Application of Acoustic Emission in Machinery and Process Monitoring

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Abstract. Vibrational analysis and technical acoustics investigations are predominantly done in the frequency range up to 20 kHz. However, rotating and reciprocating machinery and many technical processes produce acoustic signals at higher frequencies. The value of acoustic emission for the technical monitoring is still underestimated. Therefore, an approach has been developed for the simultaneous investigation of frequencies from relatively low frequencies up to about 200 kHz (and even higher) by means of modified AE-sensors for acoustic emission.

Commonly, the characteristic spectral curves of AE sensors exhibit resonances due to the material and the construction principles. Therefore, sensors made of piezo-composite material have been developed in order to optimize the characteristic curves for several applications. Specific resonances are suppressed and the frequency curve becomes more flat and can be partly linearized. Consequently, the sensors can be used for simultaneous investigations of vibrations at low frequencies and AE-frequencies as well which enables the complementary use of vibrational and AE-signal processing techniques. The relatively flat characteristic curve provides a more straightforward use of advanced spectral signal processing tools which will be also exemplified.

Furthermore, the contribution reports on ongoing developments and investigations for diagnosis on various machinery.

Some examples will illustrate the use of such sensors for the evaluation of machine fault signatures, defect diagnostics, early detection of health condition (examples for diagnosing incipient fault conditions, for cavitation in pumps, investigation of automotive brake and for the monitoring of structures).

A framework of MATLAB software tools has been developed for measuring, monitoring and interpretation of the acoustic data. The consequent MATLAB approach (from data acquisition up to monitoring information such as alarms) has been chosen in order to provide a complete chain ranging from the sensor signal up to classified monitoring information (evaluation of state history, alarms).

1. Introduction

Methods of acoustic emission have been increasingly applied for condition and health monitoring of machines and structures. Applications and advantages of ultrasonic sensors for condition monitoring has been discussed in several papers [1, 2, 3]. The spectrum covers many applications ranging from very qualitative methods such as leakage detection, testing of steam traps, detection of discharges, checking the state and the quality of lubrication, bearing diagnostics up to much more demanding and complex applications such as life time and trend analyses, heath monitoring, fracture warning and the use of advanced methods for the diagnosis of rotating and reciprocating machinery which require state-of-the art (embedded) computing.

The value of acoustic emission for maintenance and machinery inspection has been demonstrated by means of several examples including run-ups and run-downs of power generation turbines [1] or machinery fault detection [4]. The application of advanced time-frequency signal-processing considerably enhances the value of the acoustic emission approach. In contrast to the "traditional" hit-counting measurement techniques and data processing continuous signal acquisition and processing is necessary for many practical situations. Acoustic emission could be proved as a valuable tool for monitoring of bearings and other rotating parts in machinery [5, 6]. Due to sensitivity to friction, acoustic emission is used for control of lubrication and prevention of boundary friction. However, the methods are often used more or less qualitatively by the application of simple techniques and methods. The potential of acoustic emission remains very often unused. Special advantage of the acoustic emission can be found for monitoring of very low speed of bearings [7] which has been demonstrated by means of a complementary research and comparison of the machinery fault detection with traditional vibration methods [8].

Another important class are journal bearings for which acoustic emission has great diagnostic potential. Classical vibration methods often fail [6, 7]. Acoustic emission plays an important role in understanding of elementary processes caused by friction, cavitation or micro-fracture [9]. Using the advantage of higher frequencies, the acoustic emission can be favourably used for the evaluation of transient events. The relationship to condition monitoring of larger Diesel engines has been described in detail by Pontippidan [10]. It has been demonstrated that even angular position of events can be accessed by means of acoustic emission. The extraction of valuable information requires mathematical effort.

However, there is a tremendous and successful development of applications of pattern recognition in almost all fields of physics and engineering. Increasingly, reports appear in the scientific literature but still there are few industrial applications despite its potential. Caused by cheaper but more performant computing power, even on embedded systems, new applications of classification and pattern recognition methods for industrial use are expected [11, 12, 13]. The development of specialized numerical methods and algorithms is essential to extract relevant information from measurement data. Caused by higher frequencies, AE-methods are predestinated for a complementary use of transient and stationary methods. A comparison and the value of simultaneous FFT- and wavelet-based acquisition and data evaluation have been demonstrated for gear-wheel diagnosis [13, 14].

Generally, a trend can be observed, that methodical and numerical developments which have been developed for the "low frequency" vibrational diagnosis will be extended to much higher frequencies. This is, as mentioned, supported and enabled by much faster data processing, data storage and cheaper computing technique. Furthermore, there are also developments of new sensor materials, which can be applied in a very broad frequency range.

