Using rhythmograms to diagnose mechanical systems

D A Balakin and V V Shtykov
National Research University "Moscow Power Engineering Institute"
14 Krasnokazarmennaya street, Moscow, 111250, Russia
E-mail: bzzz86.balakin@yandex.ru

Abstract. The possibility of using a rhythmogram for the diagnosis of mechanical systems is discussed. The rhythmogram is obtained using the method we developed for processing quasiperiodic pulsed signals. The method is based on the principles of the theory of optimal filtration, the theory of wavelet transform and Hermite transform. The efficiency of the diagnostic method is demonstrated by the example of the operation of bearings of a gas turbine engine. A conclusion is given on the further development of the method for assessing the states of mechanical systems.

1. Introduction
In today's world, we are faced with a large number of cyclic systems including mechanical systems such as gas turbine engines, turbogenerators, internal combustion engines, various pumps, etc. The functioning of such mechanical systems has much in common with the functioning of living objects.

Indeed, if the cyclical nature of the mechanism is associated with the presence of rotating or moving reciprocating parts in it, then the leading nerve center sets the rhythm in a living organism.

In medicine, in particular in cardiology, the study of cycle variability is a well-developed and widespread method for diagnosing the patient's condition. For the purpose of such diagnostics, the cardiologist uses a rhythmogram, which reflects changes in the intervals between the pulses of the cardiogram [1]. It can be assumed that for mechanical systems, a rhythmogram will be a useful diagnostic tool. Violation of the rhythm will indicate the presence of a defect.

A direct method of obtaining a rhythmogram is to calculate the mutual correlation function (MCF) of the signal and the reference function (RF) and then fix the positions of the maxima of the MCF on the time axis. Constructing RF directly from the discrete recording of the signal can be done by representing the samples of the selected fragment as the sum of the Gauss-Hermite orthogonal functions (GHF) [2-4].

As an example of signal processing in order to obtain a rhythmogram, we consider the processing of recordings of the vibration signal of the bearings of a gas turbine engine (GTE) transmission.

2. An example of processing a real signal
Records of three signals (hereinafter $S_1$, $S_2$, $S_3$) are presented in figure 1. The sample size is 30,000 counts.
Since we do not have a priori data on the characteristic features of the signal, we will conduct a preliminary spectral analysis of the signals to construct the RF.

We will take the value of the sampling frequency equal to 1. Then, for a sample of 30,000 counts, the frequency step in the spectral region will be 1/30 000 relative units.

The recording spectra are shown in figure 2. The figure shows that the maximum frequency components in the signal spectra are concentrated in the range of approximately 0.015-0.02 rel. units, which corresponds to approximately 50–70 counts in the signal recording.

It is clear that the ideal mechanism operates cyclically. In the discrete spectrum of the signal of such a mechanism, the component inverse to the period has a maximum value. In real recordings, the spectrum is blurred (see figure 2), but its maximum can be identified with the average pulse repetition period.

We will take $S_1$ signal recording as the basis for constructing the RF, since its main spectral components are present both in $S_2$ signal spectrum and in $S_3$ signal spectrum.

Figure 3 shows, on an enlarged scale, a segment of $S_1$ signal recording. The figure clearly shows characteristic fragments with a duration of approximately 50-70 counts.

We will choose a fragment from 6020 of the count to 6080 as a reference. Fragments similar to such a reference are most often found in the record.
Figure 2. Spectra of the studied signals.

When constructing the RF, the maximum order of the GHF was 15. By increasing the number of GHF, a more accurate description of the fragment can be achieved. However, at this stage, one may encounter the fact that the formatting object will be matched only with the selected fragment. In more detail, the procedure for constructing the support function (figure 4) can be found in [3].

Figure 3. $S_1$ record fragment.

On the selected fragment, oscillations (7–8 oscillations) are observed, which correspond to the frequency components in the signal spectrum in the region of 0.12 rel. units (see figure 2a). These oscillations can be caused by both interference and the movement of other parts of the GTE. It is also possible to isolate and build their rhythm, for example, by subtracting a previously constructed RF from the standard [3].
Figure 4. The selected fragment (stroke) and the support function (solid).

Based on the support function, a quasi-consistent filter can be constructed [4]. Figure 5 shows the amplitude-frequency characteristic (AFC) of the filter, matched with the RF in figure 4, and the spectrum of $S_1$ signal.

Figure 5. Filter AFC based on GHF (1), $S_1$ signal spectrum (2).

As a result of multiplying the complex conjugate transmission coefficient of the synthesized filter and the spectrum of the signal under study, after the inverse Fourier transform, we will obtain MCF; and fixing its maxima, we can build a rhythmogram.

