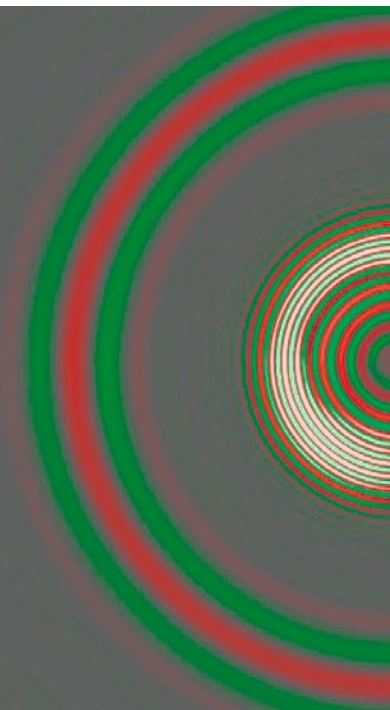


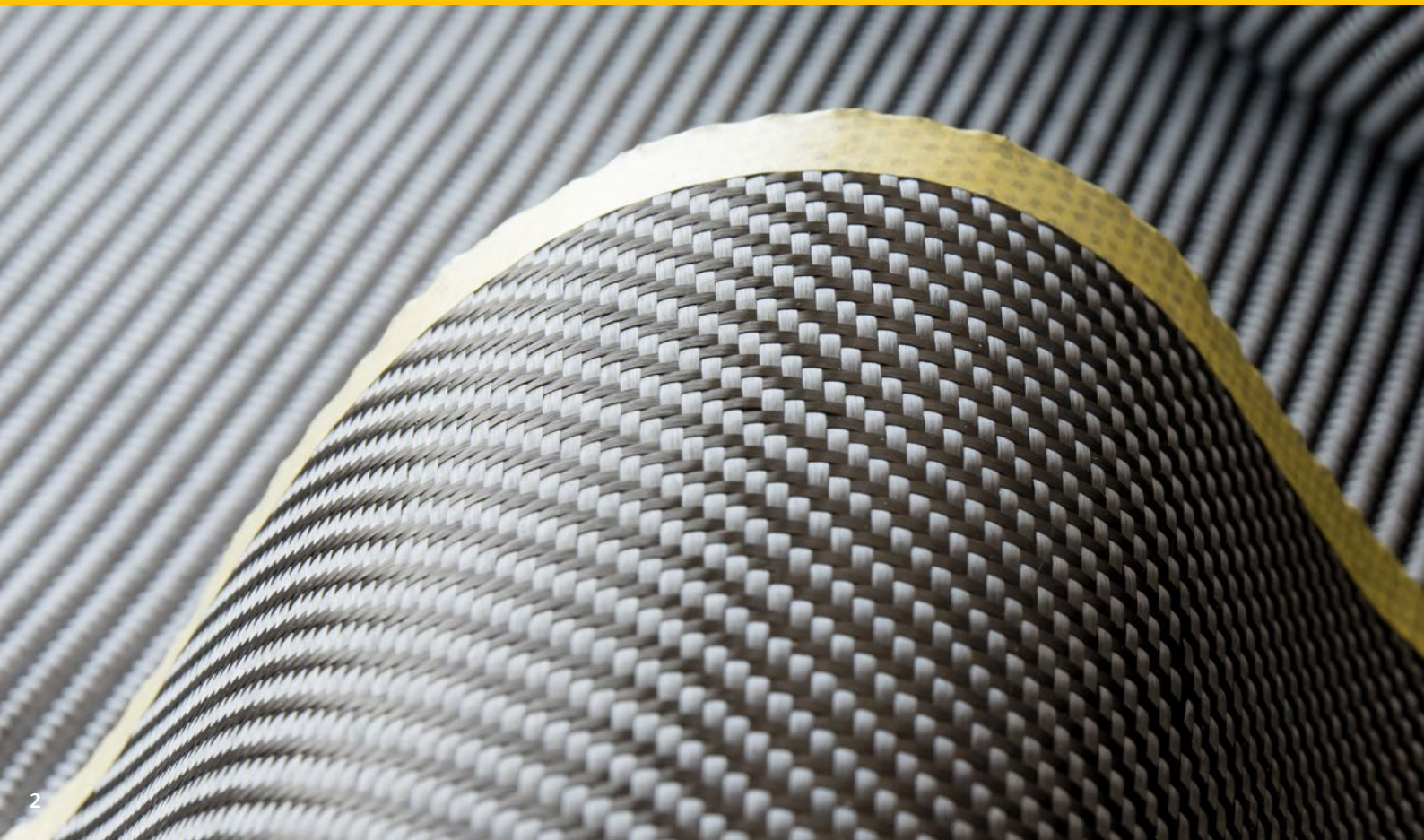


Structural Health Monitoring Using Lamb Wave Testing

Identifying Defects per Scanning Laser Vibrometry
Application Note



Structural Damage in Components is Often Invisible from the Outside. However, Ultrasonic Waves Can Be Used for Structural Health Monitoring (SHM). The Propagation of Waves and Their Interaction With Defects Can be Measured and Displayed in a Contactless, Full-Surface, High-Precision Manner Using Scanning Laser Vibrometry.



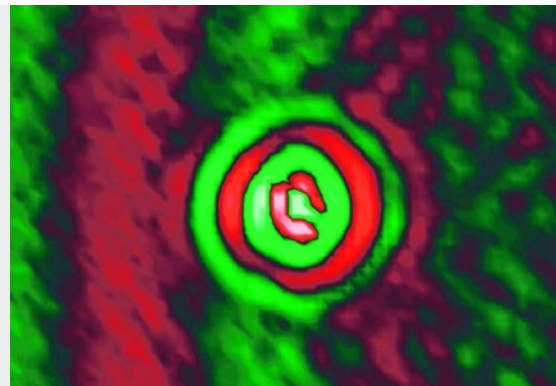
Scanning Laser Vibrometry for Structural Health Monitoring Using Ultrasonic Surface Waves

This article briefly describes the principles of the ultrasonic waves used, called Lamb waves, as well as 3D scanning laser vibrometry. The main part of the article presents measurement results obtained with this technique, using both the propagation of waves and their interaction with defects.

