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A new technique for measuring the acoustic nonlinearity of materials using Rayleigh waves

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Abstract

This note presents a procedure to generate nonlinear Rayleigh surface waves without having to drive the transmitting piezoelectric transducer at high voltages; driving at low voltages limits the excitation of the intrinsic nonlinearity of the piezoelectric transducer element, and enables an efficient measurement procedure to isolate inherent material nonlinearity. The capabilities of this proposed technique are demonstrated by measuring the material nonlinearity of aluminum alloy 2024 and 6061 plates with Rayleigh surface waves.

Keywords: Nonlinear ultrasonics; Rayleigh waves; Acoustic nonlinearity parameter

1. Introduction

The nonlinear acoustic technique has attracted considerable attention in recent years, where experimental results and physical models show that the second-order harmonic amplitude is directly related to fatigue damage [1–4]. Generally in metals, this fatigue damage first appears in the form of dislocation substructures such as veins and persistent slip bands (PSB), and these accumulate at grain boundaries to produce strain localization. Studies show that these dislocation substructures and resulting microplastic deformation do not cause large changes in the macroscopic properties such as elastic modulus, sound speed and attenuation of a material [3,4], thus the changes in the linear ultrasonic values are not large enough to be accurately measured with conventional linear ultrasonic techniques.

On the other hand, these dislocation substructures will create a slightly nonlinear stress–strain relationship in a localized volume, and their accumulation throughout the continuum will cause a nonlinear distortion in an ultrasonic wave propagating in the material with increasing fatigue damage [5,6]. This nonlinear distortion will generate higher harmonic components in an initially monochromatic ultrasonic wave signal. For this reason, nonlinear ultrasonic waves can be used to quantify the presence and the density of dislocations in a metallic material, and thus measure fatigue damage in a quantitative fashion. There are a number of advantages of using Rayleigh surface waves in nonlinear acoustics. First, Rayleigh waves do not require access to both sides (one side for generation and the second side for detection) of a component, as is the case for most bulk wave applications; this single-sided technique is particularly promising for field applications, where the availability of two parallel surfaces (each with access available to mount transducers) will be a limiting restriction. Second, most of the energy of Rayleigh waves is concentrated near the stress-free surface, which can lead to stronger nonlinear effects compared to bulk waves, since fatigue damage is typically initiated on the free surface of a component. Finally, Rayleigh waves propagate far distances, making them an ideal means to interrogate large, complex components.

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Unfortunately, material nonlinearity—an undamaged material's inherent acoustic nonlinearity plus any nonlinearity from accumulated fatigue damage—is very small, and can easily be overwhelmed by instrumentation nonlinearity. Measuring acoustic nonlinearity can be especially difficult in thin specimens, when there is not enough propagation distance for the second harmonic signal to cumulatively grow above the noise level. Nonlinear ultrasonics requires high-amplitude ultrasonic waves, which usually means driving the transmitting transducer at high voltages. The intrinsic nonlinearity of the transmitting transducer is a major source of this instrumentation nonlinearity; any reduction in transducer nonlinearity will enable a robust measurement procedure capable of isolating material nonlinearity from instrumentation nonlinearity.

This research presents an efficient procedure to generate nonlinear Rayleigh surface waves by directly exciting at an angle from the edge of a specimen. This approach enables driving the transmitting piezoelectric transducer at low voltages (below 60 V peak-to-peak, Vpp) to limit the nonlinear contribution from the transducer. The capability of this system to measure the nonlinear contribution in Rayleigh surface waves is demonstrated by measuring the acoustic nonlinearity of aluminum alloy 2024 and 6061 specimens; these results are in agreement with those available in the literature. The proposed technique is especially well suited to determine the acoustic nonlinearity of thin components, that is, plates and shells, and is much simpler than the traditional longitudinal wave technique.

