Assessment of mechanical component stress using Wavelet Transform applied to infrared thermography

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Abstract: - The analysis of maintenance in industrial field is a very important problem in order to avoid risks and to avoid the stop of the machine. In this paper it is pointed out a procedure that permits to evaluate in advance which kind of fault can happen on a general machine. The infrared thermographic technique and Wavelet Transform working together permit to achieve important results in the predictive failure analysis.

Key-Words: - IR Analysis, Wavelet Transform, Maintenance.

1. Introduction
The industrial plants are continuously monitored in order to maximize the performance, in terms of quality and productivity.

Nowadays, the study is also steered to their capability of working without any interruption or, at least, without unwanted interruptions.

One can easily understand that this aspect of the research is synergistic to the previous one because the reduction of unproductive time of machines increases the time available for production.

The predictive maintenance is based on methods and techniques which are still evolving rapidly, even on a consolidated basis; the approach to the evaluation of economic benefit deriving from its application deserves a particular attention.

Multiple benefits justify the application of predictive maintenance:
1. reduction of stops due to failure;
2. reduction of repairing times;
3. reduction of failures induced by previous failure;
4. make best use of components as their lifetime;
5. limitation of qualitative drift (e.g., quality maintenance);
6. optimization of spare parts.

2. The infrared thermography
The results achieved by the application of infrared thermography (IT) encourages for monitoring mechanical systems. In fact, it provides a complete representation of effective working conditions, putting out of sudden failures and allowing better planning of any technical intervention.

The IT is based on the detection of electromagnetic waves in the infrared band, invisible to the human eye. The bodies with a temperature above the absolute zero (0° K or -273.15 ° C), emit electromagnetic radiation depending on their temperature.

The measurement of radiation emitted from any kind of material, equipment or plant, performed by using IT, provides the corresponding heat map. The analysis of surface thermal fields allows to detect fractures and / or anomalies that may occur during the working process. In fact, every worn or not properly lubricated mechanism tends to overheat before reaching the fault.

A thermographic survey can identify such overheating since its onset and the related thermal assessment should provide the alarm before the fault occurs.

2.1 Two-dimensional Wavelets: a brief overview
Mother wavelets are special functions, whose first \( h \) moments are zero. Note that, if \( \psi \) is a wavelet whose all moments are zero, also the function \( \psi_{jk} \) is a wavelet, where

\[
\psi_{jk}(x) = 2^{j/2} \psi(2^j x - k), \quad k \in \mathbb{Z}.
\]  

(1)

Wavelets, like sinusoidal functions in Fourier analysis, are used for representing signals [1]. In fact, let us consider a wavelet \( \psi \) and a function \( \varphi \) (father wavelet) such that \( \{ \psi_{jk} \} \) is a complete orthonormal system. By Parseval theorem, for every signal \( s \in L^2(\mathbb{R}) \), it follows that

\[
s(t) = \sum_k a_{jk} \psi_{jk}(t) + \sum_{j<k} \sum_k d_{jk} \psi_{jk}(t).
\]  

(2)

Now, let us consider two dimensional signals \( f(x, y) \) which are square-integrable over the real plane: \( f(x, y) \in L^2(\mathbb{R}^2) \). A wavelet basis for \( L^2(\mathbb{R}) \) is to take the simple product of one-dimensional wavelet
\[ \Psi_{j,k_1,k_2}(x,y) = \psi_{j,k_1}(x) \psi_{j,k_2}(y). \]  

(3)

It is easy to show that \( \Psi \)'s as defined above are indeed wavelets and that they form an orthonormal basis for \( L^2(R) \).

It can been show that the “detail space” \( W_j \) is itself made up of three orthogonal subspaces as follows:

\[ \Psi^1(x,y) = \phi(x)\psi(y); \]
\[ \Psi^2(x,y) = \psi(x)\phi(y); \]  
\[ \Psi^3(x,y) = \psi(x)\psi(y). \]  

(4)

Mallat [6] notes that the three sets of wavelets correspond to specific spatial orientations: the wavelet \( \Psi^1 \) corresponds to the horizontal direction, the wavelet \( \Psi^2 \) with the vertical direction and \( \Psi^3 \) with the diagonal. For more detail see [2-6]

3. The Wavelet Transform applied to thermography

As said before, the present study involves thermal images detected by means of infrared cameras. The systems showing slow thermal evolution can be defined as apparently stable.

The study concerning criteria for evaluating the system evolution through thermal images, periodically detected, is one of the most important problem for the prediction of the state of these systems from a specific and functional point of view.

