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Journal of Sound and Vibration 287 (2005) 637–643

JOURNAL OF SOUND AND VIBRATION

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Short Communication

On a simple impact test method for accurate measurement of material properties

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Received 27 January 2005; received in revised form 27 January 2005; accepted 6 February 2005
Available online 26 April 2005

Abstract

A simple impact test method is presented to accurately measure the elastic and shear moduli and Poisson's ratio of a uniform Aluminum 6061-T651 cylindrical specimen with free boundary conditions. The elastic modulus is determined from the longitudinal vibration of the specimen and the shear modulus is determined from its torsional vibration. A new technique is developed to mount an accelerometer on the specimen to measure its torsional vibration. The Poisson's ratio determined for the specimen matches exactly with its known value.

1. Introduction

Knowledge of material properties, such as the elastic and shear moduli and Poisson's ratio, are important in mechanical design and research. Non-destructive dynamic testing is preferred over destructive mechanical testing because the specimen can be used in further experimentation. Dynamic testing is also advantageous for measurement of material properties because it is less costly than using a tensile or torsion test. Yu and Prucher [1] compared the dynamic and mechanical test methods and found that the elastic and shear moduli were determined more precisely from the dynamic test. The elastic and shear moduli determined from the mechanical test

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2005.02.016

have significantly more variance; hence it should be conducted for more specimens. The mechanical test is also limited by the size and geometry of the test object.

Different excitation methods have been used in dynamic testing for material characterization. One method is to use electromagnets to excite the specimen at a constant frequency and use a capacitance sensor to record the frequency with the maximum amplitude [2,3]. Sonic resonance methods use a speaker to excite the specimen and a ceramic pick-up, a microphone, or a capacitance probe to measure the response [4–7]. More recently an electromagnetic shaker or a piezoelectric transducer has been employed [8–11]. The shaker test can be conducted in two ways: the specimen can be bolted to the armature of the shaker [9] or a stinger can be used to link the shaker to the specimen [8]. The main problem with the former is the difficulty in clamping the specimen rigidly to the shaker armature and that with the latter is the influence of mass loading from the stinger and the force sensor. Another problem with the latter is that the test specimen needs to be drilled and threaded to allow for the attachment of the force sensor.

Impact testing is a less common method in materials testing. The impact force signal is not used in the ASTM standard and only the response is measured [12]. Nuansing and Maesnsiri [13] used the ASTM testing procedure and found large measurement errors in Poisson's ratio. The frequency limit of the impact test was restricted to 23 kHz [13], which is reasonable as the highest reliable frequency that a commercial small-sized pencil hammer (PCB Model 086D80) can excite is around 20 kHz. Only the first natural frequencies were measured in Ref. [13] and many of the calculations relied on tabulated correction factors. Impact testing was also used by Mead and Joannides [11] in exciting the longitudinal vibration to verify that the mounting of the shake did not alter the dynamics of the specimen.

The shear modulus was often measured from the flexural vibration of the rectangular beam specimen using Timoshenko beam theory [2,14]. When the length-to-depth ratio of the specimen is large and the mode number used is small, the effect of shear deformation is small and the measurement error for the shear modulus is relatively large [15]. While the torsional vibration test can be conducted for the rectangular beam specimen by offsetting the input force and measurement from its center line, the standard equation describing the torsional vibration assumes that the cross-sectional plane rotates as a whole and there is no warping, which is true only for uniform cylindrical specimens [16]. Torsional vibration tests were conducted for cylindrical specimens by Spence and Seldin [5], Spencer [7], and Simpson and Pearson [17], and in each case an extra apparatus was constructed. The specimen in Ref. [5] was weighed at both ends with longer cylinders of a high modulus material. The main difficulty with this approach is to approximate the internal conditions between the specimen and end cylinders and to know the shear modulus of the cylinders. Spencer [7] adopted a similar approach and used a loud speaker and a non-contact sensor to excite and measure the torsional vibration, respectively. By supporting the specimen on needle points at the center, an eddy-current driver, an eddy-current pick-up, and a feedback circuit were constructed in Ref. [17] to excite and measure the torsional vibration.

The objective of this work is to demonstrate a simple impact test method for accurate measurement of the elastic and shear moduli and Poisson's ratio of a cylindrical specimen. The elastic and shear moduli are determined from the longitudinal and torsional vibrations of the specimen, respectively. A new technique is developed to mount an accelerometer on the specimen to measure its torsional vibration. It is remarkable to find that the Poisson's ratio obtained for the specimen matches exactly with its known value. This significantly improves the results in Refs. [13,18].

