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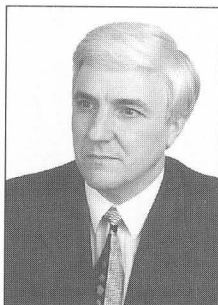
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Computer-Based Diagnostics System for Paper Machine Condition Monitoring Using Fibre-optic Measuring Circuits

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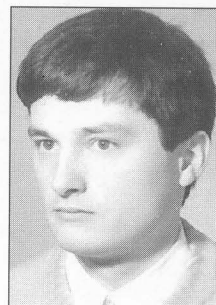
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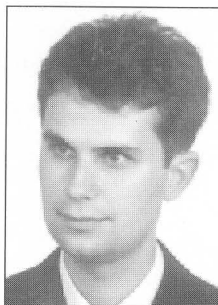
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Jest absolwentem Wydziału Elektrycznego Politechniki Lubelskiej. W 2004 r. na Wydziale Elektrotechniki i Informatyki PL uzyskał stopień doktora nauk technicznych. Od 1999 pracuje w Katedrze Automatyki i Metrologii Politechniki Lubelskiej. Zajmuje się projektowaniem układów regulacji i systemów diagnostyki procesów przemysłowych z użyciem metod sztucznej inteligencji.

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Abstract

Implementation of a vibroacoustic on-line diagnostics system for condition trend monitoring is advisable, because that system should enable to obtain early information about avalanche-like fault development. In order to eliminate strong magnetic fields impact on measurement signals, a fibre-optic measuring circuit was designed and realized. The tests of designed fibre-optic circuit proved that it can be successfully used for transmission of signals from measuring head to central measuring system. The preliminary investigations have shown that the computer-based diagnostics system using vibroacoustic processes allows to evaluate the condition of specific machine parts by means of comparative analysis of two vibratory characteristics: the reference one stored in computer memory, and the newly obtained one.

Streszczenie

W artykule podjęto problematykę implementacji systemu diagnostycznego czasu rzeczywistego maszyny papierniczej, z użyciem metody wibroakustycznej, z ciągłym monitorowaniem trendu zmian stanu technicznego umożliwiających uzyskanie odpowiednio wczesnej informacji, o lawinowo narastającym procesie uszkodzenia. Przedstawiono również zaprojektowany i wykonany dla celów eliminacji wpływu na sygnały pomiarowe silnych pól elektromagnetycznych występujących obok maszyny (źródłem ich są silniki elektryczne dużej mocy), światłowodowy tor pomiarowy. Przeprowadzone testy weryfikacyjne pracy opracowanego toru pomiarowego dowiodły, iż może on być z powodzeniem stosowany do transmisji sygnałów w takich warunkach. W artykule zaprezentowano główne założenia sprzętowe i programowe opracowywanego komputerowego systemu diagnostycznego.

Słowa kluczowe: Diagnostyka wibroakustyczna, maszyna papiernicza, światłowodowe tory pomiarowe

Keywords: Vibroacoustic diagnosis, paper machine, fibre-optics measuring systems

1. Introduction

Papermaking machine breakdowns, which take place in the course of continuous production process, most commonly are caused by machine parts wear-out failure. The breakdowns involve financial losses because of both the material damage and long term maintenance down-time.

Papermaking machine failure frequency can be reduced by means of fixed-interval (or permanent) inspection of machine parts. For this kind of inspection [1] effects of some residual processes, i.e. thermal,

frictional, and vibroacoustic (vibration, noise and working medium pulsation) could be used. In principle, in measuring circuits for machine running condition monitoring, the effects of vibroacoustic processes (VA) are applied. That enables to perform the diagnosis of machine condition without interfere with it or even touch it (in case of noise level measurement or laser vibrometer).

The newest approach to the failure problem is called proactive maintenance: that means a significant change in maintenance philosophy. Proactive maintenance is mainly intended to take a micro view on machine damage, and to search for primary causes of wear. The causes are the microscopic particles which, as well as moisture, gases and heat, contaminate lubrication (hydraulic, transmission etc.) fluids and gear oils. If implemented filtration equipment can monitor fluids cleanliness at regular intervals, the fluids and lubricants will be intensively filtered after reaching certain cleanliness level. Besides of fluid contamination control, with proactive maintenance other root causes of wear must be identified and corrected by making changes in construction, e.g. an alignment of shafts. Despite of high investment cost and the requirement of additional skills, proactive maintenance offers big cost-savings because of extending machine life, reducing overall maintenance costs, and improving machine reliability.

