ULTRASOUND REVISITED

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Both, acoustical and ultrasonic technologies provide very valuable tools for maintenance of machinery and for the monitoring of constructions. The frequency range of 20 to about 100 kHz is particularly promising for the detection of bearing defects, for finding of leakages, for the detection of discharges, missing lubrication, valve function and others. The noise in this frequency range originates from microscale friction, fluid turbulence or electro-mechanical sources which can be brought in relationship to the operation and/or condition of machinery and materials. However, current standard ultrasound handheld instruments enable users only the access to relatively simple parameters such as level measurements by means of narrow-band sensors and analogue electronics - for air-coupled and structural-borne ultrasound as well. This limits the informative value of ultrasound technology since the most physical processes generate ultrasound in a broad frequency range which could be evaluated by means of advanced signal processing techniques. A prerequisite for the frequency extension are broadband sensors and appropriate digital acquisition technique. The commonly used heterodyne technology neglects almost completely the frequency content. The concept will be demonstrated for some important industrial applications of ultrasound.

Keywords: Ultrasound, signal processing, maintenance, aurelization

1. Introduction

If we are speaking about ultrasound in the context of the paper, frequencies are meant, which are produced by operating machinery, friction processes, aero-acoustics and other. These frequencies are close to the audible range. NDT-technologies (non-destructive testing) are not involved in the considerations and discussions. This methods operate (mostly) at much higher frequencies.

Ultrasound monitoring using traditional standard technology only enables to access relatively simple parameters such as level measurements at selected frequencies by means of narrow-band sensors. The informative value of this traditional ultrasound technology is relatively poor since the physical and technical processes generate frequencies in a broad frequency range (including the audible range). The “old” narrow band technology uses analog electronics and a relatively low level of signal processing. This is in a clear contrast to the development of the acoustic technology in the last decades where time-frequency evaluations of data are standard. Simply spoken, an approach has been developed for the simultaneous investigation of the monitoring of processes which cover slow vibrations up to frequencies of about 200 kHz (and even higher) by means of new sensors for acoustic emission and innovative measurement equipment for condition monitoring. The vibrations are produced by operating machinery, friction processes, aero-acoustics and other. NDT-technologies (non-destructive testing) are not involved in the considerations and discussions. These methods operate (mostly) at much higher frequencies.

That means – at least to a certain degree – the extension of acoustical and vibrational technologies to ultrasound frequencies (up to about 100 kHz bandwidth). However, there are many peculi-
arities which arise from the nature of vibrations at higher frequencies. Modification are needed for measurement procedures and signal processing algorithms.

Nevertheless, acoustics/vibrations and the industrial ultrasound can be considered as closely related to each other. Why ultrasound technologies should be used when vibrational technologies provides similar information? There are some important differences which make ultrasound testing equipment ideal for predictive maintenance purposes.

![Figure 1: Frequency ranges in acoustics. The ultrasound range discussed in the paper is mainly used in maintenance (with frequencies from about 20 up to 100 kHz). The red indication at 40 kHz stands for the analogue narrow band technology which enables only a very limited insight into technical and physical processes.](image)

One of the most important advantages of ultrasound is concerned with early indications of wear and inappropriate operational conditions. Examples are the sensitivity with respect to bearing distress, material wear and non-optimum operational states which provides useful trend information on machinery states. In contrast to “low” frequency acoustics, an important advantage of ultrasound is its easy use in noisy and harsh environment. Vibration and ultrasound should be used complementary in predictive maintenance strategies. The introduction of digitally broadband testing equipment [1] requires proper sensors. Therefore, transducers and digital sensors (for structure-borne and airborne noise as well) have been developed on the basis of piezo-electric composite material. The physical and construction principles enable acoustic measurements in a broad frequency range [2]. These “ultrasound” sensors can be used for the simultaneous investigation of vibrational effects at low frequencies and for high frequencies (e.g. friction, cavitation and so on) as well. Applications have been modified and qualitatively improved for the diagnostics of bearing damage, for cavitation in pumps and for the monitoring of structures. The new sensor principles are part of a new modular and scalable measurement concept (which includes also airborne ultrasound) with advanced data treatment, algorithms in real-time and improved calculation and prognoses.

