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AN INFORMATIV FORMAT FOR VISUAL PRESENTATION OF RESULTS IN GEAR DIAGNOSTICS

Prof. Dr.-Ing. habil. Gottfried Meltzer
Dr.-Ing. Phong Dien Nguyen

Technische Universität Dresden (Germany)
Institute of Power Engines and Machine Laboratory

Abstract - A visual observation of displayed measuring signals is an usual tool for an exact diagnosis of anomalities, which are detected by condition monitoring before. Interesting characteristics, which should be clearly recognized by diagnostics, are the kind of anomality causing fault, its extent and its situation. In the case of tooth gear diagnostics such kinds of faults as flank fatigue, flank wear, brooken tooth edges and cracked tooth roots are most frequent. Besides of them the number of affected stage, the damaged wheel and the number of faulted tooth are objects of fault localisation. On the others side the visualization of measured vibration signal is more difficult when the rotational speed of gear is insteady.
For making this activity more easy, some powerful algorithms are combined as follows:

- synchronuous averaging of measured signal
- calculation of residual signals (instead of overall signals)
- time- frequency- distribution (continuous MORLET wavelet is preferred)
- tuning of time resolution versus frequency resolution by choose of appropriate MORLET parameter
- presentation in a polar coordinate system with rotational angle and order of rotational frequency as booth coordinates.

There is shown by examples, that all targets of gear diagnostics can be reached by visual presentation, using the recommended tools. As an additional advantages the high sensitivity of the mentioned algorithms is evident, which supports an early detection of faults.
A simple software, based on MATLAB®, will be finally explained .

Keywords: gear diagnostics; signal processing; insteady processes

1. INTRODUCTION

Condition monoitoring of machines and technical equipments is usually divided into two activities:

- monitoring - it means the early detection of anomalies in condition or performances by faults or failures
- diagnostics - it means the identification of kind of faults, their situation (by localisation) and their extent (by quantification).

For vibration monitoring of tooth gears a careful choose of diagnostic descriptors in advance is necessary for a reliable recognition of anomalies. Faults as wear at the tooth flanks or as cracks at the tooth roots do not influence global vibration features of vibration (root mean square e.g.) but more sophisticated ones (intensity of sideband components near the tooth meshing frequency e.g.). The combination of well chosen descriptors as an input of multivariate diagnostic inference systems (as classifiers or artifical neural networks or rule based systems) is a favourable approach for a good result of monitoring.
Diagnostics as the succeeding step requires the extraction of much more appropriate descriptors out of the measured vibrational signals. The visual assessment of measured signals and their characteristics can often help to detect, identify, localise and quantify faults and other anomalies more easy.
A short survey about new results in this field is given in [1], [2], a deeper insight is summarized as result of one part of a recently finished research project in [3]. Here can you also find an extended list of references.
Two former publications concerning the same topic highlight the new proposed approach for gear diagnostics more in detail and from the point of scientific content [4], [5]. In the following chapters the application in practise shall be more underlined.

2. DATA PROCESSING AND PRESENTATION

There exist a lot of proposed methods for data processing which are suitable for gear diagnostics. Some of them are well proven and already in full application. Other ones are published and used for special tasks, but not yet in common use. The third group are approaches, which are real new and either not published or not in large scale projects tested.
After a critical analysis of described in literatur methods we checked the reflection of increasing faults in visually accessible data presentations. By combination of some of the selected methods for data processing in different steps the visual recognizability of faults in symptom maps was more and more improved.
In order to accelerate the work a software package SAMEX© (see chapter 4) was created for an quick and easy processing of the raw timeseries of measured vbration. These tool can be used lateron in all tasks of diagnostics because it contains all in diagnostics usually applied signal processing methods.

