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Early Failure Detection in Large Scale Civil Engineering Structures

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Abstract

Monitoring of civil engineering structures is an important issue as a result of a rapid development in modern building techniques and growing fatigue wear during utilization of bridges, market halls etc. The complexity and diversity of civil engineering structures impose requirements on the measuring system, which are difficult to be satisfied by a single sensor. As a solution, a complex monitoring system, composed of different types of sensors properly selected according to the diagnostic parameters, are being developed. In the paper the effect of dependence of various factors on the mean system lifetime is considered. In the last part some examples are also presented.

Keywords: structural health monitoring, magnetic methods, construction monitoring, civil engineering, strain measurements.

1 Introduction

Contemporary infrastructural elements, along with entire monitoring systems, are becoming increasingly complex technical systems. At the same time, starting from the middle of the 20th century, use of computers revolutionized the process of analysis which nowadays covers not only durability of structures but also their energy efficiency and environmental impact, including the noise and the vibration they create.

Recently researchers have often addressed a problem of simulation of performance of functional tasks in different environmental conditions and under variable loads [1]. The number of attempts which prove that the degradation processes have the influence on the quality of performance of operational tasks as well as on the durability of an objects is constantly increasing. Use of the right information is the critical requirement in this case. Otherwise both the diagnosis of the machine condition, as well as its remaining operating life will be determined imprecisely and unreliably, which may hence lead to incorrect operational decisions. Due to this, the possibility of detection of information about the incoming failure at early stages of defect development evokes increasing interest, especially in the possibilities of using the information in technical risk analysis [1].

2 A proactive strategy of maintenance

In accordance with the proposal contained in [2], the relationship defining technical risk can be supplemented by adding a factor accounting for the degree of resistance and tolerance of the system to a developing defect:

$$R = (\sum_{i=1}^{n} P_i \cdot F_i) / T_o(sys) \tag{1}$$

where:

R – the risk accompanying occurrence of a defect in the system,
P_i – probability of a defect of an element or a sub-assembly on the assumption that the system consists of "n" independent components or sub-assemblies,
F_i – magnitude of the consequences of occurrence of a defect of component "i",
T_o(sys) – a parameter which describes the system's tolerance to occurrence of a defect

It should be stressed that so simplified a formula is the effect of adopting an assumption of independence of the components and defects in the system. In reality defect of one of the system's components leads to defects in other components. Intentional or unintentional, interworking and interaction may result from the fulfilment of the system's individual functions, or it could be the outcome of operation of the mechanism by means of which defects generate themselves in a complex system.

Dependence of the above risk-defining factors on not only the duration of use but above all on the technical condition and the process of defect development has significant impact on the correctness of the obtained results related to the influence of uncertainty. Hence one of the tasks of early defect detection is to reduce the uncertainty, both epistemological as well as aleatoric.

Another method is the approach involving the possibility of including the redundancy and the efficiency as a system's attributes. This could support the system or be a burden in the process of realization of its functional tasks. Analysis of the Heimann [3] high reliability systems points to the necessity of observance of several principles, starting from the necessity of introducing the "reliability culture" and relevant system organization with high priority for technical safety, to the analysis of the influence exerted by the reliability structure function.

What should be stressed in particular is the connection between the reliability structure and the possibility of reducing the type I and II faults.

In reality, occurrence of various forms of faults and the possibility of occurrence of a multi-stage process of defect development result in a situation where two-state models of fit – not fit type are only partially correct. Hence selection of the right operating strategy is becoming the issue of principal importance.

The relation between the selection properties for the operating strategy and the significant gain in efficiency and profitability has been documented sufficiently enough in economic practice as well as in scientific-and-technical publications [4, 5]. It is stated that 0.5 million USD of savings can be obtained in some economic operations by investing around 20 thousand USD into technical diagnosis systems [6].

Other factors which at the same time lead to improvements in management are the growing client requirements, changes in technology and changes in logistic systems including the possibility of realization of JIT (Just in Time) and MRP (Material Resource Planning) strategies. Other reasons, potentially affecting the choice of the operating strategy, are the environmental protection and safety requirements.

For that very reason, unscheduled, frequent downtimes can be the main obstacle en route to fulfilment of the growing requirements, especially as regards such a level of functional readiness which enables meeting the production quality criteria.

Evolution of operating systems has been extensively presented in publications, while accounting for various vintage points [7, 8].

