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Monitoring the curing process of adhesive bonds using selective excitation of guided ultrasonic waves

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Abstract: A measurement setup for the selective excitation of guided ultrasonic waves in adhesively bonded plates is introduced. Changes of the dispersive behaviour of the guided waves during the curing process is known to be accompanied by a change in the propagating waves group velocities. The proposed measurement setup is used to monitor that change during the curing process of an aluminium-epoxy-polycarbonate bond.

Keywords: Ultrasonic guided waves, Selective excitation, Non-destructive testing, Adhesive bonding, Condition monitoring

Motivation

Due to their capability of providing very strong and long-lasting material joints as well as their versatility, adhesive bonds are commonly used in a wider range of manufacturing processes. However, the standardised testing methods for adhesive bonds are predominantly destructive. Consequently, those methods can never be applied to the actual joint but only to specially produced test samples. For quality, safety and economic reasons, testing the actual joint is of great interest hence requiring a non-destructive testing (NDT) method. So far, NDT-methods for e.g. flaw detection are well established, but are currently not capable of monitoring the quality of an adhesive bond.

In previous investigations [1], broadband guided ultrasonic waves are utilised to observe the change in dispersive behaviour during the curing of an adhesively bonded aluminium-polycarbonate sample. It is shown that the overall dispersive behaviour of the sample is mainly dominated by the aluminium at the beginning and slowly transitions towards multi-layered behaviour during the curing process. This transition is accompanied by changes in the wave modes group velocities.

Based on those findings, this investigation proposes an approach for the monitoring of adhesive bonds. Utilising an experimental setup for the selective excitation and measurement of guided waves, their group delay and, consequently, their group velocities can be ascertained. The employment of this method during the curing of an epoxy adhesive in an aluminium-polycarbonate structure enables the direct observation of changes in the dispersive behaviour of the system and thus a monitoring method for the curing process.

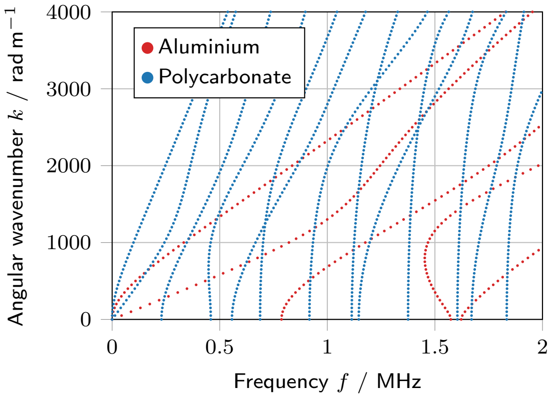

Fig. 1: Dispersion diagrams of an aluminium ● *and a polycarbonate* ● *plate. Both with a thickness of* 2 mm*.*

Guided waves in coupled plate-shaped structures

The properties of guided elastic waves strongly depend on the material as well as the geometric parameters of the waveguide. Fig. 1 shows dispersion diagrams of an aluminium and a polycarbonate plate in frequency-wavenumber-domain. Given that both plates have a thickness of 2 mm and only differ in their respective material parameters the direct comparison emphasises that material dependency. Ultrasonic guided waves are commonly used for NDT-methods due to their high sensitivity to changes of those parameters.

To calculate the dispersion diagrams for given material parameters, the scaled boundary finite element method (SBFEM) [2] can be used. A plate-shaped waveguide is only discretised in its thickness direction, with harmonic, analytical expressions describing the

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Tab. 1: Material parameters of the samples used in this investigation are determined via an inverse measurement procedure.

Material	Long. wave vel. c_{L}	Trans. wave vel. c_{T}
Aluminium	$6489\,\mathrm{m\,s^{-1}}$	$3148\,\mathrm{m\,s^{-1}}$
Polycarbonate	$2227\,\mathrm{m\,s^{-1}}$	$917\,\mathrm{m\,s^{-1}}$

waves in their direction of propagation.

