Air-Coupled Ultrasonic Inspection of Fiber-Reinforced Plates Using an Optical Microphone

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Abstract: In comparison to conventional ultrasonic techniques, air-coupled ultrasound (ACU) offers an advantage in automation of the test process. ACU can conveniently also be applied to fragile or corrosive specimens. In ACU testing, the ultrasound (US) power losses due to impedance mismatches from air to the material necessitate a high-power US source and a sensitive-enough detector on the receiver side. A novelty in our measurement setup is a laser-based optical microphone which we used together with a focusing US transducer. Due to its broad frequency spectrum and small aperture, the optical microphone has a great potential for the C-scan inspection of plates. Firstly, we use it to characterize the sound field of the US transducer. Secondly, we changed the setup configuration and performed a C-scan of plates made of CFRP with different defects (delaminations, cracks) in the through-transmission configuration. The results show a comparable sensitivity (signal-to-noise ratio) and a better spatial resolution compared to the ACU techniques which use piezoelectric receivers.

Introduction

Non-destructive testing (NDT) methods are increasingly used for quality control during production or maintenance. An inline-monitoring of a production line is technically possible using such methods even considering composite materials with complex geometries and many other materials. Ultrasound is beneficial under similar NDT methods, as it could be comparatively fast, cost-efficient, easily applicable and there exist many sophisticated methods for data processing and interpretation [1]. However, in conventional ultrasound applications, a coupling medium is usually needed since the acoustic impedance of air is magnitudes away from any solids, leading to high losses at the interfaces. This in turn limits the potential of ultrasound in highly automated production processes and can prevent this method from being used at all, e.g. for materials like uncured composites or hydrophilic materials.

The development of air-coupled ultrasound (ACU) systems has made possible the testing of various materials promising to make the automated inspection more efficient by removing the need for extra coupling media. These systems use ultrasound transducers specifically designed for generating sound in air, alongside low-noise amplifiers to overcome the extremely high sound energy losses. The first applications of this technology date back to the 1990s [2], however progress has mostly been made due to advances in piezoceramic materials. The development of new broadband emission [3] and detection [4] methods has led to new possibilities in detecting defects, e.g. in terms of time or spatial resolution [5]

Optical microphone

The general idea of the optical microphone is to measure sound pressure alterations in air with a laser beam by interferometric means. The optical path of light is significantly influenced by the refractive index of the propagating medium (e.g. air or water), which changes with the sound pressure Thus, the optical microphone can measure sound waves without moving mechanical components [4].

The benefits of this device are that there is one air-solid interface less, where sound energy losses occur (compared to conventional ACU with piezoelectric transducers on sending and receiving sides). The sound is measured directly in air, without moving components, which inherently show mechanical resonances. This promises a broadband spectrum for measurements between about 100 Hz to 1 MHz [6], without significant frequency-dependent variations in sensitivity. Another improvement is the comparatively small sensor aperture of approximately 2 mm, resulting from the much smaller form factor of the optical microphone (compared to conventional transducers). This improves the spatial scan resolution [7].

ACU transducer Sound field characterization

The geometrically focused Sonoair CF 400 US transducer manufactured by the company Sonotec with 400 kHz (+/- ±4 %) nominal frequency and an active diameter of 20 mm was characterized.

A 3-axis computer numerical control (CNC) table was used to perform automated tests. In these tests, a predefined area was scanned as shown in the Figure 1.

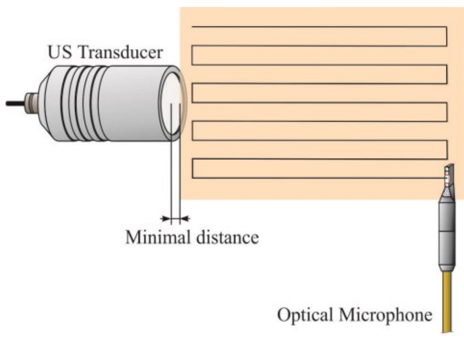

Figure 1: Schematic of the setup for the characterization of the transducer sound field. The transducer was moved with respect to the fixed optical microphone according to the meander-shaped line.

The measuring process was performed as follows: The CNC table continuously moved the transducer in a meander-like shape in relation to the measurement device, which was either the optical microphone from XARION or a laser

Doppler vibrometer (LDV) from Polytec. During the transducer movement, the LDV was excited with a predetermined pulse in periodic intervals, and the recording was started together with the excitation pulse. It is important to emphasize that for each measuring point, where the transducer was excited, the complete time response signal was recorded.

