C \ln(\varepsilon_P{}^*)][1 - (T_H)^m] \ldots.(11)$$

Where ε_P is the effective plastic strain, $\varepsilon_P{}^*$ is the plastic strain rate; T_H is the homologous temperature, which is defined by

$$T_H = \frac{T - T_{room}}{T_{melt} - T_{room}} \quad (12)$$

There are five material constants in the Johnson Cook model: A is the initial yield stress, B is the hardening constant, n is the hardening exponent, C is the strain rate constant, and m is thermal softening exponent.In the equation The first bracket indicates stress function which is similar to quasi-static process, second bracket shows strain rate dependent material constant while the third bracket describes thermal softening constant of the material [12].

6. MESHING AND BOUNDARY CONDITIONS:

Generally mesh type is selected based on its accuracy, but as model becomes more and more complex simple linear tetrahedron or hexahedron mesh is preferred, More care should be taken because linear tetrahedron elements are stiff while linear hexahedron may lead to hourglass effect. [14]

It is required to fix the model at the required location. Input velocity and the end time are taken as an input conditions for the analysis.

7. DETERMINATION OF IMPACT FORCE:

Placing the load cell in front of the required location of the model for direct measurement of external contact force may damage the strain gauges, if shields or cushions are used in between them then it may compromise its accuracy. Again if strain gauges are installed at backside of the required location then it will measure only reaction force, inertia may not be considered. Hence energy based model can be used to find impact force.

The contact force – displacement relationship can be expressed in Equation.

$$F_c = K_n \delta^P \quad (13)$$

This behaviour is represented by the spring in the 2DOF spring connected lumped mass system.

Assuming that the target is very stiff with extreme value of mass.

$$\frac{1}{2} m v^2 = \int_0^{\delta_{max}} F_c d\delta. \quad (14)$$

Putting equation (13) in equation (14).

We get

$$F_c = K_n \left(\frac{P+1}{2K_n} m v^2\right)^{\frac{P}{P+1}} \quad (15)$$

Where, K_n=stiffness of frontal spring

m=mass of impacting body

v=velocity of impacting body

P=hardening constant

Values ofK_n, m, $v$and Pshould be known to get impact contact force.

This equation is based on the assumption that no energy is dissipated in the loading phase of the impact (when the impact or is compressed). Mitigating effects which are derived from interactions between the impact or and the target have also been ignored. [14]

8. CONCLUSION

This study gives guidelines for containment testing, it also explains the physics of solving model in Finite element explicit dynamics. It gives introductions to the Johnson cook plasticity model. Energy based approach for to determine impact force is explained in this paper.

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