Lamb Waves for Defect Identification

The standard method for the detection of defects in safety-critical components is the scanning of plates/panels using ultrasonic transducers. However, this method generally requires that either the transmitter

and receiver are on opposite sides of the panel or, in the so-called „back-wall echo method“, on the same side and the transducers are coupled to the panel, for example using water, which in many cases is a limitation. An alternative method is to observe the propagation of guided waves in the panel and their interaction with defects. In thin-walled load-bearing components – in the past made almost exclusively of metal sheet, but today increasingly made of reinforced carbon fiber reinforced plastic panels (CFRP) – waves propagate as flexural waves and compression waves within the plate.



1
*Mode conversion
from symmetric
into asymmetric
Lamb waves at a
structural defect*

2

Flexural and compression waves in aluminum sheet over 250 mm, true sheet thickness 1 mm, true vibration amplitudes less than 100 nm

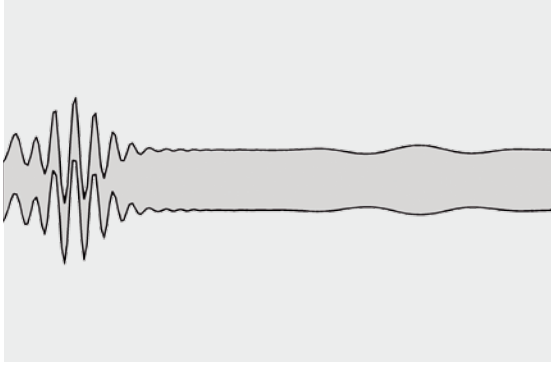


Figure 2 shows a cross-section through groups of flexural and compression waves in aluminum (actual measured data). Regardless of whether a material defect or structural damage is located on an inaccessible face or in the middle of the material, a wave, which can be monitored from the accessible face, interacts with it and thus its behavior is changed.

One way of monitoring defects during actual use in the field (for example, in panels during flight) is the installation of piezo-based sensor-actuator networks. The sensor signals can be used to determine the state of the component. In order to accurately evaluate these point-measured signals, the behavior of the waves must be continuously observed over space and time in the research and development phase – this is the only way to gain insight into the complex physical processes.

This can be easily and effectively achieved using scanning laser vibrometry. Furthermore, current vibration

amplitudes in the high tens of nanometer range and excitation frequencies up to several hundred kilohertz can be achieved without difficulty. Scanning laser vibrometry is also highly suitable for the layout of such piezo-sensor networks. In addition, it represents an independent method for defect detection in cases where traditional ultrasonic transducer methods are not practical.

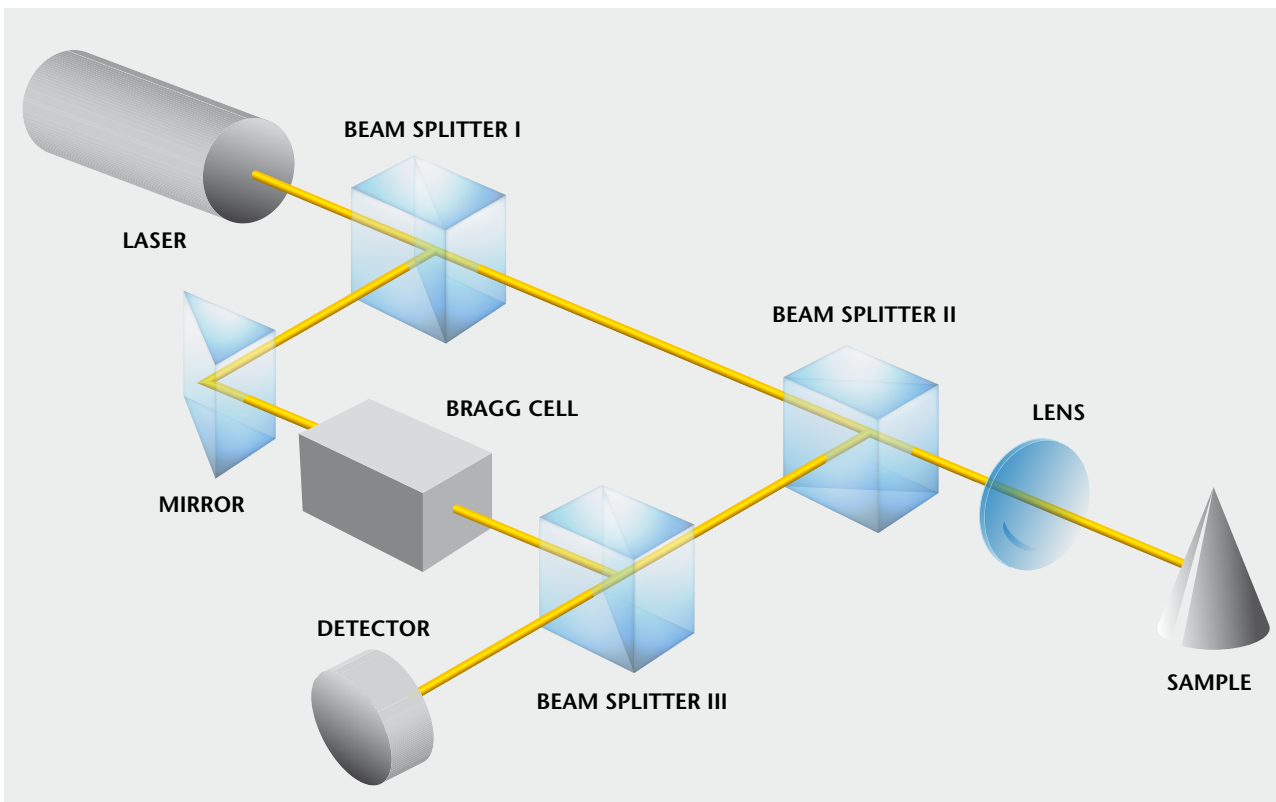
3D Scanning Laser Vibrometry

A 3D Scanning Vibrometer is a measuring system for the contactless and interference-free measurement of 3D vibrations in mechanical structures.