Division of operations schemes into reactive and proactive (Fig. 1) presents some reference to this discussion.

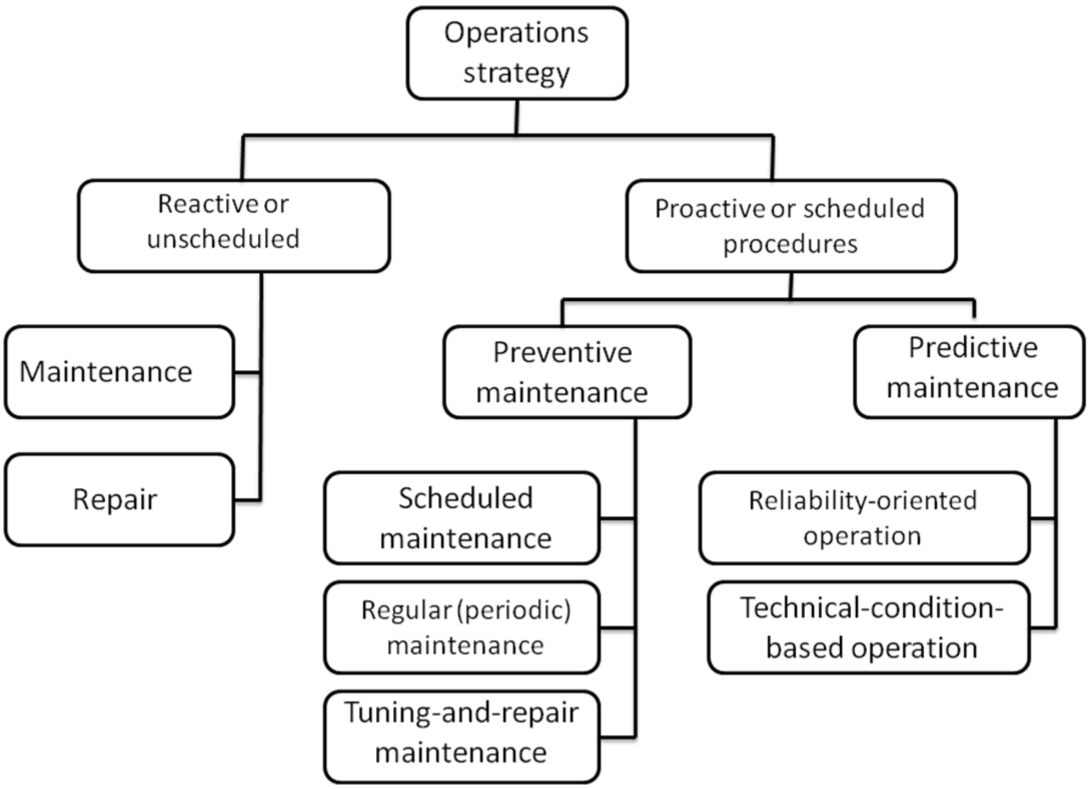

Figure 1: Taxonomy of operations schemes.

The proactive operations strategy uses various techniques of enabling extension of the operating life of machines and mean time between defects (Root Cause

Failure Analysis) which are aimed at determining the mechanisms and the reasons of occurrence of faults. As a result, the process of defect development can be analyzed and taken into account in new structural solutions while operation of existing machines can be adjusted accordingly. In respect of operations, the main task involves diagnosis of the defect initiation period (Fig. 2).

