Estimation of five elastic stiffness coefficients of unidirectional glass fiber reinforced plastic by laser generated ultrasonic

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Abstract—Five elastic stiffness coefficients of UD-GFRP were estimated by using a laser iso-angular scanning method. Four stiffness coefficients $C_{33}$, $C_{11}$, $C_{66}$ and $C_{44}$ (direction 3 being the fiber direction) were first accurately determined by using phase velocities of longitudinal and shear waves in the fiber and fiber-normal directions. The stiffness $C_{13}$ was estimated by iteration so that the slowness curve of quasi-shear waves computed to an assumed $C_{13}$ best matches the measured one. The estimated stiffness coefficients agreed quite well with those estimated by the through-transmission method in water.

Keywords: UD-GFRP; laser iso-angular scanning method; quasi-shear wave; elastic stiffness coefficients; through transmission method in water.

1. INTRODUCTION

Accurate estimation of elastic stiffness coefficients of an anisotropic medium is important for integrity and damage inspection by ultrasonic and acoustic emission (AE). Extensive researches on the elastic stiffness estimation have been conducted so far. Some researchers utilized the orientation dependency of surface acoustic wave (SAW) velocities, and some that of bulk waves. The procedure for determining (recovering) the stiffness coefficients from the measured phase velocities of bulk waves has been addressed in detail by Every [1]. It is based on the Christoffel equation [2], a relation between the phase velocity and stiffness coefficients. However, the wave energy is propagated with group velocity and, in general, the phase velocity is different from the group velocity both in direction and magnitude.
Recently a point-transmitting and a point receiving system (a PT/PR system) was demonstrated to be a convenient method for measuring group velocities [3, 4]. Chai and Wu [5] estimated the elastic stiffness coefficients of a unidirectional glass fiber reinforced plastic (UD-GFRP) using the SAW group velocities, measured by a focused laser beam and a small aperture transducer located on the surface of medium. Castagnede et al. [6] generated bulk waves by a point-focused laser and received by a miniature piezoelectric transducer of 1.3 mm aperture or a miniature capacitive transducer of 3 mm diameter. This method, called iso-angular scanning (abbreviated as IAS hereafter), measures the group velocity of longitudinal (L-), shear (S-) and quasi-shear (QS-) waves in a symmetric plane by scanning the receiver along the fiber direction. As the bulk waves are generated and measured on the opposite surfaces of GFRP plate, the IAS method needs only one plate-shaped specimen, but requires an optimized inverse scheme of the group velocity anisotropy or slowness curve of three bulk mode waves. Inverse processing of group velocity anisotropy tends to produce a large error and result in wrong properties due to falling in local minimums during inverse processing. Due to finite aperture and waveform distortion by couplant, and also due to a limited specimen size, accurate determination of the arrival times of S- and QS-waves appears to be difficult. We once attempted to monitor the QS-waves by the IAS method; however, we could not monitor them due to many reflected wave peaks.

Park and Calder [7] utilized the phase velocity anisotropy of Rayleigh waves of graphite/epoxy composites. They excited the Rayleigh waves by a line-focused pulse YAG laser 15 mm long and monitored by a dual pinducer with 2.4 mm outer diameter. This system enabled a measurement of in-plane phase velocity anisotropy of the Rayleigh wave. The contact problem of a pinducer remains, but it can be minimized by utilizing a laser interferometer. Rose and Pilarski [8] recovered elastic stiffness coefficients of UD- and cross-ply CFRP by numerical analysis of the SAW velocities in the off-axis directions. Combined utilization of bulk, surface and subsurface waves are recommended by them. We estimated five stiffness coefficients of UD-CFRP, utilizing both the phase velocities of the Rayleigh wave and SSCW (surface skimming compressive wave) [9]. A point laser SAW system, consisting of a line-focused Nd-YAG laser and a heterodyne-type laser interferometer with an argon probe laser enabled us to determine the phase velocities of SAW. The laser interferometer measured the SAW on the mirror-surface CFRP; however, we could not measure the transmitted S- and/or QS-waves through rough surface GFRP. An advanced interferometer with a high power probe laser, applicable to rough surface, was needed for GFRPs with sprayed coating.

Other ultrasonic techniques employed so far are the immersed through-transmission [10] and double through-transmission method [11, 12]. Here, the arrival times of L-, S- and QS-waves transmitted through a medium set in water were measured as a function of the sample’s rotation angle and receiver position. This technique requires a sophisticated computer controlled swivel table and a linear slider for