A novel method for localization of rotor-stator rub in steam turbines

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Abstract—The rotor-stator rub has become a pretty common phenomenon in terms of steam turbines operation in last couple of years. The reason is that clearances in flow paths of the turbines get smaller and smaller along efforts towards efficiency increase. This paper introduces a novel method based on vibration signal processing to localize rotor-stator rub in rotating machinery. The presented method utilizes the standard sensor installation in several measurement planes of the steam turbine. To investigate the behavior of the rub induced signals a Rayleigh-Lamb description of the stress waves propagation is discussed. This paper covers not only the introduction of procedures for rub signal pre-processing but also the method of automatic wave arrival time determination. The proposed localization method was tested during experiments on rotor stand and also in operation of steam turbine. Finally the accuracy of localization results was verified after an inspection of the steam turbine during the outage.

Keywords— Rotor-stator rub, localization, steam turbine, monitoring.

I. INTRODUCTION

During the operation of steam as well as gas turbines, in some situations, such as during the start-up of a turbine, when the rotor is overcoming its natural frequencies and its vibrations are at the highest level, undesirable rubbing between the stator and the rotor may occur („rotor-stator rub“ or „rubbing“). In the first phase of this rubbing it is especially the seals arranged between the rotating and statical parts of the turbine that are abraded, and, as a result, the amount of leaking medium increases and the turbine efficiency decreases. In cases when rotor-stator rubbing is not detected in time and is not eliminated by an appropriate intervention of the machine operator, such as by changing the running speed during the start-up or run-down, or by changing parameters of the jacking oil during the operation on a turning gear, both the rotor and the stator may be heavily damaged, or an breakdown of the whole turbine leading to considerable economic losses may occur.

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The rotor-stator rubbing may be either partial, when the rubbing between the rotor and the stator is brief, but at least several times repeated, or it is full annular rubbing, i.e. a continuous or almost continuous rubbing between the rotor and the stator. Nevertheless, the full annular rotor-stator rubbing is always preceded, at least for a short time, by the partial rotor-stator rubbing, see [1].

At present, detection of the partial rotor-stator rubbing is based especially on offline analysis of vibration signals, when during the measurements the machine operator monitors the overall level of vibrations as well as the phasor of the first harmonic component of the rotational frequency in vibration signals [2]. If a step change occurs in overall vibration, or in rotation of the phasor of the first harmonic component with variable or periodically varying amplitude, rotor-stator rubbing is detected, and after terminating the measurements a detailed data analysis is carried out with the purpose of excluding the possibility of false positive detection. Therefore this approach is not suitable for detecting rotor-stator rubbing during the real operation of the turbine and can only be used for laboratory research or experimental purposes.

Another approach [3] for detecting partial rotor-stator rub is based on the fact that apart from the change in the phasor of the first harmonic component of the vibration signals, the rubbing is also accompanied by formation of subharmonic spectral components, whose frequency corresponds to the frequency of impacts of the rotor on the stator. Nevertheless, the disadvantage of detecting rotor-stator rubbing based on monitoring these subharmonic components is the fact that the frequencies of some of them are too close to frequencies indicating other defects, such as the instability of the oil film in the slide bearing, etc., which may result in false positive detection of rotor-stator rubbing, or, on the contrary, in wrong interpretation of expresses of this rubbing as defects of different type. Authors of the paper have developed a monitoring system RAMS (Rub Advanced Monitoring System) which implements methods for detection of the rotor-stator rub and triggers the data for following localization procedure [4].

In this paper a novel method for localization of rotor-stator rub is proposed and verified in the operation of steam turbines. Currently, there is only few known and in practice applicable methods for localization of rubbing in steam turbines. Important is the method based on the measurement of acoustic emission (AE) on the bearing pedestals described in [5]. The authors use the replica of real labyrinth seal slices to induce
rubbing on experimental stand. A special holder allows pushing the seal against the rotor with a force up to 140 N. Within this experiment, the shaft was in contact throughout the revolution, which is a special type of rub (full annular rub). Measuring acoustic emission in the frequency range from 100 kHz to 1.2 MHz the authors concluded that the full rub expresses itself as amplitude modulation of the measured signal. The smoothed RMS values were after that calculated from the signal using Savitsky-Golay filter. Based on the course of the smoothed RMS values it was possible to estimate the rub origin and use the linear localization to determine the contact location.

