Correction of Wave Signals for PMMA Split Hopkinson Pressure Bar Setups

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The Split-Hopkinson Pressure Bar (SHPB) is a common experimental setup to investigate the dynamic properties of materials. For soft materials the SHPB setup has to be customized using plastic bars. Because such bars show wave attenuation and dispersion, the measured wave signals have to be corrected. In this study a method of signal correction by means of a spectral analysis is presented.

1 Introduction

The SHPB is an established experiment to determine the dynamic properties of materials at high strain rates [1]. When testing soft materials with a conventional steel or aluminum SHPB, problems of impedance mismatch occur. It is therefore necessary to use bars of low impedance material, e.g. PMMA bars. However, in such viscoelastic bar materials, wave attenuation and dispersion effects have a significant influence on the measured signals.

2 The SHPB experiment

The setup of the SHPB consists of striker accelerated gas gun, two long bars, namely the incident bar (IB) and the transmission bar (TB), and a data acquisition system, which processes the data of the strain gauges applied to the bars. Between the two bars, the specimen is clamped. After the striker is launched it hits the surface of the IB and induces a stress wave into the bar. The longitudinal wave propagates along the IB. At the IB/specimen interface, the wave splits into two parts. One is reflecting and propagates along the IB in the opposite direction. The other part of the wave is passed through the specimen into the TB. By considering the one-dimensional wave theory, we can derive stress and strain in the specimen.

\[
\dot{\varepsilon}_s = -\frac{2C_0}{l_s} \varepsilon_r \\
\varepsilon_s = -2 \frac{C_0}{l_s} \int_{t_0}^{t} \varepsilon_r \, dt \\
\sigma_s = \frac{E_b A_b}{A_s} \varepsilon_t
\]  

(1)

From the Eqs. (1) the dynamic properties of the specimen can be determined. In a conventional SHPB, the bars are made of metal. The strain gauges are aligned at the center position of the bars. The measured signals at the center position can be assumed to be the same as at the bar/specimen interface due to the low attenuation and dispersion. When testing soft materials the mechanical impedance mismatch is high. This means that the wave is almost completely reflected at the interface. Consequently, no transmission pulse can be measured. To minimize this impedance mismatch polymeric bars made of PMMA are used here. The bars have a length of 1800 mm and a diameter of 20 mm. The striker has a length of 250 mm and a diameter of 20 mm. Now, however, the measured signals must be corrected, since attenuation and dispersion effects are significantly higher in viscoelastic bars [2]. Fig. 1 shows the difference in wave propagation between metal and PMMA bars. In a regular SHPB experiment, strain gauges cannot be attached at the end of the IB, since the incident and reflected pulse have to be detected individually for later calculations. When measuring at the end of the IB, however, a superposition of incident pulse and reflected pulse is measured and the two pulses cannot be separated from each other. Therefore, the strain gauges have to be applied at a certain distance, typically in the middle of the bars, to record both pulses separately.

3 Signal correction

For analytical wave correction, it is necessary to record the propagating wave at different locations of the bar first. To this end, the IB was equipped with three strain gauges. The reconstruction of the wave signal is given by a spectral analysis. A spectral analysis is performed at the three strain gauges positions [3]. The spectra of position \(x_1\) and \(x_2\) are used to predict the spectrum at position \(x_3\). The spectral analysis is performed by the Fast Fourier Transform (FFT) for each recorded strain gauge signal.

\[
U_1(\omega) = \text{FFT} [u_1(t)] = \sum_n U_{1n} e^{i\omega t_n} \\
U_2(\omega) = \text{FFT} [u_2(t)] = \sum_n U_{2n} e^{i\omega t_n}
\]

(2)

The spectrum to be predicted is given by Eq. (3). The distance between the strain gauges, which are receiving the pulses...
(x_2 - x_1), is necessary for the prediction at position x_3. Here x_m is the position of the first measured incident pulse, and x_{cp} is the position of the corrected/predicted wave.

\[ U_{cp}(x, \omega) = U_{mn} e^{i\phi_{mn}} e^{(-\hat{\alpha}_n + i \hat{k}_n) \Delta x} \]

where \( \Delta x = x_m - x_{cp} \) (3)

For the correction two values have to be calculated from the measured signals respectively the spectra. The attenuation factor \( \hat{\alpha}_n \) can be found out by using the calculated amplitudes \( U_{1n} \) and \( U_{2n} \). The wavenumber \( \hat{k}_n \) is related to the wave dispersion. It can be obtained from the calculated phases \( \phi_{1n} \) and \( \phi_{2n} \) [2], [4].

\[ \hat{\alpha}_n = \frac{\ln U_{1n} - \ln U_{2n}}{x_2 - x_1} \]
\[ \hat{k}_n = \frac{\phi_{1n} - \phi_{2n}}{x_2 - x_1} \] (4)

The calculated spectrum can be transformed into time domain by performing the Inverse Fourier Transformation (IFFT) to obtain the required pulse at the location of interest. Three strain gauges are applied to the IB to validate the proposed method [5]. The pulse for position x_3 is predicted from the data of strain gauge at position x_1 and x_2. This calculated pulse can then be compared with the measured pulse at position x_3.

\[ u_{cp} = \text{IFFT} [U_{cp}(x, \omega)] \] (5)

Fig. 2a shows a good agreement between the measured and predicted pulse. The different spectra in Fig. 2b shows that there is still a difference between the measured and the calculated signal. The same procedure can be performed analogously for the reflected pulse. In the TB only the incoming pulse is evaluated in Eqs. (1). Therefore a strain gauge can be placed very close to the interface of specimen and TB and, in this case, no correction of the transmission pulse is necessary.

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