A New Concept for the Non-Destructive Testing of Fiber-Reinforced Plastics via Laser Generated Ultrasonic Guided Waves

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Abstract. Fiber reinforced plastics (FRP) play a major role in the lightweight design of future mobility. However, due to the complex fracture mechanics of FRP and their inherent sensitivity towards impacts, the introduction of FRP in structural components is accompanied by a considerable expense in inspection, creating a high demand for efficient and reliable non-destructive testing (NDT) methods. In the course of this, ultrasonic guided wave (UGW) testing allows for a thorough and yet global inspection of thin walled FRP components.

This study takes up this topic and presents a new concept for a fully non-contact NDT method that utilizes a pulsed laser source for the excitation of UGW on one side and a cw laser interferometer for the detection on the other. The key challenge here is to realize a narrowband and mode selective excitation of UGW with a high signal-to-noise ratio (SNR) that eases signal interpretation and thereby reduces the number of false positives. As a first step towards such a new system, the authors present a way for an efficient and selective excitation of UGW via laser pulse tailoring in two distinct stages. In the first stage, the generation of UGW is optimized by adjusting the wavelength of the laser according to the absorption spectra of the polymer matrix of the investigated FRP component by means of an optical parametric oscillator (OPO). Secondly, a spatial distribution of repetitive laser pulses is formed by a beam splitter in order to constrain the frequency and the wavelength of the UGW.

The method enables a mode selective excitation with a high SNR that can be adjusted online through the OPO, the pulse repetition rate control and the beam splitter. The resulting high degree of freedom in the selection of suitable UGW modes facilitates not only the characterization of wave propagation in the reference state, but also the identification of flaws through the independent observation of distinct wave mode characteristics. This paper gives technical insights into the concept and presents preliminary results of the implementation of the concept.
Introduction

Fiber-reinforced plastics (FRP) have become a vital material for the lightweight design of primary structures of aircrafts (A350, B787), passenger cars (BMWi series) and wind turbines. Whereas the flexibility in the design of the material and the structure promotes the use of FRP in these applications on one hand, it impedes the detection of damage and inhomogeneities in the scope of quality assurance and service inspection of these components on the other. Due to geometrical complexity, anisotropic properties and a heterogeneous material structure the inspection of FRP components by non-destructive testing (NDT) methods is a challenging task. Depending on the type, size and depth of the defect this task is nowadays mainly accomplished by visual inspection and tap testing as well as thermography and ultrasonic phased array testing. Among the variety of defects to detect, delaminations are in the focus of attention since they can be easily introduced through impact damage (tool drop, bird strike, stone chip) and can cause a significant loss in stiffness and strength of the structure. In the course of this, the NDT via ultrasonic guided waves (UGW) represents an alternative to the conventional ultrasonic testing allowing for a global and yet thorough inspection of FRP components. UGW develop in plate-like structures and travel parallel to the surface boundary in the form of symmetric and anti-symmetric wave modes. The velocity of UGW modes is not only dependent on elastic properties and material density but also a function of frequency and part thickness due to their dispersive nature. This relationship is fundamental for the NDT via UGW and is usually visualized in form of dispersion diagrams, that can be determined for FRP either experimentally [1, 2] or theoretically through the Global and Transfer Matrix Method [3]. Damage can be indicated by tracking changes not only in wave speed but also in wave attenuation and modal content. Several authors have successfully utilized these indicators to demonstrate the capability of detecting delaminations in FRP via UGW [4–6]. They utilized conventional piezoelectric transducers to excite and detect these waves. However, this requires adequate acoustic coupling through a coupling media and therefore impedes the application of UGW testing on complex FRP components. Furthermore, one has to be aware of the influence of the piezoelectric transducer that inevitably affects frequency and modal content of the signal through its mechanical resonance and finite aperture [7]. These issues can be overcome by replacing the piezoelectric transducers with pulsed laser sources for the generation of UGW on one side and cw laser interferometers for their detection on the other. This discipline of laser-based ultrasonic (LBU) testing combines optical inspection with ultrasonic testing allowing for a non-contact evaluation of UGW. Depending on the energy density, the generation of UGW takes place either reversible via high rate thermal expansion of the illuminated zone in the elastic regime (thermoelastic effect) and/or irreversible through recoil forces of ablated particles (ablation process) [8]. The generation itself is broadband (kHz to MHz), since excitation takes place abruptly, comparable to a sudden impact. Regarding NDT, only the thermoelastic generation of UGW is significant since damage to the part is not tolerated. Since this effect is nearly independent of the angle of incidence, there is no need for contour following robotics in LBU and hence a high potential for an efficient inspection of complex FRP components. However, although some researches have demonstrated the capabilities of LBU regarding FRP testing [9–11] the technology has not reached its breakthrough yet. Besides high acquisition costs, the major drawbacks of LBU testing are the low generation efficiency and signal-to-noise ratio (SNR) that complicate signal interpretation. The insufficient SNR can be improved by reducing the signal bandwidth and increasing surface displacement as well as optical power received by the detecting laser [12]. Since this optical power is dependent on material and surface properties, research in LBU was mainly focussed on optimizing the
resulting amplitude and bandwidth of the acoustic signal. From literature, one can identify four main approaches for the improvement of generation efficiency.