2. Experimental

Sensors based on piezo-composites have been developed [15]. Caused by the technology, several favourable properties could be achieved. Amongst a good signal to noise ratio, the sensor can be used in a wide frequency range. The sensor response curve is relatively smooth. Unwanted resonances (Fig.1) are suppressed. That means, the spectral characteristics can be linearized up to a certain extent allowing the exploitation of the spectral properties of signals and the application of advanced joint-time-frequency analysis in real-time. An important practical aspect arises from the increased number of degrees of freedom in transducer design e.g. flexible or special curved transducers. The impedance curves of the two different discs illustrate the suppression of unwanted resonances for the piezo-composite transducers. In contrast, the piezo-ceramic disc shows many resonances caused by different vibration modes of such a disc.
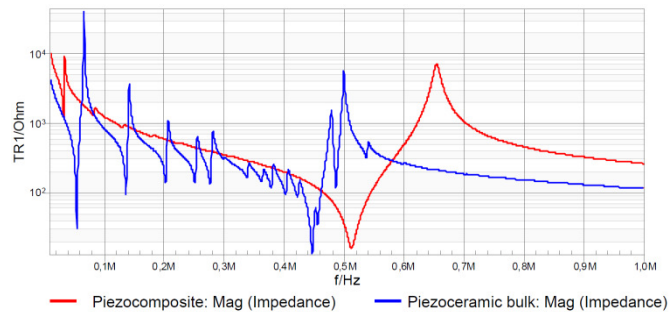

Figure 1: Impedance of piezo-electric discs with diameter 35 mm and thickness resonance at 500 kHz.

The piezo-composites used in this work were manufactured by the so-called Dice-and-Fill technology. This demanding manufacturing technique was established at SONOTEC [16] in 2008. Piezo-ceramic plates (e.g. Lead-zirconate-titanate – PZT) are partially cut by a wafer dicing machine in two directions under an angle of 90 degrees. The gaps are filled with polyurethane or epoxy resin. After hardening, the plate is grinded to final thickness. Finally, the composite is metallised and polarised.
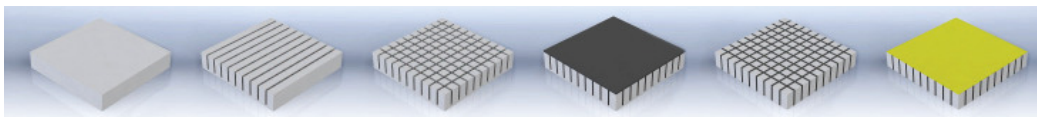

Figure 2: Piezo-ceramic plate, first cut, second cut, filling in the matrix, grinding to final thickness, metallization and polarization.

This manufacturing process is complex and has several steps with different difficulties. On the other hand, this results in a variety of possibilities enabling new properties of the transducer. Variations are possible by changes in the:
- type of piezo-ceramic
- type of plastic matrix
- pitch of the piezo-ceramic pillars
- arrangement of piezo-ceramic pillars
- gap width
- thickness of the plate
- shape of the plate and
- macroscopic pitch of transducer elements.

The first sensors were built with a fixed setup for the piezo-composite structure with a composite diameter of 20 mm. This resulted in an effective suppression of unwanted resonances. The impedance curves shown in figure 3 illustrate the effect.
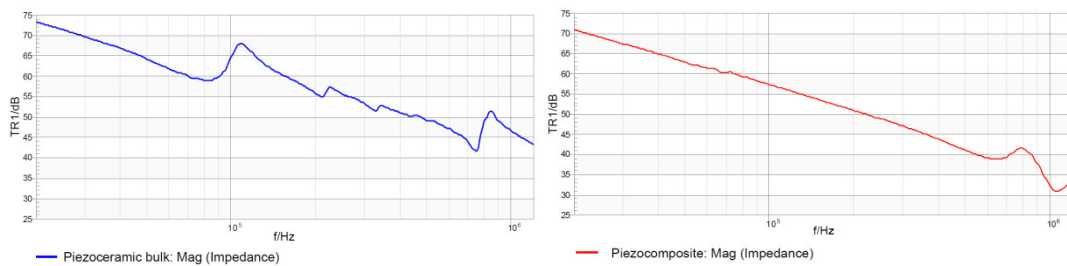

Figure 3: Left: impedance of a conventional AE sensor with piezo-ceramic disc, right: impedance of a new AE sensor with piezo-composite disc.

In comparison with piezo-ceramic sensor the impedance of the composite sensor does not exhibit any resonance in the range from 20 kHz to 600 kHz. In the next step new miniature sized AE sensors for continuous condition monitoring were developed. Two types have been built up and experimentally used: 1 MHz and 5 MHz centre frequency of the main resonance (thickness mode).