2.1 Signal averaging in time domain and rotor synchronous averaging

The measured raw signals are commonly intensivly superposed by electronic and acoustic noise as well as by random or deterministic signals outgoing from other mechanical sources than the actual diagnosed functional group of a machine.
By averaging of as much as possible timeseries of the same measured signal all random components can be reduced. Also deterministic components, which are generated from all gear wheels but one can be cancelled, if in the case of tooth gear diagnostics all averaged time series are started from the same postion of one of the wheels. This approach, called "rotor synchronous averaging" has an important adventage.
Because of small changes of rotational speed during the normal operation of any gear the frequency spectrum of an averaged signal is something smeared over. Therefore the sidebands as symptomes for faults in gear toothing can not be recognized surely. By a signal sampling in intervalls which correspond with equal rotational angles (instead of a time- equidistant sampling) the measured signal can be transferred into an "acceleration versus rotational angle" serie. These kind of series can be averaged without any problems. The FOURIER- transform changes this kind of series into an order-spectrum (instead of frequency spectrum). The distance of spectral lines are orders of rotational frequency if one revolution of the reference wheel is used as basic length of the analyzed serie.
Sampling in equal angle intervalls can be realized by mounting an encoder (which gives 2^N sampling impulses per revolution) at the reference shaft. More cheep is the well known numerical resampling, for which one impuls per revolution of the reference shaft giving information about the actual rotational speed is necessary.

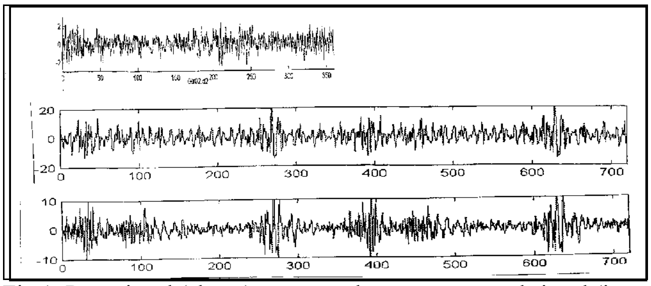

Fig.1: Raw signal (above), rotorsynchronous averaged signal (in the middle) and residual signal (below) of measured vibrational acceleration at gear case versus rotational angle

Comparing the resampled raw signal with the rotorsynchronous averaged acceleration signal in fig.1 there becomes evident an increasing information about the damages at 3 (of 14) teeth already in the time (or: angle) domain.

2.2 Residual signals and spectra

The well known fact that the components with the harmonics of tooth meshing frequency in vibration spectra or signals are induced by the change of bending and contact stiffness of teeth over their arc of action without any correlation to the looked for faults. Therefore the extinction of these dominating high energetic but redundand components out from the measured signal is suggested [6]. By this the high informativ but poor energetic sidebands gain an higher evidence.
This approach can be executed via FOURIER transform of the averages signal followed by deletion of the mentioned spactral lines and inverse FOURIER transform of the obtained residual spectrum back to the time or angle domain. The final reult is the residual serie.
An other residual signal or spectrum can be created by filtering out the eigenfrequencies. Therefore the influence of impuls excited and parametric excited vibration (both can be symptoms of teeth flank damages) can be distinguished (see fig.7).
The third line in fig.1 makes the better visual recognizibilty of faults by use of residual signals evident.

2.3 Time- frequency distribution

It is a well known part of the actual knowledge in signal analysis, that the situation of high signal energy peaks along the time- or rotational angle coordinate marks the situation of faults at that machine part, from which the trigger impuls is generated. The kind of fault influences more the spectral than the time-following composition of the measured vibration.
Therefore a simultanous analysis of chronological course of measured signal in the time domain as well as of its frequency content has to be recommended.
All signal processing methods wich follow up this kind of analysis are called time-frequency-distribution analysis. Although the SAMEX© software (see chapter 4) allows the execution of a large number of different methodes (spectrogramm; WIGNER-VILLE-distribution; CHOI-WILLIAMS-distribution; wavelet and others), continous wavelet transform (CWT) was preferred in our project. The reason of this decision is the possibility of signal adapted choose of time domain or frequency domain resolution (see section 2.5).
One of the numerous books concerning with wavelets is [7]. The basic formula of CWT, which has to be handled by computating, is

$$W_x(\tau, s) = |s|^{-\frac{1}{2}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-\tau}{s}\right) dt \qquad (1)$$

Formula (1) characterizes the CWT as an similarity-check between the measured signal x(t) and the so-called "mother - wavelet" Ψ. There exist a lot of different mother wavelets. The parameter τ shifts the motherwavelet along the time-axis. The parameter s stretchs or jolts the motherwavelet and is inverse proportional to its basic frequency. Therefore a time- frequency- map of x(t) can be calculated by variation of τ nd s.
Fig. 2 shows the real part of a MORLET mother-wavelet for different MORLET parameters ω_0 versus time and its

spectrum. There can be recognized, that a small value ω_0 results in a precise time resolution but a bad frequency resolution; a large value ω_0 has an opposite characteristic. The advantage which can be gained by changing of this quantity will be shown in section 2.5.

