Vibration Monitoring for Process Control and Optimization in Production Lines

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Abstract. The economic success of process and fabrication industries depends on the availability, reliability and the efficiency of related key components. Not only maintenance can account for an extremely large proportion of the operating costs of machinery. Additionally, machine breakdowns and consequent down times can severely affect the productivity of factories or the safety of products. Dependent on increased quality standards and the wish of costumers to get a continuous quality documentation of the production process new monitoring techniques are implemented and adapted to the production requirements combining process control, monitoring, management and knowledge based information technology. Signatures have to be found, which at the same time describe the actual machine condition (fault detection), perform process optimization (increased output rate) and describe the product quality at all production steps (total quality control).

The basic investigations and practical examples presented here are based on vibration and acoustic emission analysis during the forging, the cutting process of aluminum coils, the quality control of repaired oil pumps, and the failure source localization of exceeded vibration amplitudes at a hot galvanization line.

1. Introduction

In today’s competitive industrial environments of capital goods industries and in times of permanent increasing output rates the quality of a product is no longer the major factor which influences the purchase by customers, it is simply a prerequisite for duration in the market. To compete and survive, the necessity is to provide the product at an affordable price, a goal that can only be attained through actions as increasing the efficiency of manufacturing operations, process and quality control. A further main aspect is security and endangerment of staff and environment.

The machine utilization rate can be improved by an advanced condition and process-monitoring system using modern sensor and signal processing techniques in combination with knowledge based information technology to allow an automatical adaption of certain data evaluation routines to different processes. Base is the evaluation of the actual machine condition by useful measurement values.

Vibration analysis is more and more discovered as an appropriate tool to determine actual wear of machines and their single components. Automatical measurements with subsequent analysis in time and frequency domain like spectrum or envelope analysis allow to determine excitation sources and ongoing damages. Usually it is not possible to draw reliable conclusions about the condition of single components or the entire assembly based on one single measurement. Therefore, several measurements under comparable working conditions must be taken to enable unerring estimations about the development of defects or the condition of the process to be monitored. The obtained complex information from the measurement signals has to be reduced to the trend of few characteristical values to forecast...
the development of damages in the near future respectively to allow feedback to the process control.

Actual investigations in research and industry try to adapt the experience obtained by using vibration analysis for machine fault detection to the requirements of production and quality control, including the determination of unfortunate operation conditions up to a classification of the produced product. This paper presents some examples applying advanced vibration analysis for process and production control systems, combining the possibilities of fault detection at single components and quality control in fabrication. The global structure of the used monitoring system consisting of the data collection, the acquisition and the analysis techniques are described at practical examples of transient process monitoring and product quality control in cases of precision-forming, cutting of aluminium foils, repaired oil pumps as well as for failure source localization at a hot galvanization unit.

2. Excitation Sources, Data Acquisition and Data Processing

The knowledge of the machines vibrational signatures and their time dependent behavior are the basics of efficient condition monitoring. Vibrations of machines are the results of the dynamic forces, due to moving parts and structures (e.g. foundation) which are interlinked to the machine and its mechanical properties. Different machine parts will vibrate with various frequencies and amplitudes. All these components generate specific vibration signatures, which are transmitted and reflected in the machine’s structure. Machine condition, machine faults and on-going damage can be identified in operating machines by fault symptoms, e.g. mechanical vibration, air borne noise, and changes in the process parameters like temperatures and efficiency.

To the fulfillment of the demands on comprehensive vibration analysis an aimed instrumentation of the unit to be supervised is required, whereby displacement, velocity and acceleration pick-ups are used. State of technology in vibration monitoring of rotating machines is related to the calculation of standard deviation and/or maximum values, their comparison with thresholds and their trend behavior to determine increased wear or changes in the operation conditions. Time domain averaging is applied to separate speed related information from superimposed resonances and stochastical excitations like mechanical or flow friction. Spectrum analysis with special phase constant averaging routines allows to determine machine specific signatures by magnitude and phase relation. Correlation analysis emphasizes on common information of different vibration signals giving hints to excitation sources and signal transmission ways, supported by parallel evaluation of process data like pressure, flow-rates, temperatures, loads, etc. Cepstrum and hocerence analysis are used to quantify periodical information of spectral data [1].

