REMOTE MONITORING OF PLATE-LIKE STRUCTURES USING GUIDED WAVE ARRAYS

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ABSTRACT. A permanently attached guided wave array for the constant monitoring of defects in plate-like structures is designed and a prototype built. Employing the first antisymmetric Lamb wave mode $A_0$, the condition of large areas can be monitored from a single position of the device with minimum power consumption, necessary for long term operation independent of external power sources. The performance of the piezoelectric transducer elements used for the excitation and measurement of the $A_0$ mode is studied. Preliminary measurement results on an aluminum plate containing a model defect are presented.

INTRODUCTION

For the continuous nondestructive monitoring of remote and difficult-to-access structures it would be advantageous to permanently attach monitoring devices that run autonomously, i.e., independent of external energy supply, and transmit data about the condition of the structure wirelessly. An advantage of the permanent attachment of the device to the structure is the possibility of comparative measurements. Taking measurements at different stages in the lifecycle of the structure, an emerging defect can be detected more clearly by comparison to an initial, defect free, measurement, so increasing the sensitivity of the device. Application areas include offshore oil platforms, which are subject to adverse weather conditions, and thus should be inspected regularly for corrosion or the development of cracks. Such structures often consist of large plate-like parts which can be efficiently monitored using guided waves [1,2,3]. Guided waves can propagate over large distances of up to hundreds of meters in one-dimensional structures like pipelines, allowing for an efficient nondestructive testing [4]. In plates the guided waves can propagate in two dimensions. Therefore not only is it necessary to achieve a distinction between the different Lamb wave modes (Fig. 1), but the angular resolution of the array also has to be sufficient to distinguish between features in different directions on the structure.

The aim of the project described here is the development of such a permanently attached, autonomous device for monitoring the condition of a large area of plate-like structures from a single position of the device, resulting in a large ratio of the monitored surface to the area occupied by the device. In an array of single transducer elements, ideally each element selectively excites or receives the desired Lamb wave mode in the plate. For an omni-directional inspection of the surrounding plate, the guided wave
propagates radially outwards from the excitation source, thus decreasing in amplitude and effectively limiting the inspection range to several meters in a plate.

One of the main issues in the design of such a guided wave array is the angular resolution of signals being reflected at different obstacles lying close to each other, as defects often develop in the vicinity of stress-inducing features like reinforcement bars or connector holes. As pointed out in an earlier contribution [5], it is therefore advantageous to employ only a single mode guided wave to avoid the additional complications of multi-mode guided wave analysis. The dispersion diagram for a typical aluminum plate and the mode shapes of the two first Lamb wave modes are shown in Fig. 1.

Building on a previous study [2], it was decided to employ the $A_0$ mode below the cut-off frequencies of the higher Lamb wave modes. This mode can be excited efficiently by circular piezoelectric discs polarized in the thickness direction, applying a vertical force to the plate surface. This results in a flexural wave propagating radially outwards and thus allows an omni-directional inspection of the structure. For the autonomous operation of the device, running on battery power, these excitation transducers can be run with low power consumption. The optimization of the power consumption will be one of the main problems to be resolved in the continuation of this study, to achieve a long battery life. The excitation voltage and number of excitations (number of transducers and averages) must be minimized in order to achieve a desired measurement area and defect resolution with minimum power consumption.

The layout and operation of the guided wave array employed in the preliminary laboratory study is described in this contribution. The dynamic range actually achieved with the prototype was significantly smaller than theoretically predicted. From the evaluation of the measured data, a large amount of coherent noise was found and attributed to problems with the transducer elements employed. The selection and coupling of the piezoelectric transducer elements was studied and possible improvements shown.

