EPJ Web of Conferences **76**, 01003 (2014)
DOI: 10.1051/epjconf/20147601003

Development methods of steam turbines 3D geometry optical control for effective heat power equipment quality improvement

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Abstract. A method for steam turbines 3D geometry optical control for effective heat power equipment quality improvement is proposed. It is shown that technical characteristics of the developed optical phase triangulation method for precision contactless geometry diagnostics of steam turbines meet modern requirements to 3D geometry measuring instruments and are perspective for further development. It is shown that used phase step method provides measurement error less than 0.024% of measurement range.

In the field of increasing dynamic range of phase triangulation methods measurement it is necessary to develop phase steps method for phase field expansion for the purpose of determination an absolute value of phase shift.

Within performance of this work the new method of an optical phase triangulation with an expanded dynamic range of measurement based on phase steps method and pixels binary coding method is offered [1].

Images on a source form sequence of bitmaps (intensity can accept values 0 or 1) which unambiguously codes each pixel on a radiation source. Pixel coordinate restoration algorithm is steady against to images defocusing. This algorithm allows determining pixel coordinate within accuracy to point spread function (PSF) on the accepted image. PSF depends on geometrical arrangement of source and receiver of optical radiation and internal parameters of used optical elements. In combination with phase steps method, the pixel binary coding method provides the greatest possible range of measurement.

Thus, the offered method of an optical phase triangulation for precision contactless diagnostics of steam turbines geometry allows to increase the dynamic range of measurements in more than 10 times. Application of optical phase triangulation method for precision contactless diagnostics of steam turbines geometry, differing expanded dynamic range, will allow to increase the accuracy of turbines production and to increase the modern power effective heat power equipment quality.

We will carry out an assessment of an error of an optical phase triangulation method for precision contactless steam turbines geometry diagnostics. For an assessment of phase definition error we will use that the number of images with various phase shifts N the definition error of phase steady method won't be worse, than an error of phase shift method, on condition of uniform phase shifts distribution on an interval [0, 2Pi]. Phase value of phase shift method is defined by the following expression:

$$\varphi = \arctan \frac{\sum_{s=1}^{N} I_s \sin \varphi_s}{\sum_{s=1}^{N} I_s \cos \varphi_s} \cdot \tag{1}$$

where φ – required phase shift in a point on the image. I_s – intensity value on the image in a point. φ_s – phase shift value in phase pictures.

Source of an error in phase shift definition is the intensity measurement error of images in a point. We will assume that the relative error of intensity measurement doesn't exceed value ${}^{dI}/_{I}$. Then

$$\varphi + \Delta\varphi = \arctan \frac{\sum_{s=1}^{N} I_s (1 + \frac{\Delta I}{I}) \sin \varphi_s}{\sum_{s=1}^{N} I_s (1 + \frac{\Delta I}{I}) \cos \varphi_s}, \tag{2}$$

using the law of mistakes addition it is had:

$$\varphi + \Delta\varphi = \arctan \left(\left(1 + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \right) \cdot \frac{\sum_{s=1}^{N} I_s \sin \varphi_s}{\sum_{s=1}^{N} I_s \cos \varphi_s} \right), \tag{3}$$

$$\tan(\varphi + \Delta\varphi) = \frac{\sum_{s=1}^{N} I_s \sin \varphi_s}{\sum_{s=1}^{N} I_s \cos \varphi_s} + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \frac{\sum_{s=1}^{N} I_s \sin \varphi_s}{\sum_{s=1}^{N} I_s \cos \varphi_s}, \tag{4}$$

$$\tan(\varphi + \Delta\varphi) = \tan \varphi + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan \varphi. \tag{5}$$

Using trigonometric formulas we will receive:

$$\tan \varphi + \tan \Delta\varphi = \left(\tan \varphi + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan \varphi \right) \cdot (1 - \tan \varphi \cdot \tan \Delta\varphi), \tag{6}$$

$$\tan \Delta\varphi = \frac{\frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan \varphi}{1 + \tan^2 \varphi + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan^2 \varphi}, \tag{7}$$

$$\Delta\varphi = \arctan \left(\frac{\frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan \varphi}{1 + \tan^2 \varphi + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan^2 \varphi} \right). \tag{8}$$