In order to carry out precise simulations and thus predict the behaviour of the actual samples in a targeted manner, it is necessary to ascertain the elastic properties of the samples under test. In preparation of further investigations the aluminium and polycarbonate samples behaviour are quantified using an inverse measurement procedure based on the broadband excitation of guided ultrasonic waves [3, 4]. The material parameters of the model are adjusted through this optimisation-based approach, with the objective that the resulting simulations correspond to the measurement based equivalent of their dispersion diagrams. In the context of this study, an isotropic material model is used for the aluminium and polycarbonate layers. This reduces the necessary material parameters to the longitudinal wave velocity c_{L} as well the transversal wave velocity c_{T}. The determined parameters, as already used for the underlying simulation of Fig. 1, are provided in Tab. 1.

A spring-based, lumped-element approach is used to represent the adhesive bond between the two layer-materials for further simulations of this study. It can be shown that the transmission of shear movements, i.e. in-plane movement of the plates surface at the interface, shows greater changes during the curing process of the adhesive than normal movements. The model therefore uses separate springs (κ_{o}, κ_{i}) for the out-of-plane and in-plane-movements at the material interface [5].

Experimental Setup

A wide range of research on NDT methods is based around broadband guided ultrasonic waves. However, for a considerable number of applications, or at least for their measurement effects, it is not necessary to acquire broadband information of dispersive behaviour of a specimen. On the contrary it is usually beneficial to restrict the excitation to emphasise certain effects. The aim of the experimental procedure presented in the following is to excite a certain mode in the specimen defined by a given frequency f_{ex} and angular wavenumber k_{ex} (*selective excitation*). Fig. 2 depicts a schematic representation of the measurement setup used in this investigation. The excitation is done via a 64 element transducer array (*Imasonic*), which is directly coupled onto the surface of the specimen using a coupling gel. With the assumption that shifting an oscillation over the array's elements and thereby imprinting a guided wave with the same properties into that specimen, the individual elements are successively excited using the same sinusoidal signal with the selected frequency f_{ex}. To ensure the imprinted guided waves angular wavenumber matches the expectation, the time shift Δt between the neighbouring elements excitations has to be calculated. Since the elements excitation is pure sinusoidal, the waves group velocity c_{gr} can directly be calculated from the excitation parameters:

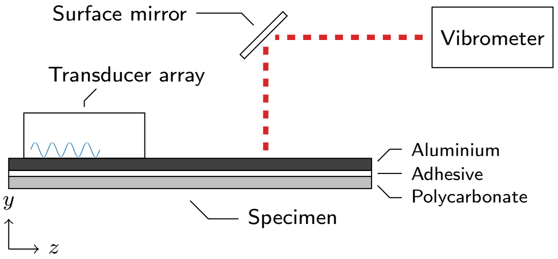

Fig. 2: Measurement setup for the selective excitation of guided ultrasonic waves.

$$c_{\mathrm{gr}} = \frac{2\pi f_{\mathrm{ex}}}{k_{\mathrm{ex}}}$$

To ensure the resulting guided wave propagates with the expected group velocity c_{gr}, the time delay Δt directly results form the distance between those elements (here $\Delta p = 1\,\mathrm{mm}$):

$$\Delta t = \frac{\Delta p}{c_{\mathrm{ph}}} = \frac{\Delta p\; k_{\mathrm{ex}}}{2\pi f_{\mathrm{ex}}}.$$

The signal generation and setting of the necessary time shift Δt are done via a purpose-build hard- and software-interface developed by Nellius et al. [6].

The detection of the propagating waves are performed using a laser Doppler vibrometer (VibroFlex QTec by *Polytec*). The laser beam is directed on to the specimens surface using a surface mirror. This mirror is mounted onto a linear actuator enabling a precise and reproducible variation of the point of detection.

For an initial proof of concept a $4\,\mathrm{mm}$ aluminium plate is used as a sample. The experiment aims for an excitation of a guided wave with a frequency of $f_{\mathrm{ex}} = 1.375\,\mathrm{MHz}$ and an angular wavenumber of $k_{\mathrm{ex}} = 2320\,\mathrm{rad\,m^{-1}}$. Using a Fourier transform on the measurement data enables an initial validation for the excitation of the correct frequency f_{ex}. For a given frequency, however, multiple modes can propagate in a waveguide (see Fig. 1). But the information

