NOVEL TECHNIQUE OF NDE IN CERAMIC BEARING BALLS

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ABSTRACT

We present a new technique for the nondestructive evaluation of ceramic bearing balls. The technique is based on measuring the quality factor (Q) of various surface wave resonant modes. Surface cracks will scatter surface waves. Thus, the existence of surface cracks will lower the surface wave resonance Q's. We have made a simple experimental set-up capable of exciting and detecting the various resonances on the bearing balls and their Q's. Low-frequency resonances of torsional and spheroidal modes are used to measure the shear wave velocity V_s and Poisson's ratio ν. High-frequency resonances of the surface waves are used to determine the presence of surface defects.

INTRODUCTION

The resonant sphere technique[1] was introduced by D. B. Fraser as a tool for material property measurement.[2] There are two types of resonance in a sphere, the spheroidal modes and the torsional modes. The notations we shall use in this paper are S_{mn} for the n^{th} mode and m^{th} harmonic of the spheroidal resonances, and T_{pq} for the q^{th} mode and p^{th} harmonic of the torsional resonances. The special cases here are the S_{0n} modes, which are pure longitudinal modes. Also, the S_{m0} modes for m large had been shown to be the resonance modes for surface acoustic waves (Rayleigh waves).[3] In the low-frequency region, the frequency spectrum can be identified and the material properties can be calculated. The torsional resonant frequency is used to calculate V and the spheroidal frequency is combined with V_s to calculate ν. The values of V_s, ν, and V_l are used to calculate the surface wave velocity V_R.

Because spheres are of finite dimensions, propagating surface waves form standing waves. When the half circumference of the sphere is a multiple of a half wavelength of the surface wave, resonance will take place. Defects on the surface of the sphere will scatter the waves and reduce the quality factor Q. Our aim is to determine the relationship between the Q of surface wave resonances and the density of surface defects.

THEORETICAL BACKGROUND FOR THE RESONANT SPHERE TECHNIQUE

The characteristic equations for a resonant sphere are derived, assuming a stress free boundary condition.

Torsional Mode[3]

For torsional resonance, the characteristic equation has the form:

$$(p-1)J_{p+1/2}(\eta)-\eta J_{p+3/2}(\eta) = 0 \qquad (1)$$

where p is an integer, $J_{p+1/2}$ is the $(p+1/2)^{th}$ order Bessel function, $\eta = 2\pi fr/V_s$, and r is the radius of the ball. Therefore, given the resonant frequency for the torsional resonance, V_s can be calculated.

Spheroidal Mode[3]

For spheroidal resonance, the characteristic equation has the form:

$$\frac{2h}{k}\left[\frac{1}{\eta}+\frac{(m-1)(m+2)}{\eta^2}\left(\frac{J_{m+3/2}(\eta)}{J_{m+1/2}(\eta)}-\frac{m+1}{\eta}\right)\right]\frac{J_{m+3/2}(\xi)}{J_{m+1/2}(\xi)}+$$

$$\left[-\frac{1}{2}+\frac{(m-1)(2m+1)}{\eta^2}+\left(\frac{1}{\eta}-\frac{2m(m-1)(m+2)}{\eta^3}\right)\frac{J_{m+3/2}(\eta)}{J_{m+1/2}(\eta)}\right]=0, \qquad (2)$$

where:

$$h=\frac{2\pi fr}{V_l},\ k=\frac{2\pi fr}{V_s},\ \xi=\frac{2\pi fr}{V_l}$$

Therefore, knowing V_s, calculated from the torsional mode, V_l and ν can be calculated.

A special case for the spheroidal mode is the longitudinal mode, where $m = 0$, and the characteristic Eq. (2) is reduced to:

$$\tan(\xi)=\frac{\xi}{1-\frac{1}{4}\eta^2} \qquad (3)$$

Surface Wave Mode

When m becomes a large number, the characteristic equation for the S_{m0} mode becomes:

$$[2-(\eta/w)^2]^2-4\sqrt{1-(\eta/w)^2}\sqrt{1-(\eta/w)^2(\eta/k)^2}=0 \qquad (4)$$

where $w = m + 1/2$.

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EXPERIMENTAL SET-UP

The experimental set-up is shown in Fig. 1. Two $LiNbO_3$ longitudinal transducers were used. The signal from the first synthesizer is sent to the bottom transducer which excites ultrasonic waves on the sphere, in this case, a ceramic bearing ball. The top transducer, which is similar to the bottom transducer, acts as a receiver. It is positioned to make a Hertzian contact with the sphere. To detect both the phase and amplitude of the received signal, the received signal is mixed with a signal from the second synthesizer with a frequency setting which is 1 KHz lower than that of the first synthesizer. After mixing, the signal is sent into a lock-in amplifier. Signals from the trigger output channels of both synthesizers are also mixed, low pass filtered at 1 KHz, and then sent into the reference channel of the lock-in amplifier. We designed a computer-controlled system to sweep over the frequency range of interest at a fixed, but arbitrary, frequency increment. We were able to measure the resonant frequency spectrum of the spheres, both in phase and in amplitude. Local maxima in amplitude are used to determine the resonance frequencies of the sphere, whereas the phase of the spectrum is used to measure the resonance Q's.