II. LINEAR LOCALIZATION PRINCIPLE

Linear localization principle can be applied in cases where the excitation generated by the rub event spreads from the source of excitation on a straight line in both directions and at the same velocity. If the excited impulse is measured in at least two measuring points and we are able to determine the exact moment of the arrival time to the measurement position, then the knowledge of measurement points distance, spread velocity in the material, and the difference in wave arrival times make it possible to calculate the position of the excitation source relative to one of the measurement points. When measuring in more than two points it is possible to refine the existing results or to exclude the propagation velocity parameter from the calculation. Sample linear localization using two sensors is shown in Fig. 1 (top).

Let's consider the total distance $L$ between the sensors $S_1$ and $S_2$. Let the distances of sensors $S_1$ and $S_2$ from the excitation sources are $L_1$ and $L_2$. The time of arrival of the impulse to the individual sensors $S_1$ and $S_2$ is $t_1$ and $t_2$. Then apply the following:

$$L = L_1 + L_2$$  \hspace{1cm} (1)

$$t_2 = t_1 + \Delta t$$  \hspace{1cm} (2)

The equation (1) can be modified as follows:

$$L = vt_1 + v(t_1 + \Delta t),$$  \hspace{1cm} (3)

where $v$ is propagation velocity of the stress waves in rotor. From previous relations follows:

$$L_1 = \frac{L - v\Delta t}{2}$$  \hspace{1cm} (4)

To determine the distance from the excitation source to one of the sensors is therefore necessary to know the distance between sensors, time difference of the event detection for both sensors and the propagation velocity in rotor material. The knowledge of the last parameter is very problematic and because the most of the rub impulses propagate through the rotor nonlinearly (dispersive waves) and the transmission path from the source to the sensor is complex, a linear localization in this case is mainly approximative. When the velocity of the rub wave propagation is properly selected and when a sufficient number of partial rub events are processed then the linear localization is successfully applicable based on a statistical evaluation of the results. The velocity evaluation of the impulse propagating from the rub origin to the sensor positions (4) depends on the method used to process the measured signals.

If we measure on the machine more than in two measuring planes, it is possible to exclude the propagation velocity from the calculation (assuming a constant impulse propagation velocity). This case is illustrated in Fig. 1 bottom.

Again, we assume that the source of excitation is located on the right side from the sensor $S_1$ and in the distance $L_1$. If it is possible to detect an event on all three sensors, then the propagation velocity could be determined from the time differences between rub impulse arrival times of sensors $S_2$ and $S_3$ (with knowledge of the distance).

$$v = \frac{L_3}{t_3 - t_2}$$  \hspace{1cm} (5)

Thus, (4) could be modified to the following form:

$$L_1 = \frac{(t_3 - t_2) L - \Delta t L_3}{2(t_3 - t_2)}$$  \hspace{1cm} (6)

Similar relations can be derived also for other relative positions of the excitation source and sensors. A more detailed analysis of this task is given in the following chapters.

III. DISPERSIVE CHARACTER OF THE STRESS WAVES PROPAGATION AFTER RUB IMPACT

Measured rub signals mainly contain running vibrations of monitored machinery ( rotor x stator ). An impact pressure wave propagates from the place of origin through the wave fronts and, along its trajectory, is subject to various deformations, reflections and damping. Reflected waves and other impact waves further deform the signal. Superposition of the impact wave fronts and current running vibrations is
measured and monitored at specific measurement planes of the turbine. The essential task of the diagnostic system based on vibration data analysis is to recognize the presence of impact wave fronts from the measurements.

An impact signal is similar to the impulse response of a slightly damped mechanical system, the so called burst shape signal. Signal reaches its maximum relatively fast (in milliseconds) but its overall length is in tens of milliseconds. With increasing distance of impact from sensor, the burst leading edge increases, signal maximum decreases and the signal-noise ratio decreases.

