International Journal of Impact Engineering 88 (2016) 139–152

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Design and verification of a strain gauge based load sensor for medium-speed dynamic tests with a hydraulic test machine

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ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form 31 August 2015
Accepted 12 October 2015
Available online 23 October 2015

Keywords:
Dynamic tests
Load measurement
Strain-rate dependence
System ringing

ABSTRACT

System ringing in load measurement during dynamic tests is investigated with a second order system consisting of a mass, a spring and a damper. According to the analysis of the time-domain and harmonic performances, a procedure for designing load sensor to relieve the influence of system ringing is proposed. Subsequently, a practical design of load sensor and its application procedure are presented. The dynamic test results of two metal materials under strain-rates of 10, 100 and 200 s^{-1} show that the sensor is effective for reducing system ringing. Based on this design, system ringing as well as the influence of several design variables is investigated with the help of Finite Element simulations. Simulation results indicate that the loading velocity and the stress–strain relation of the tested material are the two important influential factors. In the end of the paper, recommendations are made for the design of load sensor and the position for placing strain gauges.

1. Introduction

Characterization of the strain-rate dependence of material mechanical behaviors is becoming increasingly important for crashworthiness design of structures in automotive industry. Most automotive materials, such as Advanced High Strength Steels (AHSS) [1–6], polymers [7–10], magnesium alloys [11,12] and some aluminum alloys [13,14], exhibit evident strain-rate dependence in both strength and fracture behavior as reported by a large number of researchers.

Various test machines have been utilized to realize characterization of the strain-rate dependence. Fig. 1 presents a schematic representation of the applicable range covered by four typical test machines: conventional load frame like the universal test machine (quasi-static, below 0.1 s^{-1}), hydraulic system (low-speed dynamic, 0.1–10 s^{-1}) [2,6,9,15–19], drop-weight system (medium-to-high speed dynamic, 10–500 s^{-1}) [5,20–25] and bar system (high-speed dynamic, 200–5000 s^{-1}) [1,2,10,12,26–29]. More details about different types of test machines could be found in some existing publications [9,30–32]. Besides, as experimental techniques develop, some commercial high speed test machines, the maximum velocity of which can be as high as 20 m/s, have already become mature enough for scientific use [3,4,33]. However, such commercial high speed test machines are not as common as the other four systems mentioned above due to the high expense.

Among the four strain-rate divisions in Fig. 1, the medium-speed dynamic one, from 10 s^{-1} to 200 s^{-1}, is regarded as the most difficult to deal with. Testing techniques for this range are still not mature enough to obtain the material response data of good quality, including strain and load signals. As novel techniques like Digital Image Correlation (DIC) [34–36] and high speed photographing develop, the strain measurement has become less challenging. However, in the field of load measurement, there are still some problems which existing methods fail to address. One of them is the system ringing problem. It is well-known that load signal measured in dynamic tests usually shows a significant level of oscillation if a careful design of the test conditions is absent. The true material response could possibly be drowned by severe oscillations, which is obviously unacceptable. Traditional drop-weight systems, without special improvement on data measurement, usually suffer from severe data oscillation, which makes them less appealing for medium-speed dynamic tests [5,20–25,37,38].

Over the past couple of decades, great effort has been made by different research teams to improve the data quality of medium-speed dynamic tests with various strategies. The first strategy is smoothing or filtering the test data, using averaging or other algorithms [39–43]. However, the accuracy of such filtering procedure, to a great extent, depends on user's choice of the filtering algorithm. It also includes a risk of losing some important characteristics with respect to the hardening behavior of the tested material.

The second strategy is modifying a bar system for lower strain-rates [37,44–47]. For example, Othman et al [37] added a bar into

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http://dx.doi.org/10.1016/j.ijimpeng.2015.10.004

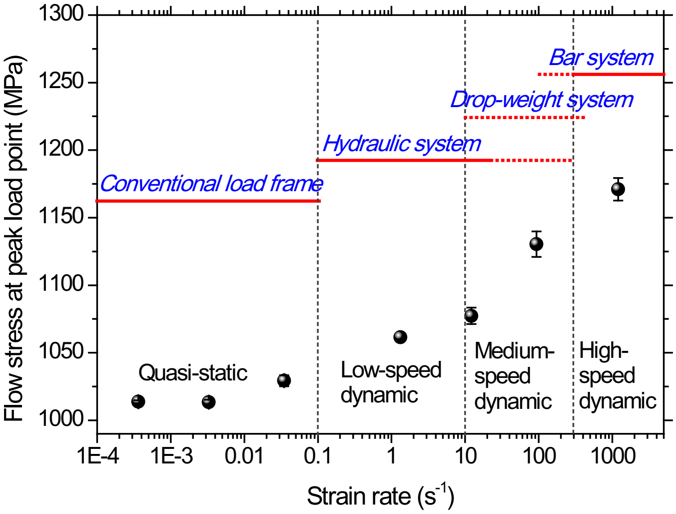

Fig. 1. Rate-dependence of the flow stress at peak load point of a DP780 steel sheet by the authors' lab and the typical strain rates covered by conventional load frame, hydraulic system, drop-weight system and bar system (solid lines: techniques are relatively mature; dashed lines: new techniques are demanded for data of good quality).

