Contactless Operational Identification of Turbine Blade Stress and Vibration

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Abstract: The study deals with the contactless vibrodiagnostic system used for identification of steam turbine blade stress and vibration. The tip-timing method based on the evaluation of time differences of blade passages in different rotor revolutions is described and the results of the development of a new contactless magnetoresistive sensor are presented. A new approach to the identification of blade stress and vibration based on the analysis of the amplitude differences of impulse blade signals is applied.

Keywords: Stress, Vibration, Blade, Turbine, Analysis

1. Introduction

Contactless vibrodiagnostic system VDS-UT has been developed in the Institute of Thermomechanics of the Academy of Sciences of the Czech Republic, v.v.i. Design and construction of this system is based on previous versions of measuring systems elaborated in the Institute for investigation of static and dynamic characteristics of blade vibration of low-pressure stages of steam turbines. The default method of these systems is so called tip-timing method, utilizing time differences comparison of passages of single blades along position sensors in different rotor revolutions. Contactless position sensors are placed usually uniformly along a circumference of a turbine stator. Amplitudes and frequencies of blade vibration are determined as a result of a relatively complex calculation procedure. An estimate of blade operational stress can be performed on the basis of the analysis of circumferential components of blade vibration amplitudes. Replacing previously used inductive sensors by magnetoresistive (MR) sensors in the system VDS-UT, a new approach to the calculations has been recently introduced.

2. Method of Time Differences in Contactless Vibrational Analysis of Rotating Turbine Blades

The principle of the contactless vibrodiagnostic system can be seen from the block diagram of the 8-channel system in Fig.1.The contactless sensors S1 to S8 placed uniformly around the stator generate impulse signals by passages of each turbine

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blade tip. The sensor S0 detects the passages of a magnetic reference mark attached to the turbine rotor shaft.

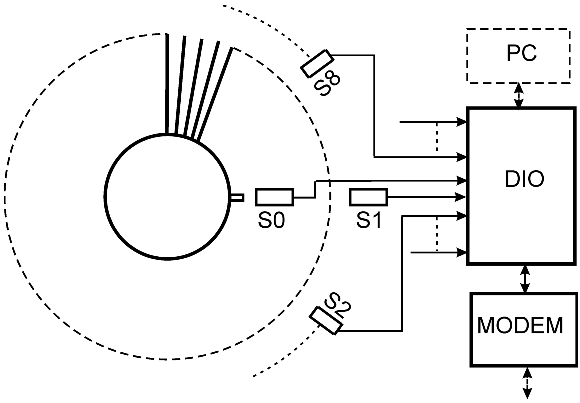

Fig. 1. Block diagram of the contactless vibrodiagnostic system.

Impulse output signals of the sensors *S0* to *S8* are digitized and connected to the central measuring unit DIO (Digital Input-Output). This unit includes a precise counter and, as the result, a numerical value of time is assigned to each generated pulse. The time data complemented by a sensor address and auxiliary operational readouts are sent to a local or distant (via modem or net) computer (PC). Time differences of each blade passage are calculated and transferred to circumferential deflections and subsequently to blade bending deflections. Using the algorithm of DFT, the amplitudes and frequencies of vibration of all blades can be ascertained. This method is referred as a time-difference method or tip-timing.

The time-difference method is based on a precise measurement of time values t_{ijk} with necessary resolution up to 10 ns, when the k-th blade (k= 1, 2, ..., n_B) passes in the j-th revolution along the sensor Si (i= 1, 2 , ... , n_S). The data acquisition process takes m revolutions (j= 1, 2, ..., m). Assuming system with $n_S = 8$ sensors, we can express the differences of the time events t_{ijk} related to the time reference t_{i0jk} for the k-th blade in *the j-th* revolution as a vector

$$\{ dt_{1jk} = t_{1jk} - t_{10jk},\ dt_{2jk} = t_{2jk} - t_{20jk}, \dots,\ dt_{8jk} = t_{8jk} - t_{80jk} \} \tag{1}$$

Selecting subsequently proper elements from all m vectors (1), we obtain after a permutation a sequence of time differences describing behaviour of a k-th blade

$$\mathcal{D}_k = \{d_{11k}, d_{21k}, \dots, d_{81k}, d_{12k}, \dots, d_{82k}, \dots, d_{8mk}\}. \tag{2}$$