![Dispersion diagram and mode shapes](image.png)

**FIGURE 1.** Dispersion diagram for an aluminum plate and mode shapes of the first symmetric Lamb wave mode $S_0$ and the first antisymmetric Lamb wave mode $A_0$ at the selected frequency-thickness operation point.
ARRAY LAYOUT AND OPERATION

The preliminary measurements were made on a 5 mm thick aluminum plate (2.45m by 1.25m) in the laboratory. The array layout used consists of two concentric circles, an outer circle with $N_R = 32$ receiving elements equally spaced on a diameter of 70 mm, and an inner circle with $N_E = 16$ excitation elements on a diameter of 50 mm (Fig. 2). Separating the receiving and excitation elements allows for simpler measurement electronics, as all the signals can be acquired in pitch-catch mode. The circular array design was introduced to achieve the same performance in all directions.

The setup shown in Fig. 3 was used, employing standard excitation and measurement devices. The excitation signal was a 5 cycle toneburst with a center frequency of 160 kHz modulated by a Hanning window. Multiplexing units were used to switch between the different excitation and receiving transducers. A time trace containing 10000 points was stored for each combination of excitation and receiving transducer. The time traces were measured using a digital oscilloscope with a sampling frequency of 5 MHz. 20 averages were taken and the signal was then transferred to a PC for analysis.
The number of elements used is limited by the number of channels in the multiplexing unit and the time and power consumption allowed for a single measurement. The maximum element spacing relative to the wavelength at the design frequency should not exceed half the wavelength, to avoid grating lobes. This limits the maximum diameter of the array for a given number of elements, and thus the angular performance of the array, as a larger array will have a better angular resolution and smaller side lobes [6].

The data processing is done in the wavenumber domain, providing effective dispersion compensation [7]. Taking the Fourier transform of each time trace \( x_i \) and employing the known dispersion relation for the plate, the wavenumber spectrum \( X_t \) is calculated, i.e., the complex magnitude dependent on the wavenumber. A phased addition algorithm is used to synthesize a guided wave beam that can be steered in any direction from the array (Fig. 2). For each of the \( N_p \) equi-spaced beam steering directions \( \Phi_p \), the correlation between the \( N_p \cdot N_p \) time traces for a guided wave propagating in that direction and being reflected back from the same direction is calculated. To simulate all transducers lying on a line perpendicular to the steering direction, a phase shift is added to each phase spectrum, correcting for the different path lengths (see Fig. 2)

\[
d_p = d_R + d_T.
\]

The correlation is calculated by summing the phase spectra for each wave number \( k \)

\[
A_p(k) = \sum_{i=1}^{N_s} X_t(i) \cdot \exp(ikd_p).
\]

The data is then Fourier transformed to the angular order domain and a deconvolution algorithm applied, which improves the angular selectivity of the array significantly. The results are converted back by means of an inverse two-dimensional Fourier transform to obtain an omni-directional B-scan in the radial-angular domain. The data analysis is described in more detail in Ref. [6].

By applying the deconvolution algorithm, the same angular selectivity can be achieved with fewer transducer elements than with a completely filled array. With the available number of elements and a maximum spacing of half the wavelength at the design frequency of 160 kHz, the theoretically achievable angular performance for a signal reflected back from the 0° direction is shown in Fig. 4. The main lobe drops to -30 dB at 16°, and two small side lobes about -30 dB lower than the main lobe can be seen at 18°. Beyond that the theoretical dynamic range of the array layout is better than 40 dB, which would allow good defect resolution. However, problems with the performance of the transducer elements limited the achieved dynamic range of the first prototype array to only 15 dB, making the detection of small defects less reliable.

FIGURE 4. Theoretically achievable angular performance of the selected array design.
TRANSDUCER ELEMENTS

Commercially available piezoelectric discs (Ferroperm Pz27), polarized in the thickness direction, were employed as transducer elements for the excitation and reception of the guided waves. Working below the cut-off frequencies of the higher Lamb wave modes in the plate, these discs act as omni-directional point sources/receivers for the guided wave. When a voltage is applied to the transducer, the disc contracts and expands, generating a vertical force on the plate surface and thus exciting primarily the first antisymmetric Lamb wave mode, $A_0$.