**Fundamentals of Ultrasound in Condition Monitoring**

The most important applications of the ultrasound methods in the sense of the article can be found in maintenance. Methods of acoustic emission and ultrasound vibration have been increasing applied for condition and health monitoring of machines and structures in recent years. The application of ultrasonic sensors and methods for condition monitoring has been discussed in several papers [3, 4, 4]. The term acoustic emission (AE) is often used as special acoustic technology to measure and evaluate transient signals [6]. We use AE rather synonymously in this paper in a more comprehensive sense for all acoustical processes at higher frequencies (continuous, transient, stochastic). The application spectrum (fig.2) covers many applications 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 applications such as life time and trend analyses, heath
monitoring, fracture warning and the application of advanced methods for the diagnosis of rotating and reciprocating machinery which require state-of-the-art computing and signal processing (embedded and post-processing). The value of ultrasound emission for maintenance and machinery inspection has been demonstrated by means of several applications including demanding tasks (e.g. run-ups and run-downs of power generation turbines [3] or machinery fault detection [7]). The introduction of state-of-the-art and advanced time-frequency signal-processing enhances drastically the value of the ultrasound approach. Generally, acoustic emission could be proved as a valuable tool for monitoring of different kind of bearings and other rotating parts in machinery [8,9]. AE is also used for control of lubrication due to the sensitivity to friction. The value of broadband ultrasound technology principles for investigations of frictional processes of timing chains has been demonstrated [10]. Friction can occur on nm- to µm-level which can influence collective vibrational effects in much larger dimensions [10]. The sensitivity to smaller dimensions is one of the physical reasons that ultrasound is suited for earlier predictive purposes (fig.1).

However, ultrasound methods are often used in maintenance more or less qualitatively by the application of simple techniques and methods (e.g. using r.m.s- or level values). Consequently, the potential of ultrasound remains often unused. Advanced applications of acoustic emission can be found for monitoring of very low speed of bearing [11] which has been demonstrated by means of a complementary research and comparison of the machinery fault detection with traditional vibration methods [12]. Journal bearings are also in the focus for the application of acoustic emission techniques and exhibit a great diagnostic potential. Classical vibration methods often fail [8,11]. The use for condition monitoring of larger Diesel engines has been described in detail [13]. It has been demonstrated that even angular positions of events can be accessed. Currently, there is a tremendous and successful development on the field of pattern recognition and its applications to almost all fields for physics and techniques. Recently, reports appeared in the scientific literature but there are few industrial applications despite its potential. However, caused by cheaper and much more performant computing power new applications of classification and pattern recognition methods for the industrial use are expected [14, 15, 16, 17]. Caused by the higher frequencies, the ultrasound-methods are predestinated for a complementary use of transient and stationary methods.

![Figure 2: The performance of industrial equipment reduces with operating time. Failures of machines tend to emit detectable levels of acoustic signals or vibration long before severe defects occur. Standard acoustic and vibration methods are indispensable for predictive maintenance. Ultrasound enables much earlier predictive prognoses caused by its physical natures. Ultrasound technologies and “low” frequency acoustics can be often used in a complementary sense.](image)

Consequently, a trend can be observed, that methodical and numerical approaches which have been successfully developed for the “low frequency” diagnoses will be extended for much higher frequencies when corresponding digital equipment (with high sampling rates) is available. This is, as mentioned above, supported and enabled by the much faster data processing, bigger data storage
capacities and cheaper computing technique. Furthermore, there are also developments of new sensor materials, which can be applied in a very broad frequency range.

Figure 3: Overview – possible applications of ultrasound in maintenance. The differentiation is with respect to airborne sources and structure born source. Some important (commercially and industrially) applications are listed.