2. Factors affecting the vibration condition of the paper machine

The working motions [2] during papermaking machine operation can be broadly classified into three components:

- rotational motion (e.g. press rolls, dryer cylinders, calendar, winder),
- translational motion (e.g. wire),
- reciprocal motion (e.g. doctors),

which can be combined. Constructional elements vibrations and medium (e.g. stock) pulsations as effects of above-mentioned motions occurs simultaneously, and produce acoustic waves (noise).

Vibrations resulting from these phenomena can be used in paper machine diagnosis research.

For many years, papermaking machine diagnosis based on vibroacoustic processes effects was investigated in Automation and Metrology Department (Lublin University of Technology) in cooperation with Institute of Papermaking and Printing (Lodz University of Technology). The investigations have shown that analysis of vibration characteristics allows for evaluating machine condition [3].

Nevertheless, sometimes vibration, noise and pulsation must not be regarded as symptoms of machine faulty operation, or poor technical condition; these effects may be caused by e.g. insufficient balancing of piston compressor (or other device). Therefore, a certain (low) level of vibrations is acceptable as typical (normal) when machine runs in good condition (failure-free operation).

The main factors affecting the normal papermaking machine operation are: unbalance of its rotational parts, misalignment of shafts and clutches, backlashes, second order critical speed of shafts, and self-excited vibrations of: slide bearings, rolling bearings and gears.

There are numerous - both external and internal - factors which cause functional features degradation and operating characteristics deterioration during paper machine operation.

Vibroacoustic diagnostic method developed in Automation and Metrology Department TU Lublin takes into account three main machine degradation processes which produce direct impact on vibration level:

- all forms of frictional wear, occurring in kinematic pairs, which cause material loss with inevitable backlashes and fretting,
- deformation wear, caused by creep (flow), connected with rheological characteristics of constructional material (produces material loss and finally backlashes),
- fatigue wear, which result in loss of constructional elements cohesion (it is an effect of dynamical overstrains).

After certain interval of smoothly running machine, the wear-out of the papermaking machine elements, dramatically accelerates and the machine is run to breakdown. As in the process of fault arising and expansion a lot of phenomena and interactions are involved, the prediction of the onset of fault condition is not feasible. The failure-free time interval of a new or fully serviced machine is a random variable, the real value of which is very hard to evaluate. Because of this, implementation of a vibroacoustic on-line (or fixed-interval) diagnostics system for condition trend monitoring is advisable. That system should enable to obtain early information about avalanche-like fault development.

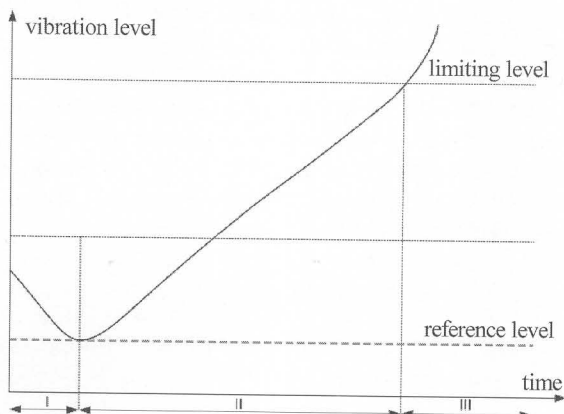


Fig. 1. Change of vibrations level in time of a hypothetical machine.
Rys.1. Zmiana w czasie poziomu drgań maszyny hipotetycznej.

The main factors of paper machine vibration level growth as indicator of condition deterioration, are:

- changes in elements balancing due to mass decrement and plastic deformation,
- increase of clearances in pivotal and rigid joints due to friction loss,
- translational motion due to plastic deformations and micro-cracks.

Practically, every cause of machine vibration level growth is functionally connected with processes of material loss, plastic deformation and micro-cracks depth increase.

Vibration level of hypothetical machine during operation process should change as follows (fig. 1):

- slight drop during running-in phase (I),
- quasi-linear increase during normal operation phase (II),
- rapid increase during accelerated fault development phase (III).