2. Acoustic nonlinearity parameter in terms of surface normal displacements of Rayleigh waves

As a first step, the acoustic nonlinearity of a material (β) is related to the fundamental and second-order harmonic displacement amplitudes of a Rayleigh wave measured with a laser interferometer. The relation has been derived in our previous work [2] as

$$\beta = \frac{8u_z(2\omega)}{k_1^2 x u_z^2(\omega)} F; \quad F = \frac{k_s^2\sqrt{k_R^2 - k_l^2}}{2(2k_R^2 - k_s^2)k_R}, \tag{1}$$

where $u_z(\omega)$ and $u_z(2\omega)$ are the fundamental and second-order harmonic amplitudes of a Rayleigh wave displacement; k_R, k_l and k_s are the Rayleigh, longitudinal and shear wave numbers. It is noted that Eq. (1) is formally analogous to the acoustic nonlinearity parameter for longitudinal waves except for the correction factor F, which is only a function of the Poisson's ratio of the material. It can be shown that the correction factor F varies from 0.234 to 0.413 as the Poisson's ratio varies from 0 to 0.5, and it is 0.326 for the Poisson's ratio 0.3. A possible physical implication regarding F is that since a Rayleigh wave is mostly shear motion, the Rayleigh wave displacements u_z contain a large contribution from this shear motion. Therefore, β when expressed in terms of these displacements is corrected as much as the shear contribution in the displacement that does not produce the acoustic nonlinearity in an isotropic material. This may be the reason F is smaller than unity and its specific value may be related to the portion of how much the shear contribution is in the surface normal displacement.

It is also noted that the ratio $u_z(2\omega)/u_z^2(\omega)$ (or $v_z(2\omega)/v_z^2(\omega)$, where v_z is the surface normal velocity) increases linearly with the propagation distance x. In the experiment, instead of taking this ratio at a single point, this ratio over the propagation distance is measured and its slope is taken as a quantity that is directly proportional to the absolute acoustic nonlinearity. Taking the diffraction effects into account, one can show that $u_z(2\omega)/u_z^2(\omega)$ or $v_z(2\omega)/v_z^2(\omega)$ produced from a finite-size source is approximately proportional to the propagation distance in the far-field.

3. Experimental procedure

A piezoelectric transducer (Panametrics A 405S, 5 MHz, Paintbrush type) is mounted at an angle to the specimen with a fixture and coupled with vacuum grease over a strip of 10 mm long and about a 1 mm wide. The couplant acts as a prism-shaped wedge having a negligibly small volume. The incident angle is adjusted to around 61° with the fixture as shown in Fig. 1. To make sure that Rayleigh waves are being generated at this angle, the wave speed is measured in the pulse-echo mode, and a wave speed of 2910 m/s, the Rayleigh wave speed in aluminum, is obtained. The advantage of this setup is that it does not require an intermediate bulky polymeric wedge to create

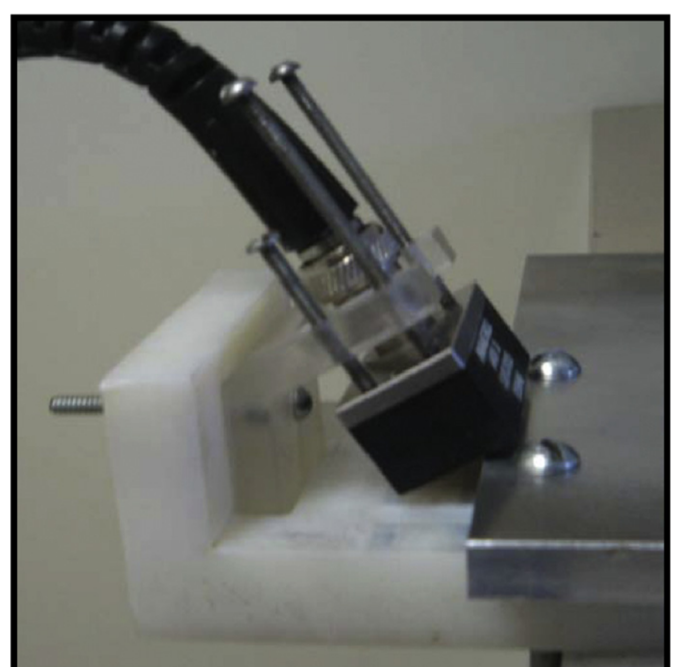

Fig. 1. Picture showing the transducer fixed at the edge of the plate specimen.