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FOURIER SPECTRUM RELATED PROPERTIES OF VIBRATION SIGNALS IN ACCELERATED MOTOR AGING APPLICABLE FOR AGE DETERMINATION

WŁAŚCIWOŚCI SYGNAŁÓW WIBRACYJNYCH ZWIĄZANE Z WIDMEM FOURIERA W PRZYSPIESZONYCH BADANIACH STARZENIA SIĘ SILNIKA MAJĄCYCH NA CELU OKREŚLENIE JEGO WIEKU

A series of computations based on the Fourier spectrum of vibration signals collected in artificial aging processes have been applied in order to tackle trends existing in the signals' sequence. In this study, features extracted from the (Fourier) spectrum of the vibration signal and expressing monotonic changes with respect to the motor age namely mean frequency, low order statistics of the power spectral density and cepstrum are used. Independence of the time domain data allows independent analysis. Results obtained in case of artificial aging are compared with results in case of controlled bearing faults with increasing severity. Clear distinctions are made and conclusions are drawn from the different behavioural patterns. Future research directions are indicated both in practical and theoretical sense.

Keywords: *motor vibration, artificial motor aging, cepstrum, power spectral density.*

Wykonano serię obliczeń opartych na widmie Fouriera sygnałów wibracyjnych zebranych podczas procesów sztucznego starzenia w celu określenia trendów istniejących w sekwencji tych sygnałów. Cechy, jakie można wyodrębnić w (fourierowskim) widmie sygnału drgań, które wykazują monotoniczne zmiany w odniesieniu do wieku silnika wykorzystanego w niniejszym badaniu, to średnia częstotliwość, statystyki niskiego rzędu widmowej gęstości mocy oraz cepstrum. Niezależność danych w dziedzinie czasu umożliwia niezależną analizę. Wyniki sztucznego starzenia porównano z wynikami otrzymanymi podczas dokonywania kontrolowanych uszkodzeń łożyska o rosnącym nasileniu. Wyciągnięto wnioski z obserwowanych, wyraźnie różnych wzorców zachowań. Wskazano przyszłe kierunki badań zarówno w aspekcie praktycznym jak i teoretycznym.

Słowa kluczowe: *drgania silnika, sztuczne starzenie silnika, cepstrum, gęstość widmowa mocy.*

1. Introduction

Question of condition monitoring and predictive maintenance is an important one in modern industry. In case of electrical motors, the question of their bearings' health and remaining useful life of the whole device can be asked. In order to diagnose abnormal states and faults, a wide range of indicators have been used, including stator current, vibration and sound [7].

In this study, we will focus on the properties of vibration signals and ability to do the motor diagnostics based on vibration content. Such approach is widely used in practice [10] with various parameters extracted from the vibration signal.

While some authors choose to base their methods of vibration diagnostics on the features of signal in time domain [12], the others use the features in frequency domain [17], which is an attractive area of research and being often considered invariant opposed to amplitude variations in time domain analysis, influenced by the motor type or the sensory equipment employed in the experiment.

In case of random vibrations, the classical power spectral density (PSD) is serving just as a foundation for more complex methods of frequency based analysis [16]. Often, in case of motor vibrations, decomposition is applied, for instance the Hilbert Huang Transform or Wavelet Transform, with a possibility of applying frequency analysis to components obtained that way [2], or simply taking time domain characteristics of such components [1]. In this work, we have chosen to work with the whole signal, without any decomposition, avoiding analysis of components' significance and noise level within each of them.

While these works often focus on known bearing faults, showing methods of detecting and identifying them, the practical situation often resembles the one seen in case of artificial motor aging: motor bearings, shaft and windings suffering the unpredicted failures and faults [4, 5]. In that case, it is important to be able to determine what the level of aging the motor is achieved, so the remaining life can be estimated [12]. An important question that arises there is what is the difference between ordinary isolated, controlled bearing faults and those emerging in (artificial) motor aging processes. Hence, this study aims to fill the gap in knowledge about the nature of bearing faults occurring in artificial aging processes of induction motors, as well as to investigate on the frequency spectrum properties of vibration produced in motor aging applicable for determination of motor age. Conclusions are given to support the claim that the aging process is not possible to approximate with a single type of bearing fault, but that characteristics common for certain types of faults appear within the frequency signature of motor vibration in characteristic aging signals.