A focusing effect can be observed in the sound field of the geometrically focusing transducer depicted in Figure 2. The highest recorded signal power was between 30 and 50 mm away from the transducer surface. Converging and diverging fields are visible in the greenish color. The near field is broadened by echoes, which is especially visible at the horizontal line of higher intensity at $z = -12$ mm.

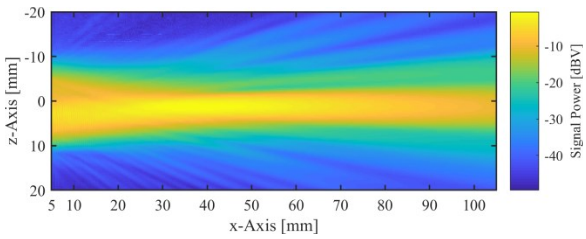

Figure 2: Power distribution of the geometrically focused transducer (frequency: 400 kHz). The image shows the signal power calculated from the data obtained as described in Figure 1. The whole signal length was considered in the time window, as only relative differences of the power were of interest. Transducer excitation was set to 5 pulses at 100 V.

The measured sound field and values agree well with the results of the manufacturer [8]. It should be noted that the resolution of the images presented here exceeds the ones of the manufacturer due to the use of the small-aperture optical microphone.

ACU transducer surface movement characterization

The measuring process for the characterization of the transducer surface movement is similar to the sound field, except for the difference that the plane of measurement (orange in Figure 3) is parallel instead of normal to the transducer surface. The transducer moves with respect to the fixed LDV according to the meander-shaped line.

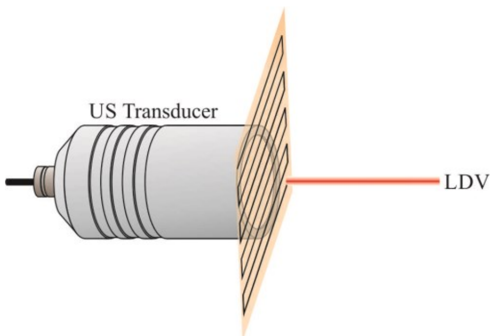

Figure 3: Schematic of the setup for the characterization of the transducer surface movement.

The left image in Figure 4 shows the measurement recorded with a marker on the transducers' housing pointing upwards. After the inhomogeneity was observed in the lower half of the power distribution a second measurement was done with the transducer rotated by 90° counter clockwise to evaluate whether it was caused by the relative orientation of LDV and the surface or by the vibration itself. The resulting power distribution (visible in the right image of Figure 4) rotates correspondingly, showing that the asymmetry was caused by the surface vibration.

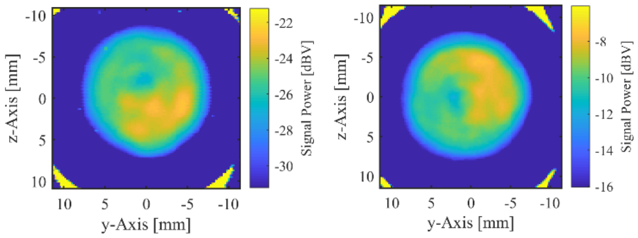

Figure 4: Power distribution of transducer displacement of CF 400 transducer. The image shows signal power calculated from the data obtained as described in Figure 3. Usual orientation with 10 V, 5 pulse excitation (left) and rotated 90° counter clockwise with 100 V, 1 pulse excitation (right). Note the different signal power levels due to the different excitation settings.

There are numerous possible explanations for the observed behavior: It is known that the matching layer can cause so-called *ringing* due to its narrow band properties, where a sound pulse is prolonged when the transducer's natural frequency is excited. Another possibility is that the inhomogeneous contact between transducer and backing material are causing some parts of the piezo element to be more damped than others. It has been shown that the transducer oscillation is significantly influenced by contact to other materials [9]. This effect depends on the backing material and bonding method, which are both unknown at this point. The last possibility discussed here is partial depolarization. As the transducer was excited with a voltage higher than its maximum rated voltage of 400 V in previous studies [10], depolarization of the material likely occurred. Depending on the actual arrangement of the electric contacts, it is possible that the piezo composite was depolarized locally. However, the asymmetry is barely observable in the forced vibration phase of the oscillation where the transducer receives the excitation voltage. Thus, this effect is regarded subordinate to the other two.

Because of this asymmetry, the signal power received by the optical microphone depends on its position relative to the transducer. The SNR can be improved, if the microphone is positioned over the transducer area with high output power.