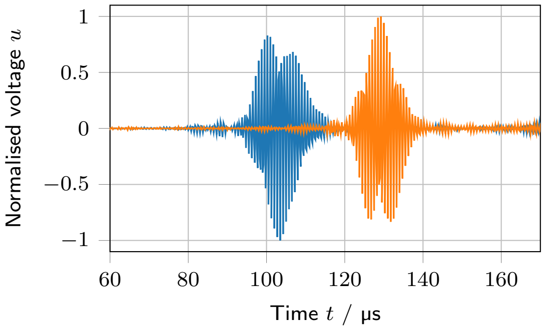

Fig. 3: Measurement signals of selectively excited guided waves ($f_{\mathrm{ex}} = 1.375\,\mathrm{MHz}$, $k_{\mathrm{ex}} = 2320\,\mathrm{rad\,m^{-1}}$). The point of detection is varied by $6.5\,\mathrm{cm}$ *between the first ● and the second ● measurement for a determination of the waves group velocity.*

regarding the wavenumber can not be extracted directly from the time-resolved measurement data. By varying the point of detection along the direction of propagation (here $\Delta z = 6.5\,\mathrm{cm}$) two different measurements with the same excitation are carried out (see Fig. 3). Based on the time difference between the two measurement signals the group velocity c_{gr} of the waves is obtained. Based on the simulations, the targeted wave is expected to propagate with a group velocity of $c_{\mathrm{gr}} = 2369\,\mathrm{m\,s^{-1}}$. An evaluation of the measurement data yields a group velocity c_{gr} of $2452.8\,\mathrm{m\,s^{-1}}$ and thus deviates $3.5\,\%$ from the prediction.

To investigate the deviation of the group velocities a line scan using the same excitation is carried out: Varying the point of detection with a step size of $\Delta z = 1\,\mathrm{mm}$ and performing a measurement at each position over a length of $8\,\mathrm{cm}$, data in time- and space-domain is acquired. By applying a two-dimensional Fourier transform to that measurement data yields information in frequency- and wavenumber domain. Fig. 4 depicts the angular wavenumber information for the selected frequency of $f_{\mathrm{ex}} = 1.375\,\mathrm{MHz}$. Since the most significant contribution is located close to the desired wavenumber the selective excitation appears successful. It can, however, also be seen that there are a few non-negligible contributions from other wave modes. Since those are notably smaller than the targeted angular wavenumber their impact on the propagating waves are presumed small but may lead to the deviation in the observed group velocity.

Monitoring of an adhesive curing process

In previous studies, the change in the acoustic behaviour of adhesively bonded plates during the process of adhesive curing has been investigated utilising broadband guided ultrasonic waves [1]. It is shown that this change can be observed by determining the group velocity of the propagating modes. Therefore, the presented approach of *selective excitation* is well suited for process monitoring in this application. This approach not only requires less experimental effort, but also provides results in a shorter time. While the previous methods required up to $15\,\mathrm{min}$ per measurement routine, the current setup takes about $50\,\mathrm{s}$ per measurement and could be enhanced further. Especially when observing transient processes, the reduced time is relevant since a single measurement assumes the system to be static and therefore summarises the change happening during a measurement period.

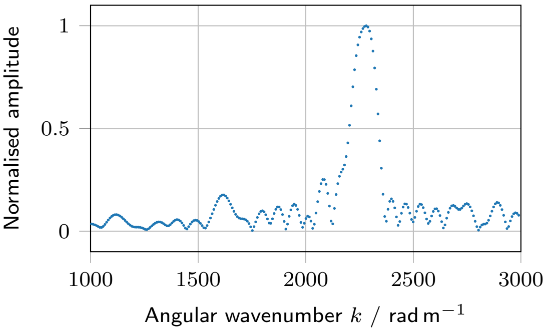

Fig. 4: Angular wavenumber of selectively excited guided waves at the targeted frequency of $f_{\mathrm{ex}} = 1.375\,\mathrm{MHz}$.

