Simulation and Experimental Research of Continuous High Impact Test Equipment

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Abstract. In order to realize the simulation test of key components under continuous high impact environment, a continuous high impact test equipment based on direct impact loading of multiple impact heads is designed. In view of the collision contact problem between the impact head of semi-cylindrical structure and the tested object, a mathematical model of collision contact force is established based on Hertz line contact theory and hysteretic damping model, the change of the contact force and the energy loss are described in the form of nonlinear elastic force and equivalent damping, provide theoretical support for impact parameter analysis of the test equipment. On the basis of theoretical analysis, the overload acceleration of continuous high impact test equipment is verified combined with dynamic simulation and experiment, demonstrate the rationality and feasibility of the test equipment design.

1. Introduction

Many of the motion components, control components and other key components in industrial production, such as engine cylinder exhaust valve, concave-convex mold, rock drill piston, cutters, long-term working under high amplitude and repeated impact loading, even though the subjected contact stress is far less than the yield limit of the material, however, the plastic deformation, wear and various types of fatigue which lead to failure will still be produced under alternating impact[1]. The existing research shows that, the changes in structure and performance of material under repeated impact loading are quite different from that of general static low cycle, there may be some unique changes in structure and performance, such as yield strength, elastic hysteresis loop, strain hardening exponent and so on[2]. Therefore, during the design and production of such components, is there an effective method to carry out continuous high impact test, plays a vital role in stability and reliability of the above components and the whole industrial equipment.

In order to realize continuous impact test, many experts and scholars at home and abroad have carried out active research and exploration, a variety impact loading methods of different principle are introduced. Wellinger[3] had introduced an impact loading method of multiple free falling balls, Li Xuemin[4] had developed a multiple impact equipment of cantilever beam structure, Xu Mei[5] had developed a hydraulic multiple impact equipment on the control of solenoid valve, He Ling[6] had researched a multiple impact loading method based on straight roller cam mechanism, Hua Minglei[7] had developed a multiple impact system based on electro-hydraulic servo actuator for the impact test requirement of precision optical component. The above researches have greatly enriched the existing continuous impact test methods, but there are still limitations in impact frequency and impact
amplitude. Therefore, in order to meet the actual engineering test requirement better, researching a test method of short interval and high amplitude continuous impact loading has become an urgent technical problem in scientific research and production.

In view of this problem, Nanjing University of Science and Technology had designed a rotary continuous impact test equipment based on direct impact loading of multiple impact heads. Comparing with the existing indirect continuous impact loading method of cam structure or cantilever beam structure, the impact loading is realized directly based on the collision contact between the impact head and the tested object, which can significant increase the amplitude of impact force and overload acceleration of the tested object; the impact loading method of multiple impact heads which driven by a high speed rotating turntable, which can meet the requirement of short interval continuous impact, the impact frequency is also can be adjusted freely, provides a new method for continuous high impact test, the research has good advancement and practical engineering value.

2. Principle of test equipment
The principle prototype of continuous high impact test equipment as shown in Figure 1, the structure diagram as shown in Figure 2, the test equipment is mainly composed of base, turntable, turntable bracket, work-holding device, stand bracket, electric motor, hydraulic station and so on. A series of impact heads are installed on the turntable and the impact loading kinetic energy is provided by the rotating turntable; the work-holding device is installed on the stand bracket and connected with the motion platform through a spring damping mechanism, the retreat and return after each collision can be realized through the compression and restoration of the spring damping mechanism; the motion platform is directly connected to the piston of the hydraulic system, the occurrence and stop of the impact test can be controlled by the retreat and return controlling of the whole impacted mechanism. During the impact test, the turntable is accelerated to the rated speed by the driven motor through the inverter, then feeding the specimen to the motion trajectory of the impact heads along the guide rail of the stand bracket by controlling the hydraulic system, a number of impact heads collide with the tested object in turn, produce continuous high impact loading on the tested object.

Figure 1. Principle prototype
3. Dynamic model

The impact performance parameter is an important indicator of the continuous high test equipment for testing the tested object, in order to simulate the impact test for the tested object of actual working condition effectively, it is necessary to analyze and establish the collision contact force model of the test equipment, so the impact parameters can be adjusted according to test requirement.