The method is based on the optical Doppler effect, which causes light waves scattered from moving surfaces to undergo a change in frequency, where the change is dependent upon the movement. The frequency change is directly proportional to the instantaneous value of the vibration velocity and, in spite of its remarkably small relative value of less than 10^{-8} , it can be precisely determined using interferometric methods. For this purpose, inside the vibrometer, the back-scattered laser light is compared to a reference beam whose frequency has been shifted by a defined amount (heterodyne process, see fig. 3). Only the velocity component in the beam direction has an effect on the Doppler frequency shift. A 3D Scanning Vibrometer (fig. 4) is therefore used to completely measure the velocity vector at the measuring point.

3

Optical design of a laser vibrometer



4

A 3D Scanning Vibrometer for full-field measurement to detect both out-of-plane and in-plane motions

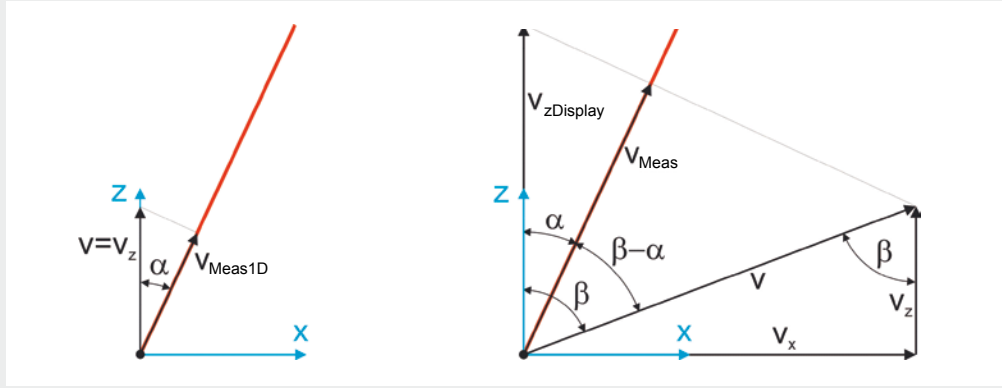


It uses three independent, differently oriented laser beams to fully measure the movement of each measurement point. In addition to the standard FFT vibration analysis mode, it's also possible, for wave monitoring, to measure in the time domain. If experimental repeatability can be guaranteed, an identical burst signal is applied to the actuator to excite waves for each point of the scanning grid, and is repeated for each point. So that individual measurements are correctly synchronized with each other, the time interval between the start of measurement and excitation must be identically triggered each time, resulting in no transfer functions. The capture and storage of a reference signal is not absolutely essential in this case.

In laser vibrometry the area is segmented by the scanning grid, while the time signal is recorded quasi-continuously. Therefore this method differs fundamentally from, for example, holography and ESPI (electronic speckle pattern interferometry), in which the area is measured quasi-continuously over the observed surface, but the time is measured in discrete steps. Through automated scanning, a single set-up process is sufficient to permit complete capture of the data record in terms of time and position.

5

Geometric conditions of the deflected laser beam and velocity vector of a scan point (left: one-dimensional vibration, right: multidimensional vibration)



1D Scanning Laser Vibrometry: Observation of Oblique Vibrations

1D scanning systems require one-dimensional vibrations in the direction of the non-deflected laser axis (usually the z-axis). In this case, the velocity vector of a scan point only has component $v_z = v$ (see fig. 5, left).

Vibrometers essentially measure the velocity component in the direction of the laser axis, so that the measured variable v_{Meas1D} must be divided by the cosine of the deflection angle α to obtain the vibration velocity v_z :

$$v_z = \frac{v_{Meas1D}}{\cos \alpha}$$

If the vibrations are no longer one-dimensional in the z-direction, as is the case for Lamb waves, this cannot be compensated by the angle correction feature of the Polytec Scanning Vibrometer software. The velocity vector v of a scan point is then rotated away from the z-axis by the angle α . The vibration detected by the vibrometer is furthermore the component parallel to the laser axis, in this case v_{Meas} .

Figure 5 right indicates the geometric relationships:

$$v_{Meas} = v \cos (\beta - \alpha)$$

Via the equation

$$v_{zDisplay} = \frac{v_{Meas}}{\cos \alpha}$$

the angle correction feature of the PSV software corrects the deflection angle of the laser. According to the Cartesian decomposition of v , the z component is

$$v_z = v \cos \beta$$

Accordingly, the error factor is

$$\frac{v_{zDisplay}}{v_z} = \frac{v \cos (\beta - \alpha)}{v \cos \alpha \cos \beta} = \tan \alpha \tan \beta + 1$$

Therefore, if a pure z-vibration occurs ($\beta = 0$) or if the laser beam is exactly perpendicular to the surface ($\alpha = 0$), here is no error. If at least one of the angles approaches 90° , the error becomes infinite. In PSV systems, the laser can be pivoted through 20° about each of two spatial axes, so that consequently a maximum angle $\alpha = \tan^{-1} (\sqrt{2} \tan 20^\circ) = 27,24^\circ$ results.

In figure 6, the mentioned error factor is marked in blue for the valid α range for various values of β (0° , $22,5^\circ$, 45° , $67,5^\circ$, 80° , 89°).