Vibrations propagate from the impact origin as a multimode waveform, whose damping and velocity are dependent on the dominant wave mode. Propagation velocity of a particular waveform mode is described by the so called dispersive curves (see [7] or [8]), which describe velocity dependence on frequency. It is possible to analytically describe the particular wave modes solving the Rayleigh-Lamb equations. Hence, the resulting waves are called Lamb waves. Analytical model of dispersive curves (Lamb curves) is the following:

\[
\tan(qh) - \tan(ph) = \frac{4\kappa^2 pq}{(q^2 - \kappa^2)^2} \\
\tan(qh) = \frac{4\kappa^2 pq}{(q^2 - \kappa^2)^2}
\] (7)

where \(2h\) is the material thickness, \(\kappa\) is the wave number, power of +1 is used for symmetric Lamb waves and power of -1 for antisymmetric ones. Variables \(p\) and \(q\) are defined as follows:

\[
p = \left( \frac{\omega}{c_L} \right)^2 - \kappa^2, \quad q = \left( \frac{\omega}{c_T} \right)^2 - \kappa^2 \quad \text{and} \quad \kappa = \frac{2\pi}{\lambda}.
\] (8)

where \(\omega\) is frequency, \(\lambda\) is wavelength, \(c_L\) and \(c_T\) are longitudinal and transversal wave propagation velocities for the current material. Wave number \(\kappa\) is thus the number of oscillation periods per a unit of length. Equation (7) can be transformed into the following form for symmetric modes

\[
\tan(qh) - \tan(ph) = \frac{4\kappa^2 pq}{(q^2 - \kappa^2)^2} = 0
\] (9)

and the following form for antisymmetric modes

\[
q \tan(qh) + \frac{(q^2 - \kappa^2) \tan(ph)}{4\kappa^2 p} = 0.
\] (10)

Real roots of the above mentioned equations are especially significant. They represent the undamped propagation of the Lamb waves in the material structure. Resulting dependency of the wave number \(\kappa\) on the frequency \(f\) (\(\omega = 2\pi f\)) is displayed in Fig. 2. It shows the solution of (3) and (4) which was computed for a steel plate (\(c_L = 5900\) m/s; \(c_T = 3100\) m/s) with thickness of 10 cm. Individual modal groups are distinguished by color: blue – symmetrical; red – antisymmetrical mode.

In reality, waves in the material propagate in the form of packets (groups). Velocity of these packets is given by the so-called group velocity \(c_g\), which is described by the following formula:

\[
c_g = \frac{d\omega}{d\kappa}.
\] (11)

![Fig. 2 Solution of (9) and (10) in wave number – frequency domain.](image)

The dependency of the group velocity \(c_g\) on the frequency \(f\) is displayed in Fig. 3.

![Fig. 3 Dispersion curves - representation of group velocity \(c_g\) depending on frequency \(f\).](image)

IV. SIGNAL PROCESSING FOR RUB LOCALIZATION

In the case when the contact between the rotor and stator does not occur, there are only fundamental oscillations of the rotor monitored by the sensor. These vibrations should be considered as stationary when considering constant rotation speed.

A. A method based on computation of moving variance

One possibility to determine the rub wave time of arrival is
to monitor the signal variance. Due to the nonstationary signal character during the rubbing phase an appropriate recursive algorithm for signal mean and variance estimation should be applied. If we choose a recursive least squares method with exponential forgetting, then the equations for estimated mean and variance have the following form:

\[ m(t) = \lambda m(t - T_s) + (1 - \lambda) x(k) \]
\[ s(t) = \lambda s(t - T_s) + (1 - \lambda) (x(t) - m(t))^2, \]

where \( m(t) \) and \( s(t) \) denotes the estimated mean value, and variance in time \( t \). The parameter \( \lambda \) is the forgetting factor.

The relation between the forgetting coefficient and time constant of the filter is as follows

\[ \lambda = 1 - \frac{1}{f_s \tau}, \]

where \( f_s \) denotes the sampling frequency.

In Fig. 4 there is time behaviour of the measured rub vibration signal (gray) together with the result from recursive estimation of moving variance (black). Automatically detected arrival time of the wave (the beginning of the leading edge) is shown with a cross. It can be seen that the position of the cross corresponds with the beginning of the impulse leading edge. The method of impulse arrival time detection will be presented in the following text. In cases when the effective signal of the rub impulse is masked by the machinery running vibrations, the suitable waveform filter should be applied (windowed sinc filter was successfully tested on operational signals from steam turbine).