Testing of CFRP plates with an optical microphone

All the inspection scans presented in this work were conducted on the same specimen – a carbon fiber-reinforced polymer (CFRP) plate (Figure 5). It had the dimensions of 150 × 100 mm and a thickness of 2.1 mm. It was impacted with an energy of 15 J according to ISO 18352 (2009). The diameter of the spherical impactor was 15.75 mm. The impact location was in x and y direction at 30 mm. The scan area is marked with the white frame in the Figure 5.

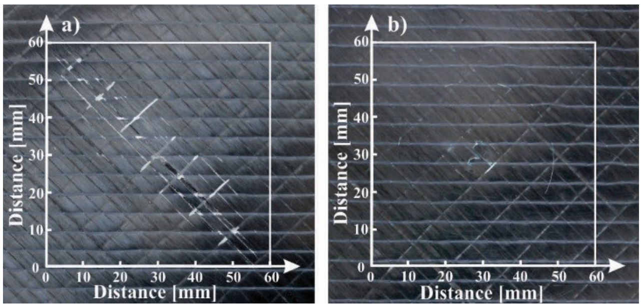

Figure 5: Rear (a) and front (b) side of the impact probe.

The ACU scans were conducted using a classical through-transmission setup with the specimen placed between the US emitter and the sensor (Figure 6). The distance between the emitter and the specimen x_1 was set to the near-field length, so that the specimen was located in the maximum of the US pressure field determined previously (Figure 2). The optical microphone was placed as close to the plate as possible. Due to the housing of the optical microphone, the distance between the plate and the etalon of the optical microphone x_2 was set to approx. 3 mm for the scans a), b) and c) and 12 mm for the scan d).

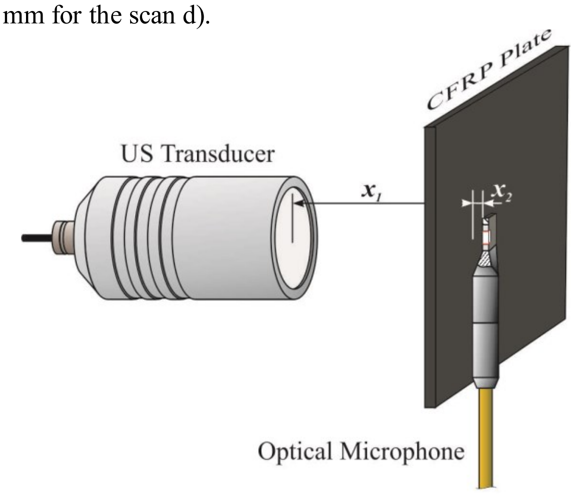

Figure 6: Testing of the CFRP plate with the US transducer and optical microphone.

In order to compare the optical microphones with the conventional piezoelectric receivers, four scans were made on the same specimen using different transmitter and receiver combinations (Figure 7). On the emitter side, a non-focused piezo-ceramic AirTech-200-transducer from Ingenieurbüro Dr. Hillger with 200 kHz (+/- 4%) nominal frequency and a bandwidth of 21 kHz was used for the scans a), b) and c). Its near-field length was 18 mm. For scan d) the piezoelectric transducer Sonoair CF 400 with a nominal frequency of 400 kHz (+/- 4%) was used as an US emitter. Its near-field length was 50 mm as specified by the manufacturer. This is slightly more than previously measured using the sound field scan (Figure 2). On the receiver side an AirTech 200 sensor was used for scan a), the optical microphone Eta 100 for Scan b), the Eta 250 for Scan c) and Eta 450 for Scan d).