The real vibration level operating characteristics measured on bearing housing of a pump and a driving motor (fig.2) illustrates the conformity between theoretical conclusions and experimental research.

Presented considerations prove that vibration process is a good indicator of actual machine running condition. As a confirmation, the graph of vibration level changes of rolling bearing obtained in operational test is shown in fig. 3.

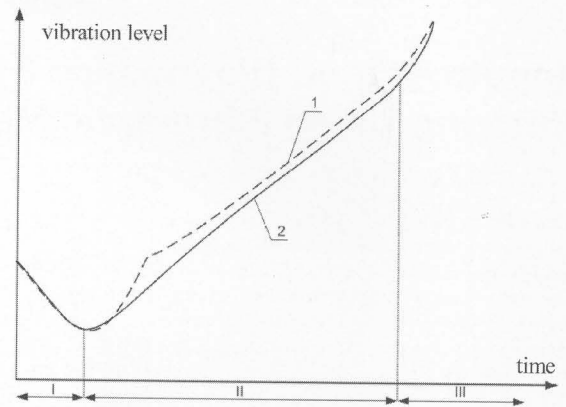


Fig. 2. Real changes of vibrations level of pumping engine bearings in exploitation time, 1- motor's bearing, 2- pump's bearing.

Rys.2. Przebieg rzeczywisty zmian poziomu drgań łożysk agregatu pompowego w czasie eksploatacji, 1 - łożysko silnika, 2 - łożysko pompy.

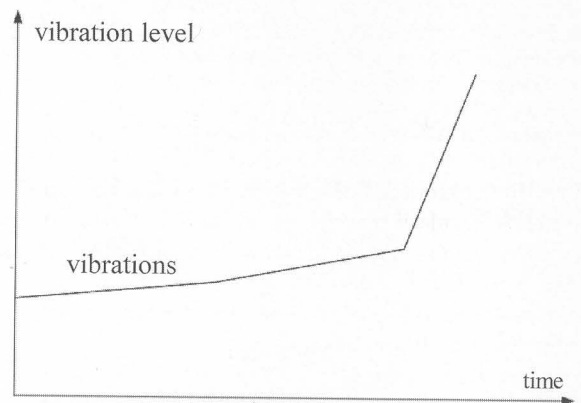


Fig. 3. Change of vibration level of rolling bearing.

Rys.3. Przebieg zmian poziomu drgań łożyska tocznego.

Diagnostic methods applying vibroacoustic processes allow more effective machine condition monitoring, because of the fact that increasing wear of elements and kinematic pairs considerably raise vibration level.

In principle, vibrational signals obtained from machines and devices contain a few dominating harmonic components of very different (low, intermediate and high) frequencies.

During research it has been found that in the case of measuring displacement amplitudes, the contribution of higher vibrational harmonics to the total measurement result is underestimated. On the other hand, in the case of measuring acceleration amplitudes, the contribution of lower harmonics to the measurement result is lower. Therefore, when assessing complex vibrations, it is necessary to measure amplitudes of vibration velocity V . Values of harmonic component velocity are proportional to both displacement amplitude A and frequency f (or: pulsation ω) - $V=A \cdot \omega$.

According to international standard ISO-2372, for paper machines (ranked among 3-rd class) following r.m.s. values of vibratory velocity limits have been specified for judging machine condition:

$V_s = 1,8$ mm/s - good conditions,

$V_s = 4,5$ mm/s - allowable conditions,

$V_s = 11,2$ mm/s - just tolerable conditions,

$V_s > 11,2$ mm/s - not permissible conditions, destruction risk.

Because of the fact that for machines with simple kinematic, constructional and functional structure, extra dynamic loads are put on bearings (which are also the elements most sensitive dynamically), and which constrain force transmission through a machine, sensors should be mounted on bearing housings.

Measurements of vibratory parameters should be made in three orthogonal directions. However, in practice for machines with rotary elements it is sufficient to perform measurements in only two directions, i.e. radial and axial.

3. Computer-based diagnostics system for paper machine on-line technical condition monitoring

Developed in Automation and Metrology Department (TU Lublin) diagnostics system uses effects of vibroacoustic processes. In order to eliminate strong magnetic fields impact (mainly produced by electric motors) on measurement signal, a fibre-optic measuring circuit was designed and realized. The functional diagram of the circuit is shown in fig.4. This circuit [4] consists of: transmitter, fibre-optic cable and receiver.