Problems were encountered with the dynamic range of the prototype. Examining the measured data sets, this limited performance was traced back to coherent noise due to the unintended additional excitation of the $S_0$ mode and reverberations of the excited wave at the other transducer elements. Therefore the selection and coupling of the transducer elements was studied in more detail. Single piezoelectric discs were coupled to the plate using either two-component epoxy glue or a rubber membrane to study the influence of element thickness and coupling on the modal selectivity. The out-of-plane component of the excited $A_0$ and $S_0$ mode was measured at a 400 mm distance using a laser vibrometer. Due to the different propagation velocities of the two fundamental Lamb wave modes, the pulses were separated in time at that distance.

![Graphs showing transfer functions and displacement ratios](image-url)

**FIGURE 5.** Out-of-plane displacement measured using laser interferometer 400 mm from piezoelectric excitation transducer in 20 kHz segments: a) transfer function of excited $A_0$ mode (arbitrary units), piezoelectric element glued directly to plate: solid ($D = 5$ mm, $H = 2$mm), dash-dotted ($D = 5$ mm, $H = 0.5$ mm); b) transfer function of $A_0$ mode (solid, arbitrary units) and ratio of out-of-plane displacement $S_0$ / $A_0$ mode excitation (dash-dotted); c) ratio of out-of-plane displacement $S_0$ / $A_0$ mode excitation ($D = 5$mm, $H = 2$mm): thin glue layer (solid), with 0.5 mm rubber coupling membrane (dash-dotted); d) transfer function $A_0$ mode (arbitrary units), $D = 5$ mm, $H = 2$mm: thin glue layer (solid), with 0.5 mm rubber coupling membrane (dash-dotted).
The diameter of the discs is limited by the element spacing of about 7 mm, and therefore discs with a diameter of 5 mm were employed. As can be seen in Fig. 5a, using thicker discs results in a significantly higher amplitude of the excited desired $A_0$ wave mode in the plate, and it was thus decided to employ standard piezoelectric discs with 2 mm thickness and 5 mm diameter. However, the measurements with the first prototype showed that the signal was not as clear as expected, which can be partly attributed to the involuntary additional excitation of the $S_0$ mode. As can be seen in Fig. 5b, the $S_0$ mode amplitude rises relative to the $A_0$ mode amplitude with increasing frequency. This is due to the increasing amount of out-of-plane displacement of the $S_0$ mode at higher frequency-thickness products (Fig. 1). To reduce the $S_0$ mode amplitude, a coupling membrane was introduced between transducer and plate. This significantly reduced the ratio of $S_0$ mode to $A_0$ mode in the desired frequency region at 160 kHz (Fig. 5c), as the membrane reduces the shear coupling between the radial expansion of the transducer and the plate. Such a coupling membrane will be necessary for real applications, to protect the transducer elements and to avoid the need for applying them separately to the structure. However, such a membrane also lowers the amplitude of the desired $A_0$ mode significantly, as shown in Fig. 5d, thus reducing the signal to random noise ratio. As the main problem encountered during the first measurements was coherent noise due to the excitation of the $S_0$ mode and reverberations of the excited wave at the other transducer elements, an improvement of the dynamic range of the array and thus on the defect detectability is expected.

PRELIMINARY MEASUREMENT RESULTS

First measurements were done on an aluminum plate, directly attaching the transducer elements to the plate using a thin layer of two-component conductive epoxy and using standard laboratory equipment as described above. The resulting omni-directional B-scan for the undamaged plate is shown in Fig. 6a, with the position of the array and the plate edges marked. The amplitude is normalized to the maximum reflection (occurring at the closest plate edge) and shown on a grayscale down to -15 dB, the dynamic range of the array prototype being limited by coherent noise in the measured time traces. The measurement shows the reflections of the guided wave at the four sides and the four corners of the plate.

The plate edges are only seen in the direction where they are normal to the waves propagating radially from the array. The data processing algorithm is designed to pass signals transmitted and received along the same radial line and to reject signals from other directions. The further away an object is from the array location, the smaller is its reflected amplitude. This is due to the fact that the amplitude of the radially propagating guided wave decreases with distance. This can be seen for the reflections at the plate boundary. The amplitude of the reflection at the closest edge (0.5 m from the array location) has the highest amplitude, and the lowest amplitude is at the edge that is the furthest away (1.45 m). The angular resolution is independent of the distance, so that objects further away show up as having a broader reflection, while in effect the angular width is constant.