A wafer dicing machine was instrumented with several new piezo-composite sensors (1 MHz type). Since the interesting frequencies were below 100 kHz, a 24 Bit acquisition card „Data Translation DT 9847-2-2" has been used. A sampling rate of 216 kHz was employed. A key role for our current developments plays the use of MATLAB (TheMathworks). Data acquisition and processing have been modular developed and enable a complete data-processing chain from the acquisition up to classification and visualization. Especially, the development of customized solutions can be realized very effectively. The data treatment can be done real time and post processing, which includes handling of large amounts of data. Signal acquisition and data processing have been done in one toolbox chain. The MATLAB toolboxes enable a highly flexible configuration of all acquisition and processing aspects ranging from automatic processing of large amounts of data up to classifications tasks.
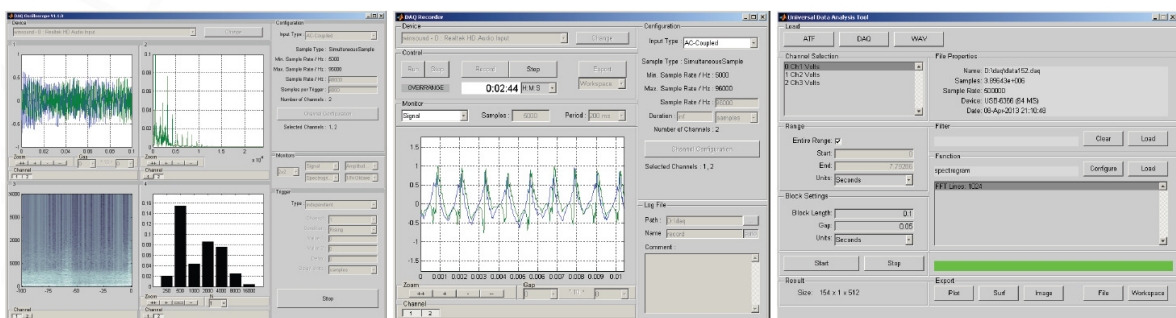

Figure 4: Typical configuration of the MATLAB GUIs, left: spectral/wavelet-tools, middle: configuration and measurement control, right: data tool for scripts and batch processing.

3. Application Example

According to figure 2, grinding is the most demanding processing step in the manufacturing chain of piezo-composite materials. Mostly used as a final process, grinding refers usually to the last and precision step of manufacturing. The degree of roughness of the material influences frictional interaction with the grinding wheel. The friction process reflects in a complex manner the processing procedure. Several examples of the use of acoustic emission for grinding processes are given in the literature (e.g. [17]). The composite material requires a low degree of roughness and very low tolerances of geometric parameters. Furthermore, an optimized service life should be achieved. Therefore, the saw has been equipped with AE-sensors (Fig. 5). It should be noticed that no further test equipment is available to control the grinding process. Monitoring the processing steps of a precision wafer dicing machine has been chosen in order to demonstrate the value of a signal based broad-band application of the composite acoustic emission sensors. The result could be used optimize dicing or grinding processes.
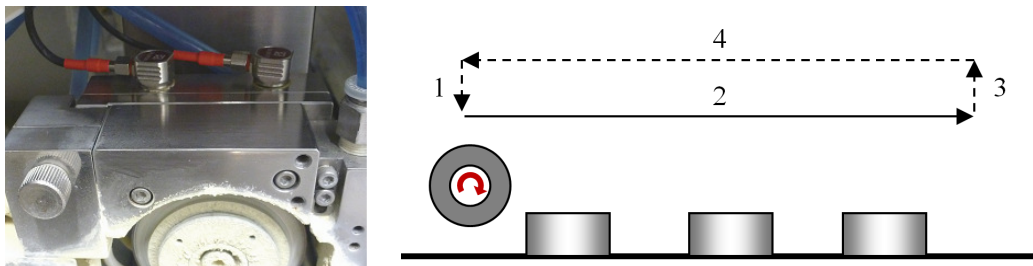

Figure 5: Left: equipped dicing machine, right: pattern of the dicing process of three ceramic discs.

The ceramic materials are so-called hard-to-cut materials which are complicate to process. Consequently, any condition monitoring of the processing steps of expansive parts is useful. From the point of view of acoustic monitoring, the wafer dicing machine provides some interesting peculiarities due to special spindles inside the machine. The spindle can speed up to 60.000 r.p.m. The spindle runs in air bearings with brushless motor. That means that there is no direct mechanical coupling between the rotating and the stationary components. Furthermore, the air bearing causes additional permanent acoustic emission (which has been checked by ¼" microphones up 100 kHz).