The global structure of the generally used monitoring system can be divided in three main parts, the data collection with data reports in digital manner, followed by the acquisition phase calculating the statistical values and functions in time and frequency domain with integrated data reduction by fault and operational pattern. The more difficult third phase of fault diagnosis is still under development and permanently adapted to the necessities of industrial applications, mainly dependent on the acting personnel at the monitoring system. New analysis techniques like wavelet analysis as well as fuzzy logics and neural networks for pattern recognition are examined. The basics of analysis technique using vibration and process parameters are demonstrated at the example of fault detection and condition monitoring at hydraulic axial piston and gear pumps [2].
3. Fault Description and Condition Monitoring of Hydraulic Oil Pumps

Hydraulic systems are used in all areas of production and power generation. With relative small units high forces can be generated, e.g. using hydraulic cylinders in shovels or hydraulic motors in heavy mine cars. The energy is transferred by hydraulic liquids with pressures of $10 \times 10^5$ Pa in tooling machine for lubrication, $250 \times 10^5$ Pa for hydraulic motors of trucks, up to $400 \times 10^5$ Pa for the hydraulic cylinders in shovels, and up to $2500 \times 10^5$ Pa in special application for plastic production. Dependent on wear, the hydraulic pumps have to be maintained in certain time intervals. Small units are substituted, big ones are reconditioned to reduce the costs.

In this case the aim was to implement a production control program, testing reconditioned and new hydraulic pumps for quality control. A test bench was built up to simulate different load conditions (pressure and flow rates) for several axial piston and gear pumps. The condition measurements are based on pressure fluctuations, flow rates and acceleration.

Figure 1 shows the averaged dynamical pressure fluctuations of three axial piston pumps with different hours of operation and different load conditions at a constant flow rate. During normal operation the signal shape is characterized by harmonical pulses, which increase at higher pressures (normal operation, pump I). Each piston “creates” one pressure pulse, dependent on its geometric properties and the mechanical interaction with the input/output control plate. In general can be distinguished between local failures (e.g. wear at certain pistons, pump III), and distributed ones. In the case of pump II wear could be proved at the swash block and the saddle with polymerous bearing. All here described faults did not endanger the pump operation and were related to oil contamination. As also becomes visible at the pulse modulation in case of pump III, different load conditions have to be examined for secured fault determination.

The influence of on-going defects is shown in figure 2 at the characteristics of a local defect (increase of radial clearance at one piston) and a distributed one (3 pistons, respectively all pistons with increased clearance). Apparent in the pressure signals are the fault related amplitude and frequency modulations dependent on the mechanical condition of the rotating and oscillating components. In the case of all pistons with increased radial clearance the signal shape does not give information about faulty operation conditions. In
this case the parallel processed parameters of flow rate and casing temperature hint to un-
fortunate operation.

Figure 2. Pressure and Acceleration Signatures for Faulty Operation

Figure 3. Spectra and Cepstra of Pressure Fluctuation and Acceleration for Faulty Operation

Contrary to the pressure signals the corresponding acceleration signals at the casing give no
direct visible indication to faulty operation. Main excitation sources are the high frequent
mechanical and flow friction, which superimpose the lower frequent speed related periodi-
cal information. Due to the fact that the determination of the dynamic pressure is a displacement based measurement technique, higher frequent excitations are damped by \(1/f^2\) \((f = \text{excited frequency})\).

That the “fault” information is also contained in the acceleration signal at the pump casing is proved by the power spectra in figure 3, dominated by the PRS (pump rotation sound = number of pistons x speed) with harmonics. If faults occur the PRS is modulated (see pressure signals figure 2) changing the amount and amplitude of the sidebands of speed harmonics in the spectra, similar to the fault criteria of gear wheels or rolling element bearings [3]. The spectra of the dynamical pressure show corresponding fault symptoms. For automatically fault classification the pattern of amplitude changes of the PRS with harmonics and the intensity of the speed related harmonics could be used, summarized by the cepstral gamnitudes, the “spectrum of the spectrum” (figure 3, bottom).

It could be stated that by vibration measurements at the pump casing or even at the base the faults can be determined. Especially in the case of field measurements the use of accelerometers is easier than the installation of additional pressure transducers.

Dependent on a high amount of guarantee claims all new sold gear pumps should be tested to detect fabrication errors or exceeded mechanical tolerances which will lead to early pump faults. The modular test bench for the piston pumps could be easily adapted to the smaller units of gear pumps, using the same instrumentation and evaluation tools. The influence of eccentricity between the shaft center and the pitch diameter of the teeth becomes clearly visible in low frequent speed related pressure fluctuation as demonstrated in figure 4. While a “good” pump shows mainly sinusoidal signal behavior of the twelve meshing teeth.