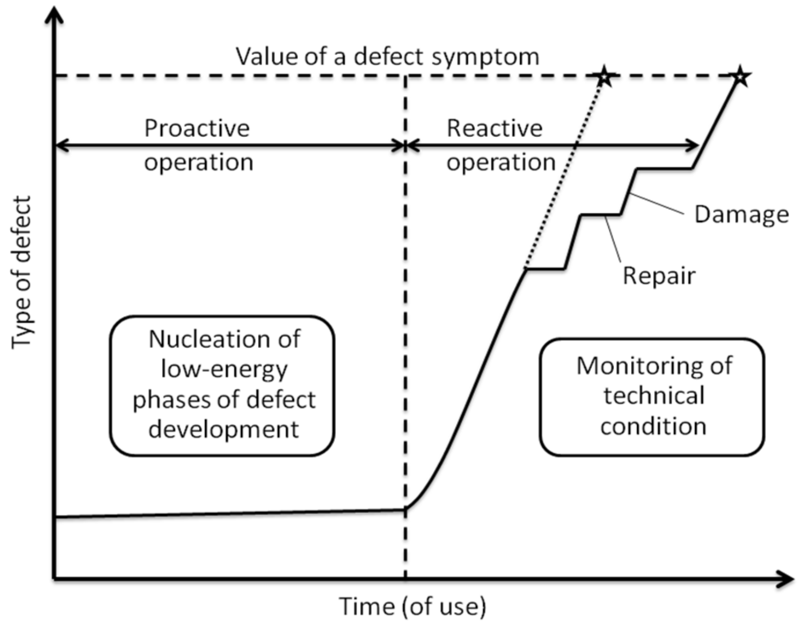

Figure 2: Diagnostic tasks in proactive operation [9].

From the point of view of relevance of diagnostic information, one of the basic problems related to the contemplated proactive operation strategy is the adoption of a relevant diagnostic-and-prognostic model. Publications contain a whole range of proposed models, starting from the models which only enable a qualitative description and understanding of the processes, through models enabling insight into the general trend of changes in diagnostic parameters, to models having the form of a virtual lab which simulates the course of real operational processes.

• Reliability-oriented operation, • Model-based defect detection and identification, • Experiment-based identification of defects, • Statistical methods of defect identification	• Proportional proactive risk models, • Bayes's estimation and updating methods, • Markov's hidden models, • Demodulation models; Hilbert transform, Hilbert-Huang transform, Hough transform, Fourier Analysis, • Neural networks, • Estimation of parameters	• Measurement techniques, • Vibroacoustic signal measurements, • Acoustic emission, • Magnetic field measurement techniques

Table 1: Diagnostic methods and means used in the pro-active strategy.

3 Early failures in machinery and infrastructure elements

Another important group of objects which require diagnosis are construction facilities. Also in this area the non-invasive methods play increasing role while the need for such systems generates continuous evolution of the already known methods as well as creation of new techniques. As it turns out numerous materials, which can potentially create risk of catastrophes, have physical properties which can be used for diagnostic purposes. Discovery of new phenomena, especially the relation between properties of a material and its condition, fosters development of various new diagnostic techniques and is seen as an opportunity for reaching the diagnostically-useful information at an early stage. With such an approach in mind, it is possible to isolate two groups of techniques from among the methods of diagnosis of civil structures: the group of the techniques which rely on magnetic properties and the non-magnetic methods.

While referring to the current state of knowledge, it is worth noting that the research involving steel structures as well as pre-stressed concrete structures and machines focuses mainly on detection of occurrence of faults and defects at possibly the earliest stage of their development. The methods which are currently used for such a purpose include: acoustic emission methods, dynamic methods (change of an object's dynamic response), x-ray methods, ultrasonic methods, thermal emission methods, tensometric methods, various types of visualization techniques as well as penetration methods and the method defectoskopy.

