Signaling Device for the Pre-Emergency State of the Elements of the Rotating Assembly of Steam Compressor of Desalination Plant

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Abstract This article deals with non-contact exploitation control method based on the treatment of the radio wave signal reflected from controlled gear teeth and its advantages in comparison with traditional methods of gear teeth control. Justification of necessity to use such control method during multiplier gears condition determination during its exploitation is given. Also this article deals with influence of different types of gear wear on typical information parameters of analyzed signals. Disadvantages of the method which are the impossibility of determination of certain types of wear are also taken into account. Certain stages of the development of mathematical model for interaction of first converter with controlled surface. Suggested mathematical model uses only the laws of geometric optics without taking wave processes into account but considering first converter direction diagram influence during its interaction with controlled surface. Structural scheme of developed experimental system for gears teeth condition control for steam compressor. Operation of the experimental system of gear control is given on the base of structural scheme. Core of the developed device is microcontroller STM32 which treat the information received from the sensors as well as connection with computer. Certain elements of the experimental control system as well as its components are described separately. Photos of experimental unit for control for control method development in laboratory conditions are presented. Design of the first converter is given in short.

1. Introduction
Modern desalination plants widely use steam compressors to achieve economical operation modes [1]. A steam compressor is a complicated mechanical block, which includes the rotor with blade assembly in the form of impeller (Figure 1). Operating rotational rotor speed is 32000 rpm. The axial and radial play of the elements of such a rotating assembly are subjected to strict requirements, which are provided by support bearings and thrust bearings, to the shaft vibration parameters and to the blades of the compressor wheel. Support and thrust elements of such dynamical system are subjected of increased requirements both on manufacturing quality and monitoring of their operational status. Many papers are published currently aimed to optimization of operating modes of different
compressors. Those include investigations of the scientists of Samara University [2, 3, 4], which display the features of compressor workflow optimization.

**Figure 1.** General view of the elements of the rotating assembly of steam compressor rotor.

### 2. Problem formulation

At the present time, the problem of condition monitoring of the blades of the impeller and steam compressor shaft in a static state on stopped compressor is solved by visual inspection of the blade row with the help of technical endoscopes, eddy current and magnetic defectoscopes. This is very painstaking work, requiring professional skills and responsibility from technical personnel. Despite all measures taken, according to statistics, there are emergencies associated with the destruction of the impeller blades and shaft (Figure 2). There are known publications that discuss the dynamic diagnostic system based on spectrum analysis of vibration sensors [5, 6]. But the spectral diagnostic method has some serious drawbacks. Diagnosis on the spectrum of the envelope signal is quite complicated for physical interpretation of the defects of the blade apparatus, because it usually requires a good theoretical training of vibro-diagnostician or presence of the specialized computer expert system in his technical arsenal. Also personal practical experience of vibro-diagnostician and his knowledge of the internal structure of the controlled equipment have great influence on the accuracy of estimate of the current technical condition and reliability of diagnostics of defects of the state of the gear pairs.

**Figure 2.** Photo of the destroyed impeller blades.

In fact, the deviation of the shape of the blades of compressor wheel (scoring, blades folding) from the design variant leads to decreasing the efficiency of steam compressor, and finally leads to the destruction of the steam compressor rotor, to recover of which, at best, significant material and time expenses are required. Thus, the diagnosis of the defective condition of the elements of the steam compressor rotor of desalination plant is important at present.

As the analysis of scientific literature shows, among various methods and means of diagnostics and control elements of the rotating machinery on operating steam generators, there is prospective contactless discrete-phase method (DPM) allowing to determine the individual deformation condition of each blade of impeller and change in the gaps between the inner surface of the steam compressor body and blade tips in the blade row [7]. The obtained information is compared with the geometric position of a specific blade in the wheel at certain times and the corresponding interpretation of the obtained values in the field of mechanical stresses and deformations.