The correspondent acceleration signals at the casing are also characterized by the mesh-frequency and harmonics superimposed with lower frequent speed related modulations. For classification of the pumps statistical time values are calculated, threshold comparison of curve shapes as well as the amplitude changes of the teethmesh frequency with harmonics and the speed related rahmonics of the cepstral gamnitudes are used as input matrix for vectorial classification.

In order to detect all mentioned failure mechanisms and their effects to the characteristical signatures vectors are calculated as a matrix of single values, e.g. the statistical time values, certain machine specific frequency components (e.g. teeth mesh, pump rota-
tion sound, etc.), and the corresponding cepstrum components. The cross-link with a weighting function can emphasize certain fault pattern. According to the type of defect, the vectors produce the largest correlation for failure and grade of damage. The distance and angle between the vectors present an easy classification and consider the correlation between the measuring vectors and the prototype or reference vector, dependent on pump type and load condition [4]. The correlation with process parameters increases the probability of secured fault detection and description. In a further step the vector itself might fit as an input for neural classification, which, if sufficient samples of reference and failure classes are available, is able to determine faults automatically initiating fast control action [5].

4. Cutting of Aluminium Alloys

One of the major sources for failures and decreased product quality in cutting aluminum alloys is tool wear and breakage. A detailed knowledge of the tool wear process is the basis of cutting optimization. An alarm can be set if the tool reaches the maximum of tolerated wear. On one hand side as result the machining costs are reduced because the complete lifetime of the knives can be used, an effective machining time can be realized combined with secure operation with less operators and manual or visual inspection. Second the failure related costs decrease. Due to early failure detection and the determination of unfortunate operational conditions further damages of machine, tool and less quality work piece are prevented.

Cutting aluminum alloys, the edge quality becomes increasingly important to producers attempting to maximize product yields. Edge critical grades require extreme attention during coil processing to insure not only high surface quality and tight tolerances, but also quality edges. Factors such as the type of scrap edge handling, quality of the knives, mechanical tolerance of arbor, strip speed and knife clearance, number of knifes and last but not least the former treatment of the material to be cut play important roles in determining edge quality.

In the simplest case the aluminum coils of non-uniform width are processed through a pair of side trimmers, consisting of two rotary knives each (one on the top and one on the bottom of the strip), which act to shear away a portion of the strip edge to create the desired strip width. Simultaneously the coil can be split up in several metal strips of different width as base material for further treatment. The mechanism of cutting, as demonstrated in figure 5, is a combination of knife penetration (nick) and strip fracture (break). As the material strip enters the knives (1) they penetrate the strip (2) until the forces exceed the tensile strength of the material and the strip separates (3). The depth of penetration is determined by the tensile strength of the material, and its relationship to the yield strength and thickness of the strip [6]. An ideal edge is one that is consistent throughout the whole coil, with minimal variations of the knife penetration and fracture zone, dependent on the material’s varying physical properties. Influence factors are also the knife settings like the horizontal

![Figure 5. Edge Trimming Process of Aluminium Coil](image-url)
and vertical clearance, the knife sharpness and their face parallelism as well as their surface wear, and speed synchronization. The base knife settings are mechanically adjusted by the operators, in certain cases the machines allow remote control during the process. The ideal knife settings are a function of the coil properties, the material thickness, mainly based on experience and the collection of empirical data by the operators.

As result, errors in the setup and deteriorating knife quality are undetected until a large quantity of material has already been processed. Even edges, which appear to be satisfactory from distance, show unacceptable quality during inspection. Occasionally supervision of the knife settings and the edge quality results in lower yields, higher knife costs, higher material scrap rates and increased risk of strip breakage. Symptoms of poor edge quality include reduced knife life, saw-tooth edges, burrs, edge cracking, wavy edges, and slivers lead to reprocessing costs and downgraded coil quality. In some cases edge problems become noticeable only when the coil is further processed.

Therefore, different monitoring systems were investigated using CCD-cameras, vibration and acoustic analysis to determine permanently the edge condition during the cutting process. In this case the above shown traditional methods of acquisition and processing of vibration data for fault detection have to be adapted to the requirements of permanent process monitoring with control and feed-back option for process optimization. Certain actual investigations are related to accommodate the threshold discrete analysis and diagnosis techniques of vibration signals at rotating machines to the transient high frequent operation conditions in production lines and to combine them with further NDT-techniques, like the optical supervision in this case.

