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# A new method for plastic strain measurement with Rayleigh wave polarization

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ABSTRACT

In this work, a new non-contact and coupling-free ultrasound method with measuring Rayleigh wave polarization (RWP) by electromagnetic acoustic transducers (EMATs) is applied for plastic strain measurement, which can provide a very promising alternative and reference-free ultrasonic testing technique with high spatial resolution. Two specially designed EMAT receivers are developed to measure the polarization of Rayleigh wave generated by an enhanced meander-line-coil EMAT. The change in RWP due to the plastic strain has been successfully measured. And the measurement results indicate that the plastic strain at the specimen surface can be evaluated with good accuracy by measuring the relative change in RWP with the proposed EMAT-based method.

## 1. Introduction

Plastic strain may happen in mechanical structures due to an unexpected load, for example, a giant earthquake. Residual plastic strain may have been introduced into the local part of the components even though deformation and macro damage were not detected by the visual inspections. Plastic strain or residual stress can have large influence on the material fatigue strength and fracture toughness. However, the plastic strain or residual stress sometimes may be helpful to increase the fatigue life (such as compressive residual stress), they may also seriously reduce the fatigue life and consequently cause structural safety problem at other time. To ensure the structural integrity after an unexpected loading process, quantitative nondestructive evaluation (NDE) of plastic strain and residual stress is very important.

Until now, several nondestructive testing (NDT) techniques, such as X-ray diffraction (XRD) technique, ultrasonic testing (UT) method and electromagnetic NDT methods, have been studied and applied for residual stress and plastic strain measurement [1–3]. Among them, XRD is a well developed method for applied or residual stress measurement. However, XRD is difficult to be used for field inspection, and it may cause some problems of radiation safety. Recently, electromagnetic NDE methods have been studied aiming at quantitative evaluation of the plastic strain and residual stress in a structural component, including magnetic barkhausen noise (MBN) method, metal magnetic memory method, nonlinear eddy current testing (NECT) method. However, there are still problems limited the application of these electromagnetic NDE methods such as the uncertain feature of the measurement results. The uncertainty may be caused by experimental conditions and also the material batch, such as surface quality, heat treatment and grain structure [1]. In addition, the relationship between the electromagnetic measurement results (for example, Magnetic Barkhausen Noise and Magnetic Incremental Permeability) and stress or plastic strain is usually not linear [2]. Comparing with XRD and electromagnetic NDT methods, ultrasonic method is more stable and easier to operate. And the relationship between the ultrasonic measurement results and the stress or elastic strain is usually linear [4–6]. However, conventional UT methods need the transducers to contact to the specimen surface with liquid coupling. Besides, until now, the wave speed is used as a measure of the stress or elastic strain in almost all references [4–8]. The measurement of the wave speed via the time-of-flight is an integral measurement. The state of stress or strain that are backed out this measurement represent average values along the propagation path of the ultrasonic wave. Furthermore, the measurement is not reference free, as the distance between the source and receiver of the ultrasonic wave has to be known very exactly. There are some theoretical researches have demonstrated that the polarization of Rayleigh wave is directly related to the state of stress, which can provide a very promising reference-free, alternative technique for stress or strain measurement. As the Rayleigh wave polarization (RWP) at a point is directly related to the stress status [9], the method based on RWP can measure the stress or strain of the test point (with the size equal to the spatial resolution of the detector and the depth related to the

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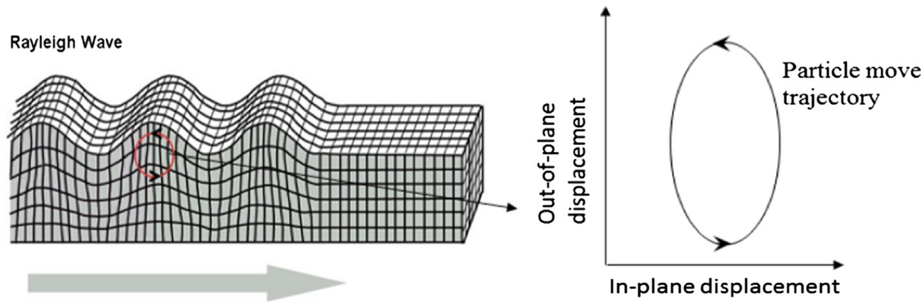


**Fig. 1.** Schematic diagram of Rayleigh wave polarization.

penetration of the Rayleigh wave), but not an average value between the transducer and receiver [9–11]. However, to our knowledge, the measurement of plastic strain by RWP has not been realized until now. This paper provides the experimental development of an alternative UT technique for plastic strain evaluation based on measuring the RWP with using electromagnetic acoustic transducers (EMATs).

## 2. Method and EMATs for RWP measurement

### 2.1. Basic theory

Rayleigh wave is a type of surface acoustic wave that travels along the surface of solids. The penetration depth of Rayleigh wave is approximately equal to its wavelength. As shown in Fig. 1, when Rayleigh wave travels along the surfaces of isotropic solids, the material particles move in ellipses trajectories in planes normal to surface and parallel to the direction of the propagation. The polarization value Π of Rayleigh wave is defined as the ratio between the maximum in-plane and the maximum out-of-plane displacement components. Previous theoretical researches have shown that the relative change in polarization of Rayleigh wave is proportional to the state of initial stress or strain in the tested materials [9–11]. Therefore, it is possible to evaluate the plastic strain by measuring the RWP.

