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Low frequency limitations of the split Hopkinson pressure bar method for identification of complex modulus

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Abstract

Low frequency limitations of a recently developed method for identification of complex modulus utilizing the split Hopkinson pressure bar (SHPB) technique were investigated using computer simulations. Specifically, the effects of truncation, noise and discretization were examined. It was shown that the low frequency limitation of the method generally corresponds to the inverse of the length of the time signal. Further, it was shown that all three factors have an effect on the low frequency accuracy of the method and that careful consideration of these factors is necessary to optimize the capability of the method. Finally, it was shown how averaging techniques can be implemented to reduce the undesirable effects of truncation and noise.

Keywords: Split Hopkinson pressure bar; SHPB; Complex modulus; Low frequency limitations

1. Introduction

Recently, a new method for identification of complex modulus utilizing the split Hopkinson pressure bar (SHPB) technique was presented [1]. This method has subsequently been used in the viscoelastic characterization of compacted pharmaceutical tablets [2]. The method is similar to traditional SHPB testing [3] in that a short test specimen is placed between two long bars, called pressure bars, and a wave is generated in one of the bars through axial impact. Analysis of the waves reflected from and transmitted through the specimen gives information about the constitutive properties of the specimen. However, traditional SHPB testing is based on the assumption of equilibrium and axial uniformity of stress in the test specimen. The time and strain required to achieve equilibrium generally precludes estimation of the modulus of elasticity in traditional SHPB testing [3]. The method discussed in this study for identification of complex modulus does not require conditions of equilibrium or axially uniform stress in the specimen, and is exact in the context of 1-D wave propagation. Spectral analysis of the waves reflected from and transmitted through the specimen is carried out to extract the complex modulus.

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When compared to other means of identifying the complex modulus, this SHPB method is unique in that it allows the determination of complex modulus in a frequency range that is difficult to obtain using other methods when dealing with brittle materials. As the method has been recently developed, it is important to investigate its limitations in order to gain knowledge that can be used, for example, to select appropriate test parameters that optimize the results. The frequency limitations of the method are of particular interest. Because the method is based on the assumption of 1-D wave propagation through long, slender rods, the upper frequency limit is determined by the diameter of the pressure bars and is on the order of 10–20 kHz. When higher frequencies are considered, the wavelengths corresponding to these frequencies approach the size of the bar diameter and thus 3-D effects become significant. The lower frequency limit of the method has not been previously investigated in detail, which is the aim of this work. Computer simulations were carried out to demonstrate the effects of truncation, noise and discretization on the low frequency accuracy of the method. Additionally, two averaging techniques are presented that improve the quality of results when noise is present or truncation of the signal is necessary. The averaging technique for cases involving truncation was also tested on experimental data to demonstrate the improvement that can be achieved.

2. The SHPB method

A detailed presentation of the SHPB method for identification of complex modulus is found elsewhere [1], and thus only a brief description will be give here. The central part of the SHPB setup is shown in Fig. 1. A cylindrical test specimen of thickness a, cross-sectional area A, density ρ and complex modulus E^* is placed between two pressure bars of cross-sectional area A_b, density ρ_b and complex modulus E_b^*. A compressive incident wave is generated at the free end of one of the pressure bars, called the input bar, via axial impact with a striker bar. This incident wave propagates along the length of the incident bar until it encounters the specimen, whereupon the wave is reflected from and transmitted through the specimen. The wave reflected from the specimen is measured by means of a pair of strain gauges attached to the input bar, and the wave transmitted through the specimen is measured similarly by means of a pair of strain gauges attached to the output bar. By considering the propagation of waves in the bars and the specimen, and the continuity of velocity and force at the bar–tablet interfaces, one obtains the frequency–domain relation [1]

$$\frac{\hat{\varepsilon}_{RM}}{\hat{\varepsilon}_{TM}} = \frac{1}{2}\left(\frac{Z}{Z_b} - \frac{Z_b}{Z}\right)\sinh\left(i\omega a\sqrt{\frac{\rho}{E^*}}\right). \tag{1}$$

Here, $\hat{\varepsilon}_{RM}$ and $\hat{\varepsilon}_{TM}$ are the Fourier transforms of the measured strains associated with the reflected and transmitted waves, respectively, ω is the angular frequency, and

$$Z = A\sqrt{\rho E^*}, \quad Z_b = A_b\sqrt{\rho_b E_b^*}$$

are the characteristic impedances of the specimen and the bars, respectively. Note that $\hat{\varepsilon}_{RM}$, $\hat{\varepsilon}_{TM}$, E_b^* and E^* are complex functions of ω. Numerical iteration procedures are used to extract the complex modulus E^*.

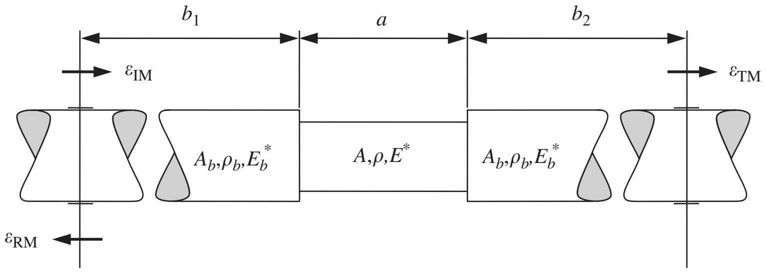

Fig. 1. Schematic of the central part of SHPB setup showing test specimen placed between two pressure bars.