Method of measuring the geometry of rotating parts of power stations based on the effect of self-mixing of laser radiation

D V Kulikov, A S Chubov, O Yu Sadbakov, S V Krotov and N N Ovchinnikov
Kutateladze Institute of thermophysics SB RAS, Novosibirsk, Russia
E-mail: kulikov.dmitriy@gmail.com

Abstract. This paper is referred to the development of a method for measuring the geometry of rotating parts of power stations based on the effect of self-mixing of laser radiation. The method is based on spectral analysis of the photodiode signal using narrowband and threshold filtering in the frequency domain. A relative measurement error of 0.5% was achieved when measuring the surface of the rotating rotor modules of the power plant under laboratory conditions.

1. Introduction
Safety and uninterrupted supply of electric and thermal energy is determined by reliable operation of power stations. Timely detection of critical conditions can significantly reduce the cost of repair and restoration work, and in many cases prevent serious man-made accidents. The severity of the consequences of accidents increases with the increase in power and, consequently, the relevance of precision non-contact diagnostic of rotating parts of loaded power stations increases. Non-contact diagnostics of rotating critical parts of power stations is connected with the solution of a number of serious scientific and technical problems [1].

At this moment, the decision on the need to adjust the shape of the stator and the rotor of generators is based on the results of measurements of their geometry in a static state at most power stations. The geometrical parameters of the rotor and stator are manually measured in several positions. At the same time, many researchers note that the air gap between the rotor and the stator in the working generator determined by the geometry can differ significantly from the gap in the static state [2-4].

Measuring instruments based on semiconductor lidars solve the problem better than others. The meters are located far from the area of low concentration of electromagnetic fields, vibration and temperature loads. Such sensors are not damaged when the shaft beats increase (for example, when the turbine of the power station passes through a mechanical resonance).

The purpose of the work is to improve the measurement methods of the increased accuracy for identification of deviations of geometry of the rotating loaded elements of power stations.

2. Method description
The method is based on the principle of frequency modulation of an optical coherent source used in low-coherent semiconductor FMCW lidars. The principle of operation is based on the effect of self-mixing in a semiconductor laser crystal. [5].

The optical frequency of the radiation is modulated by a signal of a certain frequency. The radiation is divided into probing, directed to the object and the reference, which is used as a local generator. When the radiation hits the object, it is re-reflected and a part of the scattered radiation falls back into the semiconductor laser. If the frequency of the radiation of a semiconductor laser is simulated according
to a triangular law, then during the passage of radiation to the object and back, the frequency changes by \( \Delta f \) (Figure 1). The radiation is scattered by a surface of a rotor or the stator mixes up with a radiation generated in a laser crystal.

![Figure 1. The effect of self-mixing in a semiconductor laser, the occurrence of the beat frequency \( \Delta f \).](image)

We obtain the beat frequency of the probe and scattered radiation, analyzing the signal from the photodiode. Speed of the movement of an object in the direction of a vector \( v \) and distance to an object \( D_2 \) are connected with the beat frequency \( \Delta f \) also can be calculated from ratios:

\[
 f_R = \frac{f_1 + f_2}{2} = \frac{4D_2 \cdot \Delta f}{c \cdot T_{mod}}, \tag{1}
\]

\[
 f_D = \frac{f_2 - f_1}{2} = \frac{2 \cdot v_2}{\lambda}, \tag{2}
\]

where \( \lambda \) is the wavelength, other symbols are defined in figure 1.

The implementation of a laser device for monitoring units of power station using semiconductor laser ranging required the use of appropriate methods for processing the received signals. Data processing contains the following main steps:

- calculation of the distance to the rotor surface,
- signal processing of the rotor speed indicator,
- phase averaging over several turns,
- averaging over pole points.

The algorithm of calculation of the distance to a surface can be presented as an algorithm of calculation of frequency with the maximum power of a range by the method of the center of masses:
The received frequency rate is calculated using the narrowband filter of the width of $W$ (defined during calibration) and accounting only frequencies with the power of more than $(A_m/2)$. The value $A_m$ was calculated as the maximum amplitude of a range of a signal after narrow-band filtering (fig. 2):

$$f_{\text{res}} = \frac{\sum_{f=\frac{f_m-W/2}{2}}^{f_m+W/2}(f \ast \text{Cond}(f))}{\sum_{f=\frac{f_m-W/2}{2}}^{f_m+W/2}(Sp(f))},$$  \hspace{1cm} (3)

$$\text{Cond}(f) = \begin{cases} 
Sp(f), & Sp(f) > \frac{A_m}{2} \\
0, & Sp(f) \leq \frac{A_m}{2} \end{cases}.$$  \hspace{1cm} (4)

The method allowed us to reduce significantly the measurement error of the distance to the rotor surface when using the effect of self-mixing of laser radiation.

3. Experimental results

To estimate the measurement error of the distance to the rotating surface of the rotor of the power station, an experimental prototype of the measuring system was created.
A time-frequency analysis of the photoelectric signal was performed. The result is shown in Figure 3.

Figure 3. A time-frequency analysis of the photoelectric signal for 7 seconds.

The self-mixing signal from the photo diode is amplitude-modulated, and the amplitude characteristic of a path has considerable irregularity of frequency. There are several selected frequencies in the spectrum, which significantly impair the operation of the standard FMCW lidar data splitting algorithm, adapted to work with single-frequency spectral distributions. Such nature of a signal is caused by limited coherence of the high-power semiconductor laser with wide strip of the output optical resonator and reorganization of modal structure of laser emission at modulation of a pumping current. Signal processing was supplemented by narrowband filtering in the frequency domain to improve accuracy.

The result of work of the offered algorithm is shown in fig. 4.

Figure 4. The result of frequency measurement using the algorithm presented in the paper.

As can be seen from fig. 4, the offered algorithm provides stability of measurements of distance on the basis of effect of self-mixing of laser radiation at the level of 0.5%.
Conclusion
The method of high-precision measurement of geometry of the rotating parts of power stations is described in this paper. This method is based on the spectral analysis of a signal of self-mixing with application of narrow-band and threshold filtration in frequency area. The relative error of measurements at the level of 0.5% at measurement of a surface of the power station rotating modules of a rotor is reached in laboratory conditions.

Acknowledgments
This work was carried out under state contract with IT SB RAS (AAAA-A18-118051690120-2).

References
[1] Feneyrou P Leviandier L Minet J Pillet G Martin A Dolfi D Schlotterbeck J Rondeau P Lacondemine X Rieu A Midavaine T 2018 Novel Development for FMCW Lidar (Imaging and Applied Optics: Optical Society of America) p SM3H.2
[2] Talas P Toom P 1983 IEEE Transactions on Power Apparatus and Systems 83 WM 226–8
[3] Kulikov D V Anikin Yu A Dvoynishnikov S V Meledin V G 2010 Power Technology and Engineering (Springer US) 44 (5) 416–20
[4] Lundström N Aidanpää J 2007 Journal of sound and vibration (Elsevier) 301 (1–2) 207–25
[5] Zhang X Pouls J Wu M 2019 Opt. Express (OSA Publishing) 27 9965–74