The sequence of time differences in (2) can be transferred to the sequence of deflections of the k-th blade in the circumferential direction

$$Y_k = 2\pi f_r R\, \mathcal{D}_k, \quad k = 1,2,\dots, m, \tag{3}$$

where f_r = rpm/60 is the rotational frequency of the bladed wheel, R is the radius of the blade tips. Assuming that the circumferential deflections are caused exclusively by the blade bending, the sequence of samples describing the bending movement of the blade can be expressed as

$$\mathcal{V}_k = Y_k \sin\alpha = \{ v_1, v_2, ..., v_N \}_k \,,\; N = m \,.\, n_S \,,\; k = 1,2,\ldots, m \,, \tag{4}$$

α is the blade angle to the circumferential direction, N is the total number of samples of the sequence of the bending deflections v_i . Frequency analysis of the bending vibration of the k-th blade is performed by the discrete Fourier transform (DFT)

$$X_l = \sum_{n=0}^{N-1} v_n e^{-\frac{2\pi i}{N} ln} = \mathcal{F}(\mathcal{V}_k) \,,\; l = 0,1,\ldots, N\text{-}1 \,. \tag{5}$$

Writing X_l in polar form, we immediately obtain the amplitude and phase spectrum

$$A_k = | X_l | \,,\; \varphi_k = \arg(X_l) \,, \tag{6}$$

respectively. The calculation of the amplitude spectrum is usually followed by a procedure of selecting and arranging the spectral components in order of their priority.

Estimation of the value of stress in the root of a blade corresponding to a determined bending deflection is performed on the basis of either a previous static calibration or a simultaneous operational tensometric measurement. The static calibration can be realized by a simultaneous measurement of tip deflections and strain in the root of a fixed blade. Resonant vibration of the blade has to be excited by a heavy-duty vibrator or a power electromagnet. Measurement of blade tip deflections can be advantageously realized by a laser vibrometer; corresponding strain in different locations of the blade root can be ascertained by a strain gauge system. More precise values are provided by an operational calibration, which demands embedding of a radiotelemetric system into the turbine and is consequently more expensive. The error of the static calibration ranges from 10 to 20%, whereas the error of the operational calibration is less than 5 %. It can be written

$$\sigma(t) = Q[v(t)] \quad \text{or} \quad v(t) = Q^{-1}[\sigma(t)], \tag{7}$$

where Q represents the operator of the calibration process and $\sigma(t)$ and $v(t)$ designate the bending stress and a tip deflection in time domain, respectively.

For example, for the blade 590 mm used at the power station Temelín, the values of Q = 11.8 MPa/mm and Q = 114 MPa/mm were ascertained for the first mode of vibration (170 Hz) and for the second mode of vibration (280 Hz), respectively.

The described system is capable of operation in various alternatives. The simplest version involves one reference sensor S0 and one stator sensor S1. This system has been in operation at the power plant Prunéřov II since 2005. However, the simplicity of this configuration induces several disadvantages. Low sampling rate (50 Hz at 3000 rpm) and consequently narrow frequency band of the DFT (25 Hz) are the most substantial sources of errors. Moreover, rotor speed instability and torsion vibrations of the rotor cannot be in the case of this simple system eliminated.

Increasing the number of stator sensors, the frequency band of the vibrodiagnostic system correspondingly expands. For example, the system with 8 stator sensors features the frequency band of the DFT of 200 Hz, which appears to be sufficient for most practical applications. A father step to improve the contactless vibrodiagnostic system is to increase the number of reference marks on the rotor. Sufficient number of rotor marks enables to eliminate rotor speed changes and torsion vibrations of the rotor mentioned earlier. Using more radial reference sensors or involving an axial reference sensor in the system enables to achieve a more precise elimination of interfering motions of the rotor. In the vibrodiagnostic system developed in the Institute of Thermomechanics for the power station Temelín were used 8 stator sensors, 2 radial reference sensors, 8 reference rotor marks and 1 axial reference sensor sensing the passages of holes under blade roots.