The impact loading of the continuous high impact test equipment is generated by the collision contact between the impact head and the tested object, as the structure of the impact head is semi-cylindrical, therefore, the collision contact between the impact head and the tested object is usually a line contact problem, as shown in Figure 3, the contact force can be obtained according to the Hertz line contact theory, but the Hertz theory is established on complete elastic contact, for the modeling of collision contact problem, the energy conversion process is the most complex part, the Hertz elastic model cannot reflect the physical characteristics of energy conversion during the collision[8], therefore, we introduce a hysteretic damping model based on Hertz model to analyze the collision contact force between the impacted head and the tested object; at the same time, according to the research of Hutchings and Wu, the proportion of stress wave propagation energy is small during the impact process, which can be approximately ignored[9], at this time, the collision force between the impact head and the tested object can be expressed as:

$$F_n = K\delta^n + C\dot{\delta}$$  \hspace{1cm} (1)

Where, $K$ represents the equivalent Hertz contact stiffness, $C$ represents the equivalent hysteretic damping coefficient, $\delta$ represents the embedded depth of collision contact, $\dot{\delta}$ represents the relative velocity of collision contact, $n$ is the exponential coefficient related to the shape of the collision contact object, for the line contact between the cylinder and the plane, $n$ takes 10/9.

The effective contact length between the impact head and the tested object is $l$, the contact loading is $Q$, the loading line density is $q$, according to the Hertz theory, the relationship of them satisfies:
The contact loading forms a rectangular contact surface with a length of \( l \) and a width of \( 2b \), in the range of \(-b \leq x \leq b\), the contact stress is elliptically distributed along the contact area, which can be expressed as [10]:

\[
p = \frac{2Q}{\pi lb} \sqrt{1 - \left(\frac{x}{b}\right)^2}
\]

The half contact width is:

\[
b = \sqrt{\frac{4Q}{\pi l} \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)}
\]

For the embedded depth of collision contact \( \delta \), usually lack of a theoretical solution, but according to the empirical formula which given by Plamgren [11]:

\[
\delta = 3.81 \left(\frac{1}{\pi E_1} + \frac{1}{\pi E_2}\right)^{0.9} \frac{Q^{0.9}}{l^{0.8}}
\]

The above formula can be rewritten as:

\[
Q = K \cdot \delta^{10}
\]

The equivalent Hertz contact stiffness:

\[
K = \left[ \frac{l^{0.8}}{3.81 \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)^{0.9}} \right]^{10} \]

Where \( E_1 \) and \( E_2 \) are respectively the elastic modulus of material, \( \nu_1 \) and \( \nu_2 \) are respectively the Poisson ratio of the material.

Furthermore, according to the nonlinear damping model of Lankarani and Nikravesh [8], the equivalent hysteretic damping coefficient \( C \) can be expressed as:

\[
C = \frac{3K(1 - e^2) \delta^{10}}{4\delta_0^{10}}
\]

The final expression of collision contact force can be expressed as:

\[
F_n = K \delta^{10} + C \dot{\delta} = \left[ \frac{l^{0.8}}{3.81 \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)} \right]^{10} \delta^{10} \left[1 + \frac{3(1 - e^2)}{4\delta_0^{10}} \right]
\]

It can be seen from the above formula that, the collision contact force of the continuous test equipment is related to the material, shape and collision speed of the collision pair, by changing the material, shape and impact loading speed of the collision pair, can realize the simulation test requirements of different impact parameters. it also can be concluded that, in order to realize effective comparison verification, the simulation model and experiment should be established of the same conditions.