This paper gives insights into these approaches and presents a new NDT concept that combines existing approaches in order to create an efficient and reliable inspection method for FRP components via laser generated UGW. Preliminary results of the implementation of the concept are given at the end.

1. Theory

1.1 Generating Laser Source

The generating laser source in LBU testing is responsible for the coupling of optical energy into elastic energy. Key parameters of the laser source are laser wavelength, pulse duration and pulse energy. They affect the energy, frequency content and directivity of the resulting ultrasonic waves.

The generation of ultrasonic waves via laser is highly dependent on penetration depth and thus on the laser wavelength. Since the thermoelastic generation of ultrasonic waves is based on the thermal expansion of the material, a strong absorption as well as a high coefficient of thermal expansion of the material can lead to an efficient generation of ultrasonic waves. Regarding FRP, absorption can take place in the polymer matrix and the fiber. However, since fibers (especially carbon fibers) show a considerably lower thermal expansion in comparison to the polymer matrix, it is evident to use the matrix as host material for the generation of ultrasonic waves. Preliminary work has already shown through spectroscopic measurements that strong absorptions take place in epoxy based polymers at laser wavelengths between 3 and 4 µm as well as above 6 µm [11, 13, 14]. The absorption in the mid infrared is attributed to the vibrational stretching modes of the OH and CH bonds that appear at wavelengths of 2.9 and 3.4 µm, respectively. Due to the facts that CH bonds are present in all organic molecules and that their absorption band is not sensitive to humidity variations of the environment [15], wavelengths in the order of 3.4 µm are well suited for the generation of ultrasonic waves in composite materials.

The pulse duration has an effect on the frequency content of the ultrasonic wave. Short laser pulses lead to a large bandwidth of acoustic waves, whereas long pulses result in a small one. Considering laser pulse durations in the order of 10 to 100 ns, one can achieve acoustic waves ranging from DC up to 20 and 10 MHz, respectively [11]. Although spatial resolution increases with frequency, the minimum pulse duration is limited by the damage threshold and the attenuation characteristics of the material. Especially for FRP, ultrasonic testing is limited to frequencies below 10 MHz due to strong wave attenuation.

The energy in the acoustic wave increases with pulse energy as long as the generation takes place in the thermoelastic regime [11, 16]. Besides the damage threshold of the material, the laser source limits the maximum pulse energy.