A standard dicing process of three ceramic discs fixed in one row was analyzed. The process needs about 6 seconds for each cut line. First, it moves down (z-axis direction). The actual cutting process follows as step 2. At a first glance, the time signal (Fig. 6) does not provide any valuable information for process control. Therefore time-frequency signal processing has been applied. The results of such cutting process along one cutting line are discussed in the following figures. All different phases of the cutting process can be identified by means of frequency resolved AE-intensities.
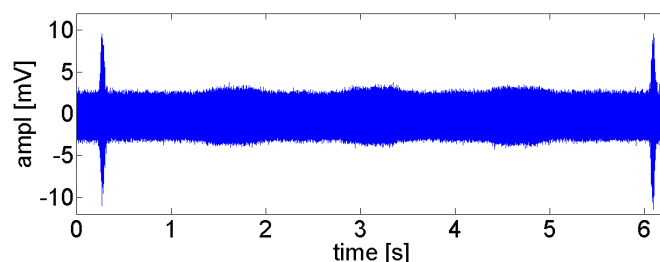

Figure 6: Time signal of dicing process.

In the following example first results are shown for a test series for feed speed optimization. While increasing the feed speed from cutting line to cutting line, a ceramic plate was cut. At present, the value of spindle driving current gives the only information. With the AE-sensors more information can be generated. Figure 7 shows a photograph of the partly diced plate. In the middle (last cutting line) a broken ceramic lamella is visible. Already 6 cutting lines before there are traces at the bottom of the grooves. Meaning the dicing process is in critical state.
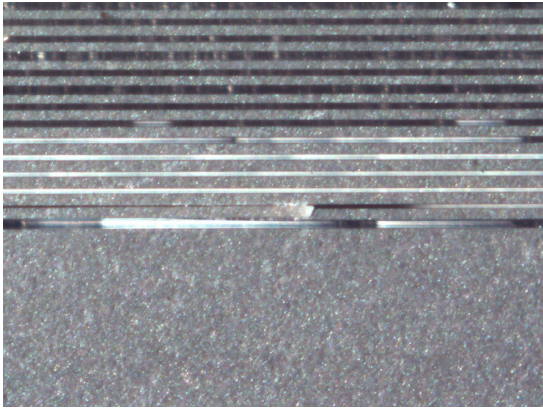

Figure 7: Photograph of fracture of ceramic lamellas and traces at the bottom of the grooves.

These effects cause changes in frequency spectra of emitted acoustic signals while the dicing blade is driving through the workpiece. The time signal, the spectrogram and a zoom of spectrogram visualise the critical process of the last cutting line. The vertical red lines in the spectrogram in the upper right diagram of figure 8 mark the beginning and the end of the ceramic plate.
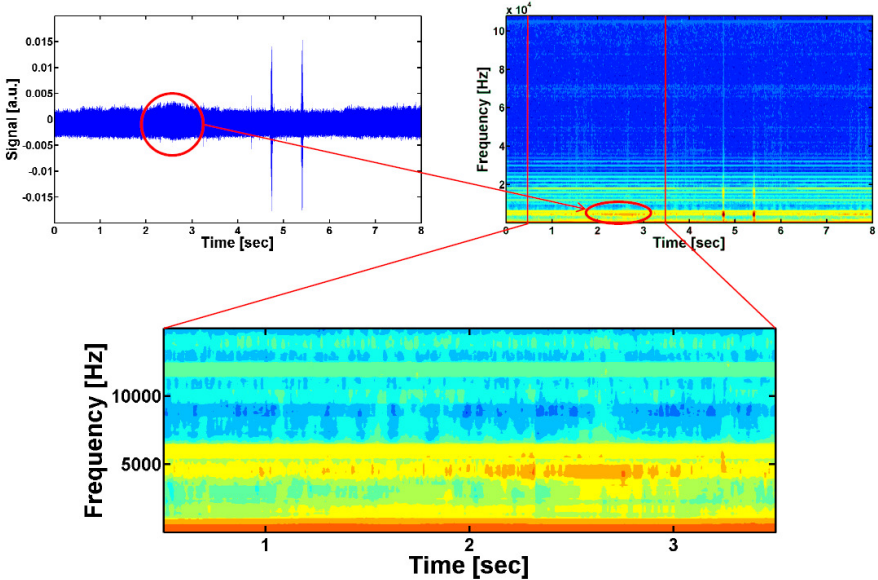

Figure 8: Top left: time signal, top right: spectrogram, at the bottom: zoom of spectrogram.

At about 5 kHz changes in the spectrogram were detected. Especially at 2.3 seconds the resonance line is interrupted. This transient event can be also detected by the sensors and could be caused by a breakage of the ceramic lamella as shown in figure 7. In conclusion, the new AE sensors based on piezo-composites can be used for condition monitoring of dicing processes but a detailed interpretation of the physical and technical effects has to be part of further activities.

4. Summary

Acoustic emission technology and sensors, in combination with acquisition and measurement techniques are valuable tools to extent the vibrational diagnostic in machinery engineering and predictive and risk based maintenance. It has been demonstrated, that broad band sensors and real time-processing of all acoustic data enables the evaluation of vibrational, stochastic and transient processes. The new piezo-composite sensors are well suitable to observe and control processing steps like precision grinding.

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