Shown additionally in red is the error factor

$$\frac{v_{Meas}}{v_z} = \frac{\cos (\beta - \alpha)}{\cos \beta}$$

which results if the angle correction is deactivated in the data acquisition software. Only for $\beta = 0^\circ$ does this result in an error factor < 1 , otherwise the error is slightly smaller than when angle correction is activated. However a quantitative analysis of the data remains invalid.

The error has a positive effect on purely qualitative investigations using 1D vibrometers where it increases the signal-to-noise ratio of the out-of-plane amplitudes of symmetric Lamb waves. Quantitative studies, however, require a 3D measurement system or can only be performed at points where the laser beam is directed normally to the surface.

Ultrasonic Waves in Plates Theory of Lamb Waves

As mentioned above, waves in plates propagate as flexural and compression waves (in-plane shear waves are not considered here). In 1917 Horace Lamb¹ was the first person to arrive at an analytical solution to the Navier-Lamé differential equation

$$(\lambda + \mu) \nabla (\nabla \cdot \vec{u}) + \mu \nabla \cdot (\nabla \vec{u}) = \rho \ddot{\vec{u}}$$

for a homogeneous, isotropic, ideally elastic continuum bounded by two planar surfaces – that is, for example, for waves in a metal sheet or plate. The solution, referred to as the Rayleigh-Lamb frequency equation,

$$\frac{\tan pd}{\tan qd} = \left(\frac{(k^2 - q^2)^2}{4k^2pq} \right)^{\pm 1}$$

where $p = \sqrt{\frac{\omega^2}{c_L^2} - k^2}$ and $q = \sqrt{\frac{\omega^2}{c_T^2} - k^2}$

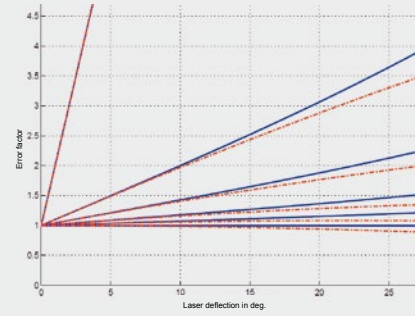
with the (circular) wave number $k = \frac{\omega}{c}$

$$c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} \text{ and } c_T = \sqrt{\frac{\mu}{\rho}}$$

are the known Lamé constants (to be determined from Young's modulus and Poisson's ratio) and ρ is the density of the material, gives information about the dispersion behavior, that is the frequency dependence of the phase velocity c , of the waves under consideration as well as their multi-modality. For each excitation frequency there are at least two solutions to the equation and thus at least two wave modes. The first two solutions are referred to as fundamental modes, S_0 and A_0 , and occur for each f respectively $\omega > 0$. They are shown in the numerical evaluation of the equation in figure 7 below as the bold curves. The solid lines represent the phase velocities of symmetric Lamb waves (compression waves), which were calculated from the equation with the exponent equal to +1, the asymmetric modes (flexural waves) are shown as dashed lines calculated with the exponent equal to -1.

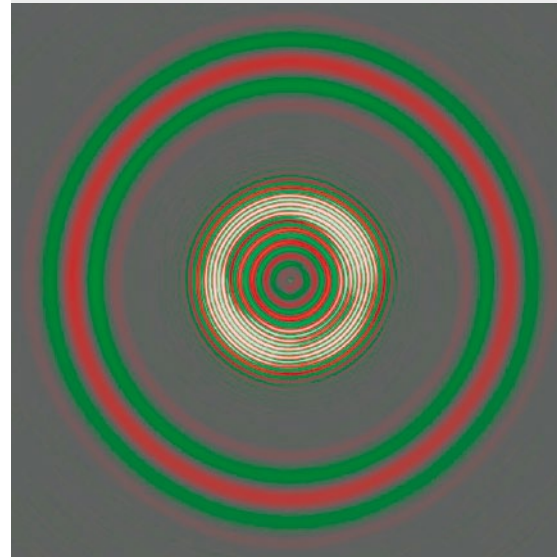
When representing such dispersion diagrams, it is common (as done here) to apply phase velocities via the frequency-thickness product of the plate, so that a diagram is valid for any plate thickness.

More detailed explanations of the theory of Lamb waves can be found in Structural Health Monitoring by Victor Giurgiutiu².



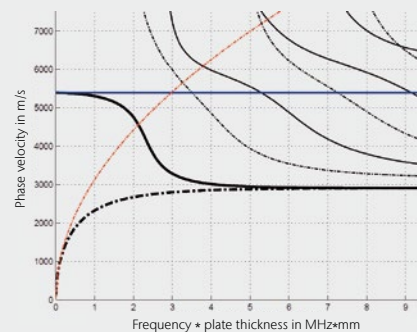
6

Error factor for out-of-plane amplitudes during 1D scanning of oblique vibrations:
 $\beta = 0^\circ, 22.5^\circ, 45^\circ, 67.5^\circ, 80^\circ, 89^\circ$ (increasing gradient) for active (blue) and deactivated angle correction (red)



7

Above:
 Propagation of symmetric (outer) and antisymmetric (inner) Lamb waves in an aluminum plate.
 Below:
 Dispersion of Lamb waves in an aluminum plate. (Solid lines: symmetric modes, dashed lines: anti-symmetric modes, bold: fundamental modes. Blue: Compression waves according to assumption of plane stress, Red: flexural waves according to Kirchhoff theory)

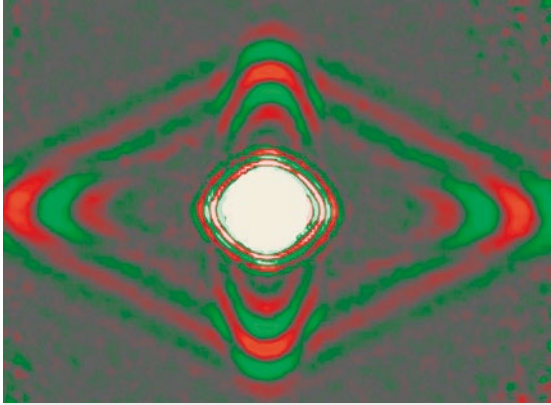


¹ Sir Horace Lamb, English mathematician and physicist, 29.11.1849 – 4.12.1934

² Giurgiutiu, Victor: Structural Health Monitoring with piezoelectric wafer active sensors