![Figure 6. Optical Edge Inspection System](image)

The optical test system consists of a CCD camera with focus objective and two additional light sources, fixed at a crossbar behind the cutter. The camera maintains a fixed distance from the strip edge, accomplished later by a motion control system, which allows horizon-
tal movement for supervision of multi-cuts. The positioning is based on the strip information, automatically received by the mill computer system. The camera continuously feeds images to the processor unit located nearby the operator’s terminal. Special image processing software is used for display and pattern recognition. Reports are available as good/bad classification or as complex image (figure 6). Characteristical data and occurred alarms are stored together with the coil number, the material and cutter properties for quality assurance and further statistical evaluation.

The relative high costs and the limited sensibility of the system in case of laminated alloys require alternative supervision techniques. Therefore, vibration and acoustical measurements were investigated for suitability, using accelerometers at the bearings of the knife block and microphones measuring the acoustic emission of the cutting process in front and behind the knives. Due to horizontal displacement of several microphones, time delay measurements allow the source localization of excited information, important in cases of multi-strip cutting. Furthermore the accelerometers can be used to monitor the condition of the drive units (bearings, gears, etc.).

![Figure 7. Time Signals and Spectra at different Operation Conditions](image)

Figure 7 shows characteristical time signals and the corresponding power spectra for ideal reference cutting conditions, burr, slivers and the background noise without cutting process.
Significant changes of the time signal’s shape are obtained in cases of slivers. Due to less vertical and horizontal knife clearance, dependent on the mechanical material properties, high frequent acoustic pulses are excited while the reference condition is mainly characterized by homogeneous signal levels. In the case of a burr also high frequent pulses are excited, but of less frequentness. The change of the “cut to fracture ratios” of the material in the case of burr is the cause of the lower overall signal levels. A fast signal classification is obtained using the statistical time values of variance $\sigma^2$, which summarizes the overall signal intensity, and the kurtosis factor $\beta$, which emphasizes exponentially short pulses against the signal overall level [2].

The corresponding power spectra prove mainly high frequent broad banded information related to the cutting process itself, while the frequency range up to 5 kHz includes mainly the signatures of the drive units (gear-meshing, rolling element bearings, structure resonances, ambient noise, etc.). Therefore, by high pass filtering of the time signals the sensitivity of the statistical time values against changes of operational conditions can be increased significantly, as becomes obvious on the right hand side in figure 7. The influence of the ambient noise gets negligible.

The use of several acoustical measurement devices allows by time-delay measurements of certain information (single events, figure 8) an excitation source localization, used in cases of multiple strip cutting to determine which knife is responsible for the burr or slivers. High pass filtering increases significantly the probability of fault detection, too.

The visualized signatures in time and frequency domain have to be summarized to obtain an actual condition classifiers of burr, sliver or normal operation to get an automatical feedback for process regulation. In this case a vector classification was applied, where the single vector elements consist of the general descriptive values of the time signals (variance, kurtosis), the linear and logarithmic signal ground level in certain process specific frequency ranges of the averaged amplitude spectra as well as a special peak analysis known from the evaluation of AE-signals in cases of crack detection and material phase transfor-

**Figure 8. Determination of Vibration Source using Acoustic Propagation**

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Four thresholds were defined, and the amount of limit violation respectively the time delay until decrease is measured within defined time intervals, characterizing the pulse intensity and decay. To facilitate the visualization, for reference operation all values are normalized to “one”. The actual signatures can then be calculated as differences as shown in figure 9 or percentage deviations.

For comparison purposes of different operation conditions the actual vector amplitude, the phase angle and the difference to the reference vector are calculated. As seen in figure 9 several signal classes can be separated dependent on the cut condition. The actual operation vector then is classified with a certain probability. The system only works, if the distances between the condition classes “burr”, “sliver”, ”reference” and “environment” are sufficient dependent on the selected signal classifiers. Influences by the material properties, the process parameters and the used machine require a certain database to guarantee satisfactory signal classification.

As proved by experimental investigations the mechanical properties of the processed strips have a considerable influence on the acoustic emission of the cutting process, as well as the knife arrangements and the mill itself. Therefore, a general applicable supervision system using acoustic and vibrational fault patterns should include an automatical “training phase” to create the process-parameter and material specific ”reference pattern” for optimal operation conditions.

5. Vibration Analysis at a Hot Galvanization Production Line

Modern capital good production lines in industry are characterized by increased automation and the integration of complex process flow sheets. Therefore, often these systems are prototypes. In this case an automatical hot galvanizing production line for endless steel plates from 0.1mm up to 5mm thickness and width up to 1.5m. Dependent on the steel plates the feed velocity has to be changed leading to increased vibration amplitudes at certain structure elements.