An artificial model defect was introduced into the plate by drilling a through hole with a diameter of 30 mm at a distance of 0.36 m from the sensor, marked in Fig. 6b. The scattering of the guided wave at such a model defect can be calculated and measured [8]. An additional reflected signal from that defect is visible with an amplitude about 12 dB lower than the maximum reflection at the plate edge. This allows the detection of such a model defect, but care must be taken in the interpretation of these B-scans, as is evident when looking at the same B-scan on a 20 dB scale in Fig. 6c. Here other reflection signals are visible at about -17 dB, which are well above the theoretically predicted dynamic
range of $-40 \, \text{dB}$ and might be accidentally interpreted as defects. However they are due to
problems with the transducer elements, namely the unwanted excitation and measurement
of the $S_0$ mode studied above. Such a ghost reflection can be seen between the array and
the upper edge of the plate, at a position corresponding to the faster propagation velocity of
the $S_0$ mode (marked as "Ghost"). Further problems encountered with this prototype were
reverberations of the excited wave at the other transducer elements in the densely
populated region of the array. This led to the time signals showing not only the expected
single pulse propagating radially outwards from the piezoelectric disc, but overlaid smaller
signals from the reverberations. These two effects led to a significant level of coherent
noise in the measured signals, which can be reduced by improving the coupling properties
between the transducer elements and the structure, as suggested above.

It is therefore important to test the guided wave array on an undamaged structure first
to ascertain the achievable signal to coherent noise ratio and thus the dynamic range of
the device. However, as the array is permanently attached to the structure, it is possible to
compare current measurements to previous results and to search for changes in the
reflection signature of that structure. This is shown in Fig. 6d, where the difference in
amplitude between the measurements on the undamaged and damaged plate is plotted
relative to the main reflection at the side of the plate. The defect signal is seen very clearly
with the larger dynamic range, which is only limited by changes from one measurement to
another. It is of interest that the defect not only produces a signal due to the direct
reflection of part of the incident wave back towards the device, but also changes the
reflection from the plate corner behind the defect. The incident wave is scattered at the
defect, thus reducing the energy of the wave reflected at the plate corner behind the defect.

**FIGURE 6.** Radial-angular B-scan of plate (edges marked) from shown array position, grayscale
representing the correlation of signals reflected, center frequency 160 kHz; a) measurement without defect,
15 dB scale; b) measurement with defect (through hole, $r = 15 \, \text{mm}$), 15 dB scale; c) measurement with defect
(through hole, $r = 15 \, \text{mm}$), 20 dB scale; d) measured difference due to defect (through hole, $r = 15 \, \text{mm}$), 20
dB scale.
CONCLUSIONS

The first prototype of a guided wave array for the permanent monitoring of plate-like structures was designed and tested. The first antisymmetric Lamb wave mode $A_0$ was excited and measured using piezoelectric transducer elements. Preliminary measurements with an array prototype and standard laboratory measurement equipment were made on an aluminum plate. The current array has a signal to coherent noise ratio of $-15$ dB, significantly smaller than the theoretically predicted dynamic range of $-40$ dB. This is insufficient for the reliable detection of small defects. The main sources of coherent noise are the unintended excitation of the $S_0$ mode and reverberations of the excited wave pulse at the other transducer elements in the densely populated area of the array. Further improvements to the dynamic range of the device have to be made for the reliable detection of small defects. The selection of the transducer elements and their coupling to the specimen has been studied and possible improvements for the mode selectivity investigated. An artificially introduced large defect could be detected just above the noise level in a single measurement. By comparing measured reflection patterns before and after the defect was introduced, the dynamic range could be extended and the defect clearly distinguished.

ACKNOWLEDGEMENTS

We would like to thank Guided Ultrasonics Ltd. for the use of their multiplexing equipment. This work was supported by EPSRC (Engineering and Physical Sciences Research Council), with additional support from the HOIS consortium of oil companies.

REFERENCES

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