As a non-contact ultrasonic transducer, EMAT can be used to generate and detect ultrasonic waves in different modes in metal structures based on the electrodynamic mechanism. The basic design of an EMAT consists of a coil with permanent magnets for setting up static magnetic fields with a material under inspection [12,13]. In generation mode, high frequency eddy currents induced by a transient current in the coils interact with the static magnetic flux to yield a transient electromagnetic force, which subsequently induces ultrasonic waves in the material under the EMAT. In detection mode, the static magnetic flux interacts as a result of ultrasonic motion with particles having a velocity within the material. This produces transient eddy currents within the sample, which can be sensed by the coil as a pick-up signal of the ultrasonic waves. EMAT has very good capability to generate and receive Rayleigh waves. And what's more, EMAT can be designed to be sensitive to preferential ultrasonic motions, either in-plane vibration or out-of-plane vibration, with using different magnetic configurations [14].

### 2.2. EMATs for RWP measurement

Fig. 2 shows the setup of the EMAT for Rayleigh wave polarization measurement. Firstly, an enhanced meander-line-coil (MLC) EMAT was used to generate Rayleigh wave with large amplitude. The enhanced MLC EMAT was composed with a meander line coil and two same square magnets laying alongside of each other in opposite polarity. With using such modified magnet configuration, the generation efficiency of the EMAT was increased by more than one time. The details of the modified MLC EMAT has been given in our previous paper [12].

In order to obtain the Rayleigh wave polarization, a couple of EMAT receivers with different magnet configurations have been developed to measure the in-plane and out-of-plane particle velocity components of the Rayleigh wave with high sensitivity at the specimen surface, respectively. As shown in Fig. 2(a), the in-plane EMAT receiver is composed of two neodymium cubic magnets (20 mm × 30 mm and 10 mm thick), with facing north (N) poles separated by about 2 mm, and a multi-turn pick-up coil inserted between the two magnets. The pick-up coil was made up of enamel coated, fine copper wire wrapped around a miniature cubic PCB board in between the two permanent magnets. To obtain good spatial resolution, the lateral width of the pick-up coil was set about 1.5 mm. The effective area of the coil was about 1 $cm^2$ (5 mm × 20 mm). Such magnet configuration of the in-plane EMAT can generate a strong magnetic field penetrating to the specimen with magnetic flux predominantly perpendicular to the specimen surface under the coil. Previous researches has validated that the magnetic flux density on the end face of the magnetic configuration is about a factor 2 higher than from a single disk magnet [14]. The generated out-of-plane magnetic field ($\overrightarrow{B_z}$) interacts with the in-plane particle vibration ($\overrightarrow{v_x}$) of the Rayleigh wave. Eddy currents density ($\overrightarrow{J}$) is induced by the interaction and sensed by the coil as a pick-up signal. So, the in-plane EMAT receiver detect predominantly the in-plane component of the Rayleigh wave.

To measure the out-of-plane component of the Rayleigh wave, an out-of-plane EMAT composed of a coil same with that of the in-plane EMAT but a different magnet configuration was developed. As shown in Fig. 2(b), the out-of-plane EMAT composes with two cubic magnets (20 mm × 30 mm and 20 mm thick) arranged to be of opposite polarity with a separation about 2 mm. With such magnet configuration, the out-of-plane EMAT can generate a magnetic field penetrating to the specimen with magnetic flux predominantly parallel to the specimen surface under the coil. The generated in-plane magnetic field ($\overrightarrow{B_x}$) interacts with the out-of-plane particle vibration ($\overrightarrow{v_z}$) of the Rayleigh wave and induces the eddy current. Therefore, the out-of-plane EMAT receiver detects predominantly the out-of-plane component of the Rayleigh wave.

Before validation with experimental measurement, magnetic configuration of both the in-plan and out-of-plane EMAT receivers were modelled to examine the distribution and strength of the magnetic field external to the magnets themselves with using the equivalent magnetic charge approach [13,15,16]. According to this approach, external magnetic field of a magnet is produced by magnetic charge distributed in and on the magnet. For a uniform magnetized magnet, the magnetic charges only appear on the surface of the two magnetic poles. The charge surface density is equal to the remanent magnetic intensity $B_r$ of the magnet. The magnetic flux density $\mathbf{B_s}$ in any field point can be given as

$$\mathbf{B_s} = \mu_0 \int_{S+} \frac{B_r}{4\pi\mu}\frac{\mathbf{r}}{r^3}dS - \mu_0 \int_{S-} \frac{B_r}{4\pi\mu}\frac{\mathbf{r}}{r^3}dS \quad (1)$$

where $\mathbf{r}$ denotes the vector from the source point of magnetic charge to field point, $S_+$ the surface with positive charge, $S_-$ the surface with negative charge, $\mu$ the magnetic permeability of magnet and $\mu_0$ the vacuum permeability.