Furthermore, simple statistical measures that are selected for demonstration of emerging patterns in motor aging can readily be used for detection of motor age, without the need for introduction of more complex machine learning and intelligence components. Simplicity of patterns also indicates an existence of a logical theoretical basis for the results obtained.

The paper is structured as follows: after an introduction, frequency-based methods and experimental data from motors used in this study are presented in the second part. Third part presents the results of methods applied with a discussion. Finally, conclusions and future work directions are given.

2. The methods and experimental data

In order to determine the existence of usable patterns in artificial motor aging data, several frequency domain features are to be extracted from the spectrum. Before that, the spectrum has to be estimated and represented in a suitable manner. Finally, results obtained on the artificial motor aging data had to be compared with results obtained on controlled bearing faults in order to compare the processes. This section introduces both the methods used to extract the frequency features and the data the research was conducted on.

2.1. The methods used

Spectral methods in general have been extensively used in signal processing [8], processing of vibrations being just one part of it. While the straightforward approach is to find spectrum for the signal by applying (Fast) Fourier Transform to its time series, methods based on autoregressive models have shown to be applicable in wide sense of signal processing applications, vibration being one of them [3].

The Burg method for AR spectral estimation stems from minimizing the forward and backward prediction errors and satisfying the Levinson-Durbin recursion [11]. The autocorrelation function is not calculated, reflection coefficients are estimated directly. Burg method is able of resolving closely spaced sinusoids in signals with low noise, which makes it applicable for vibration. It is also computationally efficient and the produced system is stable. In this work, it is straightforwardly applied to the signal and then the statistical properties (minimum, maximum, mean and standard deviation) of the obtained spectrum are examined. There are of course other methods for autoregressive estimation of PSD, but in the experimenting with data in this research, the Burg method shows the best results in displaying the characteristic points of the PSD for the motor vibration in case of artificial aging.

Another way of representation for the signal's spectrum is cepstrum which is the inverse Fourier transform of the logarithm of spectrum estimate. While it has been well known for its application in speech processing, there are known successful applications of it to vibration analysis [18].

Finally, zero crossing represents a very crude method of estimating the mean frequency of the (zero mean) signal, but extensions on the basic principle have been used for much more complex analysis of signals [15]. In this study, it is the basic principle that is being employed, counting the zero crossings of signal having its mean subtracted.

2.2. The data

Central point of this study is the accelerated aging process. The accelerated aging test conducted on induction motors according to IEEE Std 117-1974 test procedures involved thermal and chemical aging together with fluting [1, 4, 5, 13]. Thermal and chemical aging suggests heating the motors and soaking into water to cause corrosion, while fluting is the passage of electrical current through the device. After making the motor go through a cycle of accelerated aging described through these processes, it is put on a performance testing platform where vibration is measured at frequency of 12 kHz for 10 seconds under full load. Hence this data contains eight vibration time series, one for each aging cycle before the final motor breakdown, 120,000 samples long and measured at the load end.

On the other hand, the controlled bearing faults are produced in the form of single point faults using electro-discharge machining [9]. Fault diameters of 7 mils, 14 mils and 21 mils have been used for this study. Vibration data used here was collected at 48 kHz for approximately 10 seconds. In order to keep the data comparable, vibration records were taken from the load end at full load. All three characteristic types of faults: ball, inner and outer race defects were tested, but in the results only ball and inner race fault cases were presented for brevity.

3. Results and discussion

PSD estimates obtained using Burg method have shown to keep the most information in this particular application, so they are presented in Figures 1 and 2 in case of artificial motor aging and bearing faults, respectively. Throughout this section, ball and inner race faults are used as characteristic cases. Outer race faults are usually showing similar behaviour as inner race faults, hence omitted.