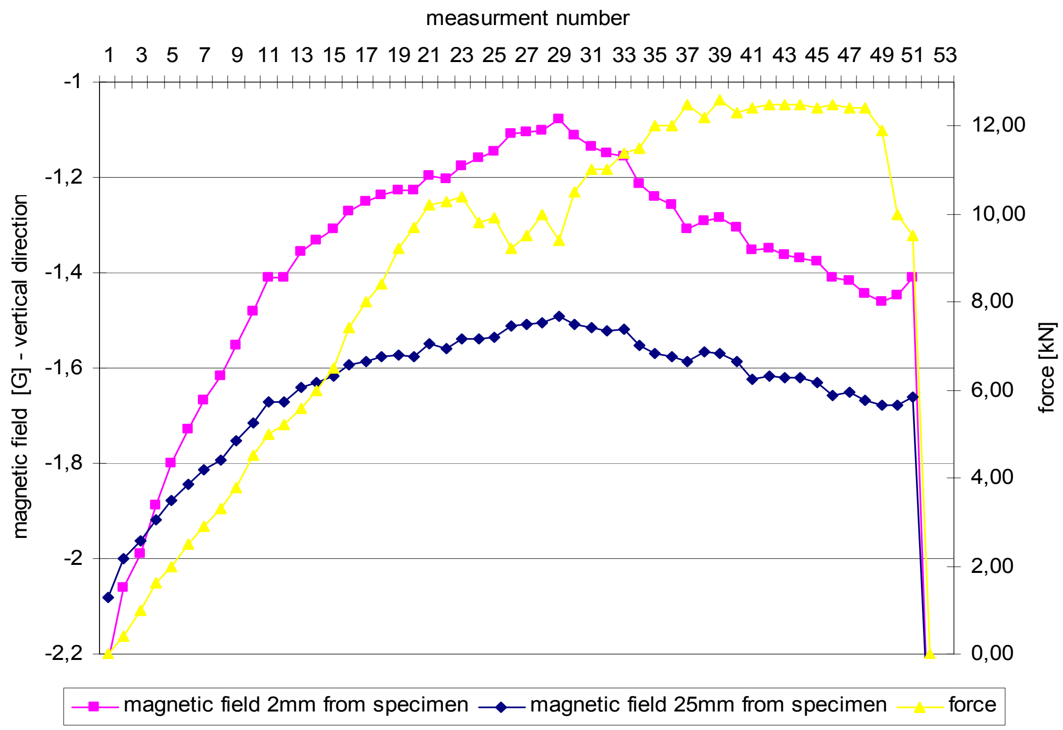

Figure 3: Change of magnetic field during the break test - vertical direction (z) [10]

The weaknesses of existing methods belonging to this group include their use for local measurements only, difficulty in maintaining diligence of measurements during the research, and above all lack of clear possibility of assessing the threat that the discovered defect poses for the analyzed object.

Passive magnetic methods rely on interaction of the construction material with the earth's magnetic field. Even in case of the small intensity of the field, the change of stress in the materials with magnetic properties leads to the transformation of its magnetic properties (magnetic material memory or the remnant magnetic field. Generally it should be stated that there exists a relation between stress and degree of magnetization (Fig. 3). In reality this relation is complex since it additionally depends on the type of magnetization, history of magnetization, deformation and temperature. These properties have been used to develop the passive diagnostic methods.

All mechanical effects were clearly visible during the tension (force course) and they also could be identified in the magnetic representation (magnetic field course). As long as we work in the range of elastic deformations, for this particular specimen and a fixed distance from it, it is possible to estimate the magnitude of tension inside the sample using its own magnetic field. Tracking of this qualitative change of eigen magnetic field of an object could provide the information as to whether the object has come into the zone of plastic strain which is dangerous for structures [10].

While accounting for these remarks, prior to formulating the task of estimation of the remaining useful life of a device ((*RUL*), let us assume that there is a possibility of occurrence of other defects, however let us say that the periods of initiation and propagation of such defects are random values (Fig. 4). Let us note that such an approach complies with the guidelines of ISO 13381-1 norm .

In addition let us note that the possibility of detection of defect initiation occurs with a certain probability and that we are able to define the probability of defect initiation and propagation for the assumed threshold value. The assumptions apply to each of possible defect mode.

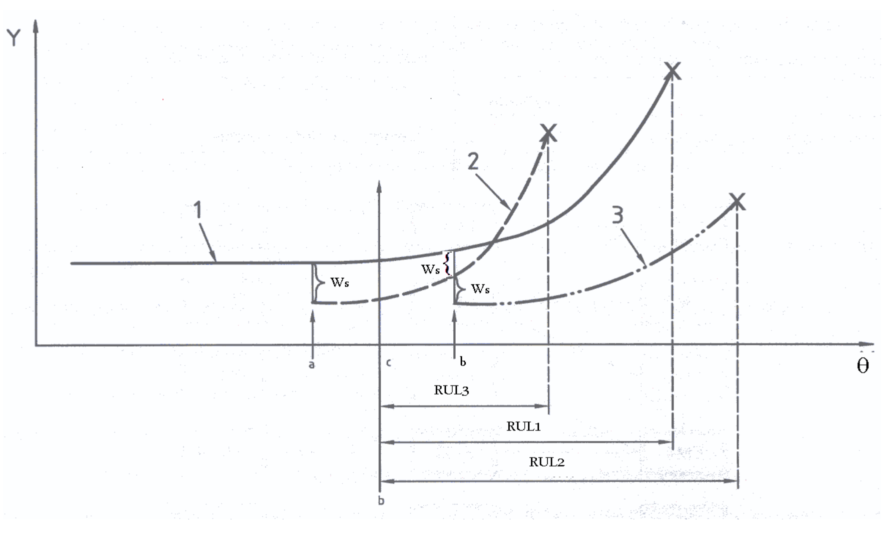

Figure 4: Illustration of multi-modal defect evolution [ISO 13381-1].

