International Journal of Impact Engineering 108 (2017) 295–302

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

System ringing in impact test triggered by upper-and-lower yield points of materials

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ARTICLE INFO

Article History:
Received 1 January 2017
Revised 11 April 2017
Accepted 25 April 2017
Available online 29 April 2017

Keywords:
Impact test
System ringing
Upper-and-lower yield points
Rate dependence

ABSTRACT

In the mechanical tests of materials under impact loading, the measured load signal usually exhibits severe oscillation known as system ringing. A lightweight load sensor was designed and has successfully overcome this problem for many metal materials, but was found to fail when dealing with steel with apparent upper-and-lower yield points. In order to investigate this problem, two representative steels, DP780 without yield peak and B340LA with significant yield peak, are chosen for comparison. Using both experimental and numerical analysis of the test system consisting of specimen, gripper and load sensor, it is found that upper-and-lower yield points can trigger the system ringing under impact loading. Furthermore, a series of preloading-reloading tests are conducted, the results of which can validate the experimental conclusion. Additional numerical simulations of the preloading-reloading tests are carried out to verify the test results, and the simulation results indicate that the tangent modulus change of stress-strain curve in the transition from elastic stage to plastic stage can generate an excitation to the test system. This excitation can trigger system resonance and result in severe oscillation in load signal. Based on the test and simulation results, it is suggested that the specimen should be loaded statically to a strain beyond its yielding range before dynamic test in order to obtain an accurate hardening curve.

1. Introduction

Advanced engineering materials with low density and high strength are springing up in the automobile industry. Application of novel materials demands a comprehensive understanding of their mechanical properties as well as properly-calibrated material models. It is often challenging when structures and materials of vehicles need to be studied under impact loading condition for crash safety design. In typical vehicle collisions, local strain rate of components can reach as high as $500\ s^{-1}$ [1,2], which is in a strain rate range that we refer to as intermediate. Consequently, material testing in this strain rate range for obtaining the mechanical properties is very critical. The limit of the traditional loading devices like universal test machine is approximately $1\ s^{-1}$. For the impact test above $1\ s^{-1}$, Hopkinson bar system [3–5], hydraulic machine [6–13] and drop-weight system [8,11,14–17] are three common choices.

Hopkinson bar or Kolsky bar system are initially designed for strain rate above $1000\ s^{-1}$. For the intermediate strain rate range, low impact velocity of the striker yields low kinetic energy, which is not sufficient to induce large strain in the specimen and the stress waves propagating in the bar superpose upon each other [18]. To overcome the first drawback, the striking wave generator in conventional bar system is usually replaced by a hydraulic actuator to provide sufficient kinetic energy. For the second drawback, one approach is enlarging the length of transmitted bar (can be as long as 40 m [19]), which can provide enough test duration for the stress wave to travel and reflect. However, the cost of manufacturing such a long bar increases exponentially with length. Therefore, some labs started to employ wave separation methods to split the ascending wave and the descending wave propagating along the bar, expanding the test duration without increasing the bar length [18]. However, the modified bar system still has some drawbacks, such as the mismatch of the impendence and the fluctuation of test strain rate caused by wave reflection [20].

Compared to the bar system, hydraulic machine and drop-weight system are more commonly used for intermediate strain rate test. The mechanism of hydraulic machine and drop-weight system is similar. Hydraulic actuator or drop-weight serves as the loading devices, and force signal is measured by built-in load sensors, which means that the one-dimensional wave theory in bar systems is no longer adopted. However, there is also one drawback for such devices – the measured force signal usually suffers from severe oscillation if a careful design of the test method is absent (see Fig. 1a). Such oscillation can not only overwhelm the real mechanical property of the test material, but also lead to erroneous result due to the phase

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http://dx.doi.org/10.1016/j.ijimpeng.2017.04.020