A monitoring of an adhesive curing process is carried out using the specimen configuration as depicted in Fig. 2: A $2\,\mathrm{mm}$ aluminium and a $2\,\mathrm{mm}$ polycarbonate plate are bonded using an epoxy adhesive (see Fig. 2). The parameters for the selective excitation are chosen as $f_{\mathrm{ex}} = 0.65\,\mathrm{MHz}$ and $k_{\mathrm{ex}} = 740\,\mathrm{rad\,m^{-1}}$. Fig. 5 visualise numeric simulations of the selected mode curve for a weakly coupled

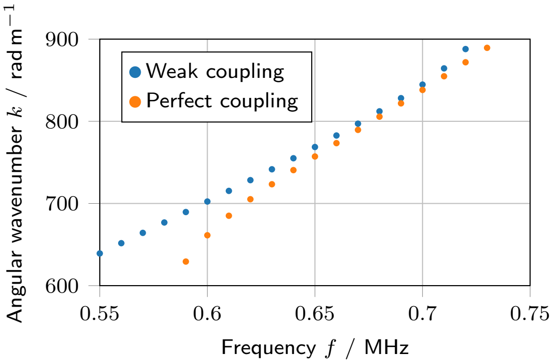

Fig. 5: Computed dispersion curves of a low and high coupled variation of an aluminium-polycarbonate system using a spring-based coupling model.

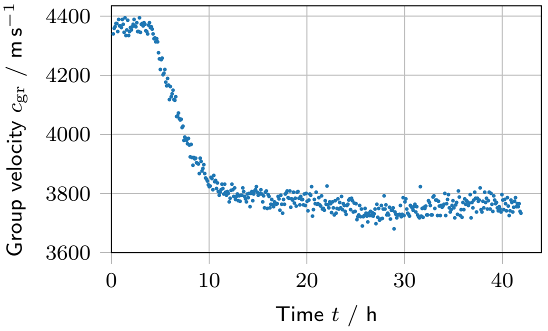

Fig. 6: Change of group velocity of a selectively excited wave mode ($f_{\mathrm{ex}} = 0.65\,\mathrm{MHz}$, $k_{\mathrm{ex}} = 740\,\mathrm{rad\,m^{-1}}$) during the adhesive curing process of an aluminium-epoxy-polycarbonate bond.

($\kappa_{\mathrm{o}} = 10^{13},\ \kappa_{\mathrm{i}} = 10^{9}$) as well as for a perfectly coupled ($\kappa_{\mathrm{o}} = 10^{15},\ \kappa_{\mathrm{i}} = 10^{15}$) system. The gradient of the mode curve does increase with increasing coupling strength. It is therefore expected to observe a decreasing group velocity during the curing process.

To monitor the curing process a measurement is performed every $5\,\mathrm{min}$. By evaluating the change in runtime of the excited propagating guided waves, their group velocities are determined for each of those measurements. Fig. 6 visualises the change of the waves group velocity c_{gr} in relation to the passing time during the curing process. One can clearly observe the change in the acoustic behaviour of the specimen. While the group velocity does not change much during the initial phase of about $4\,\mathrm{h}$ it decreases significantly over the following time period of about $12\,\mathrm{h}$. The overall behaviour is presumably dominated by the aluminium component at the beginning and changes over time towards the expected multi-layered behaviour. The nearly static value of the group velocity ($c_{\mathrm{gr}} \approx 3750\,\mathrm{m\,s^{-1}}$) after the curing process terminates ($t \geq 20\,\mathrm{h}$) is slightly smaller than the simulation based estimation of $3830\,\mathrm{m\,s^{-1}}$. This again may be due to the influence of additionally excited wave components (see Fig. 4).

Conclusion

The investigation at hand introduces and evaluates a measurement setup for the selective excitation of guided ultrasonic waves. This setup is based on the targeted time-delayed excitation of the individual elements of an ultrasonic transducer array. By imprinting a spatiotemporal, sinusoidal wave into plate-like specimens, guided waves with a given frequency and group velocity are excited.

Using this method of selective excitation during the curing process of adhesively bonded aluminium-epoxy-polycarbonate structures, the change in acoustic behaviour can be observed. While the material bond is still dominated by the aluminium behaviour at the beginning, a clear change towards multi-layered behaviour can be observed in the change of the waves group velocity. The method is therefore well suited as a monitoring system for adhesive curing processes.

Nevertheless, evaluations of the measurement method still demonstrated a considerable scope for improvements regarding the selectivity. The bandwidth of the generated guided waves should therefore be further reduced, especially in wavenumber domain. Furthermore, it is important to acknowledge the statistical deviations in the obtained group velocity values, particularly in areas where the specimen under test is expected to exhibit static behaviour. Additional measures will have to be implemented to reduce these deviations further.

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