θ - time, D – defect-defining parameter, W_s- impact coefficient, a – time of occurrence of a known defect mode, b – time of occurrence of the third defect mode, c-time of performance of the analysis, RUL_i (i=1,2,3) – remaining useful life considering the i-th defect mode.

One should note that breaking of a tooth can also be modelled as a two-phase breaking in a situation when the period of crack propagation (phase three) is very short. Such a method of modelling of a fatigue-related defect is presented in the paper [11] which assumes analysis of two features: the qualitative change of the defect development process and the possibility of observing the individual times at which defects occur. In addition it has been assumed that the times of defect occurrence are independent of each other. In the analyzed case, while relying on the adopted model (Fig. 4), we assume the possibility of occurrence of three types of defects. Hence the observed time of breaking of teeth can be determined based on the following relationship:

$$U = \min(T_1, T_2, T_3) \tag{2}$$

Thus :

$$\begin{aligned} R_U(t) &= P(U > t) = P(\min(T_1, T_2, T_3) > t) = P(T_1 > t, T_2 > t, T_3 > t) = \\ &= P(T_1 > t)P(T_2 > t)P(T_3 > t) = R_1(t)R_2(t)R_3(t) \end{aligned} \tag{3}$$

Assuming the Weibull's model of the degradation process, relevant for the formula (3), the function of defect intensity will be expressed in the following form:

$$\lambda_U(t) = \lambda_1(t) + \lambda_2(t) + \lambda_3(t) \tag{4}$$

where:

$\lambda_1(t) = \gamma_0$, $\lambda_1(t)$ – corresponds to the 1st phase of defect development,

$\lambda_2(t) = \gamma_1 t$, $\lambda_2(t)$ – corresponds to the 2nd phase of defect development,

$\lambda_3(t) = \gamma_2 t^2$, $\lambda_3(t)$ – corresponds to the 3rd phase of defect development.

While accounting for the relationship (6), the formula (5) can be expressed in the following form:

$$R_U(t) = \exp(-(\gamma_0 t + \frac{\gamma_1 t^2}{2} + \frac{\gamma_2 t^3}{3})) \tag{5}$$

The probability density function will thus be expressed by the following formula:

$$f_U(t) = \lambda_U(t)R_U(t) = (\gamma_0 + \gamma_1 t + \gamma_2 t^2)\exp(-(\gamma_0 t + \frac{\gamma_1 t^2}{2} + \frac{\gamma_2 t^3}{3})) \tag{6}$$

If the defects are interdependent the problem of selection of the starting point of failure development phase is more complicated than in case of independent failures.

Assuming that the relationship fulfils the positive quadrant dependence according to [12] the equation could be written as:

$$R_U(T > t_1, T > t_2, T > t_3) \geq R_1(T > t_1) \cdot R_2(T > t_2) < R_3(T > t_3) \qquad (7)$$

This results from the generally known relationship:

$$R_U(t) = R_1(t) + R_2(t) + R_3(t) - R_1(t) \cdot R_2(t) - R_2(t) \cdot R_3(t) - R_1(t) \cdot R_3(t) + \\ + R_1(t) \cdot R_2(t) \cdot R_3(t) \qquad (8)$$

Taking into consideration [12], equation (8) will have the form:

$$R_U(t) = e^{-\gamma_0 t} + e^{-\gamma_1 \cdot \frac{t^2}{2}} + e^{-\gamma_2 \cdot \frac{t^3}{3}} - e^{-(\gamma_0 t + \gamma_1 \cdot \frac{t^2}{2})} - e^{-(\gamma_1 \cdot \frac{t^2}{2} + \gamma_2 \cdot \frac{t^3}{3})} - e^{-(\gamma_0 t + \gamma_2 \cdot \frac{t^3}{3})} + \\ + e^{-(\gamma_0 t + \gamma_1 \cdot \frac{t^2}{2} + \gamma_2 \cdot \frac{t^3}{3})} \qquad (9)$$

Therefore:

$$f_U(t) = \frac{dR_U(t)}{dt} \ (10)$$

Finally the relationship will be calculated as a Remaining Useful Life (RUL):

$$RUL = \frac{\int_{T_i}^{\infty} t f_U(t) dt}{R_U(T_i)} - T_i \qquad (11)$$

where T_i – the time of initiation of defect i.

While summing up the obtained results, one should stress the significant influence of random disturbances which demonstrate that there exist additional, important yet unidentified factors which may affect the decision-making process.