**B. A method based on instantaneous amplitude computation**

Another characteristic that describes the changes of signal oscillations is the envelope. Let's consider a complex signal \( z(t) \) in the following form:

\[ z(t) = z_r(t) + jz_i(t) \]

The envelope or instantaneous amplitude is defined as the modulus of the complex signal (16)

\[ A_i(t) = |z(t)|. \]

Definition of signal instantaneous amplitude is also important for multi-component signals (unlike the instantaneous frequency). Firstly, it is necessary to calculate the complex signal imaginary component when applied to real signals. Useful method to do this is the Hilbert transform defined as follows:

\[ H[z_r(t)] = \frac{1}{P} \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau, \]

where \( P \) denotes the Cauchy principal value. The real part of the analytic signal \( z(t) \) is formed by the measured signal \( z_r(t) \) and the imaginary component is the Hilbert transform:

\[ z(t) = z_r(t) + jH[z_r(t)] \]

In Fig. 5, the vibration signal (gray) together with time behaviour of instantaneous amplitude is displayed. Again, the cross sign indicates the detected time of rub wave arrival.

**C. A method based on signal stochastic normalization**

The principle of stochastic normalization was described in [6] and the method is based on normalization of each frequency line of the amplitude spectrogram by its estimated mean and standard deviation, which are determined recursively. Originally, this method was applied to a spectrogram calculated using a discrete short-time Fourier transform. However, this method of normalization is able to normalize any of the time-frequency representations of the vibration signal. The results reported in this paper have been obtained by application of stochastic normalization on approximation of continuous Gabor transform [9]. Gabor transform is a special case of continuous short-time Fourier transform, where the Gaussian function is used as a window. Gabor transform of a signal \( x(t) \) is defined as

\[ G(t,f) = \int_{-\infty}^{\infty} x(\tau) e^{-\frac{\pi}{\tau^2}} e^{j2\pi ft} d\tau. \]
Changing the parametr $\sigma$ the resolution of the time-frequency spectrogram could be changed. The result of the stochastic normalization is the function $G_n(t,f)$.

$$G_n(t,f) = \frac{G(t,f) - M(t,f)}{S(t,f)} \tag{20}$$

The functions $M(t,f)$ and $S(t,f)$ are determined from the following recursive computation formula:

$$M(t,f) = \lambda M(t-T_s,f) + (1-\lambda)G(t,f) \tag{21}$$

$$S(t,f) = \lambda S(t-T_s,f) + (1-\lambda)(G(t,f) - M(t,f))^2$$

where the parameter $\lambda$ has the same meaning of forgetting factor as in the section A.

![Figure 6](image1.png)

**Fig. 6** Stochastic normalization of signal $x(t)$ - time domain (top), amplitude spectrogram (middle) and normalized amplitude spectrogram (bottom).

This method uses a similar principle for detecting the impact in the signal, such as the method based on calculation of the signal moving variance, i.e. the suppression of the stationary signal components and on the contrary highlighting the nonstationary components. The difference is that the method of stochastic normalization is applied not in the time domain, but onto the time-frequency representation. The origin of the nonstationary components in the signal can be detected using the resulting $k$-value. It describes the overall change of the amplitude normalized spectrogram in a certain frequency band and can be defined as follows:

$$k(t) = \frac{\int_{f_s}^{f_e} G_n(t,f) df}{f_e - f_s} \tag{22}$$

The original rub signal with the corresponding $k(t)$ value are shown in the top part of the Fig. 6. In the middle of the Fig. 6, there is an amplitude spectrogram, where the broadband excitation associated with the rub impact is evident. In the bottom part of the figure, the normalized amplitude spectrogram calculated with parameter $\lambda=0.995$ is shown. Due to the normalization, the impact can be detected also in frequency bands where it was not significant in the former amplitude spectrogram.

**D. A method based on spectral variance computation**

It is also possible to use function $S(t,f)$, which was defined in (21) to detect impacts in signal. This function carries the information about origination of nonstationarity in signal. In the same manner as in section C, the characteristic k-variance value $k_s$ can be introduced. This value describes the transient changes of the signal in summary.

$$k_s(t) = \frac{\int_{f_s}^{f_e} S(t,f) df}{f_e - f_s} \tag{23}$$

The resulting $k_s$ value is shown in top part of the figure 7. The spectral variance representation is displayed in the bottom part of the figure, i.e recursively estimated variance behaviour on each frequency of the spectrogram.

