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The Vibration Diagnostics of a High Engine Speed High Performance Centrifugal Compressor

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1. Introduction

The contribution deals with a diagnostic monitoring system by which the technical state of a large centrifugal compressor, operating at an ammonia plant, is traced. The compressor consists of three independent coaxial bodies and is driven by a 20 MW performance steam turbine. The normal compressor speed is 11 000 revolutions per minute and the discharge pressure 30 MPa.

2. The Conception of the Monitoring System

Primary data for the monitoring system are provided by the set of piezo-electric accelerometers. At one point on each body of the compressor they scan the acceleration of mechanical vibration in three perpendicular directions : radial, tangential and axial. Their amplified signals are recorded by a tape recorder.

Data thus stored are later processed by a real time analyser that cooperates with a minicomputer. From each registered course a statistically sufficiently reliable estimation of the power spectral density (PSE) is made, in the first stage, within the $0 \div 10$ kHz frequency band. To essentially lower the data scope, the PSE thus established continues to be processed. Peaks of diagnostic significance are searched automatically in it and compared statistically with those recorded in previous diagnostic measurements.

According to need, the entire system may provide diagnostic information on the examined compressor in one of the following forms:

a) graphically representing PSE behaviour in a linear or logarithmic display within the entire frequency band or in its part.; information of minor significance may be summarily suppressed;

b) printing out data on diagnostically significant peaks in PSE and comparing them statistically with similar data from preceding measurements;

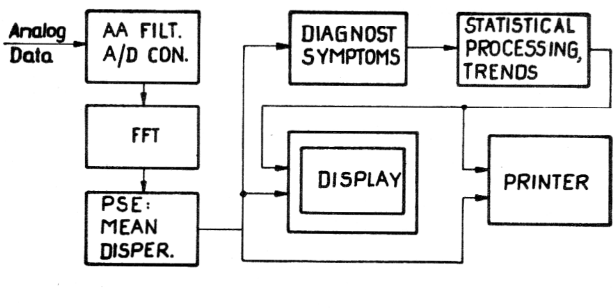

Fig. 1
Functional scheme of the entire diagnostic system operation

c) estimating trends, by regression analysis, in the development of the individual diagnostically significant peaks in the spectrum and representing them in form of a graph or table. The operation of the entire system is schematically shown in Fig. 1.

3. Diagnostic Symptoms in PSE

Conspicuous peaks in PSE whose frequency position in course of the PSE is unambiguously and rationally tied up with processes in the examined machine, are considered to be diagnostic features. We shall divide them in synchronous and asynchronous ones, as it is done in other papers.

To the synchronous ones belongs primarily the peak at the rotation frequency $f_{rot} \doteq 183$ Hz. It uses to be but little conspicuous since the rotors applied are, as a rule, very well balanced.

Another group of synchronous symptoms are the peaks at blade frequencies f_{Bi} $(i = 1, 2, \ldots)$

$$f_{Bi} = n_{Bi} \times f_{rot} \, .$$

The number of blades n_{Bi} on the individual (i-th) rotor wheels differs because in course of the PSE several peaks of this type are observed. Sometimes they are very conspicuous and are obviously due to the flow feature in the engine. It is noteworthy that, following the exchange of otherwise geometrically congruent rotors, essential deflections in the height of these peaks may be observed in some cases that may be indicative of the sensitivity of this symptom to minor changes in the flow feature in the engine, occasionally to minor changes in the rotor parameters.

In addition to the blade frequencies f_{Bi}, peaks at $2 \times f_{Bi}$ and $3 \times f_{Bi}$ may almost always be registered. In the diagnostic interpretation of PSE they are to be taken into account together with the peaks at blade frequencies.