3. Magnetoresistive sensors

Further improvement of the vibrodiagnostic system can be accomplished by using sensors operating on a suitable principal. Generally, optical, induction and capacity pick-ups are used for contactless sensing of instantaneous position of moving machine parts. Novel sensors based on the magnetoresistive principal have been developed for the purpose of contactless position sensing of a structure in the Institute of Thermomechanics [2]. These sensors have not only brought higher accuracy and better dynamic characteristics of the sensing process, but have also promoted introducing the method of amplitude differences.

MR sensors consist of a magnetoresistive pick-up and either internal or external source of a magnetic field. These sensors allow sensing rapid changes of magnetic field with a frequency range up to 10 MHz and thus feature wide measuring range of velocity from 0 m/s up to 700 m/s at a distance from a moving blade up to 10 mm. Temperature range up to 200°C by 100% humidity can be achieved by a suitable construction of the sensors, including resistance to erosion caused by water drops.

A necessary condition for the use of MR sensors is that blades are made from a magnetic material. The source of the magnetic field can be formed directly by the magnetized blades. Using an internal source of magnetic field located inside the sensor, e.g. permanent magnets, forms a more convenient variation with a higher stability of the magnetic field. In this case, however, the blades should be thoroughly demagnetized. An example of this arrangement can be seen in Fig. 2. The resulting intensity of the blade magnetic field can be expressed as

$$H_b = \frac{m}{4\pi\mu_0 r^3}\sqrt{4\cos^2\gamma + \sin^2\gamma}\,, \tag{8}$$

where $m = J.V$ is the magnetic moment of the magnet, J is magnetic polarization in a magnet volume V, r is the distance between the middle point of the permanent magnet and a selected point of the blade tip, γ is the angle between the line connecting these two points and the axis of the magnet.

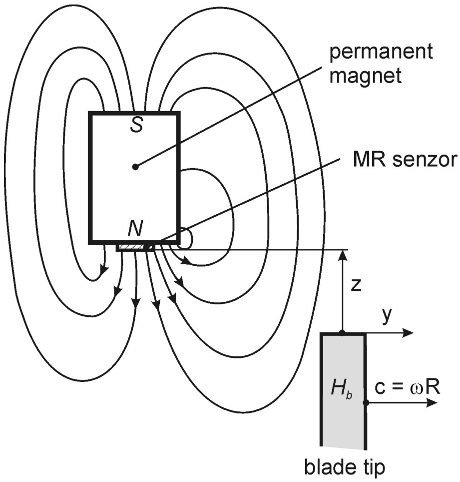

Fig. 2. Change of direction and distribution of magnetic field lines by moving blade tip.

A movement of a blade tip in the magnetic field of the permanent magnet has a consequence of a change of the direction and distribution of the magnetic field lines, which induces a change of an electrical resistance of the magnetoresistive pick-up. Used magnetoresistors of the brand Philips are based on the magnetoresistive phenomena of a thin layer of magnetic material permalloy. The dependence of the resistance R of the pick-up on the angle β of the intensity of the resulting magnetic field has an anisotropic character

$$R = R_0 + \Delta R \cos^2 \beta , \tag{9}$$

R_0 is the resistance of the magnetoresistive element by the intensity of the magnetic field H=0, $\Delta R=(R_{max} - R_{min})/2$, R_{max} is the resistance R by β=0, R_{min} is the resistance R by β=90°. Produced pick-ups have layers of permalloy coated by skew aluminium stripe layers with a consequence of the shifted current direction in the layer by ± 45°, which enables to create an active bridge of these elements. The advantages of this arrangement are a quadruple increase in sensitivity, compensation of temperature dependence of the sensor, and particularly common-mode signal rejection, which is important especially in operational conditions.

As follows from the expressions (8) and (9), the output bridge voltage of the magnetoresistive sensor U_S is a function of the intensity and direction of the magnetic field and it can be written as

$$U_S = c_S \ U_N \ H_{S0} \sin 2\beta \, , \tag{10}$$

c_S [m/A] is the sensitivity of the sensor, H_{S0} [A/m] is the value of the resulting intensity H_S of the vector of magnetic field to which is the sensor exposed by y=0, β is the angle between the axis z and the direction of H_S. Using a supply of the bridge with a constant current I, the temperature dependence of the sensitivity c_S can be reduced to approximately a four time less value and the supply diagonal voltage drop can be used for the measurement of the internal temperature of the sensor.

