Statistical analysis of hidden periodicities in machinery vibration

I. M. Iavors'kyj, V. Y. Mykhajlyshyn, O. P. Drabich
Department of Statistical Signal Processing Karpenko Physico-Mechanical Institute
National Academy of Sciences of Ukraine 5, Naukova str., L'viv, Ukraine, 290601
Tel.: (0322) 633-355, Fax: (0322) 649-427
E-mail: iavor@ah.ipm.lviv.ua

The new probabilistic model of machinery vibration in form of periodically correlated processes (PCRP) is considered in the paper. The problem of feature extraction of hidden periodicities in data series is formulated based on the developed statistical methods of probabilistic characteristic PCRP estimation. Narrow-band non-stationary process is considered as a particular case of PCRP. The given theoretical analysis gives ground for designing new algorithms of recognition of hidden periodicity structure.

1. Introduction

Working process of many machines is subordinated to periodical law. It first applies to rotating machinery including electric motors, generators, pumps, funs, rolls and blowers. In mechanical vibrations monitoring and diagnosis for machinery, periodicity arises also from revolution, and reciprocation of gears, belts, chains, shafts, propellers, bearing, pistons, and so on. In fact, periodicity never could be precisely. Therefore, hidden periodicity models are used in the analysis of vibroacoustical signals.

The presence of periodicity in temporal changeability of vibroacoustical processes in mathematical models describing those processes in many cases is represented by some property of spectral characteristics. Stochastic changes are represented in the form of randomly changeable amplitudes and phases of harmonic components, stationarity of such a representation is postulated.

Over a long period, study of vibration phenomena in machines has been an important application of probabilistic models and statistical methods of hidden periodicity detection. At present, the problem continues to evolve. Most known methods of vibration signal processing are united within the framework of the conception of spectral-correlation analysis of stationary random processes.

2. Vibration description

The description of stochastic oscillation properties in terms of spectral density of stationary random process gives a possibility to analyze only distribution by frequencies of their power. At the same time is evident insufficiency of such an approach in the presence of periodically parameter excitation or self-oscillation in mechanical system. Since it is an averaged characteristic of oscillations, their temporal (phase) structure remains unconsidered. The latter consists in some recurrence of properties of oscillations including form conservation. Such a recurrence is the basic feature of an oscillatory process. It is natural to describe the recurrence in terms of temporal changeability of probabilistic characteristics, that is some type of non-stationarity. A probabilistic model of stochastic recurrence of the simplest type (with one period) is a periodically correlated random process (PCRP) [1], the first- and second-order probabilistic characteristic of which are periodical time-functions. Those probabilistic characteristics describe regularities of stochastic amplitude and phase modulation of its basic and multiple harmonics:

$$\xi(t)=\sum_{k\in Z}\xi_k(t)\exp(ik\omega_0 t),\qquad \omega_0=\frac{2\pi}{T},\qquad (1)$$

where $\xi_k(t)$- are stationary related random processes. In terms of the hidden periodicity model in the form of PCRP, the problem of the analysis of vibroacoustical signals is formulated as the problem of estimation of correlation period T, and the first and second order probabilistic characteristics: mean, correlation function, spectral density, and their Fourier components.

Application of first- and second-order probabilistic characteristics of PCPR allows describing cinematic features of machine vibration-period, form and amplitude of signal, stochastic modulation of component amplitude and phase.

3. Hidden periodicity detecting

Developed methods of the vibroacoustical signals analysis are generalized to the PCRP class of the well known Buys-Ballot's technique and the method of Fourier transform which have been created for searching for periodicities described with periodic and almost periodic functions. They enable us to divide the problem into searching for both regular periodic vibrations and periodic change of fluctuation properties. Such an approach reformulates the problem based on the logical and capacious notion of hidden periodicities in the form of PCRP. Both coherent and component statistics have certain "resonance" properties concerning the correlation period. They take extreme values in point, which in asymptotic behavior are the real values of the period[2].

4. Narrow-band non-stationary properties

The representation (1) allows considering a PCRP as a common model of amplitude- and phase-modulated signals. The simplest model of amplitude and phase modulation is the so-called quadrature model, when in (1) only the first components are not zero, and then the process (1) could be represented in the form

$$\xi(t) = \xi_c(t)\cos\omega_0 t + \xi_s(t)\sin\omega_0 t, \quad (2)$$

$$\xi(t) = \mathrm{A}(t)\cos[\omega_0 t - \varphi(t)],$$

where $\xi_c(t) = \mathrm{A}(t)\cos\varphi(t)$, $\xi_s(t) = \mathrm{A}(t)\sin\varphi(t)$.

The results of the statistical analysis of narrow-band signal (2) as PCRP are given in the paper.

Further, in the paper we consider the basic issues of statistical analysis of narrow-band signal (5) as PCRP. Properties of its correlation and spectral characteristics are analyzed and much prominence is given to those characteristics that are related to information about signal non-stationarity. Properties of Hilbert's transformation of narrow-band PCRP, and possibilities of picking out quadrature components by means of that transformation are considered [3]. Their correlation and spectral characteristic relations are derived. Principal distinctions from stationary case are analyzed. Much attention is devoted to the carrier frequency determination problem. For this purpose, methods are supposed, which are based not on properties of spectral density (in one of such methods, for example, ω_0 is chosen as "weight center" of spectral density), but on these properties of both the first- and second-order probabilistic characteristics which are determining for PCRP, on their periodical changes in time. Those methods are more correct and more effective.

5. Conclusion

In conclusion, it should be noted that application of one or another model in the analysis of narrow-band vibration should be well grounded. It would be strange if all of amplitude- and phase-modulated oscillations were described by stationary model because it is correct under rather strict conditions. If stationary model is not true then blunders can be committed while solving problems of signal transformations, their processing and so on. It specially concerns such transformations and such a processing, operation carrying-out with which does not commutate with time averaging. It is not quite logical to renounce a priori the consideration of any signal properties that are objectively intrinsic in it without considering specific problems when analyzing properties of spreading environment, diagnosing, recognizing or studying physical nature of objects that generate the signal.

In the case of machinery and construction vibration, periodical non-stationary of narrow-band components is naturally arisen with periodical parametrical excitation and self-oscillations of gear elements. These phenomena considerably decrease stability of machinery operating and it could lead to their fault. The developed methods of vibration statistical analysis is taken as a basis of designed portable computer based information measuring system which was approbated on some objects of power and machinery building complex. It gives an opportunity to detect harmful processes and parametrical excitation and estimate their influence on the technical state and level of machinery reliability in the process of normal equipment exploitation on the early stages of development of the above faults.

References

[1]. Ya.P.Dragan, V.A.Rozhkov and I.M.Iavors'kyj, The Methods of Probabilistic Analysis of Oceanological Rhythmics, Leningrad: Gidrometeoizdat, 1987 (in Russian).

[2] I.Iavors'kyj and V.Mykhajlyshyn, Probabilistic Models and Investigation of Hidden Periodicities, Appl. Math. Lett. Vol. 9, No 2, 21-23, (1996).

[3]. V.Mykhajlyshyn and I.Iavors'kyj, The Non-stationary Modulated Random Processes, Reports of National Academy of Science of Ukraine, N2, 70-74,1996 (in Ukrainian). Analysis of Hidden Periodicities in Modulated Vibroacoustical Signals.