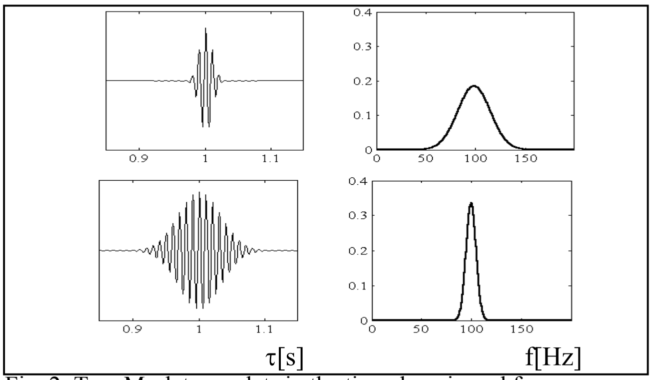

Fig. 2: Two Morlet wavelets in the time domain and frequency domain; left: MORLET6 (ω_0=6); right: MORLET20 (ω_0=20)

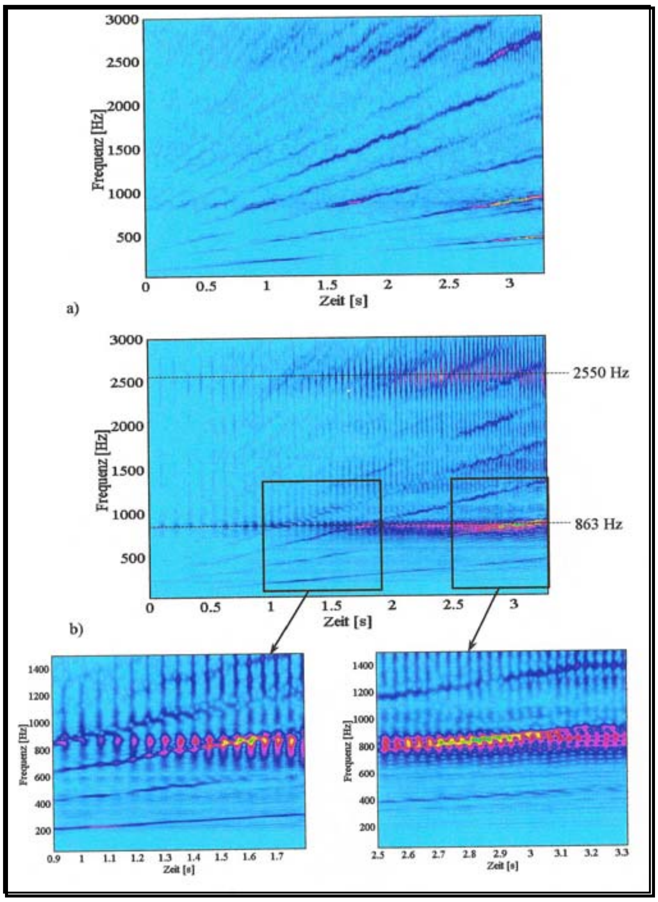

Fig.3: Wavelet amplitude maps calculated from raw vibration signals measured during a gear run-up test

a) 10% seeded flank fatigue fault,

b) 60% seeded flank fatigue fault on a single tooth of the pinion

Booth plots are dominated by the tooth meching components, plot b) shows additionally free vibration excited by one impuls per revolution..The left zoom of the map b) shows this transient vibrations at the eigenfrequency, the right one also sidebands near the 2[nd] meshing harmonics during resonance passing.

Fig. 3 shows the efficiency of this approach of signal processing for analysis of nonstationary vibration. During the start-up of an single stage spur-gear both of the characteristic vibrations appaerances of fault generated vibrations occur: the modulation of parametric vibration excited by faults (reflected by sidebands) and the mutual impact between a damaged teeth pair (reflected by transient free vibration with eigenfreqencies and an intervall according the actual rotational frequency).

2.4 Polar presentation of angle-order-maps

When sampling the measured time function in steps of equal rotational angles (see section 2.1) the time abscissa of discrete measuring values converts into a angle axis. The abscissa of the belonging to spectrum is logically spread by orders of the rotational frequency. The time-frequency-distribution converts in an angle-order-map. The intensity of components is furthermore expressed by the colour.
The next step follows automatically: this is the display of the angle-order-map not in Carthesian but in polar coordinates. Now the plot looks similar the geometric shape of the gear wheel under diagnostics. There is also able to project the situation of real existing teeth into this map (see fig. 4 and [8]).