a hydraulic machine and used the improved system to carry out tests under strain-rates from 1 s^{-1} to 200 s^{-1}; Shim and Mohr [44] improved the split Hopkinson pressure bar and successfully performed large strain compression tests of polyurea material at strain-rates of 10 s^{-1}, 36 s^{-1} and 110 s^{-1}. In the medium-speed range, the test duration is so large that the superposition of waves is almost inevitable. Because it is quite difficult to manufacture the slim bars several times longer than those for high strain-rate tests, and it is also impractical to provide a space to accommodate such long bars, nearly all the existing studies related to medium-speed tests kept the limited bar length and adopted sophisticated wave separation methods [48–52].

The third strategy for the medium-speed dynamic tests is modifying the measurement system of the hydraulic machine. Instead of employing one-dimensional wave theory, this strategy aims to optimize the existing frame of the machine to eliminate, or at least attenuate the data oscillation phenomenon based on a comprehensive understanding of its causes. It is also the objective of the present paper to treat the ringing effect with this strategy. Following is a more detailed review of this issue.

Typically, the oscillation of data in a medium-speed dynamic test on a hydraulic machine mainly comes from two sources, i.e. wave propagation and system ringing. The former one is almost inevitable because stress wave will surely generate and then travel in the specimen, resulting in the non-equilibrium of stress. Therefore, some existing publications [33,53] suggested that more than 3 round-trips of the stress wave through the gage length should be guaranteed to reach dynamic equilibrium. And for polymers, at least 10 elastic reflected waves should propagate through the specimen gage length from the time of loading to the time of yield [9,54]. In this way, the inevitable influence of the wave propagation is expected to be limited within the elastic period, which is usually regarded to have a lower priority than the plastic response in the mechanical behavior characterization of metal materials. Note that as the loading speed increases to high-speed range, the test duration decreases to a level of 0.1 ms, which is comparable with the 3-round-trip time. That is one of the main reasons why hydraulic test systems have a strain-rate limit (about 200 s^{-1} for metals), above which the bar system is preferable.

Another important source of data oscillation is the system ringing, which is caused when the impulse during load introduction excites the test system to oscillate [9,15,30,31,33,40,41,47,55]. Load input methods, specimen geometry, clamping methods and measurement devices are the four well-known factors which are closely related to the ringing effect [9,30,31]. Each of the factors needs elaborate considerations according to the practical testing conditions. Among them, load measurement device is probably the most frequently discussed issue. For target strain-rate below 100 s^{-1}, piezoelectric load washer of low mass is usually recommended [30,31]. But it is inappropriate for tests under higher strain-rates since lag and oscillation can often be observed in the measured results [15,56]. A common and applicable solution is to attach strain gauges on the grip section of the specimen [9,30,31,56], as shown in Fig. 2a. However, such a method is very costly since a vast number of strain gauges are needed and each of them needs to be calibrated before dynamic tests. For this reason, some researchers [58] started to use high-speed cameras for measuring strain, acting as strain gauges. But as far as the authors are concerned, the expense of this approach is still not low, considering the price of a high-speed camera.

Faced with these facts, a new concept of load sensor, which combines load measurement and the specimen gripping functions

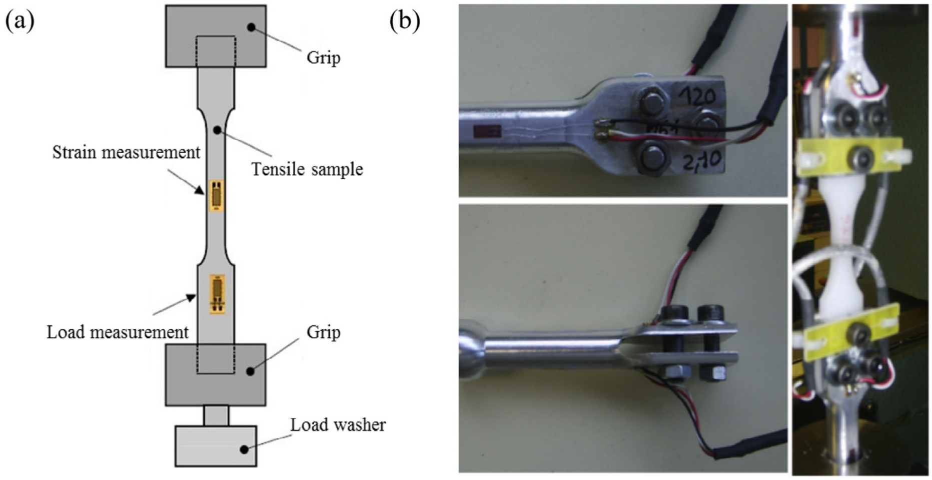

Fig. 2. Two solutions to reduce signal oscillation in dynamic force measurement: (a) attaching strain gauges on the grip section of the specimen, and (b) attaching strain gauges on the fixed grip of the test machine (an example of load sensor from open literature [57]).