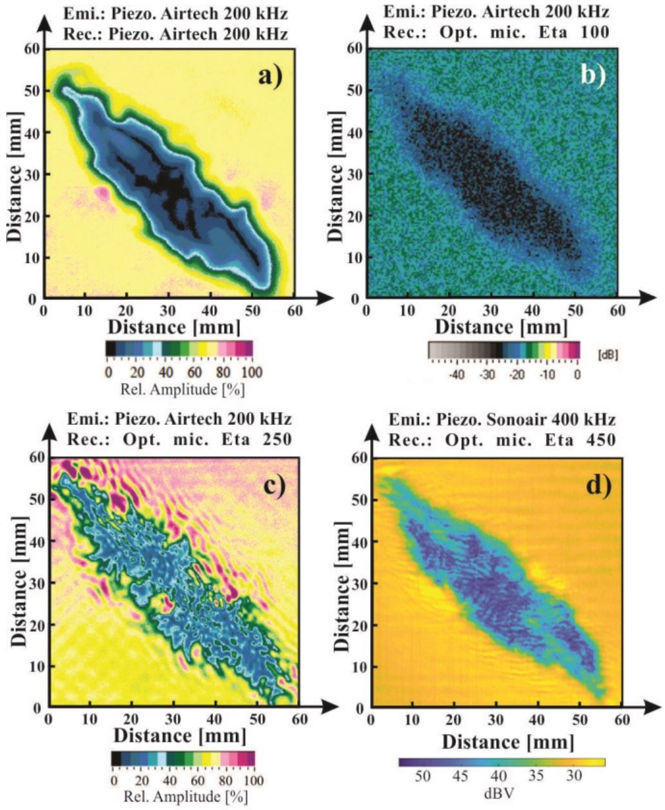

Figure 7: Comparison of different ACU testing configurations: a) piezoelectric transducer pair (AirTech 200), b) AirTech 200 in the combination with an optical microphone Eta 100, c) AirTech 200 with the sensor Eta 250 and d) a piezoelectric transducer Sonoair CF 400 with the Eta 450 [7, 10, 11].

The C-scans represent the maximum amplitude values of the transmitted ultrasound at the characteristic nominal frequencies of the piezoelectric emitters (200 kHz or 400 kHz, respectively) for each scan position.

In scans b), c) and d) in the Figure 7, we observe the improvement of the scan accuracy over the development of the newly released versions of the optical microphones. The wave-like pattern at the margin of the defect in the scan c) of Figure 7 is obviously an artifact of the measuring system. It is most likely a consequence of the diffraction, interference and non-linear effects of the US on the damaged area.

The higher US frequency of 400 kHz was suitable only in the combination with the optical microphone Eta 450. The other sensor versions were not sensitive enough in this configuration, to detect the US, as higher frequencies are attenuated more by the inspected CFRP material. This combination delivers better results compared to the conventional piezoelectric emitter-receiver combination.

Comparison to immersion ultrasonic testing method

Ultrasonic immersion testing can be considered as a reference technique compared to ACU C-scan results. Such a scan was conducted in classical pulse-echo configuration: for the ultrasound emission and its detection the same ultrasound transducer (H10MP15) was used. Its peak frequency was 10 MHz. The near field length in water was 15 mm.

Below the specimen a flat reflector plate was located. Consequently, the ultrasound was reflected on the front and back specimen surfaces and on the reflector plate surface. Due to the different arrival times, these reflections can be easily isolated from each other with the time windowing. In Figure 8, back surface echo a) and reflector plate echo b) C-scans are shown.

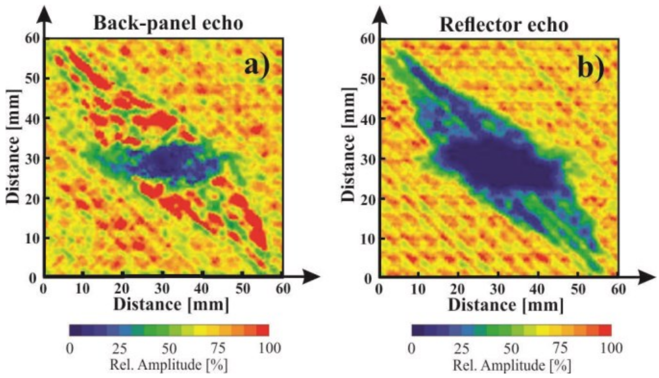

Figure 8: Immersion ultrasonic testing method applied on the specimen: a) back specimen surface echo and b) reflector echo [12].

The C-scans represent the maximum amplitude of the US signal at the emitters' peak frequency during the time windowing interval.

From the comparison of Figure 7d and 8b, it can be observed that the piezoelectric transducer Sonoair CF 400 - optical microphone Eta 450 combination deliver comparable results to the immersion ultrasonic testing, while inspecting the impact damage on the CFRP plate. A quantitative analysis of the delaminated area using appropriate sizing techniques [12] needs to follow.

Conclusions

We showed that the optical microphone (in the combination with a laser Doppler vibrometer) can be used for the ACU piezoelectric transmitter characterization. We observed an asymmetric distribution of the US intensity emitted by the transducer.

The comparison of the different ACU testing methods was made, using different versions of the optical microphone. The scan results with an optical microphone show a comparable or better sensitivity (signal-to-noise ratio) and a better spatial resolution, compared to the classical ACU techniquesusing piezoelectric receivers.

The ACU to the immersion ultrasonic testing method was compared, while performing the scans on the same specimen. The optical microphone Eta 450 in the combination with the piezoelectric transducer Sonoair CF 400 delivers the comparable results to the immersion ultrasonic testing method. However, this ACU method is faster and more suitable for the applications in an automated testing environment, especially, when inspecting large and geometrically complex composite components.

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