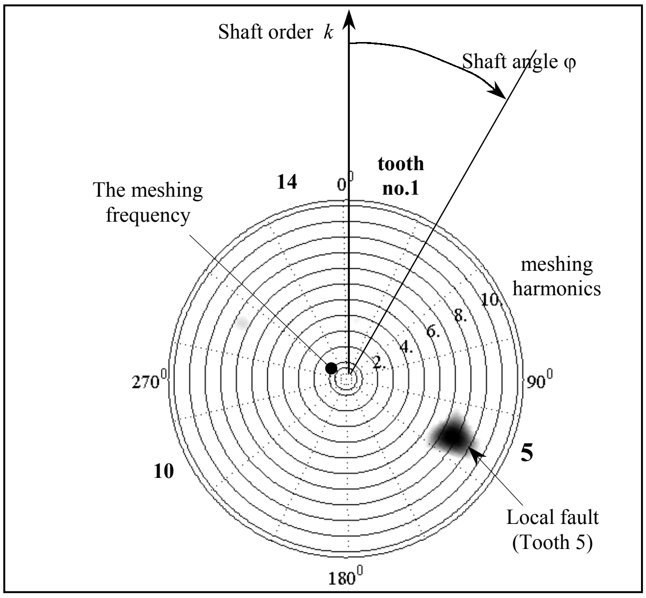

Fig. 4: Polar angle-order-map of residual case acceleration of an one-stage-frontgear with one of 14 teeth is damaged

The polar map in fig.4 is created by continuous wavelet transform with MORLET10 (it means: ω_0=10).Therefore also the nomination "polar wavelet plot" is used). It is an residual angle-order-distribution made from a time function after rotor synchronous averaging and deletion of higher harmonics of meshing frequency (the polar wavelet map of the same vibration before making the residual version can be seen in fig.5). The reference wheel was the pinion with 14 teeth. The position of teeth is marked by numbers. There is evident, that tooth no. 5 have a strong damage, but the kind of damage can not be identified without more deep diagnostics..

2.5 Tunig of time domain or frequency domain resolution

Continuing the ideas of section 2.3 now we show the influence of various MORLET parameters ω_0.
Fig.5 shows the overall angle-order-plot (it means: no deletion of higher harmonics of meshing frequency was done) after processing of the same measured time series as used in fig. 4 by rotor synchronous averaging and continuous wavelet always with MORLET motherwavelet, but different MORLET parameters ω_0.
The left part of fig.5 with an small MORLET parameter has an excellent time (or angle) resolution. The siruation of faulted teeth is well recognizable. In the actual case all the teeth excite more or less parametric vibration, but the vibration excited by the damaged tooth no.5 dominates.
The right part of fig.5 shows the polar wavelet map of the same measured signal, but created by use of MORLET50. Here the kind of damage can be identified by analysis of dominating orders. Free vibration order components are generated by impulses, it means unregulary high short time forces (shocks) between two striking teeth. Sideband components near the meshing frequencies are reflections of parametric vibrations which are irregulary modulated by single or distributed damages.
The additional use of residual approach (see section 2.2) makes this discrimination much more precise.

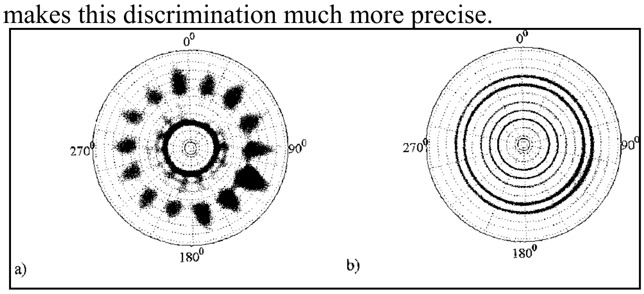

Fig.5: Polar wavelet maps of the same measured acceleration processed by a) MORLET 10 (left) and b)MORLET50 (right)

3. EXAMPLES

Fig. 6 shows as a first example the polar residual angle-order-map of an accelation signal, measured at the gearbox of an bad-conditioned on-stage frontgear. The left plot is made by continous wavelet transform of the signal after rotorsynchron averaging triggered by the pinion (14 teeth), for the right one came the trigger impuls from the other wheel with 39 teeth. The distinguished and sensitive display of anomalies is evident.