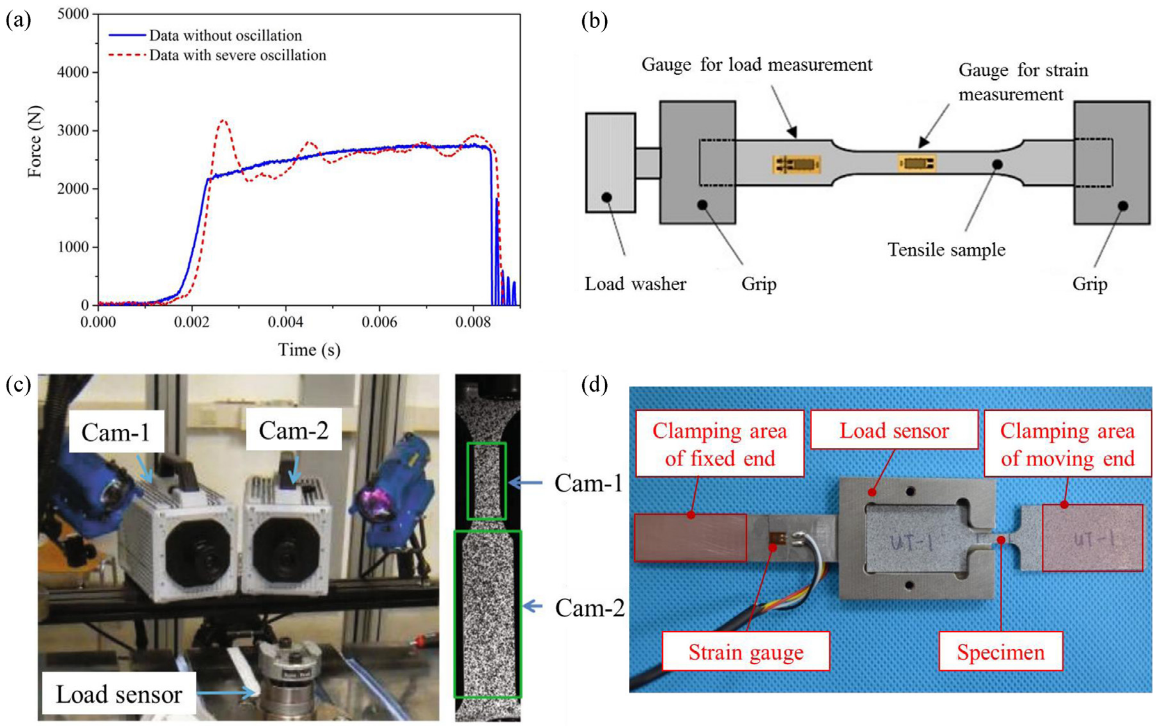

Fig. 1. (a) Force-time curve suffering from severe data oscillation [9] (b) The first method to reduce data oscillation – attaching strain gauges on specimen [21] (c) The second method to reduce data oscillation – using DIC to measure the elastic deformation of the fixed end of specimen [24] (d) The third method to reduce data oscillation – attaching strain gauges on the fixed grip (strategy of lightweight load sensor) [8].

delay. On one hand, the oscillation in data is from the test system, not real material properties, and therefore, they are also called system ringing. On the other hand, it may be affected by the property of the test material, which could make the ringing phenomenon more prominent and more difficult to overcome. One of the interests of the study is figuring out the mechanisms of system ringing.

To reduce/eliminate the ringing effect, there are three typical methods for the load measurement of hydraulic machine and drop-weight system. The first one is attaching strain gauges directly on the grip section of specimen [7,21–23], as shown in Fig. 1b. Since there is only elastic deformation in the grip section, the load is proportional to the measured strain for most metallic materials, and hence the force history can be obtained based on careful calibration before test. Such a method can greatly simplify the load measurement chain and consequently obtain satisfactory data quality in force measurement. However, the test efficiency is low since each of them needs to be calibrated respectively before test in order to build up a linear relation between the measured voltage signal and the sectional force. Moreover, it consumes a great number of strain gauges.

The second method is to use a high-speed camera to measure the elastic deformation of the grip section of specimen [24] (see Fig. 1c). With the Digital Image Correlation (DIC) method, the elastic strain in the loading direction can be processed and subsequently be used to calculate the sectional force. In this way, the high-speed camera actually substitutes the function of the strain gauge on the grip section in the first method. It greatly reduces the workload of impact test by avoiding calibration of every strain gauge. However, it should be pointed out that the cost of two high-speed cameras is considerably high, and moreover, a perfect synchronization between the two systems is required to obtain good data quality.

Faced with the drawbacks of the two methods above, a method of designing a lightweight test system is proposed. A lightweight load sensor that combines the functions of gripper and sensor together (see Fig. 1d) was developed by the authors' research group [8,9,11]. Instead of attaching strain gauges onto the specimen and calibrating all of them before test, the advantage of this design is mounting the strain gauge onto the end of gripper, hence making it reusable. DIC method is used for strain measurement.

The lightweight load sensor strategy has achieved remarkable success for reducing ringing effect. It has been applied to High Strength Steels [6,25,26], aluminum alloys [8,9], copper films [27], magnesium alloys [28] as well as polymers [8], and smooth curves without oscillation can be obtained. However, we have found that the applicability of the lightweight load sensor has limitations too. For test materials with apparent upper-and-lower yield points, such as low-carbon steels, using the lightweight load sensor cannot completely eliminate the oscillation. Fig. 2 shows two impact test results of High-Strength Low-Alloy (HSLA) steel under 8.33×10^{-3} m/s and 1 m/s, respectively. For both cases, there are certain degrees of oscillation, even though they are not as severe as that in Fig. 1a (indicating that the effect of lightweight load sensor). For the 1 m/s case, the oscillation not only happens near the yield peak, but also in the strain hardening range. What is more interesting is that a significant rise of strain rate during the upper-and-lower yielding behavior is observed (see Fig. 2). The mechanism of this phenomenon is the same as the upper-and-lower yielding behavior – caused by the interrupted motion of Luders band along the specimen [29,30]. The motion of dislocation is not a continuous process. When dislocation meets an obstacle, such as a solute atom, it is arrested temporarily. During this time, the movement of the dislocations near the band front becomes locked. Macroscopically, the stress has to rise to release the band front again, and the strain will have a sudden peak, after which the Luders band will travel along the specimen (see Fig. 3).

The purpose of the present paper is to analyze and overcome the system ringing for materials with yield peak, such as the HSLA steel. The first task is to identify the origin of the oscillation. In Section 3, two independent groups of tests are carried out. In the first group, two different steels are tested using the same method and test