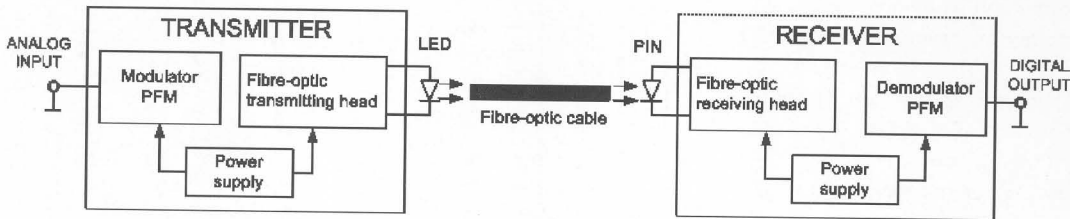


Fig. 4. Functional diagram of fibre-optic measurement circuit.
Rys.4. Schemat funkcjonalny światłowodowego toru pomiarowego.

Fibre-optic receiving head is the main part of the receiver. Receiving head perform light-pulses to electric-pulses conversion. These impulses, which are the measure of vibration parameters, are subsequently demodulated, digitalized and transmitted to computer measuring center.

The transmitter consist of: PFM modulator (with analog input and digital output), fibre-optic transmitting head (with digital input and optic output) and power supply. The receiver is built of PFM demodulator (with digital input and analog output), fibre-optic head (with standard optical input and digital output PFM), and power supply.

The modulator (part of the transmitter) converts analog electrical signals (acquired from sensors proportionally to mechanical vibrations) to digital. The digital signals (electrical pulses) are in turn converted into light-pulses in the transmitting head. The statical characteristic of voltage-frequency transducer (located in the transmitter) $f = f(U)$ is shown in fig. 5.

The measurement results have shown that transducer nonlinearity error is no more than 0.4% for input voltage range 0.2÷11.0 V. Conversion factor $K_{U/f}$ defined as the ratio: "the change of input signal frequency to the change of input signal voltage" is 1000 Hz/V (with accuracy ± 0.4%). The voltage range of input signal is 0÷12.0 V.

The source of optical power is light-emitting diode LED controlled by current source circuit, which is modulated by head

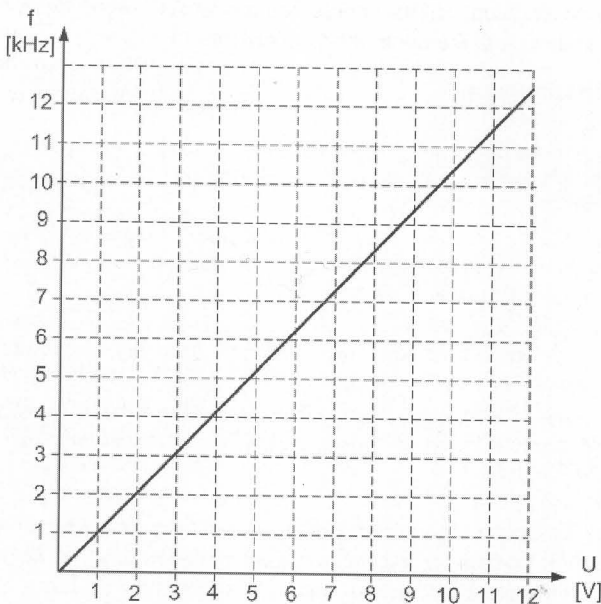


Fig. 5. Statical characteristic of voltage-frequency transducer.
Rys. 5. Charakterystyka statyczna przetwornika napięcie-częstotliwość.

input voltage. LED is connected with fibre-optic cable directly so that maximum of the optical power is fed into cable.

In the measurement system, transmitting head ATS-10-N (made by OTO Lublin) was used. Connection of the transmitting head with the fibre-optic cable is realized by fusing two optical fibers sections together.