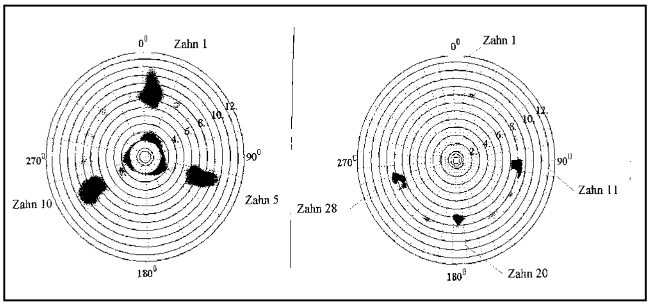

Fig.6: Residual polar wavelet maps with MORLET10 for a damaged pinion (n=14) and the also damaged wheel (n=39)
Fig. 7 shows as an second example the precise investigation of an detected fault by adaptive tuning of angular as well as order resolution. The overall angle-order-map (a) shows a dominating broadband anomaly near but not in the middle of the tooth no.5.
By creation of the residual map (b) a peak of signal energy seems to be situated between teeth no.4 and no.5 on booth sides of the 7th meshing order, but also an other one between the 6th and 7th meshing order shifted half of the tooth distance along the arc to the center of tooth no.5.
One of the mentioned phenomena is by the residual map (c) identified as a free vibration excited by the teeth meshing impact. The other phenomena belongs according to residual map (d) to the modulation of the 7th and 8th meshing order of parametric vibration by the damaged flank on tooth no.5. Both phenomena ar typical symptoms for heavy flank damages.

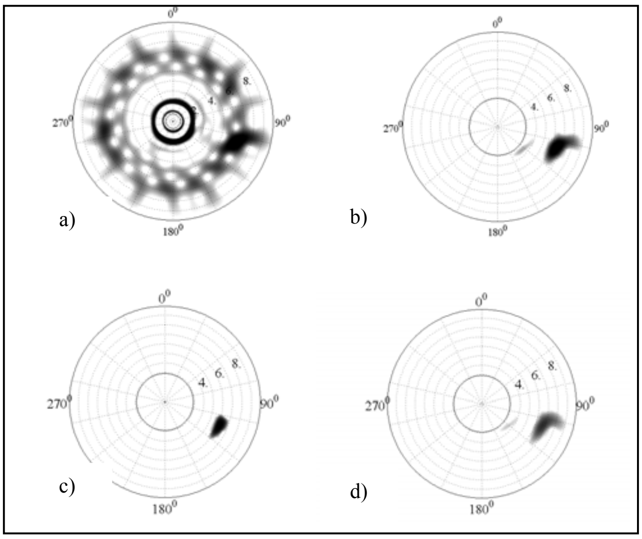

Fig.7: Polar wavelet maps of measured acceleration processed as (a) overall map; (b) residual map without meshing orders; (c) residual map with eigenfrequency orders only; (d) residual map with sidebands only.

A third example is illustrated by fig. 8. This figure shows polar angle-order-distribution maps for measured at the gearcase acceleration, generated by increasing fatigue cracks in the tooth roots at a wheel with 27 teeth. These cracks diminish the bending stiffnesses of involved teeth. Therefore the normal parametric torsional vibration is modulated, which is reflected by sidebands in the wavelet maps near the faulted teeth.
The state 1 is at the start of the fatigue test. State 2 is after 30 min with a crack depth 0.2mm in tooth no.8.; state 3 with a crack depth of appr. 0.6mm 1 hour and 45 minutes later. Beginning from this state also cracks in other teeth arise. State 4 was reached 2 hours and 15 minutes after start. Tooth no. 8 was broken immedtiately following state 4. Additionally the depth of cracks was approximately measured by eddy current inspection. The fatigue crack depth immediately before the forced fracture of tooth no.8 was approximately 1.8mm. In comparision with the tooth root width of 10 mm the resdidual polar wavelet map is proved as an very sensitive and instructive tool for visual inspection.