Common sources for the generation of ultrasonic waves are Nd:YAG and CO₂ laser systems. Due to the strong absorption of epoxy-based polymers in the mid infrared, CO₂ lasers with a fundamental wavelength of 10.6 µm have been mainly utilized for the generation of ultrasonic waves in polymer composite materials [13]. Nd:YAG lasers have a fundamental wavelength of 1.06 µm where epoxy based materials show less absorption [11, 13, 14]. However, it has been shown that generation efficiency for bulk wave motion is in fact higher for Nd:YAG lasers than for CO₂ lasers due to the formation of a buried ultrasonic source that results from the major absorption of laser energy by the first graphite layer [11, 16]. In addition to that, Nd:YAG lasers are compatible with fiber delivery (flexibility), easier to operate (low maintenance) and broadband in the generation of
ultrasonic waves (DC to > 20 MHz) [17]. However, the downside of Nd:YAG lasers is the associated low damage threshold that results from the short pulse lengths in the order of 5-10 ns and the fact that the majority of energy is absorbed by the first graphite layer. A trade-off between the two laser sources can be achieved through the use of optic parametric oscillators (OPO) that allow for wavelength shifting. In combination with a Nd:YAG laser the wavelength can be tuned from the fundamental 1.06 µm up to 12 µm, giving the potential to dynamically adjust the wavelength to the absorption bands of the material to be inspected. In fact, with the introduction of OPO the generation efficiency of ultrasonic bulk wave generation in polymer composites has been significantly improved through the selective excitation of the CH and OH bands at 2.9 and 3.4 µm wavelength [13, 14, 16, 18].

1.2 Laser Beam Geometry

Laser Beam geometry affects frequency content and directivity of the resulting ultrasonic waves. In its simplest form, the laser beam is a symmetrical spot, creating an omnidirectional source for the generation of UGW. However, the resulting spread of the acoustic waves is not optimal for NDT because the detection of acoustic waves is usually performed by a single probe of finite aperture where only a small fraction of the generated ultrasonic energy is captured. The frequency content of the resulting acoustic waves can be regulated through the variation of spot diameter. With decreasing spot diameter you can observe an increase in the high frequency content of the resulting ultrasonic waves, similar to the aperture effect on the detection side. However, the minimum spot size is limited by the damage threshold of the material when laser spot energy is kept at maximum for a reasonable SNR. An improvement regarding wave directivity and frequency content can be achieved through line sources [19]. They can be created by means of cylindrical lenses and lead to a highly directional source for UGW with considerable amplification perpendicular to the center of line axis. Since the frequency content is determined by the line dimension along the path of ultrasonic wave propagation, the line width is in the focus of attention here. In contrast to the point source, line width can be considerably reduced through compensation of laser energy density via adjustment of line length, allowing for higher frequency content and spatial resolution. Since a line source can be regarded as a superposition of in-phase point sources, constructive interference can take place, resulting in pronounced plane waves that ease defect detection as well as material characterization once more. Further improvement of SNR in LBU testing can be achieved through converging wave configurations in form of annular or ring shaped laser spots that can be created via focused axicons or patterned templates [20]. In this case, the resulting acoustic waves are focused in the detection point, taking into account that detection is performed by the laser probe on a small local spot. Furthermore, the area under investigation is not confined to the direct line between the center of excitation and detection here but includes the whole area between them, offering higher detection sensitivity. Regarding FRP, however, annular-shaped laser spots would have to be geometrically adjusted in order to compensate for the anisotropic wave propagation.

1.3 Spatial Modulation of Laser Pulses

Spatial modulation in form of an array of laser pulses leads to the selective superposition of acoustic waves of a distinct wavelength. In fact, the modulation favors the acoustic wave mode with a wavelength equal to the distance between the laser spots (wavelength matching method). This way, the energy is concentrated into a single wave mode resulting in a strong signal with narrow bandwidth. The resulting increase in SNR is proportional to the square of the number of laser spots [12]. However, there is a limitation in the number of
laser spots due to the resulting extension of the generated burst signal that reduces temporal resolution.

Besides the number of laser beams and their spacing, the spatial dimension of the laser spots can be optimized once more in order to increase SNR. In an analytical model for the narrow-band generation of surface waves via spatial modulation of line shaped laser beams, an optimum line width can be found that supports narrow-band generation in accordance with the spatial modulation [21].

The spatial modulation itself can be achieved through lenticular arrays [12, 22], optical diffraction gratings [21], multiple laser arrays [23] or shadow masks [24, 25]. Although all of these techniques have been implemented successfully with a significant increase in SNR, they greatly differ in acquisition costs, generation efficiency and their ability to dynamically adjust the spacing between the laser spots for a flexible wave mode selection.