The behaviour of a MR sensor and the level of the output voltage at the sensor bridge during a blade passage with a circumferential velocity $c=\omega R$ can be seen in Fig. 3. The adjacent graph in Fig. 3 shows the measured dependence of the peak-to-peak value of the output sensor volage $U_{Sp\text{-}p}$ on a distance z between the sensor and the tip of the blade 590 mm. A necessary requirement for the symmetry of the negative and positive pulses generated by a blade passage and equality of amplitudes ($|U_{Smax}|=|U_{Smin}|$) is the symmetry of orientation of the magnetoresistive pick-up in the direction y.

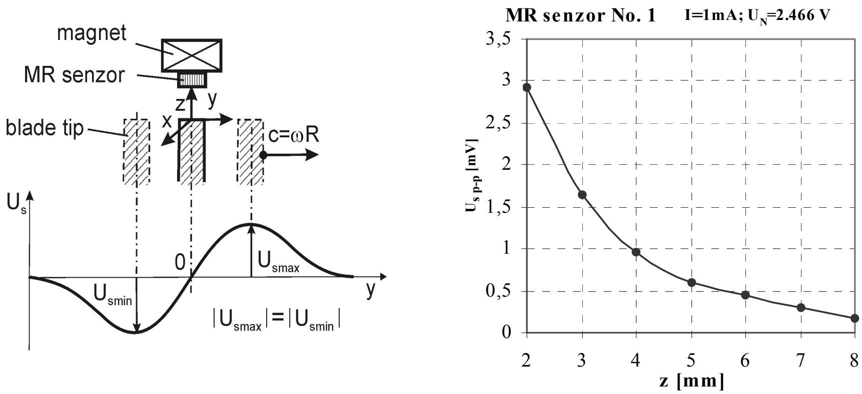

Fig. 3. Course of the output voltage of a magnetoresistive bridge by a blade tip passage; dependence of the peak-to-peak output voltage on a distance z between the sensor and a blade.

Results of measurements of static characteristics of the same sensor No.1 are presented in Fig.4. The data have been obtained by measurements on the precise positioning desk realized with the blade 590 mm used in the power station Temelín. As can be seen, the amplitudes of the generated pulses are dependent on the distance z between the sensor and the blade. Very important fact for the measurements by means of the method of time differences is that all curves go through the zero voltage level in the same time instant. In other words, the time of the passage of the output voltage of the sensor through the zero level is independent on radial blade distance, and measurements of circumferential blade deflections can be performed on the basis of precise time measurement.

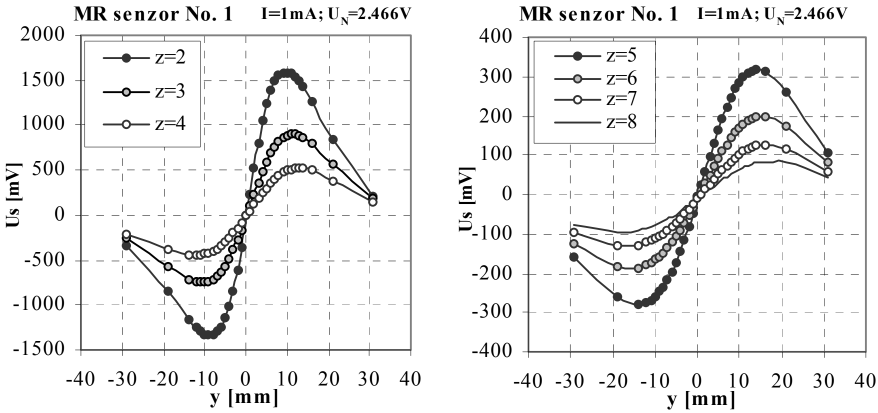

Fig. 4. Static characteristics of the MR sensor No.1: Output voltage in dependence on circumferential a distance *y* and a radial distance *z* between the sensor and the blade 590 mm.