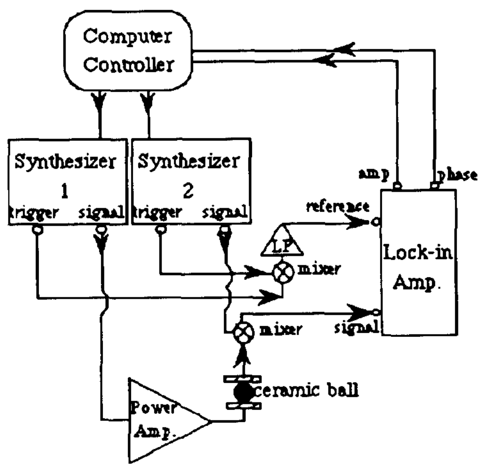

Fig. 1. Experimental set-up for the resonant sphere measurement.

There is an important reason why we want to measure both amplitude and phase. Using amplitude alone to measure samples with high Q's is time consuming because of the small frequency increment necessary for an accurate measurement. The importance of phase measurement is evident for the following reason: at resonance, phase undergoes a change of π and its slope:

$$\frac{d(\text{phase})}{d(\text{frequency})}$$

is almost constant. The equation for phase near resonance is given by:[4]

$$\theta = \theta_0 - \tan^{-1}\frac{(f^2-f_0^2)Q}{f\,f_0} \tag{5}$$

where θ_0 is the phase value at resonance, f_0 is the resonance frequency, f is the frequency at each point, and Q is the quality factor. This character is commonly observed also in resonant circuits for large values of Q.

Therefore, to determine the resonance Q for a particular mode, we simply determine the resonant frequency to the desired accuracy by amplitude measurement, measure several points around resonance, and fit a curve to the measured phase according to the above equation.

RESULTS AND ANALYSIS

Three Si_3N_4 ceramic bearing balls of 1/2 inch diameter were used as samples for the experiment. The first ball is perfect with no cracks. The second had a series of cracks made with a 10 g load on a Knoop indenter, and the third had cracks made with a load of 50 g on the indenter (we will refer to these three balls as balls A, B, and C, respectively).

First, we determine the mechanical properties of the samples. Figure 2 shows an example of the amplitude frequency spectrum of ball C. Figure 3, in turn, zooms in on the amplitude and phase of a particular high Q mode T_{12} of ball A. Among the numerous torsional modes of a sphere, the T_{p2} modes showed the highest Q value. This may be due to the fact that the large displacement amplitudes of the T_{p2} modes are mainly inside the sphere.[2] High Q modes are more frequency selective, and are chosen to calculate the mechanical properties. Table 1 lists the material constants calculated from the resonant frequencies for the three samples. T_{12}, the highest Q mode observed in the low frequency range, was used to determine V_s. Poisson's ratio ν was determined from the T_{12} and S_{01} modes by solving the characteristic equations. V_l was calculated from V_s and ν. V_R was calculated from the characteristic equation for surface waves.[3]

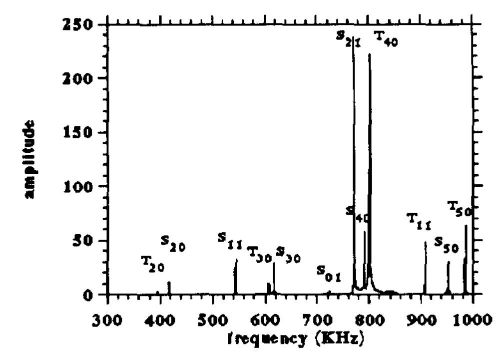

Fig. 2. Spectrum in amplitude for the fundamental modes of ball C.

In the higher frequency region, the resonance spectrum becomes more complicated as there is an increasing number of closely-spaced higher order resonance modes. Still, it was possible to isolate the surface wave resonances when the frequency was high enough, such as around 14.25 MHz. As shown in Fig.4, several dominating resonance modes, which are almost equally spaced in the frequency domain, are in evidence. Several reasons lead us to conclude that these dominating modes are indeed surface wave resonance modes. First, surface waves on a sphere tend to dominate in the higher frequency region. Second, when combining the asymptotic characteristic equation of

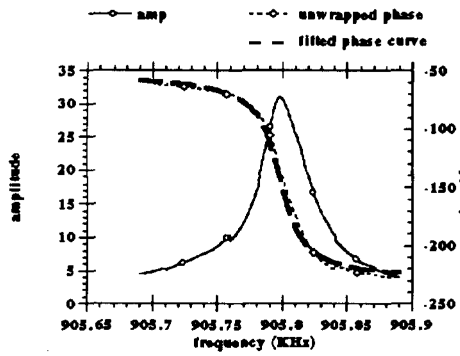

Fig. 3. Spectrum in both amplitude and phase for mode T_{12} of ball A. Curve fitting the phase information gives Q = 34799 . One can see clearly the phase change near resonance.