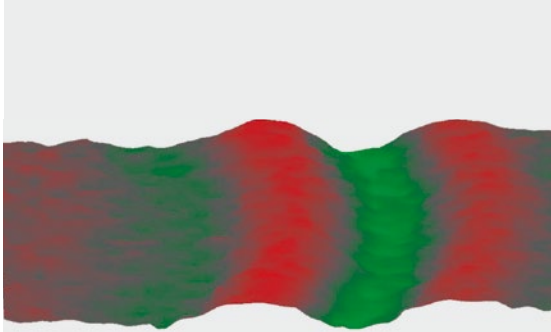
8

Propagation of compression waves in a strongly anisotropic carbon fiber reinforced plastic panel



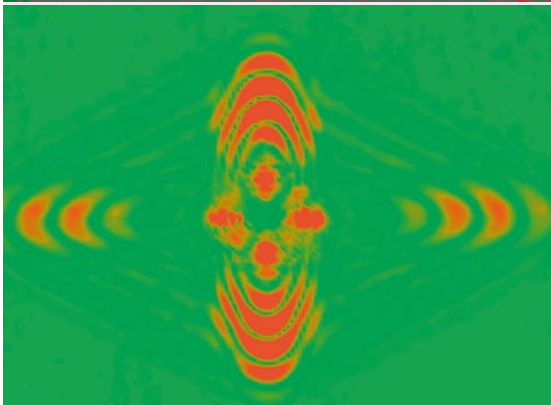
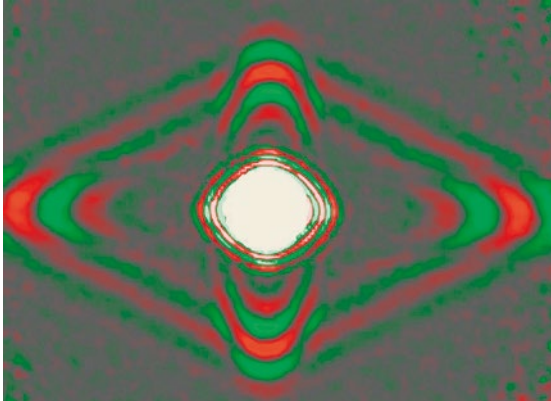
9

Symmetrical (compression) wave fronts with greatly magnified amplitude from a 1D measurement



10

1D (out-of-plane, left) and 3D measured data (all three movement components x, y and z, right) of compression waves in an anisotropic panel



Alongside the exact description of Lamb waves based on the mathematics of continuum mechanics, compression and flexural wave characteristics can also be derived from simplified plate theories. At low frequencies, the results obtained in this way are consistent with those from Lamb wave theory. However, at higher frequencies, the simplifications lead to enormous errors. The non-dispersive plate compression wave velocity (red curve) from the assumption of plane stress

$$C_L = \sqrt{\frac{1}{1-\nu^2} \frac{E}{\rho}}$$

corresponds to the S_0 phase velocity, and the flexural wave velocity (blue curve) from Kirchhoff plate theory

$$C_F = \sqrt[4]{\frac{D}{\rho h}} \sqrt{\omega} = \sqrt[4]{\frac{E}{12 \rho (1-\nu^2)}} \sqrt{\omega h}$$

corresponds to the A_0 phase velocity. The diagram indicates overlap and deviation areas.

Figure 7 above shows the out-of-plane displacement field from a 1D measurement of Lamb waves (S_0 and A_0 modes) in an aluminum plate after a burst excitation by a piezoceramic actuator in the middle.

Theory of Ultrasonic Waves in Composite Fiber Panels

Lamb wave theory only applies with the following limitations:

- ideal elasticity,
- homogeneity, and
- isotropy.

A good approximation to ideal elasticity can be assumed (in the technically relevant frequency range) for fiber-plastic composites based on thermoset matrix materials. For materials with greater internal damping this simplification cannot be assumed. By definition, homogeneity is as inapplicable to fiber composites as isotropy. The anisotropy of the elasticity parameters causes deviations of the wave fronts from the circular to varying degrees.

And numerical calculation methods such as the finite element method quickly reach their limits in the prediction of the propagation and interaction behavior of waves. The realistic modeling of individual carbon fibers would be associated with unacceptably high costs, however each simplification requires experimental validation of its replace admissibility with acceptability. Therefore, measurements are essential for modelling the propagation of Lamb waves.

Figure 8 shows a typical example of the propagation of a compression wave (S_0 Lamb wave) in a strongly anisotropic composite fiber panel. The data record was captured using a 1D Scanning Vibrometer. The wave was excited by a sinusoidal burst signal applied to a piezoceramic actuator in the middle of the panel. Due to the difference in the phase velocity of the two fundamental wave modes excited in this way, the wave groups are separated from each other and can be individually observed. The middle is recessed due to the amplitude increase in the proximity of the actuator.

3D Scanning Vibrometry for Wave Observation

The vibration amplitudes for Lamb waves are small – a few hundred nanometers at wavelengths in the millimeter to two-figure centimeter range. So that the waves can be easily visualized, the amplitudes are shown (fig. 9), with a greatly magnified height. Such a spatial visualization is no problem for 1D measured data. However, with spatial movement and considerable in-plane components, the movement trajectories of differently vibrating points in the animation can overlap each other and thus suggest a false distortion profile.