Using the described algorithm, three records were processed; they are presented in figure 1. To construct the rhythmogram, the MCF was subjected to threshold processing. The processing results are shown in figure 6.

When constructing the diagram, the minimum positive value from the set of maxima of the MCF of $S_1$ signal was taken as a threshold.
3. Discussion of results

We will begin the discussion with a visual analysis of the rhythmograms. The rhythmograms look like a random process with an average value. It is approximately equal to 50 counts and gives an estimate of the average period of the processed signals.

The outbursts of the rhythmogram indicate inhibition (surges up) or acceleration (surges down) of the mechanism. Ejections upward, commensurate with the average value of the rhythmogram, indicate that the algorithm skips the beat due to the fact that the maximum MCF does not exceed the set threshold. There are few such emissions in figures 6a and 6c, while in figure 6b there are a lot of them. In the presence of noise, downward spikes may appear, commensurate with the average value of the rhythmogram, due to the appearance of false maxima. There are no such emissions in figure 6.

A preliminary visual analysis suggests that the bearings, the signals of which are shown in figures 1a and 1c, are operational, and the bearing with $S_2$ signal has a defect. We confirm these preliminary considerations with quantitative estimates.

A rhythmogram can be considered as a discrete signal that can be processed by one of the traditional methods. You can, for example, get a spectrum of a rhythmogram or calculate its statistical parameters. We will perform a statistical analysis of the obtained rhythmograms. We will calculate the expectation, standard deviation, mode and median, as well as the minimum and maximum values. The calculated parameters are presented in table 1.

| Parameter          | $S_1$ | $S_2$ | $S_3$ |
|--------------------|-------|-------|-------|
| Mathematical expectation | 55.2  | 47.5  | 55.9  |
| Standard deviation  | 8.55  | 11.5  | 6.75  |
| Midpoint           | 54    | 44    | 56    |
| Mode               | 52    | 43    | 56    |
| Minimal value      | 32    | 31    | 32    |
| Maximum value      | 101   | 109   | 88    |
In medical practice, the diagnosis of pathology is based on the value of the standard deviation [1]. The values of the standard deviation given in table 1 differ by a dozen percent. $S_2$ signal has the highest standard deviation value.

The median and mode of recording $S_1$ and $S_3$ signals have close numerical values of statistical parameters that are close to average. This indicates that the distribution of emissions relative to the average is close to symmetrical. For $S_2$ signal, surges down (jerks, bumps) prevail.

Based on the totality of the parameters, we can assume that $S_1$ and $S_3$ bearings are in good condition, but there is a high degree of probability that $S_2$ is faulty.

4. Conclusion

Modern methods for diagnosing mechanical systems are effective when a defect manifests itself as a periodic component of the signal. However, if the mechanism is tested in the operating mode, it is highly likely that the defect will appear sporadically and even with random parameters. In this case, widespread methods lose their effectiveness.

The rimogram allows exploring the system in various modes, both standard and special. Therefore, it is able to provide some additional diagnostic information about the state of the dynamic system. Thus, it can be hoped that such a diagnostic method may be of practical interest for assessing the characteristic dynamic signs of the functioning of various mechanisms, devices and apparatuses.

Of course, the rhythmogram will have a different look if you select another fragment of the record as a reference due to a change in RF. The question of choosing a standard requires additional research with the involvement of diagnostic specialists in each case. The development of databases of various RF will allow for the rapid diagnosis of devices.

A feature of the proposed and developed method for processing quasiperiodic pulsed signals using the Gauss-Hermite function also lies in the possibility of varying the RF scale along the time axis [2-4]. Variation in scale allows us to identify not only violations of the periodicity of the system, but also a change in the shape of the signal pulses, which, in turn, provides additional means of detecting and predicting the development of a malfunction. So, for example, the duration of the pulses of the near-radar system reflected from the blades of a turbofan jet engine depends on the angle of attack [5]. Variations in the RF scale will make it possible to reveal the rotations of the blade around its longitudinal axis not only constant in magnitude, but also randomly changing in time.

Acknowledgments

The authors of the paper express sincere gratitude to T. P. Gryzlova for the provided recordings of the vibration signals of the gas turbine engine bearing.

References

[1] Kulaichev A P 2016 Computer electrophysiology and functional diagnostics (Moscow: SIC INFRA-M)
[2] Balakin D A and Shtykov V V 2018 Digital signal processing 3 59
[3] Balakin D A, Churkin S S and Shtykov V V 2018 Infocommunication and radio-electronic technologies 1(1) 48
[4] Balakin D A and Shtykov V V 2014 Journal of Electronics 9
[5] Noskov V Ya, Ignatkov K A, Chupakhin A P, Smolsky S M and Shtykov V V 2017 IV All-Russian Scientific and Technical Conference "Communication and Radio Navigation Systems" pp 197–201