2. Experimental setup

A uniform Aluminum 6061-T651 cylindrical specimen with a diameter of 0.0191 m is used. The length of the specimen is $l = 0.796\,\text{m}$ and the mass density is $\rho = 2715\,\text{kg/m}^3$. A computer is used to control and collect data from a dynamic signal analyzer (Siglab Model 20-42). Inputs from the accelerometer (PCB U352C66) and impact hammer (PCB Model 086C01) are conditioned using a signal conditioner (PCB Model 482A17). The accelerometer has only 2 g of mass to keep mass loading to a minimum. The boxcar window is used for the impact force and the exponential window is used for the response from the accelerometer. The exponential window helps to force the response to zero near the end of the measurement, which reduces leakage. The frequency response functions for the longitudinal and torsional vibrations are measured using the dynamic signal analyzer, from which the natural frequencies are identified.

Free boundary conditions are used for the specimen because they are more easily verifiable than fixed boundary conditions. They are approximated by attaching thin threads close to the ends of the specimen, as shown in Fig. 1. To excite and measure the longitudinal vibration, the specimen is impacted at one end of the specimen perpendicular to the face with the accelerometer affixed to the other end. Measurement of the torsional vibration presents a challenge because the accelerometer needs to be affixed tangentially to the specimen. To this end, a bracket is made by bending a thin steel band around the bar, leaving a tab for the accelerometer (Fig. 2). The bracket is attached to the specimen using Petro wax. To excite the torsional vibration, the specimen is struck at the same angle as the accelerometer. Generally speaking, the locations of the impact and bracket should not coincide with a nodal point of a torsional mode to be measured. They are chosen to be slightly away from the center of the specimen to minimize the difference of the

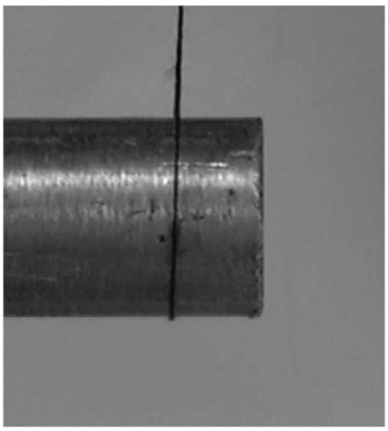

Fig. 1. Photograph showing a free boundry condition of the cylindrical specimen.

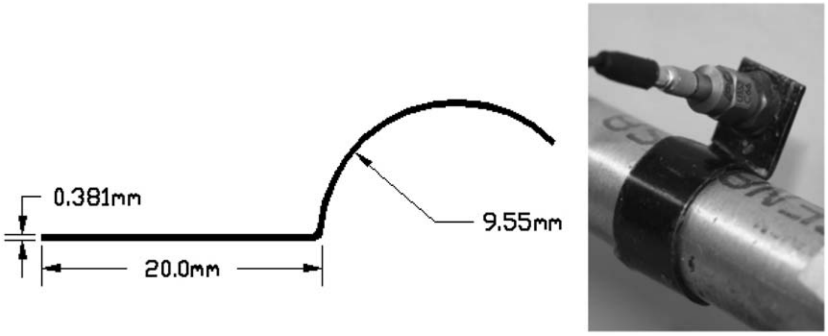

Fig. 2. Schematic and photograph showing the accelerometer bracket used for torsional vibration measurement.

tensions in the threads. The bracket works well because its fundamental frequency is much higher than that of the specimen.

The steel hammer tip is used to excite the longitudinal vibration due to its relatively high natural frequencies. The bandwidth used for the first longitudinal mode is 5 kHz and that for the second and third modes is 10 kHz. The Derlin tip is used to test the first torsional mode and the steel tip is used for the higher modes. The bandwidths used for the first and second torsional modes are 2 and 5 kHz, respectively, and that for the third and fourth modes is 10 kHz. In all the cases a record length of 8192 samples is used in the frequency domain.

For every impact test three impacts are averaged to ensure repeatable results and to obtain a coherence measurement. The coherence at resonance is essentially 1 for the longitudinal modes, and is above 0.95 for the torsional modes due to some difficulty in impacting the specimen at the same angle in each test.

3. Method for determining material properties

The equation of motion for the longitudinal vibration of the specimen is [16]

$$\left(\frac{E}{\rho}\right)\frac{\partial^2 w(x,t)}{\partial x^2} = \frac{\partial^2 w(x,t)}{\partial t^2}, \tag{1}$$

where w is the longitudinal displacement of the specimen at position x at time t and E is the elastic modulus. The free boundary conditions are

$$\frac{\partial w(0,t)}{\partial x} = 0, \qquad \frac{\partial w(l,t)}{\partial x} = 0. \tag{2}$$

The longitudinal natural frequencies are

$$\omega_n = \frac{n\pi c}{l}, \tag{3}$$

where n is the mode number for the longitudinal vibration and $c = \sqrt{E/\rho}$is the longitudinal wave speed.

The equation of motion for the torsional vibration of the specimen is [16]

$$\frac{\partial^2 \theta(x,t)}{\partial t^2} = \left(\frac{G}{\rho}\right)\frac{\partial^2 \theta(x,t)}{\partial x^2}, \tag{4}$$

where θ is the rotation of the specimen about its central axis at position x at time t and G is the shear modulus. The free boundary conditions are

$$\frac{\partial \theta(0,t)}{\partial x} = 0, \quad \frac{\partial \theta(l,t)}{\partial x} = 0. \tag{5}$$

The torsional natural frequencies are

$$\Omega_k = \frac{k\pi d}{l}, \tag{6}$$

where k is the mode number for the torsional vibration and $d = \sqrt{G/\rho}$is the torsional wave speed.