Based on the theoretical prerequisites of the DPM, a block diagram of the signaling device for the pre-emergency state of the blade assembly of the steam compressor [8] is presented, shown in Figure 3. The block diagram is based on the principle of measuring the current time intervals (steps) between the ends of the rotating blades, determining the maximum and minimum values of each step, finding
the average value of each step and comparing them with the average pitch of the blade wheel at each turn of the rotor of the steam compressor.

3. Analytical expressions

In accordance with Figure 3 block diagram works as follows. Peripheral sensor 1 mounted in the housing of steam compressor over the trajectory of the ends of the blades generates an electrical signal which by the shaper 2 is converted into a rectangular pulse. The time intervals $\tau_i$ between the rectangular pulses corresponding to a circumferential step between the blades are converted into digital codes in the block 3. In the same block, the values of the maximum and minimum values for each step are determined on N present rotor revolutions. Obtained extreme values of each step are received by block 4, which determines the average value $\tau_{av}$ of each step accordingly with expression:

$$\tau_{av} = (\tau_{max} + \tau_{min}) / 2.$$ 

In addition, the rectangular pulses from shaper 2 are received by block 5, where the time intervals $\tau_i$ are summed within N rotor revolutions, and then the average rotation period for N rotor revolutions is determined according to expression (1):

$$T_s = \frac{1}{N} \sum_{j=1}^{N} \sum_{i=1}^{K} \tau_i$$

(1)

If the design implementation of the steam compressor allows the sensor 6 of the reference revolution mark to be installed, then its electrical signals are converted into rectangular pulses by means of the shaper 7, which are fed to the block 8, in which then the average rotation period of the rotor is determined for N turns according to expression (2):

$$T_s = \frac{1}{N} \sum_{j=1}^{N} T_j$$

(2)

The switch block 9 allows to provide the necessary mode of operation of the device, both with the sensor of the reference revolution mark, and without it. The values $T_s$ obtained in block 10 are divided by the number of blades K in the wheel, thereby determining the average pitch along the impeller for N rotor revolutions: $\tau_s = T_s / K$.

Further, the so determined $\tau_{av}$ and $\tau_s$ are compared among themselves in the comparison unit 11. If $\tau_s$ differs from $\tau_{av}$ on a certain threshold value p, then a signal about the occurrence of a defect in one or more blades is generated at the output of the block 11.

When using amplitude criterion in signaling device for the pre-emergency state of the blade assembly of the steam compressor [9], accordingly with Figure 4, for intact, defect-free blades one can write:

$$A_i = \frac{y_{min} - y_{max}}{4}.$$ 

In accordance with this formula, for all characteristic operating modes of the compressor, it is possible to determine the average amplitude of the blade vibrations, and after statistical analysis to select the maximum and minimum values of the vibration amplitudes of the blades, which, when compared with the average amplitude of the oscillations, give an algebraic difference.
\[ \Delta = A_{\text{max}} - A_{s} = \left| A_{\text{min}} - A_{s} \right|, \]

characterizing the structural and technological deviations that occur in the manufacturing of blades of a specific wheel.

Further, taking into account the average vibration amplitude of the blades on the operating mode of the compressor the current average value of the oscillation amplitudes of the blades is continuously determined and compared with the average value.

As soon as \( |A_{c} - A_{s}| > \Delta \), it is stated the change in the amplitude of oscillations of the \( i \)-th blade, i.e. registering the appearance of the defect in it. For identified interblade interval, the amplitude of vibrations of defective blades is determined as it is stated in equation (3):

\[
\begin{align*}
 y_{\text{dmax}} &= y_{d} + A_{d} + A_{s}, \\
y_{\text{dmin}} &= y_{d} - A_{d} - A_{s},
\end{align*}
\]

therefore \( A_{y} = \frac{y_{\text{dmax}} - y_{\text{dmin}}}{2} - A_{s} \).