1.4 Temporal Modulation of Laser Pulses

Temporal modulation describes the generation of a train of acoustic pulses through the repetitive arrival of laser pulses in a distinct frequency. Similar to the spatial modulation, signal bandwidth can be reduced via temporal modulation as well. However, temporal modulation constrains the generation to acoustic waves of a distinct frequency whereas spatial modulation favors the generation of waves of a specific wavelength. As mentioned above, there is also a reasonable limit in the number of laser pulses due to the extension of the generated toneburst that leads to drawbacks in temporal resolution. In the past, temporal modulation has been achieved through repetitively Q-switching lasers, long cavity-mode locked laser [12], scanning laser beams [26] and optical fiber arrays [27, 28].

2. The new Concept

The new concept aims at the reliable detection of flaws in FRP through a fully non-contact NDT method. The concept is based on the analysis of UGW which allow for a global and yet thorough inspection of thin walled structures due to their considerable range and their high sensitivity towards damage. Whereas excitation of UGW is accomplished via short pulse laser, the detection is realized through a two wave mixing interferometer. The key features of the new concept allow for an efficient and mode selective generation of UGW through shifting of laser wavelength along with spatial and temporal modulation of laser pulses. The technological implementation of the concept along with a suitable inspection methodology is outlined in the following paragraphs. A visualization of the concept is drawn in figure 1.

2.1 Mode Selective Excitation and Detection

In order to increase SNR and ease signal interpretation, excitation as well as detection of UGW is realized with mode selectivity. This way, damage can be easily tracked through observation of changes in wave propagation of a single mode. On the excitation side, laser pulses are modulated spatially as well as temporally in order to force the superposition of wave packets of a single mode. Whereas temporal modulation is realized via repetition of laser pulses in the selected frequency, spatial modulation is achieved through a beam splitter that separates the main beam into several partial beams that hit the surface with a spacing equal to the selected wavelength λ (see figure 1).
This way, only a single mode with the specified frequency and wavelength will be generated predominantly. Flexibility in mode selection is given through the variation of pulse repetition rate and distance between the beam splitter and the object under inspection. This way, one can dynamically adjust the primary wave mode and hence utilize the individual sensitivity of every wave mode in order to find a specific flaw. The shape of each beam is implemented as a line through the use of cylindrical lenses that are positioned in front of the beam splitter. The line shape is preferred over the converging arc or ring shaped spots since anisotropic properties would have to be taken into account in the shape of the arc in order to achieve a focusing effect. Through the adjustment of line width one can furthermore support the mode selective generation and SNR as stated above.

On the detection side, a laser interferometer based on photorefractive two wave mixing is utilized that allows for the simultaneous evaluation of in-plane and out-of-plane displacement through the detection and analysis of backscattered light with respect to its angle of incidence [29]. Since symmetric and anti-symmetric modes differ greatly in their portions of in- and out-of-plane displacement, mode selectivity can be achieved on the detection side as well.

2.2 Material Adequate Coupling

For the adequate coupling of laser energy into elastic energy in the form of UGW, an OPO is introduced to the NDT concept. This allows shifting of laser wavelength in the mid infrared (2 to 12 \( \mu m \)) covering the absorption bands of OH and CH bonds at 2.9 and 3.4 \( \mu m \) wavelength and leaving flexibility in order to react to changes in the matrix or fiber material. This allows high generation efficiency with the ability of adjusting heat input as well as penetration depth for a variety of polymer composites.
2.3 Inspection Methodology

The inspection methodology consists of the following three steps that build up on each other:

1. Determination of dispersion diagrams
2. Capturing of baseline properties
3. Damage detection

Although each step has a different goal, they are all realized in a fully non-contact way through the use of the mentioned generation and detection lasers.