The group of asynchronous symptoms is numerous in PSE. Significant is the peak at the first eigenfrequency of the rotor $f_{eig} \doteq 69$ Hz. Changes in its size may be due to alterations of forces destabilizing the first eigenmode of the rotor bending vibration, hence considerable attention is paid to this symptom. Along with this symptom in PSE, the peaks at $2 \times f_{eig}$, $3 \times f_{eig}$ and $4 \times f_{eig}$, arising through the action of nonlinearities in the system, are also traced. Sometimes there arises a peak in PSE in the neighbourhood of $f_c \doteq 100$ Hz. Experience has shown that its rise is due to the successive impairement of oil seals which, from the dynamic point of view, start to take over the function of virtual bearings. This shortens the effective length of the rotor between the bearings, giving rise to its eigenfrequency in the 100 Hz domain.

A series of significant peaks in PSE at frequencies f_{Dj} ($j = 1, 2, \ldots$) is responsible for the vibration of rotor wheel disks. Their higher number is due to the fact that the individual wheels on one rotor differ in dimensions and that several vibration modes are simultaneously excited on the individual wheels. The dependence has been observed of their frequency position in PSE on the operating speed as well as a rather conspicuous frequency shift when exchanging the engine rotor, although both rotors are geometrically identical. There has so far been no occasion to trace the changes of the frequency position of these peaks when cracks occur on the wheel disks. Apart from keeping track of the symptoms referred to, the monitoring system also envisages the possible occurrence of additional peaks in PSE that might be due, for example, to various types of the flow destabilization of the working medium in the engine (f_s).

The typical behaviour of the observed PSE is shown in Fig. 2.

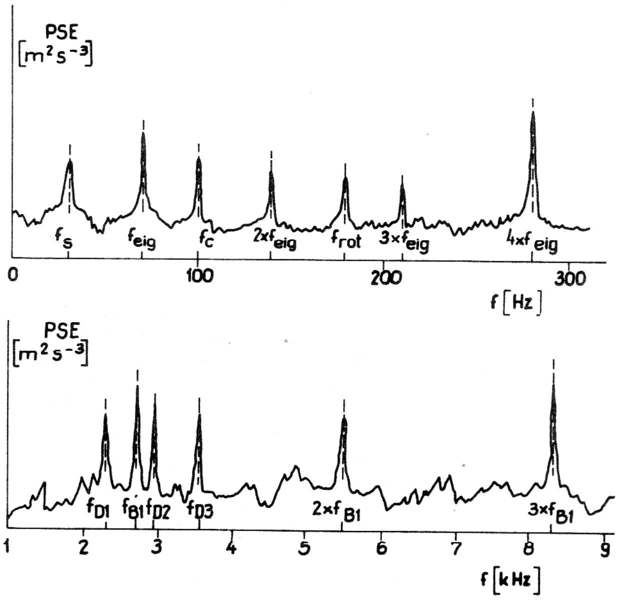

Fig. 2
Typical PSE behaviour in the examined turbo-compressor

4. The Algorithmisation of Symptom Determination in PSE

Each line of the power spectrum S_{ij}, calculated by applying FFT to the digitalized analog signal, is a (j-th) realization of the random variable S_{ij} whose frequency position in the power spectrum is given by frequency f_i $i = 1, 2, \ldots L$.

If these realizations amount to total of N, ($j = 1, 2, \ldots N$), then the PSE line at the frequency f_i is calculated as the mean out of N individual realizations:

$$\hat{S}_i = \frac{1}{N} \cdot \sum_{j=1}^{N} S_{ij} . \tag{1}$$

Similarly for the lines of the amplitude spectrum ϑ_{ij}

$$\hat{\vartheta}_i = \frac{1}{N} \sum_{j=1}^{N} \vartheta_{ij} \; ; \; \vartheta_{ij} = \sqrt{S_{ij}} . \tag{2}$$

Dispersion is another important statistic characteristic. For the i-th line of the mean amplitude spectrum it is defined from the relation:

$$D_{\vartheta i} = \frac{N}{N-1} (\hat{S}_i - \hat{\vartheta}_i^2) \; ; \; \sigma_{\vartheta i} = \sqrt{D_{\vartheta i}} \tag{3}$$

