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Optical microphone-based acoustic response analysis for non-contact non-destructive testing

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Summary:
In this paper, we present a compact, non-contact non-destructive testing setup based on laser excitation and air-coupled detection of ultrasound within a 2 MHz acoustic bandwidth. The setup is comprised of a miniaturized Optical Microphone as air-coupled ultrasound detector, and a compact excitation laser head, both of which are fibre-coupled. We show results from applying this setup to differentiate between production batches of small ceramic components with varying quality in terms of their acoustic response. We demonstrate that the acoustic data is well suited for AI-based data analysis.

Keyword: optical microphone, sensor, coda wave, laser excitation, ultrasound testing, air-coupled ultrasound, contact-free NDT, in-line

Introduction

The steadily increasing complexity of production processes in combination with ever decreasing tolerances for manufacturing errors drives a strong need for fast, in-line capable non-destructive testing (NDT) methods for quality control.

Here, we present a compact, contact-free NDT setup making use of laser-excited ultrasound for identifying defective parts within a production line. The approach is based on a highly optimized, air-coupled optical ultrasound sensor, with a unique bandwidth of 10 Hz to 2 MHz in air. Combined with a laser to excite ultrasound in a part under test, the 'acoustic fingerprint' of the component under test is analysed. These fingerprints allow to distinguish between defective and good parts with high selectivity. The setup is compact and easy to (retro-)fit into production lines. Due to the contact-free nature of the method, it allows fast in-line testing in various production settings, offering significant advantages to state-of-art contacted ultrasound testing methods.

Optical Microphone

The core technology behind the presented method is an innovative approach to measure soundwaves with an all-optical effect. A soundwave locally modulates the density and therefore the optical refractive index of air. These small variations (~10^{-9} per Pa) are detected by making use of a laser-probed Fabry-Pérot interferometer (see Fig. 1). It converts the refractive index change into an optical signal suitable for photo-detection [1].

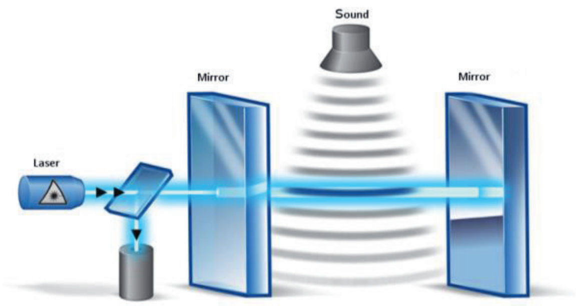

Fig. 1: Function principle of the Optical Microphone.

This all-optical approach is not influenced by any mechanical resonances, therefore it offers an uncommonly broad bandwidth as well as a flat frequency response. The sensor head has a small footprint (5 mm diameter) and is optically fiber-coupled.

Laser excitation

By exposing the surface of a sample to a short, high energy laser impulse, the photo-thermal mechanism [2] will excite a thermo-elastic shockwave. This shockwave propagates as a broadband ultrasound transient through the sample.

Acoustic response analysis

The ultrasound propagation is strongly influenced by the mechanical properties and structure of the sample. Defects, such as cracks or delaminations, lead to scattering, diffraction and interference, and consequently alter the ultrasound response emitted to the surrounding air, causing distinct 'acoustic fingerprints'. The Optical Microphone is able to detect these signals in a broad frequency range enabling spectral analysis. In the following, we show the application of the presented setup to the characterization of quality variations between different production runs for small ceramic components.

NDT of small ceramic elements

The presented setup was used to differentiate between production batches of cylindrical ceramic elements with ~15 mm length. The production batches vary in quality, with one batch previously identified as prone for failure. The samples were illuminated by the excitation laser on one end. The acoustic response formed by waves propagating along the cylinder axis was recorded on the other cylinder end with an optical microphone (Eta450 Ultra).

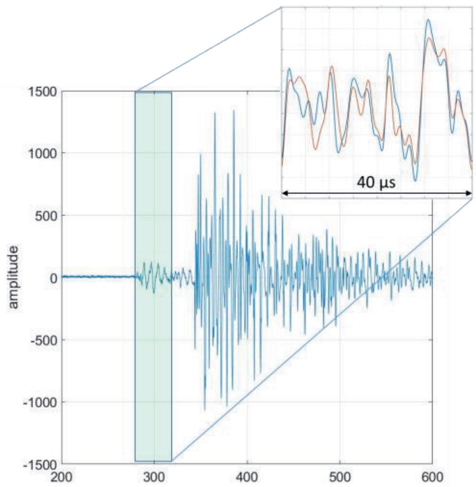

Fig. 2: Exemplary acoustic signal. The signal consists of a sound wave propagating through the ceramic part, relevant for analysis (highlighted), and a high-amplitude delayed component travelling through air from the excitation zone to the microphone.

Results

Segments of the recorded signals (Fig. 2) from 175 different samples were subjected to a correlation analysis, revealing clustering according to the different production batches. Figure 3 displays the Pearson correlation coefficients for each pair of signals, where brighter areas indicate higher correlation. While certain batches feature significant cross-correlation, notably the nOK-labelled batch (cluster 5 in Figure 3) deviates from the remaining samples in terms of its acoustic response.

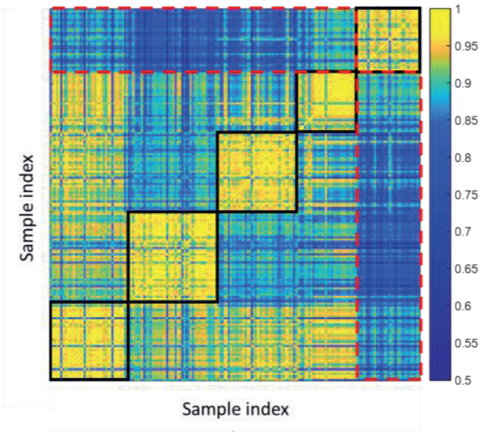

Fig. 3: Pearson correlation between acoustic signals as shown in figure 1 from 175 samples. Black boxes indicate production batches, the red-dashed box highlights the low-correlation between faulty batch 5 and the rest of the samples.

The recorded signals are well-suited for classification by different machine learning algorithms. The preliminary result of classification by a support vector machine (SVM), trained on 50% of the available data, is shown in figure 4.

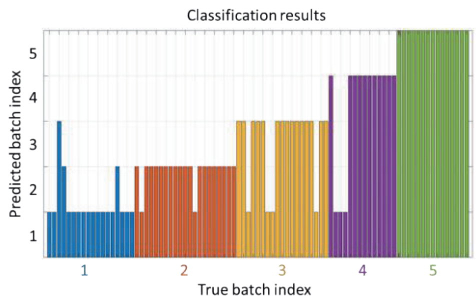

Fig .4: Classification by machine learning. Different colors indicate production batches, the y-axis indicates the batch classification by the algorithm.

86% of the test data has been classified correctly according to the batch labelling provided for the samples. The influence of quality variations within each batch on the classification results is a question under current investigation.

Conclusions

We presented an innovative non-contact ultrasound NDT setup and its application towards quality control for small ceramic components. The setup has interesting prospects for in-line integration in various industries, such as testing of precision welds or quality control in semiconductor industry.

References

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