Magnetic adapted accelerometers at different measurement positions should determine single excitations by amplitude and frequency component. Aim is to find out the im-
provement potential for the construction of a planned second unit. The acquisition of the vibration signals took place by means of an 8 channel vibration monitoring system in several frequency ranges from 400Hz to 25kHz. This enables the simultaneous determination of high frequent burst excitations, mechanical friction due to the interaction of the several drive units, as well as the low frequent structural resonances. During the actual performed test procedure the machine parameters were fixed to metal sheet velocities of 174m/min, sheet dimensions of 0.53mm thickness and 1244mm width.

A global visual impression of the vibration levels presents figure 16 at the example of measured velocities at different measurement positions on the platform and the rougher just in front of the hot galvanizing unit, achieved by integration of the measured acceleration signals to emphasize lower frequent excitations. At the rougher the vibration signals show clearly different amplitude and frequency modulations dependent of the measurement direction with mainly periodical components. As becomes visible the excitations are mainly periodical ones, proved by the logarithmic amplitude spectra, where the narrow banded peaks mark harmonic speed related excitations of the multistage gear drives and multi stage bearing arrangements which have the task of reorientation and pre-stressing the endless steel plates. The broad banded peaks characterize structure resonances, which are partly superimposed by the speed related excitations, as become visible at all measurement positions on the platform. Main component in all spectra is a rotational excitation at about 20Hz with its higher harmonics. The narrow banded sidebands are related to modulations of this component with the slip and the transmission interaction of the single bearings and gearings.

Dependent on the local damping of the structure, on the platform at certain measurement positions the vibration levels exceed up to ten times the excitation levels on the drive units due to a broad banded structure resonance at about 21Hz. In case of larger steel sheets, the hot galvanization process requires lower feed rates. Therefore, the narrow banded speed related excitation component at 20 Hz is shifted to lower frequency ranges. As result the operational staff determine significant lower vibration levels. The amount and modulation of the different speed and drive related excitations within the spectra can be used as classifiers of initiated or increasing fault symptoms, as well as general signatures for the „quality“ and „reliability“ of the actual machine’s condition in operation. Descriptive values are the amplitudes of cepstra components as visible in figure 10, where the narrow banded peaks prove the above described spectra information as mainly harmonically speed related, on the platform as well as on the rougher.

To determine transmission ways and common information in two different vibration signals for excitation source localization, the coherence function is applied. The high frequent coherence between the acceleration signals on the platform show mainly narrow banded common information up to 1.5kHz (speed related) and broad banded once above 15kHz (friction related due to the here fixed guide roller). The coherence between the acceleration on the rougher and the platform confirms even higher frequent speed related signal components with common excitation source.

The low frequent coherences prove in both shown cases common narrow banded excitations at 20Hz and harmonics. But only on the platform this component is superimposed by a broad banded structure resonance. Therefore, the source must be the platform itself, hinting to required system stiffening to increase the structural resonances. The broad banded common information below 20Hz in all vibration signals is related to the concrete foundation. Due to the system damping, the absolute vibration amplitudes in this area are neglectable.
Figure 10. Vibration Measurement at an Automatic Hot Galvanization Unit
Concluded can be stated that the aimed determination of single excitations and their interactions can not only be used for the description of the actual operation condition (in general mainly related to the topic of fault detection), but also for the optimization of process parameters, to avoid increased wear, loads, combined with the loss of machine’s availability due to unfortunate process parameter adaptation. In this case the problem of exceeded resonance excitation at certain feed rates could be fixed as source of the high vibration levels on the platform. The result can be used as experience for the actual installation of the second hot galvanization line. The shown test vibration measurements have only informative character. For the complete global description of the whole machine the complex information of process control, process and material variation have to be included.

6. Summary

It could be shown that there exists a great potential to improve a machine tool utilization rate by advanced condition monitoring. The results of the analysis show, that vibration, sound and acoustic emission combined with other NDT-techniques like optical measurements are more reliable for quality control and wear monitoring than most of the standard methods, like power consumption, current and force or pressure measurements used in commercially available systems. On-line vibration monitoring systems, which are based on algorithms of statistical and automatical frequency analysis methods, have to be adapted exactly to the system to be monitored. Industrial-grade hardware has to be combined in test benches as well as in industrial production lines with precise and easy visualization tools of the actual operation condition or the product quality.

References