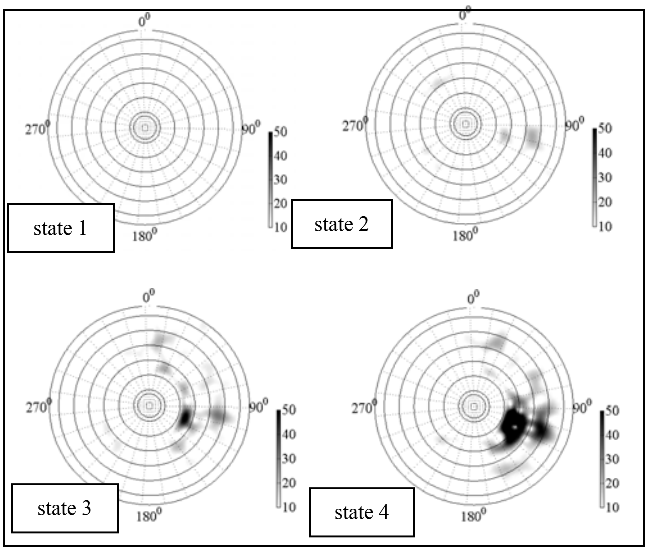

Fig.8: Residual polar wavelet maps for a pinion (n= 27) during the fatigue crack test (MORLET10)

4. SOFTWARE TOOL FOR SIGNAL PROCESSING AND EXTRACTING OF DIAGNOSTIC FEATURES

The software tool SAMEX© [9] (it means: **S**ignal **A**nalyse und **M**erkmals **Ex**traktion) on the base of MATLAB® [10] was applied during the project concerning with gear diagnostcs improvement. Besides of the explained in chapter 2 approaches all traditional signal processing routines in time-domain, frequency-domain and time-frequency-domain can be executed, outgoing from measured digital datasets in *.bin; *wav and ASCII format.

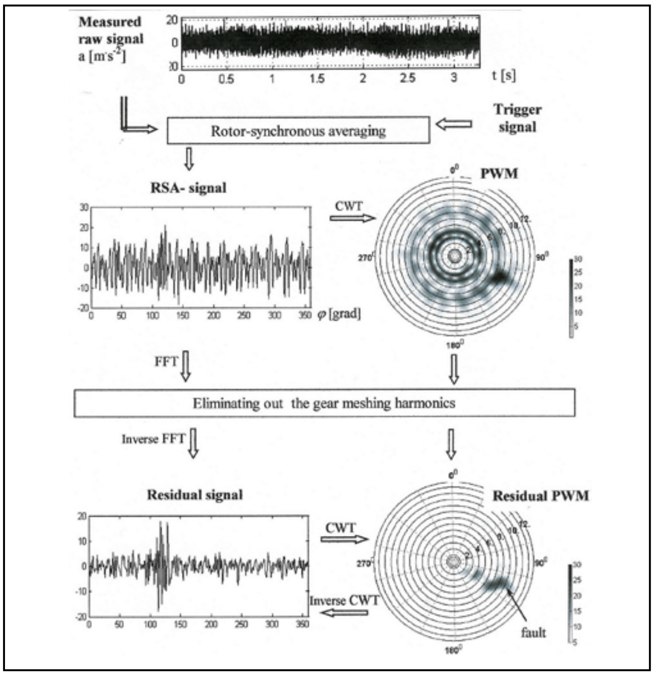

Fig. 9: Signal processing procedure for getting the most sensitive and clear visual presentations by means of SAMEX©
RSA= rotorsynchronous averaging
CWT= continuous wavelet transform
PWM= polar wavelet map

Fig. 9 shows the connection of the mentioned before specialized routines. Starting-points are the measured vibration raw signal (acceleration at the gear case e.g.) and the trigger impuls (given once per revolution by the reference shaft).
SAMEX© involves also routines for the calculation of some single-value-descriptors out from the processed signal functions. These descriptors can be used in monitoring and diagnostic for automatic assessment of the actual condition of any machines, like gears in our project.

5. CONCLUSIONS

The combination of different high sophisticated signal processing approaches enables an improvement of sensitivity and recognizibility in visual as well as automatic vibration monitoring and diagnostics of machines.
Some of powerful methods are explained here. Their advantages are demonstrated here by means of examples, which were obtained during an research project concerning the improvement of gear diagnostics.
The created software for signal processing and extraction of diagnostic features SAMEX© is high efficent and can be used in diagnostics in general.

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CONTACT WITH AUTHORS via
Prof. Dr.-Ing. Gottfried Meltzer; Technische Universität Dresden, Institut für Energiemaschinen und Maschinenlabor,
D 01062 Dresden.
Phon +49 351 46335372; Fax +49 351 46337298
E-Mail: meltzer@mal.mw.tu-dresden.de
Gottfried.Meltzer@t-online.de