Even through visual inspection one may draw conclusions on applicability of PSD in classification. Namely, while the trend in case of artificial motor aging is clearly visible, only disrupted in the case of data set 5, any trend in case of bearing faults that might be established doesn't hold for both types of faults. Some low order statistical features extracted in tables 1 and 2 confirm this hypothesis and suggest potential use of PSD minimum, mean and standard deviation as indicators of motor age. They are shown in Figures 3 and 4 to illustrate obvious trends in case of aging and lack of trends in case of bearing faults (only ball fault results are presented graphically, since outer race results show the same lack of trends). One may note that the standard deviation in case of ball fault is even growing, opposed to the trend of decline in case of artificial aging.

Cepstral representation of the vibration signals in this case is not visually insightful, so the figures showing the cepstrum are omitted. Low order statistical analysis on the other hand shows again that, for example, standard deviation of cepstra in case of motor aging has a monotonic growth with respect to motor age (again, with exception of data set 5), as shown in Figure 5. One may notice that a trend similar to this one exists in ball fault data and does not exist in case of inner race fault data, visible in Figure 6. A hypothesis that this implies dominant ball faults in motor aging does not have more support than a hypothesis inner (or outer) race faults dominate in the process, though. For instance, in [14] it has been shown that the behaviour of Hurst exponents for motor aging resembles the behaviour in case of inner and outer race faults. Hence, we may safely conclude that it is not reasonable to approximate whole aging process with just one type of bearing fault.

Finally, number of zero crossings within the vibration signals has been analyzed. In order to obtain meaningful results, the mean of signals has been subtracted to produce zero mean sequences. Counting zero crossings and dividing that number with the total length of vibration sequences produces results shown in Figures 7 and 8. Visible opposite trends in the two regimes are observed and the already customary monotonic behaviour (with exception of data 5) is observed in the aging case.

Interesting fact concerning the data collected in controlled bearing faults experiment is that PSD and cepstrum standard deviation have the same values for vibration on the load end and the drive end.

At this point, it is important to provide a physical interpretation of results as well. The zero crossings monotonic increase observed for artificial aging implies increase in the overall frequency of the signals (as shown in Figure 9 (a) in time domain representation of vibration data), while such behaviour is not present in controlled (ball) fault data (as shown in Figure 9 (b)).

The same monotonic trend of cepstral standard deviation in case of motor aging and controlled ball faults follows opposite trends in PSD standard deviation, implying a more complicated relationship, but in general suggesting that peaks in cepstra of these signals are increasing with time, widening the distribution.

The trend of increasing minimum and mean PSD for the aging process implies increase in power caused by additional elements contributing to the motor vibration as the aging process mechanically disrupts the normal state. Since the standard deviation is essentially measuring the "height" of the PSD as shown in Figures 1 and 2, we may say that the monotonic increase in standard deviation for aging process is a consequence of the maximum value (not shown in the table for its lack of monotonicity) or the mean value increasing faster than the minimum value, therefore widening the PSD. Such behaviour is not a characteristic of the signals produced by controlled faults which implies that the other mechanical sources of vibration in aging processes influence the power of the vibration strongly, unlike the case of controlled faults where all possible additional vibration is caused solely by the bearing fault.

An interesting feature that was expected and noted in the Figures 1 and 2 is a substantial difference in nature between the healthy case and all faulty cases. In case of controlled bearing faults (Fig. 2), it is related to the already mentioned defect frequency which is not appearing in the healthy case, i.e. no peaks in the PSD, while it appears as a peak in the faulty cases.

On the other hand, in the case of artificial motor aging, shift in the peak suggests a bearing fault at that particular frequency visible in all