Therefore it is advisable to assess the data obtained from 3D scans either using the color palette and largely foregoing the geometric animation, or to visualize the three vibration directions separately as 1D representations. Figure 10 again shows the propagation of symmetric waves in an anisotropic plate from figure 8, but this time the results are shown contrasting with each other as 1D (left) and 3D measurements (right). The images show the same section of the same experiment. In 3D representation space, however, the software cannot allocate an unambiguous sign in general, hence the color palette only extends over the unsigned contributions of the amplitudes. On the left then, green and red stand for negative and positive amplitudes, while on the right green stands for stationary and red represents a high

amplitude of any sign. Consequently, on the right, the wavelength appears halved, which must be considered in the evaluation.

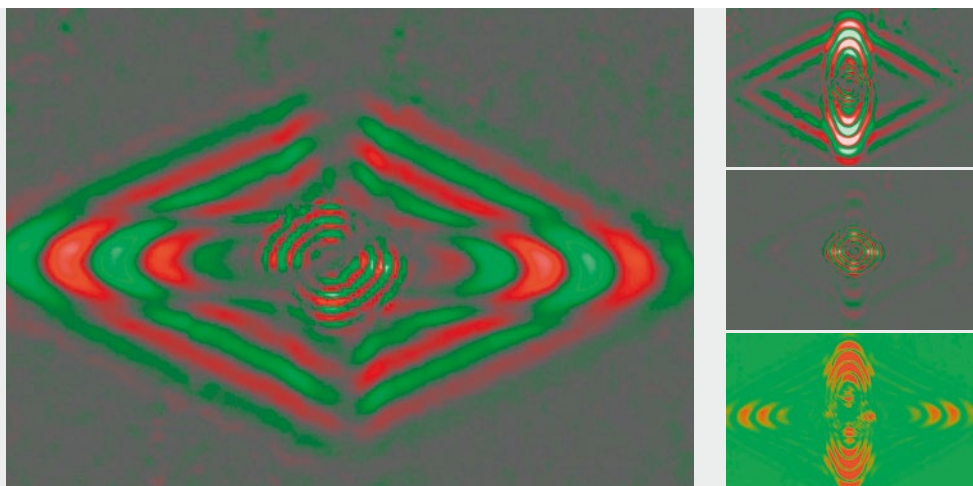
In the following, all 1D representations are shown in green-black-red and all multidimensional representations are shown in green-red.

In experiments on (flat) CFRP panels, the obvious solution is to define the measuring surface in the x-y plane and to align the x- and y-axes of the Cartesian coordinate system of the software with the main axes of the panel under test, as was done in the present case. Thus, in a simple way, the in-plane and out-of-plane amplitude components are displayed.

Figure 11 shows the experiment broken down into its movement components:

- In-plane, x component
- In-plane, y component
- Out-of-plane, z component
- In-plane, x-y component

It is apparent that the compression waves mainly generate vibrations in the plane of the plate and in this respect, the most significant fraction of the vibrations occur in the propagation direction. Where out-of-plane vibration is concerned, only light shadows are identifiable for the same scale. The more slowly propagating antisymmetric flexural waves can be identified in the middle of the plate in the z-amplitudes. Its movement fraction is greater out-of-plane than in-plane. However, this statement is only true up to certain limiting frequencies in which the actual situation is reversed, and is angularly dependent in anisotropic materials. The ratio of bending to longitudinal stiffness of the plate, both anisotropic and directional values, have an influence on the cut-off frequency.



11
Compression waves in an anisotropic panel: Amplitudes in the x (left), y (above), z (center), and x+y direction (below)

Detection of Structural Damage Caused by Wave Interaction

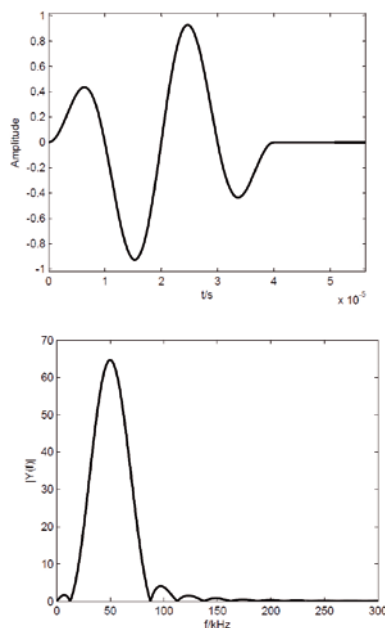
As mentioned in the introduction, structural damage and material errors are frequently indistinguishable. An important example is impact damage to CFRP structures, which often manifests as delamination, i.e. detachment of individual laminate layers from each other.

Damage Detection Experiment

3D measurements are carried out on an undamaged, quasi-isotropically laminated CFRP panel to obtain reference data. The excitation is provided by a sine-windowed burst signal $v = \sin(\omega t) * \sin(\frac{1}{4}\omega t)$ of two sine wave periods in length applied to a piezoceramic wafer, with the measurements taking place in the time domain. Figure 12 shows the signal and its amplitude spectrum. Application of the window reduces the unwanted secondary maxima in the spectrum. The experiment is repeated for different excitation frequencies. Initially, a group of compression waves passes through the observation area, subsequently, because of the lower phase velocity, a group of flexural waves. To cause an area of impact damage, a drop hammer with a kinetic energy of 2.5 J and a circular impact area of 12.5 mm² (fig. 13, above) strikes the rear side of the panel. This results in an impression on the surface of 0.05 mm in depth (fig. 13, below).

12

Excitation signal in the time domain (upper) and corresponding amplitude spectrum (lower)



13

Above:
Front face of the
drop hammer
Below:
Impression after
the 2.5 J impact

The measurements were repeated under the same conditions after the damage. Figure 14 shows a snapshot of the out-of-plane velocity field in the observation area before (above) and after (below) the impact event. By way of example, a 50 kHz excitation was used here.