It is expected that many new applications of ultrasound technologies maintenance will be developed. A view on the broad range of the different physical nature ultrasound source suggests many improvements and new ideas when digital devices with computing power becomes available [18]

Physical sources of Ultrasound:

- Aero-acoustic phenomena
- Cavitation
- Friction
- Vibration with natural frequencies (of small structures)
- Operational impacts
- Electrical discharges
- Electro-acoustics (for active excitation)
- Other sources (biological – bats, insects)

Ultrasound signals originate from different processes and exhibit various signal forms

- (Steady-state) Stochastic signals (flow, friction, continuous excitation)
- Transient signals (impacts, electrical discharges, crack processes)
- Modulated signals (bearings, gears)
- Mixed signal forms (in general)

It is obvious that modified and adapted signal processing algorithms are needed in order to extract the (sometimes hidden) information. This includes recent numerical and methodological developments of classification, pattern recognition and machine learning methods [19].
2. **Broad-band Sensors**

Broadband sensors on the base of piezo-electric composite material provide the unique advantage that the complete frequency range can be used for data evaluation. The technology for this type of ultrasound sensors is described elsewhere [20]. The transducer form also the core of the new digital ultrasound sensors (fig. 4)

![Image of broadband sensors](image)

Figure 4: Upper row: Processing technology of piezo-electric composites, process steps of the piezo-ceramic plate - first cut, second cut, filling in the matrix, grinding to final thickness, metallization and polarization. Lower row: Examples for broad-band sensors which operates at ultrasound frequencies (the two right figures stands for digital sensors for higher frequencies – structure-borne noise, high-frequency microphone)

3. **Examples and Case Study**

Some typical experiments demonstrate the bandwidth of the ultrasound measurements and give some impressions for typical applications in maintenance (according fig. 2)

As examples for airborne noise, two applications are mentioned. The electrical discharge is an interesting example (fig. 6). Electrical discharge produces highly transient signals providing very broad (unspecific) spectra. The type of the discharge process can be estimated from the time characteristic of repeating elementary discharges events.

![Image of electrical discharge](image)

Figure 5: Typical electrical discharge,

Probably the most important application (from the economical point of view) is the detection of leaks in pressurized air systems. Pressurized air leakages are huge source of energetic losses. Here, a new technology has been introduced. It bases on a combination of ultrasound broadband microphones, digital acquisition technique and new algorithms [19,20].
Figure 6: Functional chain of the physical influence on the acoustics of leaks and schematic representation of the flow chart of the data treatment. The calculation includes the complete broadband time signal [19].

A typical example for structure-borne noise of rotating machinery is the testing of bearings (fig. 7).

Figure 7: Time signals and spectra of roller bearings – comparison between an intact (left) and a faulty (right) roller bearing (same colours in the spectrum).

An interesting feature of the spectrum shown in figures 7 and 8 is that the sensors can also be used to measure lower frequencies in a complementary sense (simultaneously - audible and ultrasound vibration). From the time signal, certain properties of the rotation system can be extracted (envelope calculations, side bands).

An industrial case study has been done for pumps [20]. Figure 8 demonstrates, that the dominant part of the vibrational energy can occur in the ultrasound part of the spectrum. The pump has been equipped with four broadband sensors at the indicated position.
Figure 8, Spectra measured at a position on the housing of the plain bearing on the suction side (sensor D) at varying rotational speeds n [21]

4. Aurelization of Ultrasound

An interesting and important feature of the use of ultrasound testing in maintenance is the aurelization of the high frequency signal. Testing persons can listen to fluctuations (via headphones) in ultrasound signals by means of several techniques in real-time. Heterodyning is used in analogous narrow band devices. The complete frequency information is preserved by shifting into the audible [17] range. By introducing a vocoder based transformation algorithm. The frequency range is then compressed (e.g. by a factor of 32, see figure 9 middle).

![Figure 9: Left: The effect of heterodyning on the selection of frequencies from a broad-band spectrum. The narrow band around 40 kHz generates an unspecific 4 kHz audible band. Middle: Preservation of the spectral shape by the vocoder technique with a reduction of the spectral width by a factor of 32 and the shift towards the audible frequencies. Right: (higher) Data reduction using shifted 1/n-Octaves [17].](image)

The vocoder-algorithm represents the original data with such a small reduction of the information content that the reduced data can used for practical purposes in maintenance – e.g. for long time recording.

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