4. Simulation analysis

For the actual continuous impact process, because of the high amplitude and high dynamic characteristics of collision contact force, it is usually difficult to be measured directly, but for the collision contact process of rigid body, the overload acceleration is mainly produced by the collision contact force, therefore, on the basis of theoretical analysis, we can take the overload acceleration as the parameter and combine with rigid dynamic simulation and experimental research to analyze the
continuous impact process. ADAMS is a widely used simulation software in mechanical analysis of interactive image environment and part library, constraint library and force library, a completely parametric dynamic model of mechanism system can be created for static, dynamic and kinematic analysis[12]. In the research of this paper, because of the interested object is the collision contact process of continuous impact, in order to reduce the interference of noncritical components to simulation process and simulation result, adjust the full-scale 3D model of the test equipment in SolidWorks, remove the unnecessary components, only reserve the key structures which produce continuous impact, at the same time, according to the experimental model, the tested object is modeled as a frame with a horizontal boss on the top and a cylindrical specimen with an acceleration sensor inside, import the above model into ADAMS simulation environment, as shown in Figure 4. The material of each component in simulation model is defined according to the actual principle prototype, the driver and the constrain is also created based on actual assembly relationship and working principle. Defining the collision contact type of 8 impact heads and tested objects of solid to solid, and calculate the collision contact force based on impact function method, due to the friction force is less than normal collision contact force, so the friction force can be ignored in the simulation.

![Figure 4. Dynamic simulation model](image)

In order to make the simulation conditions consistent with the experiment, set the rotary speed of the turntable as 720r/min, then can be obtained that 1 turn of the turntable is about 0.083s, thus the simulation time can be configured as 0.1s, the simulation step can be configured as 2000, the obtained continuous impact overload acceleration of the tested object as shown in Figure 5.

![Figure 5. Simulation result of overload acceleration](image)

It can be seen from the figure that, the peak acceleration of continuous impact is usually about 5500g, affected by the natural motion period of spring mass system of the retreat and return mechanism, it is difficult to ensure the tested object of the same motion state and motion position as the original after each impact, result in inconsistency of continuous impact overload acceleration, but the peak acceleration does not change significantly, also presents the periodic change rule.

5. Experimental verification

Carry out experimental research based on continuous high impact test equipment, the tested object is a cylinder specimen of an acceleration sensor inside, as shown in Figure 6, the specimen is installed in
work-holding device of the continuous high impact test equipment, ensure that the cylinder specimen will not oscillate during continuous impact process, the overload acceleration of the test equipment can be obtained by the output of the acceleration sensor.

![Figure 6. Cylindrical specimen and installation](image)

The obtained overload acceleration curve as shown in Figure 7, it can be seen from the figure that, the overload acceleration of continuous 10 impact is well achieved by the acceleration sensor, affected by the natural motion period of the spring mass system, the measured overload acceleration presents a similar change rule to the simulation result, but the fluctuation is obviously stronger than the simulation, and the change rule is also more complex, this is because the simulation is based on ideal parameter conditions, but in actual continuous impact process there will be more reasons that can affect the motion rule and the overload acceleration of tested object, the reason is also more complex. The actual measured overload acceleration peak can reach as 7000g, higher than simulation result, this is because the dynamic simulation is established on the ideal rigid body, the overload acceleration and collision contact force satisfy Newton's second law, but in actual impact process, the tested object cannot be an ideal rigid body, both structural deformation and stress-strain under high impact loading will result in the measured overload acceleration is higher than that of ideal condition, moreover, affect by the structural response vibration under high impact loading, there will be multiple accompanying sub-pulses after each main pulse of the impact overload acceleration, the peak value of the sub-pulse is obviously lower than that of main pulse, and also change irregularly, it reflects the complexity of actual impact process, especially for these continuous impact process, however, because there is no other external reinforcement after each impact, the structural response vibration of the tested object will gradually attenuate, therefore, the acceleration sub-pulse of each impact also presents an attenuation trend.

![Figure 7. Measured overload acceleration](image)
6. Conclusion
Aiming at the designed continuous high impact test equipment of direct collision contact method, a collision contact model is established based on Hertz line contact theory and hysteretic damping model, analysis the reasons that affect the collision contact force, provide theoretical support for simulation test of specified parameters. The dynamic simulation of continuous high impact test equipment is established and the experimental research is also carried out, considering the feasibility and convenience of measurement, taking the overload acceleration as the parameter, comparative analysis and discussion of the simulation and experimental results. The simulation result and experimental result both reflect the actual performance of the continuous high impact test equipment, verify the rationality and feasibility of the designed impact test equipment, provide a new method for continuous high impact testing, the research is of good advancement and practical engineering value.

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