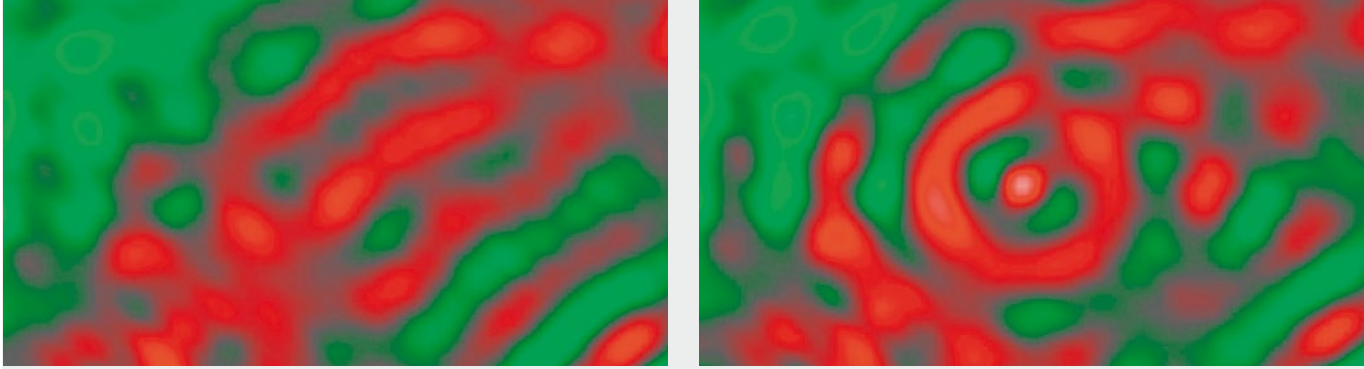
In the lower snapshot, the defect is faintly identifiable due to the circular secondary waves. The difference between the two data records is imaged using the signal processor (software option PSV 8.7 or higher) or via MATLAB. Figure 15 shows, at left, only the out-of-plane components; at center, only the in-plane components; and, at right, all the vibration directions simultaneously.

The difference data give a clear indication of the position of the structural damage. Here also it is clearly apparent that out-of-plane vibrations give much clearer results than in-plane vibrations.

Not apparent from the still photos is the fact that not only does the passing of the primary S_0 -group (fig. 16, left), but also the subsequent passing of the A_0 -group (fig. 16, right), give rise to new flexural waves forming around the damage. However, the difference image (fig. 15) shows greater secondary waves for the primary A_0 -group.

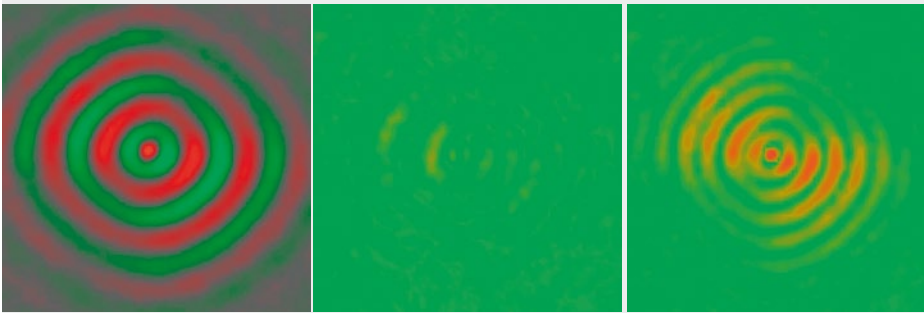
14

Out-of-plane velocity field before (above) and after (below) the impact



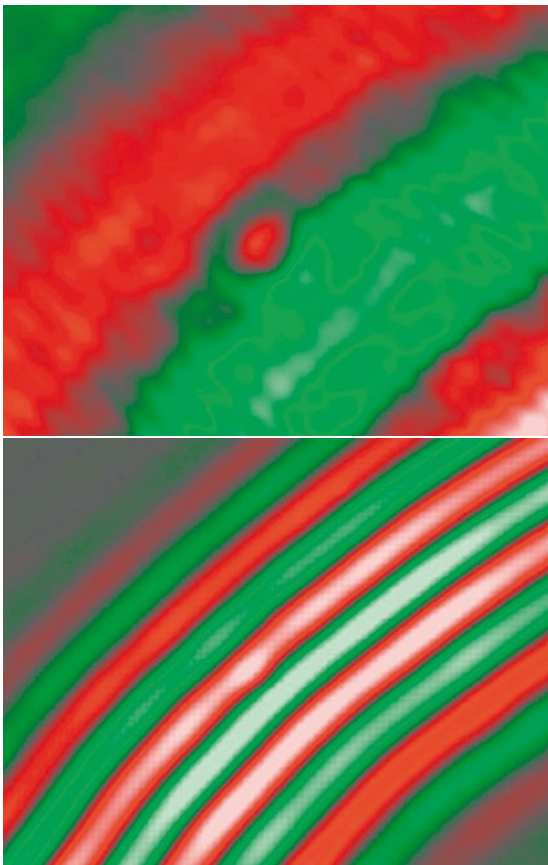
15

Difference data (Left: out-of-plane, Center: in-plane, Right: all components)



16

Primary compression waves (left) and flexural waves (right) in the measuring area after impact at 50 kHz (out-of-plane velocity fields)