For the definition of the algorithm used in defining the significant peaks in PSE, the power spectrum density of the noise background is of importance, the estimation of which is equal to

$$\hat{S}_N = \frac{1}{L} \sum_{i=1}^{L} \hat{S}_i . \tag{4}$$

The greatest out of several neighbouring lines in PSE, exceeding the tenfold of S_N, will be primarily considered the peak in PSE.

$$\hat{S}_P \geqslant 10 \hat{S}_N . \tag{5}$$

Further those lines in PSE that are tied up with some of the outstanding frequencies are referred to in the 3 rd part of this paper, even if they do not satisfy relation (5).

Should the lines adjacent to the one defined as the peak, differ from the peak by less than 2 dB, a correction of the peak height is carried out that follows from the known picketfence effect [1], [2].

The height of peak $\hat{\vartheta}_P$ in the amplitude spectrum and the dispersion $D_{\vartheta P}$ pertaining to it are defined by an entirely analogous procedure.

5. Statistical Comparison of Peaks from two Measurements

In the preceding sections of the paper a description has been given of the way of processing and evaluating a signal that is recorded in course of the diagnostic examination of the engine. Denote the time datum, that is the hour and date of this examination, by symbol τ_1. Denote all quantities measured and calculated for this time, by index 1.

After a definite space of time, say one week, the next diagnostic examination of the engine is carried out. Denote the date of this examination by τ_2 and furnish all quantities connected with this examination, with index 2.

For both the first and the second diagnostic examination the symptoms in PSE may be defined together with their statistic characteristics, as referred to in the preceding sections of this paper. From the diagnostic viewpoint it is of importance to decide whether the difference in data from both measurements are of statistic significance or not.

The first two characteristics to be assessed from this aspect are the dispersion of the traced symptom in the amplitude spectrum. As far as relation [3]

$$1 \leqslant \frac{D_{\vartheta P1}}{D_{\vartheta P2}} < F_{\alpha/2} (N_1 - 1 \; ; N_2 - 1) \tag{6}$$

is satisfied, where $F_{\alpha/2}$ (k_1 ; k_2) is the critical value of F-distribution on the significance level α, the difference between both dispersions is statistically but little significant. As far as $N_1 = N_2 = 20$, and $\alpha = 0{,}05$, we have

$$F_{0,025}(19\,;19) \doteq 2{,}53$$

In this case both dispersions differ with statistic significance, if the larger of them is greater than the 2,53 multiple of the smaller.

If both dispersions are found not to differ with statistic significance, we step up to testing the statistic significance of the height difference of peaks $\vartheta_{P1}, \vartheta_{P2}$ in the amplitude spectrum, established in course of both measurements. To be able to carry out this test, we set up the testing quantity [3]

$$t = \frac{\vartheta_{P1} - \vartheta_{P2}}{\sqrt{D_d}} \qquad (7)$$

$$D_d = \frac{N_1 + N_2}{N_1\, N_2} \cdot \frac{D_{\vartheta P1}(N_1 - 1) + D_{\vartheta P2}(N_2 - 1)}{N_1 + N_2 - 2}$$

Both defined peak heights will differ with little statistic significance, if

$$|t| < t_{\alpha/2}(N_1 + N_2 - 2) \qquad (8)$$

where $t_{\alpha/2}(N_1 + N_2 - 2)$ is the critical value of the Student distribution on the significance level α. For the parameters previously used, we shall have

$$t_{0,025}(38) \doteq 2{,}025\,.$$

6. Conclusion

A diagnostic system has been described in the paper for monitoring the operation of a centrifugal compressor running under relatively high parameters. It will probably be possible to maintain the conception of such a system also in monitoring the operation of other, simimar engines. In interpreting both measured and recorded data, their statistic evaluation, by which the developmental trends of the individual symptoms in PSE may also be traced, has appeared to be a significant factor.

References

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