To determine the elastic modulus, the theoretical longitudinal natural frequencies using an assumed elastic modulus are plotted against their measured ones. If the theoretical versus experimental line from a linear curve fit, which passes through the origin, has a slope greater than 1, the assumed elastic modulus is too large and needs to be decreased. Similarly, if the theoretical versus experimental line has a slope less than 1, the assumed elastic modulus is too small and needs to be increased. The assumed elastic modulus is the measured elastic modulus of the specimen when the theoretical versus experimental line has a slope of 1 [19]. The shear modulus of the specimen is determined from the torsional vibration using the same method. The Poisson's Ratio v is determined subsequently from the measured elastic and shear moduli:

$$v = \frac{E}{2G} - 1. \tag{7}$$

4. Results

The measured longitudinal and torsional natural frequencies of the specimen are shown in Fig. 3 and Table 1. The elastic and shear moduli of the specimen are found to be 70.50 and 26.45 GPa, respectively. The Poisson's ratio determined from Eq. (7) using the measured elastic and shear moduli is 0.33, which is the exact known value for the Poisson's ratio of Aluminum 6061-T651 [20]; the above results are repeatable. The resulting line from the linear curve fit of the experimental and theoretical longitudinal natural frequencies has a slope of 1.002 and that from the linear curve fit of the theoretical and experimental torsional natural frequencies has a slope of 0.998 (Fig. 3); both slopes are nearly 1. The theoretical longitudinal and torsional natural frequencies using the measured elastic and shear moduli are listed in Table 1; the maximum difference between the theoretical and experimental values is within 0.3%. Due to the small difference between the theoretical and experimental values, the natural frequency of a single longitudinal mode can be used to measure the elastic modulus and that of a single torsional mode can be used to measure the shear modulus; this yields a similar Poisson's ratio. Also, the response from the accelerometer can be directly processed using the Fast Fourier Transform to extract the

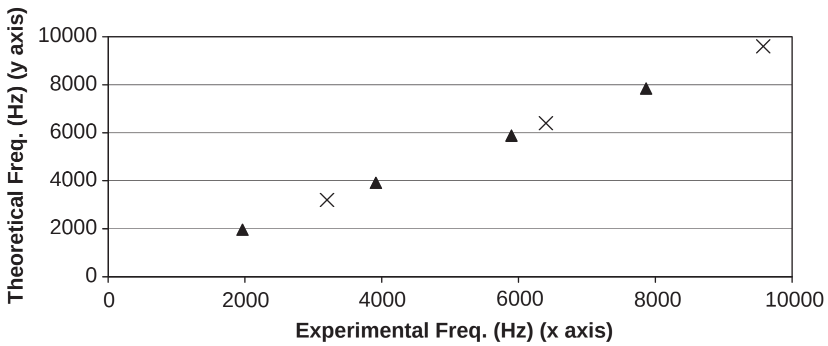

Fig. 3. Theoretical versus experimental natural frequencies for longitudinal (×) and torsional (▲) vibrations of the specimen. The equations of the lines from the linear curve fit through the origin are $y = 1.002x$ and $y = 0.998x$, respectively, for the longitudinal and torsional vibrations.

Table 1
Experimental and theoretical natural frequencies for longitudinal and torsional vibrations of the specimen

Longitudinal modes			Torsional modes		
Exp. (Hz)	Theo. (Hz)	Dif. (%)	Exp. (Hz)	Theo. (Hz)	Dif. (%)
3200	3201	0.03	1965	1961	−0.20
6400	6402	0.03	3915	3921	0.15
9578	9603	0.26	5896	5882	−0.24
			7865	7842	−0.29

measured longitudinal or torsional natural frequencies; this eliminates the need of a dynamic signal analyzer and an instrumented hammer. Note that the shear moduli should be measured as accurately as possible because the Poisson's ratio can have an error nearly 4 times that for the shear modulus. For example, if the elastic modulus is 69 GPa and the shear modulus is found to be 26.4 GPa while it should be 25.9 GPa (i.e., a 1.9% error), the Poisson's ratio will drop from 0.332 to 0.307, a 7.5% error.

5. Concluding remarks

Accurate measurement of Poisson's ratio is a challenging task because it is sensitive to the measurement error in shear modulus. With the new technique for mounting an accelerometer on the cylindrical specimen to measure its torsional vibration, the shear modulus is measured accurately from the simple impact test and the resulting Poisson's ratio matches exactly with its known value. The method can be used for other cylindrical specimens.

Acknowledgement

The authors wish to thank the National Science Foundation for the partial support through the award CMS-0116425.

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