4. Results and discussions

Based on the proposed algorithm and the block diagram, a signaling device for the pre-emergency state (SDPES) of the blades assemblies of steam compressors operated at desalination plants was developed. The appearance and functional composition of the SDPES are shown in Figure 5. It includes: pulse sensor installed in the housing of steam compressor; measuring unit with USB interface to connect to computer; noise-proof communication cables; special software.

A signal about the occurrence of a defect of one or more blades in the form of warning light and sound signals is issued to the operator control panel. If the defect of the blade continues to develop, the SDPES generates a signal for the automatic control system of the equipment for normal (or emergency) shutdown of the steam compressor.

To monitor the current state of the blades, express analysis of their operability, to memorize their operational status, to record the inspection results, to create a technical passport of the blades, it is possible to communicate SDPES with a personal computer via a serial USB interface. To implement this possibility, special software has been developed that allows real-time field operational diagnostics of blades.

In addition, the SDPES provides an autonomous internal storage device, which is activated after the warning signal is issued and fixes the dynamics of the development of the defect of the blade. In this case, the date, time and deformation state of all impeller blades are recorded in the internal non-

Figure 4. Element of circumferential development of the blade row with two adjacent blades on the compressor operating mode.

Figure 5. The appearance and functional composition of the SDPES.
volatile memory. SDPES was developed and implemented on a modern electronic component base, which allowed to receive a compact and reliable device with a two-fold redundancy with an operational adaptation to any kind of steam compressors and impellers with a different number of blades.

SDPES has the following technical specifications:
1. Operating rotational speed range of the steam compressor rotor: 100 ... 33000 rpm.
2. Operating temperature range of pulse sensors:
   - option 1 -40 ... +150°C;
   - option 2 -40 ... +1000 °C.
3. The operating temperature range of the measuring unit -40 ... +50 °C.
4. Power supply of SDPES 27 VDC.

Laboratory tests of the SDPES were carried out, in which a defect was introduced in one of the compressor blades in the form of deflection of the end of the blade. Figure 6 shows the screenshot of the operator's program of the SDPES, which shows the deviations of all blades, including simulation of the defect, reaching 6 mm. The natural technological spread of the deviations of the other blade ends, the so-called misplacement, lies within ± 0.5 mm.

![Figure 6. The screenshot of the operator's program of the SDPES with a defective blade.](image)

On the basis of the experimental studies, recommendations have been made on the choice of threshold levels corresponding to the pre-emergency (2 mm) and emergency (2.5 mm) deviations of the ends of the blades for the steam compressor blades.

### 5. Conclusions

The experience gained in the testing of various steam compressors showed that the initial dynamic position of the blades in the wheel is such that the spacing of the blades (misplacement) can be very different from the average pitch for the wheel. The difference sometimes reaches 1.5...2 %, so comparing the current operational measurements with the average step, which may be greater than some inter-blade interval, leads to an incorrect interpretation of the deformation state of the blades.

Thus, when comparing the current deformation states of the blades with the threshold values (set points), the question arises of the reference value relative to which the comparison will be made.

To solve this problem, usually at the beginning of operation, the time intervals between pulses of the peripheral sensor are measured for the responsible operating conditions of the turbine-unit for each blade [10]. The measurements are carried out for a certain number of revolutions of the compressor rotor, then the measured values of the time intervals are averaged and the average base time intervals, as a rule, referred to the rotation period of the rotor, which are taken as basic or reference positions of the peripheral parts (ends) of the intact blades. Thus, a kind of passport of deformation state of the blades of the controlled stage of the compressor is created.

In the subsequent operational period, for each blade, the current values of the time intervals between the sensors are measured and averaged for each blade. Then the obtained results are compared with the corresponding averaged basic (passport) time intervals, after which the magnitude and speed of the discrepancy between the results of the comparison are judged about the occurrence and development of damages or defects of the corresponding blades.
This approach to determining the set-points takes into account the vibrational motion of the blades and, therefore, can serve as an objective justification for finding the basic support positions of the peripheral parts (ends) of the blades by averaging for each blade the required number of measurements in the beginning of the operational regime.

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