While accounting for the fact that the possibility of detection depends on the ratio of useful signal value to noise, the probability of non-detection of the defect-initiation phase can be expressed in the following form:

$$\mathrm{p_d} = \begin{cases} \exp(-\frac{c - c_0}{W_0}), & c > c_0 \\ 1, & c \leq c_0 \end{cases} \qquad (12)$$

where:

c – the diagnostic parameter,

c_0 – the threshold value at which crack initiation can be detected,

W_0– is the parameter which characterizes the diagnostic receptivity of the monitored quantity.

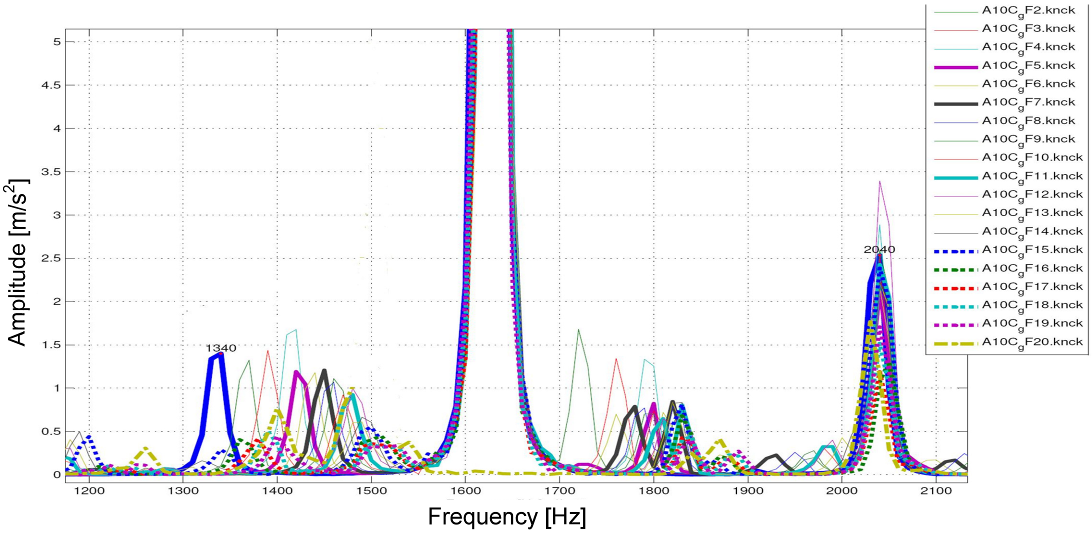

Figure 5: Part of the signal's spectrum for a sample to which load was applied in the form of a transverse force with a frequency of around 1630 Hz, with the effect of dispersion [14].

As an example of parameters selection the changes in spectrum of the modulated signal were selected. Modulation effect is caused by existing of the group velocity apart from the wave velocity propagation.

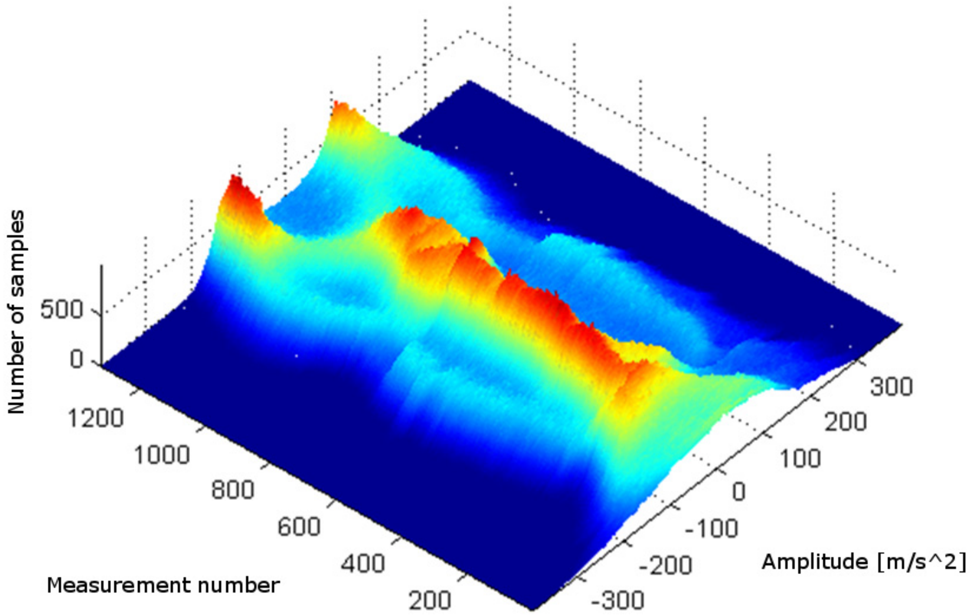

Figure 6. Changes of the distribution of amplitudes of the gearbox acceleration signal as a function of lifetime (consecutive measurements) [1]