		Ball A		Ball B		Ball C	
T_{12}	f(KHz)	905.80		905.74		905.50	
	Q	34799		42242		32985	
S_{01}	f(KHz)	720.41		724.42		721.40	
	Q	20058		19245		16918	
V_s(m/s)		6270.5		6270.1		6268.4	
n		.26447		.26573		.26522	
V_l(m/s)		11081		11100		11082	
V_R(m/s)		5779.9		5780.8		5778.8	
Results for Surface Waves							
$\frac{\pi r}{\lambda_R}$		f (MHz)	Q	f (MHz)	Q	f (MHz)	Q
49		14.1963	10810	14.2090	7905	14.1790	3655
49.5		14.3409	11321	14.3547	7998	14.3252	4348
50.		14.4855	9573	14.4988	8546	14.4677	4607

Table I. Data obtained by the resonant sphere technique for three ceramic bearing balls, each with a diameter of 1/2 inch. Ball A is a perfect ball with no cracks. Ball B has a series of cracks made with a 10 g load on a Knoop indenter, and ball C has the cracks made with a load of 50 g on the Knoop indenter. V_R is the surface wave velocity and $\lambda_R = V_R/f$ is the wavelength of the surface wave at frequency f.

surface waves on a sphere with the material properties acquired in the low-frequency region, we calculate the surface wave velocity V_R and the corresponding wavelength:

$$\lambda_R = \frac{V_R(\text{calculated})}{f(\text{measured})}$$

As discussed earlier in this paper, we then ascertain that an integer number of half wavelength fits on the surface of the sphere according to the relationship:

$$\frac{\pi r}{(\lambda_R/2)} = n$$

where n is a large positive integer, around 50 in our case. Third, for the same sphere, the values of the resonance Q's for the dominating modes are of similar values. This indicates that these modes are of similar character. We therefore conclude that these dominating modes are surface wave modes.

Table 1 also shows the results of measurements of the three balls for three surface wave resonance modes. As can also be seen from Fig. 5, the widening of the amplitude response is evidence for the existence of cracks. We note that the Q of the surface wave resonances decrease as the load on the indenter, and consequently, the size of the surface cracks increase. Thus, we have a direct relationship between the value of the Q of the surface wave resonance and the density of surface defects.

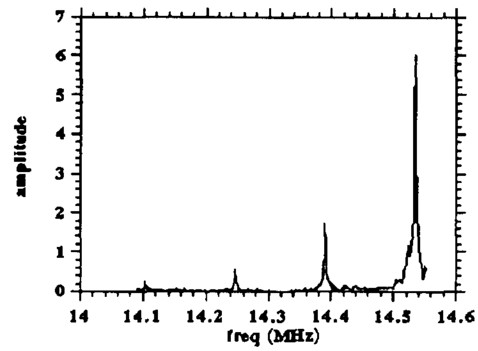

Fig. 4. Spectrum in amplitude for ball A around 14.25 MHz . The dominance of surface waves is evident.

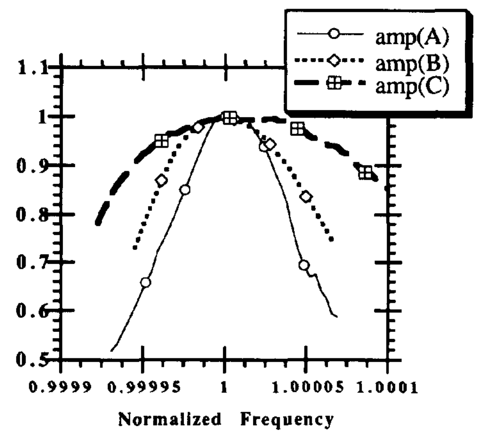

Fig. 5. Amplitude spectrum for the n = 50 mode for the three spheres. Note both amplitude and frequency have been normalized.

CONCLUSION

We have successfully used the resonant sphere technique with an improved amplitude and phase measurement system to identify low-frequency resonances from which we acquire material properties. We also demonstrated, for the first time, that this technique can be applied in the higher frequency region to identify surface waves on a sphere, and we related the quality factor of surface wave resonances to the density of surface defects.

ACKNOWLEDGMENT

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