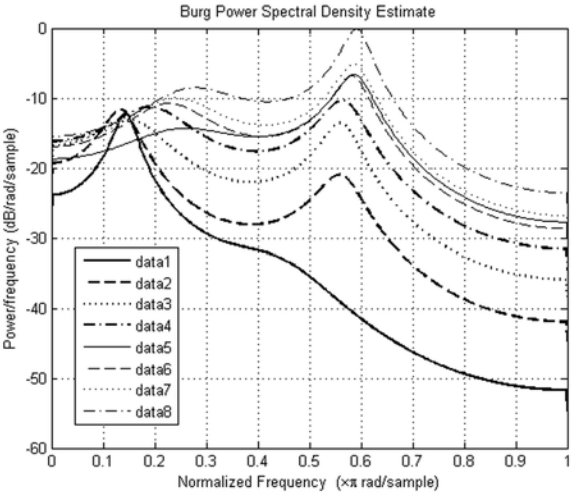

Fig. 1. PSD estimates for artificial motor aging data

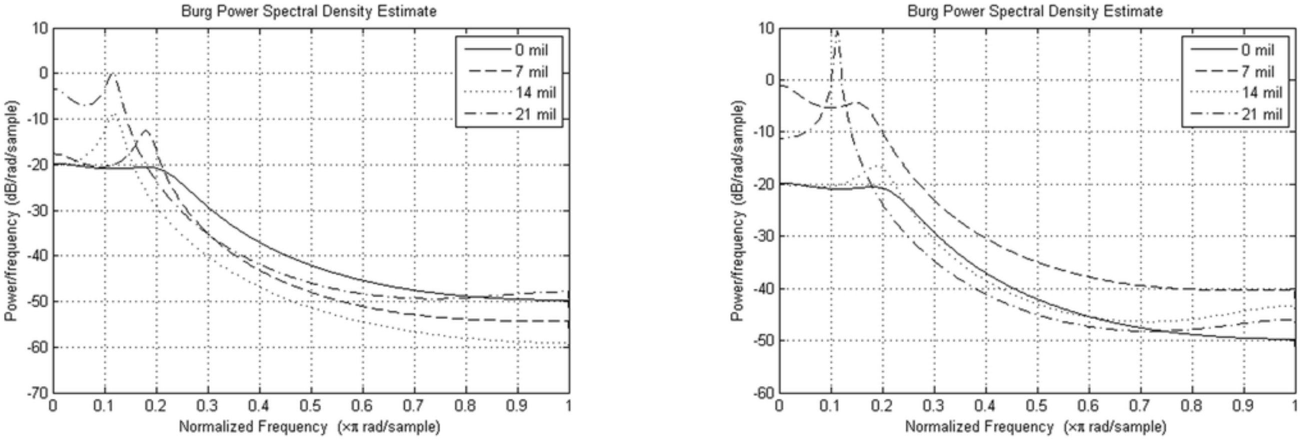

Fig. 2. PSD estimates for bearing faults: (a) ball fault, (b) inner race fault

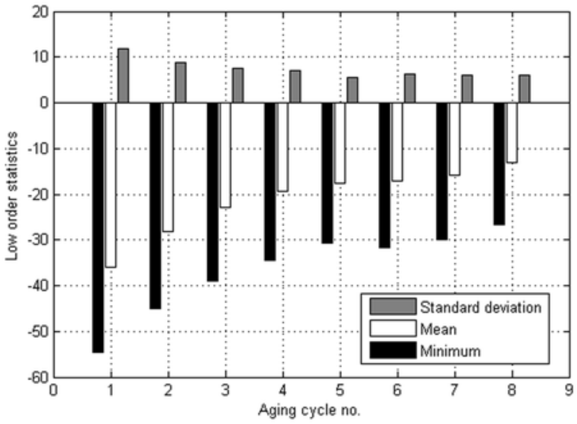

Fig. 3. Low order statistics for PSD in Figure 1

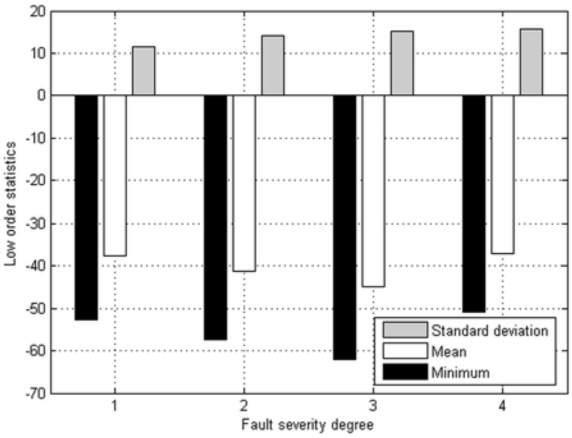

Fig. 4. Low order statistics for PSD in Figure 2(a)