The transmitting head ATS-10-N interacts with the fibre-optic line TS-21, which enable the transmission of optical signals through the dielectric fibre. The line TS-21 consists of quartz-polymer fibre-optic cable, and two BNC-50 connectors with LED diode and PIN photodiode. The PIN photodiode is a optical pulses photodetector. It interacts with standard receiving head ATS-10-0 (made by OTO Lublin). The receiving head ATS-10-0 consists of an amplifier and a shaping circuit. The demodulator (part of receiver) converts digital signals (rectangular pulse train) to analog voltage signals. The

values of voltage are proportional to input signals frequency. The statical characteristic $U = f(f)$ of frequency-voltage transducer (accompanied with low-pass filter) is shown in fig. 6. For input signal frequency range: 0.2÷11 kHz, the transducer nonlinearity error is no more than 0.5%, and conversion factor $K_{f/U} = 0.001$ V/Hz (with accuracy ± 0.5%). The tests of designed fibre-optic circuit proved that it can be successfully used for transmission (without significant distortions) of signals from measuring head to central measuring system in presence of strong magnetic fields.

In the developed measurement and diagnostic system, the piezoelectric sensors KD-23 are used. Analog signals corresponding to values of vibration parameters are sent from KD-23 sensors to the transmitter (fig. 4) where the conversion of input electrical pulses to optical pulses is performed. The optical pulses will in turn be transmitted through fibre-optic cable to the receiver. After receiving and digitizing in the receiver, the signals - as measure of vibration parameters - are finally transmitted to the computer measuring centre.

At the computer measuring centre, comparative analysis would be applied to the vibratory characteristics in order to judge machine condition. The newly obtained vibratory characteristic containing present features of particular machine element condition should be compared mathematically with the reference characteristic. That reference standard characteristic (stored in the computer memory) must be recorded after the machine running-in phase was

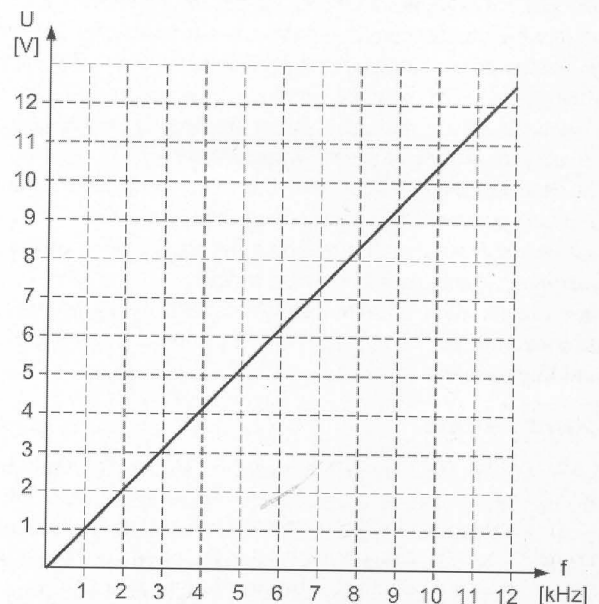


Fig. 6. Static characteristic of frequency-voltage transducer.
Rys.6. Charakterystyka statyczna przetwornika częstotliwość-napięcie.

accomplished, and the machine was running smoothly and correctly. That analysis would allow for selective judging of particular machine parts condition (this is applicable to the parts with mounted sensors).

The computer measuring centre is based on IBM-class personal computer of medium specification level (processor Intel or Pentium 4, Dram 512/400 Mhz, HD 80 GB). As a rule, the standard versions of PC are not dedicated for DAQ on-line systems; the industrial exploitation conditions cannot be neglected, either. But the choice of PC measuring centre of paper machine diagnostic system may be supported by positive factors: wide spread, relatively low cost, well-known and functional both software and hardware.

These above mentioned features make a medium IBM-class PC a match for industrial computer.

The following components are comprised by the applied computer system:

a) hardware:

- measurement and control interface which contains a set of programmable electronic circuits to allow unfailing acquisition of reliable on-line measuring signals from measuring circuits, and directing subsequent control signals;
- operator's interface, consisting of a set of devices for interference and dialog between the operating personnel and the system as well as visualization, reporting and communication with the superior level (including monitor, printer,
- keyboard, mouse, net card etc.);

b) software:

- operating system features approximating to classical real-time system, e.g. Windows 2000, NT ;
- applications for A/D converters, loading and processing of measuring signals (filtration, calibration, transformation, estimation of parameters and state variable, etc.) as well as reports and diagnosed process control signals generation. The external measuring interface is connected to the PC serial port; such arrangement allows significant costs reduction, and makes possible easy extension of the system.

