Lamb Waves Generation in Composite Plates with a Thin Linear Array of Piezoelectric Elements

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Abstract: Within the context of health monitoring of composite plates using Lamb waves, thin linear array transducers have been developed and evaluated experimentally. Moveable prototypes have been first designed in order to understand the generation process. Then, linear array transducers, consisting of several thin PZT bars, have been bonded on composite plates of different lay-ups. Experimental results are presented in this paper.

INTRODUCTION

The extensive literature available on nondestructive evaluation (NDE) methods relying on the use of Lamb waves tends to prove the abilities of these guided waves, especially in the case of carbon-epoxy composites (1,2). Then, health monitoring of these materials should take advantage of Lamb waves properties (quick evaluation of large composite laminates) provided that transducers do not change the properties of the structures drastically (high stiffness and strength, fatigue resistance). As the conventional Lamb waves transducers, like angled transducers, cannot be reduced to a very low thickness, linear array transducers, consisting of several independent piezoelectric bars, have been developed. Special care has been taken to keep the properties of the conventional transducers, especially the mode selection which is of paramount importance for some NDE methods, and to reduce the thickness and the stiffness of the array transducers. Concerning the mode selection, two excitation methods can be used with these transducers. In theory, when all the elements are excited in phase, the transducer must behave like the comb transducer (3), and the wavelength must be equal to the element spacing. Moreover, as the piezoelectric elements are independent, suitable delays introduced between the elements must allow the generation of arbitrary wavelengths.

A preliminary study of the Lamb waves propagation in stratified composite plates and their interaction with defects has been carried out in order to identify the appropriate modes. They must be defect-sensitive and less dispersive when excited in adapted frequency-thickness regions. Previous studies concerning both points are available (4,1). The computation of the dispersion relations as regards the wavelengths for every lay-up of interest allowed the determination of the transducer's geometrical parameters.

MOVABLE TRANSDUCERS AND GENERATION PROCESS

According to the computed wavelengths, a first couple of transducers has been designed (5). The piezoelectric material is a plate of PZT. This plate is welded onto a glass slide previously coated with gold and then chopped into 1.2 mm strips with a 0.3 mm cutting width. It allows element spacing equal to 1.5 mm, 3 mm, and other multiples. Finally, a perspex layer protects the connexions. Experimental results concerning the response levels were satisfactory compared with those of angled transducers. However, the length of the responses and the influence of the element spacing and the delays over the generated wavelength were disappointing. Then, it was impossible to verify the theoretical generation process of the array transducers. The main causes may be the insufficient number of active elements or the presence of the glass slide which disrupts the generation process.

Then, new prototypes have been designed in order to remove the support between the elements and the plate to be inspected. However, as this support is necessary to move the transducer and maintain the elements, it is located above these elements. To simplify the electronic part (excitation monitoring), we have decided to reduce the number of items from 16 to 10. As this choice prevents from verifying the theoretical generation process, special effort has been made to take advantage of the number of active elements. To remove the mechanical link between the elements, they are cut out before the sticking stage. The element spacing is equal to 2.5 mm, and the total height of the transducer is reduced to 1 mm (6).

Experimental work has dealt with both methods of excitation. It has allowed the comprehension of the generation process. Unlike comb transducers, each element generates a separate wave and suitable time delays or
spacing between the elements can improve the global response in keeping with linear rules. Then, the delays can be easily determined from the responses of each element (using cross-correlation, for example) and the corresponding global response is nearly equal to the sum of each contribution suitably put back.

**BONDED TRANSDUCERS AND NDE**

These results have been applied to bonded transducers. As the global response depends on each individual generated wave, the first task has consisted in optimizing the piezoelectric elements (material, geometry, ...). On the one hand, their geometrical parameters have been estimated according to the working frequency determined beforehand. As the height of the transducer must be small, the resonance frequency of the elements must correspond to a transversal mode of vibration. On the other hand, a mathematical model has been developed in order to optimize the geometrical parameters, especially the elements width and spacing, near the resonance frequency. This model deals with orthotropic plates, it relies on Fourier transform and numerical integration (7).

Then, plates of different lay-ups (unidirectional and cross-ply laminates) have been equipped with transducers whose properties are in keeping with the computed results. The number of elements is reduced to three or two, which have been sufficient to verify the generation process. The high response levels obtained with the bonded array transducers allow to envisage propagation over long distances, higher than one meter with only three active elements on unidirectional and cross-ply laminates (16 and 32 plies).

Different NDE methods have been evaluated with these transducers. The first one consists in detecting a defect through time-of-flight measurements. This method must be used when a free-defect reference signal is not available, for example when a problem has occurred during the manufacturing process. The group velocity is easily determined with the time-of-flight, and the phase velocity is deduced from the element spacing of the receiver and the delay measured between two elements. When phase and group velocities are not in accordance with the dispersion relations, mode conversion must have occurred. Of course, special care must be taken to avoid applying this method to end of plate reflections featuring high amplitudes when the transducer is situated near the edge of the plate. Indeed, each element of the emitter generates the same wave in both directions and, if the optimal delays do not reduce the rear side wave, significant reflexion may appear. Nevertheless, it is possible to take advantage of this feature provided that additional distance and mode conversion at the edge of the plate are taken into account. Another NDE method consists in comparing the optimal delays (excitation signals) corresponding to the healthy plate with those of the damaged plate. Experimental results concerning an impacted unidirectional laminate have brought to fore significant changes in the optimal values of the delays. Finally, more standard methods, like attenuation or phase delay detection, have been successfully evaluated on different plates.

**CONCLUSION**

Even if additional experiments are required to evaluate the NDE methods introduced in this work for more complex lay-ups, the potential of array transducers within the context of health monitoring has been already established. Indeed, Lamb waves generation is very efficient and many NDE methods relying on these waves are available. However, optimization of the elements with numerical methods (FEM and BEM) is essential to improve the generation (SN ratio, mode selection, excitation monitoring, ...) in order to reduce the number of transducers necessary to inspect large structures and to facilitate their evaluation.

**REFERENCES**