As a first step, the dispersion diagrams of the component to be inspected have to be determined experimentally in a prescribed frequency range (e.g., 100 kHz up to 10 MHz for FRP). These diagrams give information on the resultant velocity and wavelength of wave modes as a function of frequency and are therefore fundamental for the realization of mode selective excitation in the consecutive steps. They can be captured through broadband excitation via laser pulse and mode selective evaluation of group and phase velocity. Signal processing tools like the wavelet [30] and 2D-Fourier [31] transform can be considered here in order to separate wave modes through temporal or spatial filtering. The selective detection of in-plane and out-of-plane displacement by means of the two wave mixing laser interferometer supports this evaluation. Due to the fact that dispersion is a function of elastic constants, density and wall thickness, there is more than one dispersion diagram to a FRP part. Hence, this process has to be repeated in order to track the dispersion behavior with respect to the direction of wave propagation and changes in wall thickness of the part. This is realized by moving primarily the excitation beam by means of positioning units over the surface of the area to be inspected while keeping the probe beam of the interferometer as stationary as possible due to its high sensitivity towards changes in surface quality and angle of incidence. For spatial filtering of wave modes the distance between the excitation and detection point is altered in equidistant steps. While this can be a time-consuming process in the beginning, it can likely be reduced through the limitation to critical areas and the validation via simulation in the future.

Once the dispersion behavior is characterized, the baseline properties can be captured via mode selective excitation and detection. These baseline properties represent the fingerprint of the undamaged state and serve as damage indicators for future inspections. Regarding UGW, these baseline properties include wave speed, wave attenuation and modal content as well as resulting reflection patterns. As already done in the first step, these properties have to be captured for the area to be inspected by scanning the excitation beam over the surface while detecting the waves with the laser interferometer. In this process, the excitation is realized in consecutive steps with varying excitation frequency in order to improve SNR via lock-in technique. The result is a map of the inspected area that visualizes the local baseline properties for the selective excitations of the symmetric and the asymmetric wave mode as a function of excitation frequency. In addition to that, amplitude and phase images can be generated through the application of the lock-in technique in order to support signal interpretation once more.

These maps and images are the reference for following inspections where the process in step two is repeated in order to check for deviations in baseline properties compared to the undamaged state. With the calculation and specification of critical deviation factors, signal interpretation can be reduced to a simple comparison between the
actual deviation and the critical one. If a critical deviation is observed, a more detailed inspection can be realized through the increase of inspection frequency as well as the reduction of scan distance, giving potential for adaptive spatial resolution.

3. Experimental Work

In order to validate the fundamental principle of the concept, first experiments were conducted on aluminum plates. In contrast to FRP, anisotropic properties and polymer matrix degradation can be omitted with aluminum, thus, simplifying the implementation of the concept in the first step. The generation of UGW via short laser pulses was treated separately from the detection via laser interferometer in order to have an independent look at the fundamental aspects of both techniques. In this paper, preliminary results of the detection of UGW are presented.

3.1 Experimental Setup

Experiments were conducted on an aluminum plate with dimensions of 600 x 600 mm and a wall thickness of 2 mm. The experimental setup along with the inspected area on the plate is shown in figure 2.

![Experimental Setup Diagram](image)

**Fig. 2.** Experimental setup for the detection of UGW via laser interferometer (left) and sketch of the aluminum plate with indication of point of excitation as well as inspected area (right). Dimensions are shown in mm.

A two wave mixing laser interferometer with 500 mW output, a nominal wavelength of 532 nm and a bandwidth of 10 kHz to 20 MHz was utilized for the detection of UGW on the front side of the plate. The plate itself was mounted on a positioning stage in order to allow for scanning in the x- and y-direction. The distance between the plate and the laser outlet was set equal to the focal length of 30 mm for high SNR. The excitation of UGW was realized in the center of the plate through a piezoelectric transducer with a bandwidth of 100 to 900 kHz. A high voltage amplifier was introduced to the setup in order to translate and amplify the generated burst signal from a function generator to the piezoelectric transducer. The signal was chosen as a burst of 100 kHz with 5 cycles enclosed in a Hanning window. Data acquisition was performed with 60 MS/s, recording 60,000 samples (1,000 µs) per scanning position. The area of interest was placed 50 mm
away from the point of excitation and sized to a box of 20 x 20 mm where scanning was performed with a step size of 1 mm in the x- and y-direction, resulting in 400 spatial samples total. At each position one burst signal was generated through the transducer and captured by the interferometer before translation in x- or y-direction took place.