Summary

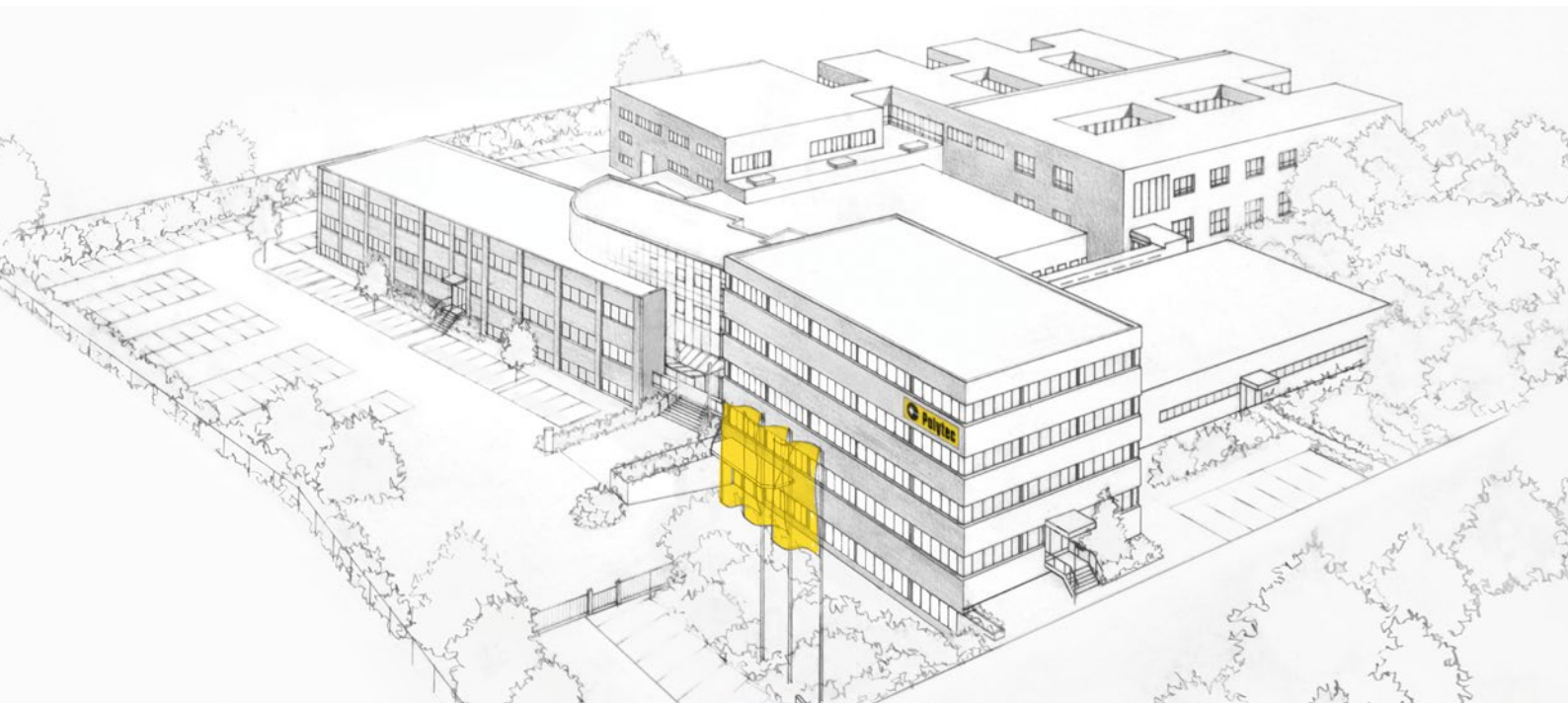
The observation of Lamb wave propagation using scanning laser vibrometry is a promising tool for damage detection in panel structures. The measurements allow the observation of both compression and flexural waves. The propagation of the entire wave field is made visible, thus permitting conclusions to be made about the structural properties. Systematic errors, which always arise using 1D measuring technology, can be avoided using 3D measuring technology and allow for more precise results to be obtained.

Defects are visualized as distortions in the wave field, primarily in the form of secondary waves created from mode conversion. Therefore, using this method, defects can be detected in samples where it would not be possible to detect them using conventional ultrasonic testing or where it would only be possible with considerable extra expense and complexity.

Authors

Dipl.-Ing. (FH) Mirko Nikolaj Neumann and
Prof. Dr.-Ing. Rolf Lammering, Mechanics
Institute, Helmut Schmidt University -
University of the Federal Armed Forces
Hamburg, Germany

Dr. Jochen Schell and Dr. Reinhard
Behrendt, Polytec GmbH



 **Polytec GmbH
(Germany)**
Polytec-Platz 1-7
76337 Waldbronn
Tel. +49 7243 604-0
info@polytec.de

**Polytec GmbH
(Germany)**
**Vertriebs- und
Beratungsbüro**
Schwarzschildstraße 1
12489 Berlin
Tel. +49 30 6392-5140

 **Polytec, Inc.
(USA)**
North American
Headquarters
16400 Bake Parkway
Suites 150 & 200
Irvine, CA 92618
Tel. +1 949 943-3033
info@polytec.com

Central Office
1046 Baker Road
Dexter, MI 48130
Tel. +1 734 253-9428

East Coast Office
1 Cabot Road
Suites 101 & 102
Hudson, MA 01749
Tel. +1 508 417-1040

 **Polytec Ltd.
(Great Britain)**
Lambda House
Batford Mill
Harpenden, Herts AL5 5BZ
Tel. +44 1582 711670
info@polytec-ltd.co.uk

 **Polytec France S.A.S.**
Technosud II
Bâtiment A
99, Rue Pierre Semard
92320 Châtillon
Tel. +33 1 496569-00
info@polytec.fr

 **Polytec Japan**
Arena Tower, 13th floor
3-1-9, Shinyokohama
Kohoku-ku, Yokohama-shi
Kanagawa 222-0033
Tel. +81 45 478-6980
info@polytec.co.jp

 **Polytec South-East Asia
Pte Ltd**
Blk 4010 Ang Mo Kio Ave 10
#06-06 TechPlace 1
Singapore 569626
Tel. +65 64510886
info@polytec-sea.com

 **Polytec China Ltd.**
Room 402, Tower B
Minmetals Plaza
No. 5 Chaoyang North Ave
Dongcheng District
100010 Beijing
Tel. +86 10 65682591
info-cn@polytec.com