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Pulse shaper design for dynamic testing of viscoelastic materials using polymeric SHPB

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ABSTRACT

Pulse shapers are commonly used in SHPB (Split Hopkinson Pressure Bar) to extend the initial rise time and the duration of the incident pulse to achieve an early uniformity of the internal stress and a constant strain rate loading within the specimen. In this study, a method for optimal design of a pulse shaper for polymeric SHPB system in testing soft materials is proposed based on wave propagation analysis. Firstly, an inverse parametric identification technology is used to obtain the constitutive parameters of PMMA and the RTV630 silicone rubber to be tested, respectively. Then, the optimal incident waveform for testing viscoelastic specimen is determined. Finally, taking the WSXJ-208 silicone rubber under impact using polymeric SHPB as an example, by comparing the incident wave gotten from the numerical simulation and the optimal incident waveform considering the dispersion and attenuation effects of wave propagating in polymeric bars, an optimal shaper geometry is obtained, and showing an obvious modification in the waveform so as to get more accurate and reliable results.

1. Introduction

Viscoelastic materials, such as polymers, silicone rubbers and muscle-like materials have been widely used in various fields. Their dynamic behavior is the most concern of scientists and engineers. As well known, spilt Hopkinson pressure bar (SHPB) apparatus [1] has been successfully applied to study dynamic response and constitutive laws of metals at high strain rate (in the range of 10^2/s to 10^4/s). In recent years, the experimental apparatus is extended to test various viscoelastic materials.

However, due to the low impedance of viscoelastic materials, the transmitted signal is too weak to be accurately measured by the strain gages mounted on the bars. Therefore, Gamby and Chaoufi [2], Zhao and Gary [3], Sawas [4] and Wang et al. [5] recommended that viscoelastic bars can be used to increase signal-to-noise ratio and to obtain sufficiently high transmitted signal. Whereas because of dispersion and attenuation effect of viscoelastic materials, waveform change during wave propagating in viscoelastic bars, and then signals measured by the strain gages at the middle of incident and transmitter bar, may not be the same as on the interfaces of the specimen and the bars. Therefore, the wave dispersion and attenuation effects have to be taken into accounted by various correction techniques [6–11].

In addition, the stress uniformity within viscoelastic specimen is difficult to achieve due to the characteristics of the viscoelastic material. From a quantitative analysis within elastic deformation, Yang and Shim [12] found that the ratio of wave impedances of the bar and the specimen, and the incident waveform both have a significant influence on stress uniformity. Furthermore, Song and Chen [13] investigated the dynamic stress equilibrium when testing soft material and indicated that the specimen thickness and the strain rate both affect the stress equilibrium within specimens. Moreover, Zhou et al. [14] discussed the stress nonuniformity in early stage of testing when using polymeric SHPB. Zhu et al. [15] used a characteristics method illustrating that viscoelastic relaxation time, ratio of wave impedance of bar and specimen, rise time of incident wave and strain rate can remarkably affect stress equilibrium during testing viscoelastic materials.

In SHPB testing, maintaining a constant strain rate loading is one of basic requirements. Employing a pulse shaper, in between the striker and the incident bars is one of the good approaches to achieve this requirement. Pulse shaper in the traditional SHPB experiment was initially used to filter out high-frequency components in incident wave [16]. Later, Franz [17] and Follansbee [18] discussed the influence of the pulse shaper on the incident waveform. Nemat-Nasser et al. [16] established the correlation among the incident stress waveform of metal bar and the geometry,

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material of the pulse shaper and the striker's velocity. Frewet al. [19,20] modified the correlation and applied for testing brittle materials and elastic materials. Then, pulse shaper technique had been practically used in testing metal [21], brittle [22] and soft materials [23,24].

Due to the viscoelasticity characteristic of the material, the pulse shaper design becomes much complex. When using viscoelastic SHPB to test viscoelastic materials, design of pulse shaper will encounter the following difficulties (1) How to determine the constitutive parameters of viscoelastic polymers? (2) Which incident waveform can be helpful to achieve the stress uniformity? (3) The incident wave of the front end of specimen is no longer the incident wave after shaping in polymeric bar. Aiming at testing viscoelastic materials using polymeric SHPB apparatus, effective method of a pulse shaper design is presented in the paper. Firstly, an inverse parametric identification technology is used to obtain the constitutive parameters of PMMA and the silicone rubber to be tested, respectively. Then, the optimal incident waveforms are determined. Finally, by comparing the incident wave gotten from numerical simulation and the waveform deduced from optimal one taking into account of the dispersion and attenuation effects, optimal shaper geometry is determined.