3.2 Results

In order to test the ability of flaw detection via UGW, the plate was measured in the original state and after machining a 1 mm deep pocket hole of 10 mm diameter in the previously inspected area. The 20 by 20 mm scan was repeated 6 times for each state in order to increase SNR through averaging amplitude-time data at each position. Figure 3 shows the results of the scans for the original (left) and modified state (right) of the inspected aluminum plate at an elapsed time of 72.8 µs after signal generation.

![Figure 3](image)

**Fig. 3.** Color coded Amplitude (in V) of $A_0$ mode in the aluminum plate as function of scan position in x- and y-direction (in mm) according to the coordinate system in figure 2. The original state (left) is compared to the state after machining of a 1 mm deep blind hole of 10 mm diameter (black dotted line) in the center of the inspected area (right). The images were captured 72.8 µs after signal generation.

At the excitation frequency of 100 kHz a strong $A_0$ mode could be identified by its wavelength, representing the desired case of a quasi-single mode excitation as can be seen in both diagrams. The blind hole affects wave propagation in two ways. On one side, the reduced wall thickness in the area of the hole (black dotted line) results in a decrease of wave speed and thus a displacement of wave fronts. On the other side, the change in wall thickness is responsible for a reduction of local stiffness and thus an increase in displacement, as can be seen by the captured amplitude in the area of the hole.

Although SNR is already sufficient for damage identification in this case, an improvement can be achieved through the illustration of signal magnitude and phase at the excitation frequency. This can be done by performing a Fast Fourier Transform of the amplitude-time data at each position, and visualizing phase and magnitude of the Fourier coefficients at the corresponding excitation frequency in respective diagrams. These are shown in figure 4 for the original (left) and the machined plate (right). The frequency with maximum amplitude was selected for the construction of both images. Due to the characteristics of the piezoelectric transducer, the transient signal and the strong dispersion of the $A_0$ mode, this frequency of 114 kHz is slightly shifted from the original excitation frequency of 100 kHz. The blind hole can be clearly recognized in the amplitude and phase image through pronounced amplitude and phase shifting in the area of the hole.
Fig. 4. Color coded Amplitude (top) and phase (bottom) images at 114 kHz as a function of scan position in x- and y- direction (in mm) according to the coordinate system in figure 2. The original state (left) is compared to the state after machining of a 1 mm deep blind hole of 10 mm diameter (black dotted line) in the center of the inspected area (right).

**Conclusion**

The combination of excitation and detection of ultrasonic guided waves via laser offers great potential for a fully non-contact inspection of thin walled FRP components. However, the breakthrough of laser based ultrasonic testing methods has been limited due to low generation efficiency and signal-to-noise ratios. In order to overcome these drawbacks, the authors presented approaches from the past regarding the generation of ultrasonic waves via pulsed laser sources in the thermoelastic regime. In the course of this, the effects of laser wavelength, beam geometry as well as spatial and temporal modulation of laser pulses on the bandwidth, directivity and magnitude of the resulting acoustic waves were discussed. On this basis, the authors presented a new concept that combines current approaches in order to create a flexible and reliable NDT method for the inspection of thin walled FRP components. By combining high repetition rate laser sources with an optical parametric oscillator and a beam splitting optic in one setup, the new concept allows for an efficient and mode selective generation of UGW through shifting of laser wavelength along with spatial and temporal modulation of laser pulses. The detection is realized with a two wave mixing laser interferometer that allows for a mode selective evaluation through the simultaneous tracking of in- and out-of-plane displacement even on the detection side. Along with the suggested setup, the authors presented a robust inspection methodology that is based on the registration of changes in wave speed, wave attenuation, modal content and reflection patterns compared to a reference state. Regarding the implementation of the concept, first experiments on the detection of UGW in aluminum via laser interferometer were presented. An artificial damage in form of a blind hole was successfully identified through the illustration of phase and amplitude at the excitation frequency.
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