We will find φ value, when function will have the maximum value. At the value of φ aspiring to 0, tan (φ) aspires to zero too. Then expression (8) will aspire to arctan(0) = 0. If $\varphi = 90$, tan(φ) will strive for infinity and expression (8) will aspire to zero. Since arctan is a monotonously increasing function, the expression (8) will reach a maximum at a maximum of the following expression:

$$M(\varphi) = \frac{\frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan \varphi}{1 + \tan^2 \varphi + \frac{2}{\sqrt{N}} \cdot \frac{\Delta I}{I} \cdot \tan^2 \varphi} \cdot \tag{9}$$

Expression (9) accepts the maximum value at the minimum value of expression:

$$K = \frac{1}{\tan\varphi} + \tan\varphi\left(1 + \frac{2}{\sqrt{N}}\cdot\frac{\Delta I}{I}\right). \tag{10}$$

Expression (10) accepts the minimum value if K ($\tan(\varphi)$) accepts the minimum value. From an function K extremum condition it is had:

$$K'(\tan\varphi) = 0 \tag{11}$$

$$-\frac{1}{\tan^2\varphi} + 1 + \frac{2}{\sqrt{N}}\cdot\frac{\Delta I}{I} = 0. \tag{12}$$

We receive that expression (8) will accept a maximum at:

$$\tan\varphi = \sqrt{\frac{1}{1 + \frac{2}{\sqrt{N}}\cdot\frac{\Delta I}{I}}}. \tag{13}$$

Then φ will be estimated by expression:

$$\Delta\varphi = \arctan\left(\frac{1}{\sqrt{N}}\cdot\frac{\Delta I}{I}\cdot\sqrt{\frac{1}{1 + \frac{2}{\sqrt{N}}\cdot\frac{\Delta I}{I}}}\right). \tag{14}$$

Therefore, the relative measurement error based on initial phase shift measurement will be expressed:

$$\theta = \frac{\Delta\varphi}{\pi} = \frac{\arctan\left(\frac{1}{\sqrt{N}}\cdot\frac{\Delta I}{I}\cdot\sqrt{\frac{1}{1+\frac{2}{\sqrt{N}}\cdot\frac{\Delta I}{I}}}\right)}{\pi}, \tag{15}$$

The range of measured phase values is limited by a sinusoid half-cycle π.

We will construct dependence θ of value k:

$$k = \frac{1}{\sqrt{N}}\cdot\frac{\Delta I}{I}, \tag{16}$$

Then at $k \to 0$

$$\theta = \frac{\arctan\left(k\cdot\sqrt{\frac{1}{1+2k}}\right)}{\pi} \approx \frac{k}{\pi}, \tag{17}$$

or

$$\theta = \frac{\Delta I}{\pi\cdot\sqrt{N}\cdot I}. \tag{18}$$

Then the relative measurement error caused by phase steps method will be estimated

$$\theta = \frac{\Delta I}{\sqrt{N}\cdot I}, \tag{19}$$

as the arctan function range in which it accepts univocity is equal π.

Received analytical assessment of measurements error, caused by phase steps methods, allows to estimate an error of three-dimensional geometry measurement method based on existential modulation of optical radiation source.

We will estimate an error of phase steps method measurement of 3D geometry which can be reached, using the modern equipment. The relative error of a path source – receiver of optical radiation can be estimated:

$$\frac{\Delta I}{I} = 2^{(1-b)}, \tag{20}$$

where b is a number of the bits coding a colors depth of optical radiation source. Modern digital video cameras provide depth of color 14 and more than bits for the channel (for example, Leaf Digital Camera Black). LCD projectors which can be used as spatially modulated source of optical radiation, provide depth of color of 8 bits on the channel. In expression (20) we will take value b equal 8 for an assessment of measurement error. Then, the relative error of source-receiver path of optical radiation can be estimated as 0.0078. Suppose that in our realization of optoelectronic measuring system the number of the radiated images having various initial phase shifts $N = 1000$. Then the relative 3D geometry measurement error of optoelectronic method based on existential modulation of optical radiation source, caused by use phase steps method will be 0.024%.

It is shown that the technical characteristics of the developed optical phase triangulation method for precision contactless geometry diagnostics of steam turbines are perspective for further development and meet modern requirements to 3D geometry measuring instruments. The measurement error caused by phase steps method will be less than 0.024% of measurement range.

Reference

[1] Dvoynishnikov S. V., Shpolvind K.V. Optical phase triangulation metod with expanded dynamic measurement range / “Topical issues of thermophysics and physical hydro- gas dynamics” theses of reports on the X International conference of young scientists, Novosibirsk, 2012. – p.39