2. Parametric identification of viscoelastic material

2.1. Wave propagation in viscoelastic bars with inertial effects

The theory developed for elastic bars in evaluating the relationship between the wave propagation coefficient and the frequency was extended to viscoelastic bars [9] by replacing the elastic constants by the complex material parameters. The resulting frequency equation is then given by.

$$f(\gamma) = (2p/a)\left(q^2-\gamma^2\right)J_1(p\cdot a)J_1(q\cdot a) - \left(q^2+\gamma^2\right)^2 J_0(p\cdot a)J_1(q\cdot a) + 4\gamma^2 p\cdot q\cdot J_1(p\cdot a)J_0(q\cdot a) = 0 \quad (1)$$

where

$$p^2 = \frac{\rho\omega^2}{\lambda^*(\omega)+2\mu^*(\omega)} + \gamma^2, \quad q^2 = \frac{\rho\omega^2}{\mu^*(\omega)} + \gamma^2$$

$$\mu^*\left(\omega\right) = \frac{E^*(\omega)}{2(1+v^*(\omega))}, \quad \lambda^*\left(\omega\right) = \frac{E^*(\omega)v^*(\omega)}{(1+v^*(\omega))(1-2v^*(\omega))}$$

a is the bar radius, $\lambda^*(\omega)$ and $\mu^*(\omega)$ are two coefficients representing complex Lamé constants of the viscoelastic material. J_0 and J_1 are the zero-order and first-order Bessel's functions of the first kind. $E^*(\omega)$ is complex modulus, and $v^*(\omega)$ is Poisson ratio of viscoelastic material of the bar. p and q are coefficients which depend on frequency and the material properties.

If the complex Young's modulus and Poisson's ratio $E^*(\omega)$ and $v^*(\omega)$ are known in advance, then Eq. (1) can be solved numerically through iteration scheme to evaluate the propagation coefficient $\gamma(\omega)$. Alternatively, if the wave propagation coefficient $\gamma(\omega)$ is evaluated using a wave propagation experimental technique [11], the material parameters can be identified inversely by using Eq. (1).

2.2. Parametric identification of material parameters

A viscoelastic material model can be represented by a Generalized Maxwell Model (GMM) which consists of one elastic spring parallel with n numbers of Maxwell elements. Each Maxwell element comprises a spring and a dashpot in series. The whole GMM system is illustrated in Fig. 1. Moreover, the parameters of this model are representative of Prony series [25] which are usually input in commercial FE software to definite constitutive behavior of viscoelastic materials. The complex modulus of a GMM can be obtained by Eq. (2).

$$E^*(\omega) = E' + iE'' = E_l + \sum_{j=1}^{n} E_j \frac{i\omega\eta_i}{E_j + i\omega\eta_i} \quad (2)$$

where $E^*(\omega)$ is the complex Young's modulus of the viscoelastic material. $\boldsymbol{E'}(\boldsymbol{\omega})$ is storage modulus and $\boldsymbol{E''}(\boldsymbol{\omega})$ is loss modulus (Fig. 2). E_j and η_j represent the stiffness of the spring and the viscosity of the dashpot for each Maxwell element.

So far, there is no well-defined guideline available in open literature for selecting the number of branches of Maxwell elements, n, for material identification through wave propagation testing. In our cases, $n = 2$ is found to be accurate enough to describe the constitutive behavior of viscoelastic material, which leads to a five-parameter GMM model with three springs and two dash pots. Eq. (2) can be expanded explicitly for a five-parameter GMM as follows.

$$E^*\left(\omega\right) = E_l + E_1\frac{i\omega\eta_1}{E_1+i\omega\eta_1} + E_2\frac{i\omega\eta_2}{E_2+i\omega\eta_2} \quad (3)$$

The set of unknowns can be written as a vector $\vec{x} = [E_l \quad E_1 \quad E_2 \quad \eta_1 \quad \eta_2\,]$. Once the wave propagation coefficient is determined through wave propagation experiments using the viscoelastic bars, the set of unknowns is estimated using an inverse identification technique, by using Eq. (1), assuming the Poisson's ratio as a constant equal to 0.3. Details of this inverse identification technique can be referred to Ref. [26].

Once we obtain the constitutive parameters of PMMA, $\gamma(\omega)$ of the PMMA bar can be calculated, and dispersion and attenuation correction of the propagating wave can be conducted. The evaluated parameters of the GMM are converted into Prony series terms, and then are input in ABAQUS software, for simulation of wave propagation in the viscoelastic bar. Fig. 3 shows the comparison of the reflected wave obtained by simulation and that the theoretical predicted using $\gamma(\omega)$ evaluated through identified material model. A close agreement indicates the validity of the viscoelastic material parameters.

3. Optimal incident wave for SHPB test of viscoelastic specimen

3.1. Stress and strain uniformity

Traditional SHPB technique is based on the assumptions of the stress uniformity s. But due to the characteristics of the viscoelastic

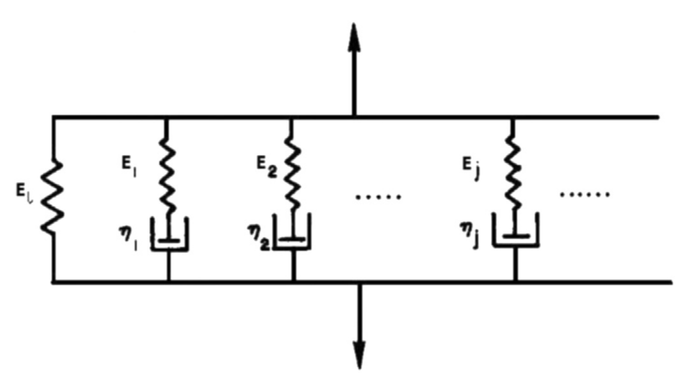

Fig. 1. Generalized Maxwell model (GMM).