Relevant combination of loads (ratio of transverse forces to longitudinal forces) contributes to the occurrence of the effect of dispersion, differentiation of group velocity and causing the accompanying effect of amplitude modulation, as presented in Fig. 5 [14].

Another example of detection of the early stage of failure development is presented on Fig. 6 where the changes of the distribution of the second meshing frequency harmonic could be observed indicating the nucleation of the tooth breakage in the toothed gear.

4 Conclusions

Many materials, that could be related to the risk of an accident, have physical properties that could be used for the diagnostic purposes. Discovering new phenomena, particularly relationships between the material properties and their current technical state, leads to the possibilities of creating new diagnostic techniques that allow for acquiring of useful diagnostic information about early stages of construction defects. Taking this into consideration several different methods and techniques could be used for assessing the technical state of the construction.

As a source of information about the current load of the construction, data from strain gauges (classic or FBG optical sensors) and passive magnetic field sensors could be used. By measuring the changes in the magnetic field of the analysed steel structure it is possible to obtain the diagnostic information about the type of strain and stress intensity. On the other hand modal parameters obtained through the use of acceleration sensors applied to the construction give information about the overall changes in the technical state of the structure. Based on this data the remaining useful life of a structure could be calculated.

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References

[1] R. Gumiński, "Use of diagnostic information in the analysis of technical risk", PhD thesis, 2010

[2] S. Flumerfelt, G. P. Haladu, F. J. Kahlen "Complexity by Design", Mechanical Engineering Vol 134/No3 pp29-33, 2012

[3] L. Heimann, "Repeated Failures in the Management of High Risk Technologies", European Management Journal Vol 23 No1 pp 105-117, 2005

[4] R. Kothamasu, S. H. Huang, W. H. VerDuin "System Health Monitoring and Prognostics – A Review of Current Paradigms and Practices", The International Journal of Advanced Manufacturing Technology 28(9) pp 1012-1024, 2006
[5] M. Saranga, Knezevic "Reliability analysis using multiple relevant condition parameters", Journal of Quall in Maintenance Engineering, 2000
[6] B. K. N. Rao "The need for condition monitoring and maintenance management in industries", Hanbook of condition monitoring, Elsevier Science, Amsterdam, 1996
[7] L. R. Kinclaid "Evolution of condition monitoring and the management of maintenance", Proceedings of International Conference on Condition Monitoring, 1987
[8] J. Dybała,J. Mączak, S. Radkowski, "Use of vibroacoustic signal in the analysis of technical risk", ITE, Radom, 2006
[9] S. Radkowski ,"Vibroacoustic monitoring of mechanical systems for proactive maintenance", Diagnostyka, Vol. 47, No. 3, pp 157÷164. (Proc. of 4th International Congress on Technical Diagnostics, Olsztyn, 9÷12.09.2008), 2008
[10] S. Gontarz, S. Radkowski, "Impact of various factors on relationships between stress and eigen magnetic field in a steel specimen", IEEE Transactions on Magnetics , Vol.48, No. 3 ,pp 1143-1154, 2012
[11] A. Pieravi, N. Dehganmongabadi, "Accelerated Life Testing Based on Proportional Mean Residual Life Model for Multiple Failure Models", Journal of Applied Sciences 8(22), pp. 4166-4172, 2008
[12] S. Kotz, Ch. D. Lai, M. Xie, "On the effect of redundancy for systems with dependent components", IIE Transactions, 35 pp 1103-1110, 2003
[13] J. J. Xiong, R. A. Shenoi, "A durability model incorporating safe life methodology and damage tolerance approach to assess first inspection and maintenance period for structures", Reliability Engineering and Safety, doi: 10.1076/j.ress. 2008.01.05, 2009
[14] S. Radkowski, K. Szczurowski, "Use of vibroacoustic signals for diagnosis of prestressed structures" – Maintenance and Reliability, Vol. 14, No. 1 , pp 84-91, 2012