![Figure 7](image2.png)

**Fig.7** Spectral variance of the signal.

In above sections, there were described and discussed some of the proposed methods for the arrival time determination of the rub induced impacts covered in the measured vibration.
signals. The method based on variance and envelope computation operate only in time domain and their use is conditional upon the rub impulse amplitude exceeds the value of the overall vibrations. The remaining two methods are based on the signal processing in the time-frequency domain, which increases their usefulness also in the case of arrival time detection of weak impacts. In general, these methods process changes and attributes of signals that can be used to localize the source of impacts. As already discussed, all these methods filter the signal by the certain manner and hence the estimated propagation velocity of the stress waves in the rotor can slightly vary according to the used method. Using the measured signal from only two sensors is then necessary to compute the velocity analytically from the Rayleigh-Lamb equations described in chapter III. When three or more sensors with sufficient amplitude increase are available, the propagation velocity could be calculated directly from the measured signals (see chapter II.)

E. Determination of the wave arrival time
To identify the wave arrival time in the predefined frequency bands, a method based on a comparison of signal characteristics in two consecutive sliding windows of length $N$ is used. It is necessary to identify the local signal change, therefore two windows were selected, whose ratio shows changes in local properties. Consider a signal $s$ and its $n$-th sample. A quantity $w$, which characterizes changes in the signal, is determined by dividing signal part between samples $n$ and $n+N-1$ to the previous signal part from $n-N$ to $n$. The wave arrival time of rub impacts are characterized by an increase in the signal amplitude, therefore the absolute value of the signal difference was chosen as an indicator of the increase in amplitude.

$$w(n) = \frac{\sum_{i=n}^{n+N-1} |s(i) - s(i-1)|}{\sum_{i=n-N}^{n-1} |s(i) - s(i-1)|}$$ (24)

Quantity $w$ thus displays the ratio of signal amplitude changes for two consecutive signal parts.

The whole localization algorithm is used for quasi offline data processing after event detection, therefore noncausality of the wave arrival time detection method is not a limitation for the localization algorithm. Fig. 8 plots the vibration amplitude in a selected frequency band (black curve) and the time behavior of the $w$-value (red curve). At the time of the $w$-value maxima, the position of both running windows is marked.

Already from the calculation of the structure of the $w$-value in (24), it is clear, that at the time of wave arrival the $w$-value will take its local maximum. Due to signal stationarity before the rub wave arrival and its relatively low damping, the appropriate choice of window length $N$ can also guarantee that the wave front peak yields the global maximum in the $w$-value. In practice, the window length of $1$ ms (i.e. $N = 100$) was proved for the sampling frequency of $50$ kHz. The advantage of this method is its adaptive nature in determining the beginning of the rub event, which is successfully used in determining the wave arrival time at different frequencies in the time-frequency domain.

V. EXPERIMENTAL ROTOR STAND AND TEST VERIFICATION
The experiments on the rotor stand have been part of the research and development of the rub localization method. The rotor kit RK4 by Bently Nevada was utilized to carry out several rub experiments, where we took the chance to change the position of the rub source, which was primarily a teflon seal. The copper and bronze seals were further also covered into the experiments. The vibration signals were measured on the bearing pedestals where the accelerometers measuring absolute vibration speed were installed. The photo of the experimental stand with the sensors of relative and absolute vibration is displayed in the following figure.

![Experimental rotor stand](image)

The sampling frequency of the measured signals was $51.2$ kHz (based on configuration of the measurement chain). The distance between the two measured planes was $0.48$ m. Let's label the measured position near the motor as bearing 2 (right bearing in Fig. 9) and the farther position as bearing 1 (left end of the shaft).

For the purpose of rub localization methods verification, various manifestations of rub were analyzed in time and time-frequency domain. Based on knowledge of the seal position, the actual propagation velocity was also analyzed.

In Fig. 10 (top), there is time behaviour of a signal containing rub impacts for the signal measured on the bearing 1. There are three impacts in the time view resulting from the contact of the shaft with the copper seal by the rotation speed of $2160$ rpm. In the bottom part of the figure, the amplitude spectrogram in frequency band $0$- $10$ kHz is displayed. The spectrogram was computed as approximation
of the Gabor transform. This time-frequency representation serves more accurate resolution than the commonly used discrete short-time Fourier transform. In Fig. 11 the same signal analysis but for the farther sensor on bearing 2 is displayed.