Dynamic characteristics of the developed MR sensors have been tested on the experimental bladed wheel of the Institute of Thermomechanics. Special testing equipment has been developed to establish accuracy of the MR sensors. Impulse magnetic field with a frequency from 0 to 10 kHz has been generated to simulate passages of a blade along the tested sensor. Both rising and falling edges of the sensor output signal were below 0.1µs. Typical delay of the signal was 1 µs with a reproducibility better than 10 ns. On the basis of static and dynamic tests a new type of the MR sensor has been developed and used in the vibrodiagnostic system VDS-UT operating at the power plants Prunéřov II and Temelín.

4. Method of amplitude differences

The amplitudes of MR sensor output voltage are indifferent to the velocity of blades in a wide range of rpm. Measuring amplitudes of impulses belonging to single blades and evaluating their differences (see Fig. 5) in every *j*-th revolution, we obtain after a conversion a sequence of samples $\{b_j\}$ j=1,2,..,m of a quantity $b(t)$, which represents deflections of a selected blade due to a vibration.

Supposing a harmonic vibration, a non-linear regression model can be formulated

$$a_0 + a_m \cos(2\pi f_0 t - \varphi) = b(t) \ . \tag{11}$$

The aim of the identification is to ascertain the coefficients $\{a_0, a_m, f_0, \varphi\}$ from the measured discrete values $\{u_{ijk}, t_{ijk}\}$. At first, an estimate of coefficients $\boldsymbol{a_0}$ and $\boldsymbol{a_m}$ is obtained from

$$\boldsymbol{a}_0 = \left(\boldsymbol{a}_{\max} + \boldsymbol{a}_{\min}\right)/2 \,; \quad \boldsymbol{a}_m = \left(\boldsymbol{a}_{\max} - \boldsymbol{a}_{\min}\right)/2 \,, \tag{12}$$

then the equation (11) can be rewritten in a matrix form [4]

$$\boldsymbol{A}\,\boldsymbol{x} = \boldsymbol{b} \quad \text{with a solution} \quad \boldsymbol{x} = \boldsymbol{A}^{-1}\boldsymbol{b} \,, \tag{13}$$

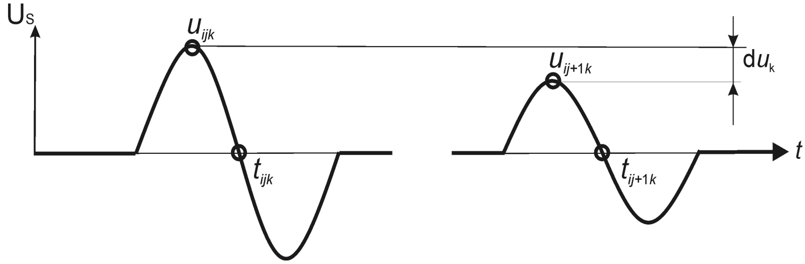

Fig. 5. Measuring of amplitude differences at the output of a MR sensor.

$$A = [\cos 2\pi f_0 t; \sin 2\pi f_0 t], \quad x = \left[\begin{smallmatrix} cos\varphi \\ sin\varphi \end{smallmatrix} \right], \quad b = [(a_m - a_0)/a_m]. \qquad (14)$$

The expected values of frequencies of blade vibrations f_0 for particular mode shapes are determined by tensometric measurements or by using the procedures of the time-difference method following the eqs. (1) to (6). Additional characteristics of the blade movements are obtained (e.g. blade prolongation and untwisting) and components of shaft vibration can be calculated and then eliminated.

5. Conclusions

After many years of intense research and development, the contactless vibrodiagnostic methods have been improved in the Institute of Thermomechanics, which resulted in the operational utilization of the contactless systems VDS-UT at the power stations Prunéřov II and Temelín. New magnetoresistive sensors have imposed further development of the contactless vibrodiagnostic methods. These sensors feature wide operational velocity range of blade tips in the range from 0 m/s to 700 m/s with a constant value of the output voltage amplitude. The original tip-timing method based on the precise measurements of time differences has been extended by the method of amplitude differences. This method enables to measure not only vibration and stress of particular blades, but also orbits of the bladed turbine wheel and components of the shaft movements.

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