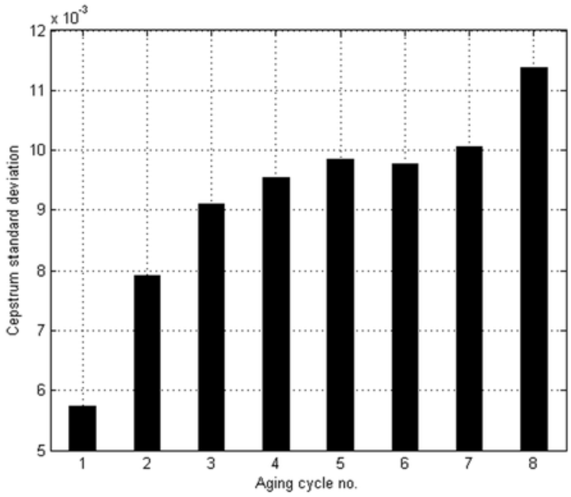

Fig. 5. Standard deviation of cepstra for artificial motor aging data

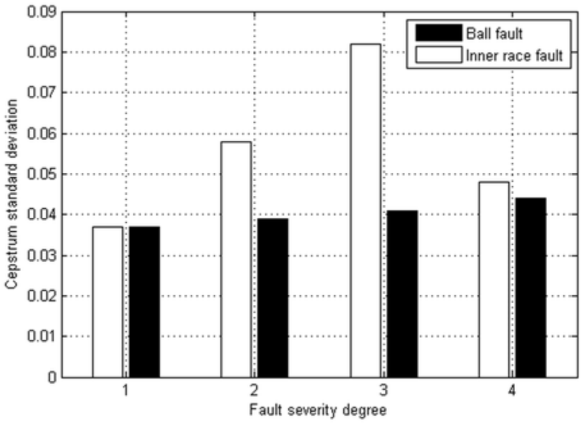

Fig. 6. Standard deviation of cepstra for bearing faults

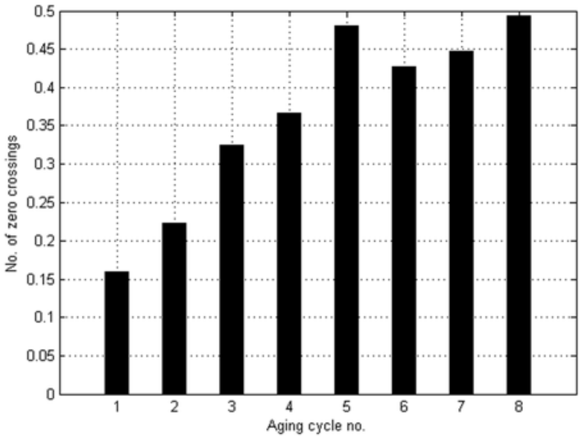

Fig. 7. Number of zero crossings for artificial motor aging data

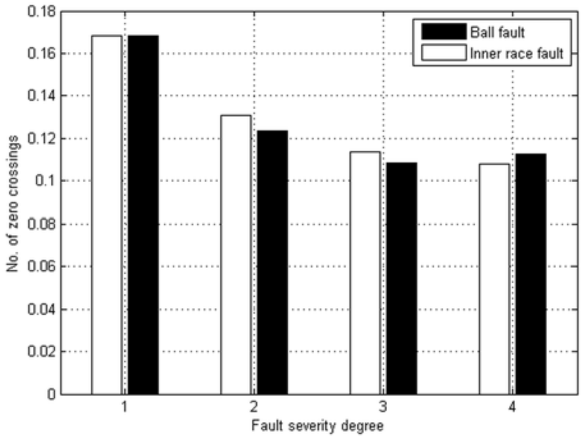

Fig. 8. Number of zero crossings for bearing faults

Table 1. Summary results for artificial motor aging data

	1	2	3	4	5	6	7	8
PSD min	−54.7	−44.93	−38.92	−34.59	−30.74	−31.68	−29.85	−26.57
PSD mean	−36.1	−28.06	−22.94	−19.29	−17.69	−17.23	−15.79	−13.09
PSD std. deviation	11.87	8.857	7.641	6.954	5.603	6.339	6.116	6.086
Cepstrum std. deviation	0.0057	0.0079	0.0091	0.0095	0.0099	0.0098	0.0100	0.0114
No. of zero crossings	0.1604	0.2226	0.3242	0.3663	0.4805	0.4277	0.4473	0.4939