![Fig. 10 Expression of rub impacts in time and time-frequency domain for the measured position near the seal (bearing 2).](image1)

![Fig. 11 Expression of rub impacts in time and time-frequency domain for the measured position farther from the seal (bearing 1).](image2)

**VI. LOCALIZATION OF RUB IN MACHINE OPERATION**

An example of localization results for the seal position of described experimental rotor stand configuration is shown in the following Fig. 12. The true position of the seal is shown as a blue vertical line. The recursive variance computation of the vibration signal was used for the processing and in the section E chapter IV described method was applied for the wave arrival time detection. On the basis of the performed experiments the mean propagation velocity of 560 m/s was evaluated. The resulting histogram displays the rate of the localization outputs depending on the localized distance to the bearing 1.

The set up of the histogram column width covers a localization error of 5 mm. The results show relative good match between the true and evaluated seal position, especially if we accept the fact, that the seal width is 30 mm.

![Fig. 12 Localization of the seal position in the experimental rotor stand, distance of 0.192 m to bearing 1.](image3)

The symptoms of shaft and blade rubbing were successfully detected and measured by the RAMS monitoring system during the steam turbine operation in the year 2012 (see Fig. 13). The symptoms of the rub were significant and simultaneously detected in three measured planes. Consequently, the rub origin localization was performed.

![Fig. 13 Time-frequency representation of the shaft and blade rubbing measured by the operation of steam turbine.](image4)

The blade rub was identified by the excited frequency (276 Hz) which agrees with the frequency of shrouds crossing the swirl brakes installed in stator part above the blades. The excitation of the low frequency band in the signal was due to the shaft rubbing - rub of the rotor and stator labyrinth seals.

It is really difficult to determine the transmission path and the propagation velocity of the rub impact signals though the rotor and stator parts of the machine. Therefore it is appropriate to simplify the determination of the probable rub place by the use of linear localization and direct distances between the measured planes (bearing pedestals). In this case, the localization principle processes three measurement planes, and that is why there is no need to know the wave propagation velocity. A signal in frequency band of 270-280 Hz was used for analysis of the blade rub and the frequency band of 1-6Hz was determined as a shaft rub region. Dependency of the amplitude on time in the selected frequency bands was...
calculated using the Gabor transform. To estimate the arrival time of the rub impact wave, the method implementing the (24) was used.

In Fig. 14 there is the resulting axial localization of the shaft rubbing in form of histogram. The column width is 50mm. It can be seen the scheme of the HP part of the turbine in the background and also several rotating blades stages are noticable in the figure. The measurement planes are also highlighted and marked as BV1 - BV3 (Bearing Vibrations measured on bearing pans).

According to the obtained results, the highest occurence of the rubbing impacts is between the 4th and the 6th bladed wheel. The variance of the obtained results is caused by the noise in measured signals and also (as it was found by the turbine inspection) the rub occurs on slightly different places depending on the operational deflection shape of the rotor.

Except the axial localization, there is also need to localize the contact place on the circumference of the turbine stator. An approximate tangential localization is possible when using signals from both absolute and relative vibration sensors. When fusing the information from the sensors of absolute and relative vibrations the angle of the maximum rub intensity could be obtained. The method is based on the representation of the rotor motion in the measured plane. From the relative shaft vibrations an orbit of the rotor motion is reconstructed. The time behaviour of mean amplitudes in selected frequency bands, ie rub characteristic values, can be taken into account when rendering the filtered orbit of the rotor motion. Time synchronization is ensured by the keyphasor.

In Fig. 16, the result of tangential localization for blade rub is shown. The upper part shows the waveform of average amplitudes versus time for the signals from the front and rear bearing block of the HP steam turbine part, i.e. BV1 and BV2. At the bottom the filtered 1X orbits corresponding to the signals of shaft vibration SV1 and SV2 are displayed. The amplitude of the characteristic frequencies is scaled in colors, where blue corresponds to the minimum amplitude and red is the maximum value. From this figure it is evident when the highest intensity of the contact between the rotor and sator occurs and it is only a matter of processing to automatically evaluate the angle of maximum.

VII. CONCLUSIONS

In summer of 2012 the HP part of the turbine was opened and the estimated places of rub were inspected. The results from the linear localization presented above (axial and tangential part) were in accordance with the results of inspection. Between the 4th and 6th bladed wheel, there were the most significant damages of the seals.

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