On the block diagram in fig.7, the main steps of the diagnostic process of the paper mill, carried out by the measuring and diagnostic centre, are shown.

The initial step of the diagnostic process is to determine the standard of the normal operation condition, based on vibratory characteristics of the machine's elements. The peculiarities of different machine conditions (newly-serviced, after maintenance etc.) should be obtained. Next, the actual machine condition must be determined by examining the measuring signals (filtration, extraction of symptoms). The extracted symptoms are then compared with the standard features, for estimation of actual machine condition. If failure mode is detected, the failed element is localized. The failure extension is estimated and its consequences are predicted. If an immediate maintenance is necessary, the service team is alarmed.

When no failure was detected, but some noticeable incipient symptoms appeared, the predictive procedure of localization of the potential failure and estimation of its possibility as well as the scheduling of maintenance, are activated.

After the maintenance (replacing of wearing parts or units, modernization of the machine) the machine condition standard should be updated.

4. Conclusions

As the preliminary investigations have shown, the computer-based diagnostics system using vibroacoustic processes allows to evaluate the condition of specific machine parts by means of comparative analysis of two vibratory characteristics: the reference one stored in computer memory, and the newly obtained one. This is of capital importance because both catastrophic failure and heavy losses could be avoided.

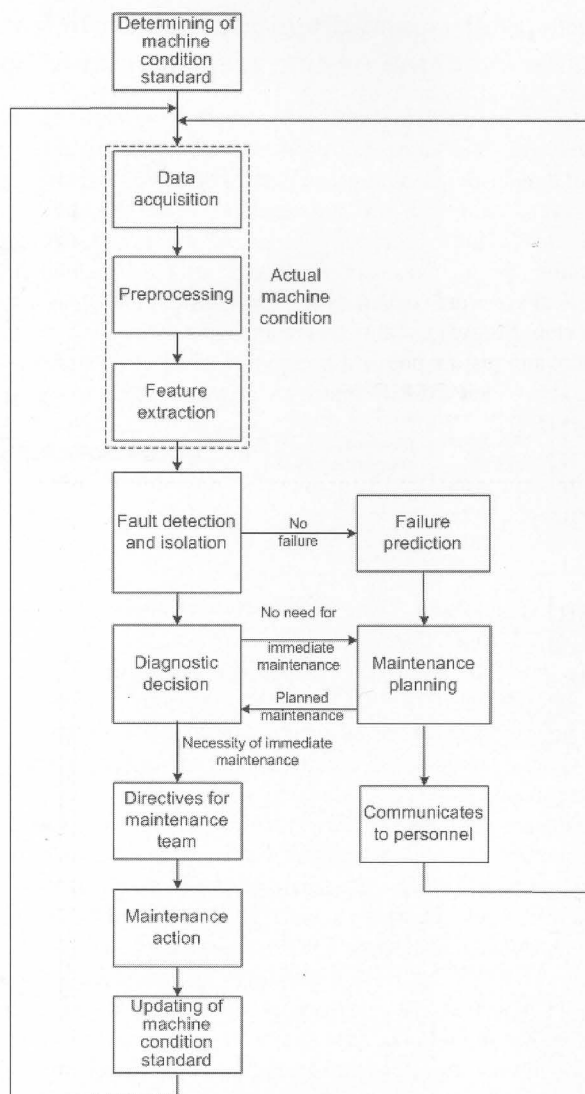


Fig. 7. Simplified block diagram of the algorithm of paper mill diagnostic process.

Rys. 7. Uproszczony schemat algorytmu diagnostyki maszyny papierniczej.

The implementation of the condition monitoring system is particularly purposeful when more than one papermaking machine are operating in the paper mill. Then the computer measuring centre would be employed optimally, because the actual vibratory characteristics would be recorded in fixed intervals, e.g. 4 times a week for 2 hours, and comparative analyses for new machines would be performed. That is important because of cost reduction of the installation and operating of the system.

5. References

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Title: Komputerowy system diagnostyczny przeznaczony do ciągłej kontroli stanu technicznego maszyny papierniczej, ze światłowodowymi torami pomiarowymi.