Table 2. Summary results for bearing faults

		Ball fault			Inner race fault		
	0 mil	7 mil	14 mil	21 mil	7 mil	14 mil	21 mil
PSD min	−52.72	−57.38	−62.05	−50.85	−43.37	−46.38	−48.98
PSD mean	−37.61	−41.26	−44.79	−37.19	−28.18	−36.42	−36.67
PSD std. deviation	11.45	14.17	15.28	15.82	13.82	10.8	14.87
Cepstrum std. deviation	0.0036	0.0039	0.0041	0.0044	0.0057	0.0077	0.0048
No. of zero crossings	0.1684	0.1236	0.1083	0.1125	0.1307	0.1136	0.1077

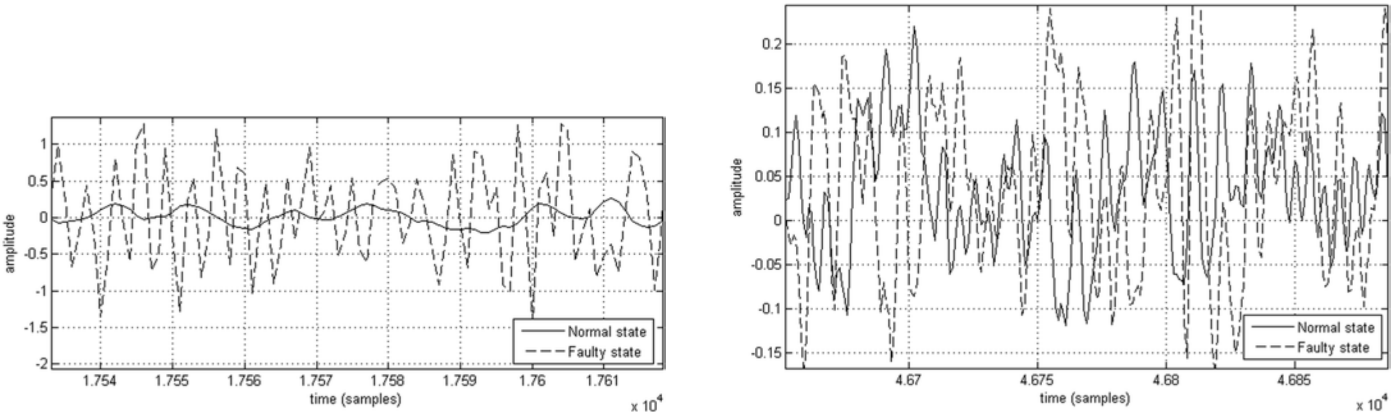

Fig. 9. Time domain representation for the vibration signals in case of motor aging (a) and controlled ball faults (b)

faulty cases, significantly different than the base frequency observed in healthy case.

4. Conclusions and future work

Analysis conducted has led to two important conclusions concerning artificial motor aging vibration. A pattern in frequency domain representation of artificial motor aging vibration has been detected, disrupted at only one vibration time series out of eight. Different statistical features have shown the same behaviour, indicating its significance. It can obviously be used for determining motor age, hence having a big practical impact on condition monitoring. This pattern does not appear in case of controlled bearing faults, and sometimes it is even reversed in that case. Therefore, we conclude that an approximation of motor aging with a common bearing fault growing is not justified.

Future work may include a real-time implementation within a condition monitoring system based on an FPGA embedded system, alongside with theoretical consideration of results on experimental data presented in this study. Furthermore, these results may have implications on question of modeling vibration in artificial aging processes, which represents another path future work may take. Important question that might have to be settled first is whether this pattern emerges in aging processes of different motors and is it characteristic both for artificial and natural motor aging.

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