For this reason, in order to analyze this evolutionary factor we consider crucial the detection of the smallest detail, with reference to the thermal map, significative for predicting the real situation of the system.

In many cases, the thermal gradient determines the density of pixel forming the image. For that reason the study was conducted by specific models, with the aim to resolve reflectance of the observed object and thermal radiation emitted during its observation.

In the following we show the method developed for the image processing which allows to distinguish the image features and its thermal radiation emitted during its observation.

4. Experimental Analysis

Four thermographic analyses were performed at different epochs on the same mechanical component (Fig.1).

For each thermal recording ten images sequentially sampled (roughly two minutes) were analyzed. The signal processing analysis, performed on the samples, was made by applying the Wavelet Transform combined with calculation and representation techniques related to chaos theory.
does not provide sufficient evidence to predict any anomalies related to the observed system.

5. Data processing through WT
The first sequence of data named T₀ provides basic historical information. It is true that starting from this sequence of data it is already possible to obtain interesting information by applying the WT both to thermographic images and to numerical vectorial sequence.

In particular, it is possible to evaluate and to take out the information characterizing the pattern of the signal as well as morphological features and mean dynamics, related to the various epochs.

Table 1 shows the results achieved by comparing the matrix (i.e., horizontal, vertical and diagonal, obtained by wavelet decomposition of the image) referred to each thermal map. The comparison is made between matrix referred at various periods.

<table>
<thead>
<tr>
<th>MATCH REFERENCE</th>
<th>GREY LEV. CORR.</th>
<th>H CORR.</th>
<th>V CORR.</th>
<th>D CORR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₀#T₀ (CALIBRATION)</td>
<td>0.9983</td>
<td>0.8600</td>
<td>0.8756</td>
<td>0.8600</td>
</tr>
<tr>
<td>T₀#T₂</td>
<td>0.9982</td>
<td>0.0017</td>
<td>0.0520</td>
<td>0.0017</td>
</tr>
<tr>
<td>T₀#T₃</td>
<td>0.9980</td>
<td>-0.0549</td>
<td>-0.0546</td>
<td>-0.0549</td>
</tr>
</tbody>
</table>

Table 1

For instance, the first row shows the values of the parameters selected for evaluating the correlation level of two frames randomly sampled from the same sequence, recorded at time T₀.

The figures 3-8 show the enlarged frames at time T₀, T₂, T₃ and a detail of the equivalent gray level maps.

As said for the first row, the next rows of the Table 1 show the results of the comparisons between maps at time T₀ # T₂ and T₀ # T₃. Qualitative and quantitative differences are quite evident.
The diagrams in Fig. 9 show, respectively, the periodogram, the quadratic dynamical oscillation and the factor form of two frames obtained at $T_0$, employed for calibrating the IT equipment.

Information collected from the frames at $T_0$ shows a stable phenomenon, characterized by a well-defined morpho-dynamical pattern.

The point circled in figure was highlighted in white and was pointed out by wavelet analysis. In fact it does not exhibit a significative variance in terms of colour and chromatism if compared to neighboured points. A signal processing performed by means of standard analysis or through FFT does not highlight any change or beginning of decay.
6. Results analysis

The diagrams represented in Fig.10 show the steady decay of system under control. In particular, the comparison of thermographic findings, referred to periods $T_0$ and $T_1$, no significative decay shows.

Fig 10 Comparison $T_0$ vs $T_1$

Fig 11 Comparison frames at $T_0$, $T_1$, $T_2$, $T_3$ – periodogram (up), quadratic oscillation index (mid), factor form (bottom)
The comparison of thermographic sequences made later (Fig.11) clearly shows a placement of the thermographic signal made at T_3 in a singular position defined as outlier (absolutely not deducible from the observation both of thermographic image, shown in Fig.2, and data sequence, reported in the second column in Tab.1). This result suggests a preventive maintenance to be performed on the system under control.

Finally, the figure 12 compares the initial thermographic pattern of the mechanical component, i.e., when the monitoring test started at T_0, with the situation at T_3, i.e., before the collapse, due to fatigue, of a rotating mechanical object happens. It is clear the dynamical and morphological difference showed by thermographic patterns.

7. Conclusions

Image analysis is actually a special case of signal processing, one that deals with two-dimensional signals representing digital pictures in which are included also the noise [7].

This study illustrates an application of a new method for signal processing based on the decomposition of two-dimensional signal performed by wavelet.

It was focused that the integration of the wavelet with the infrared thermography technique allows to reveal the dynamical and morphological difference showed by two thermographic patterns.

The contribution of wavelet signal processing is determining also for the noise reduction. In fact one of the most important application of discrete wavelet transform (DWT), to day, is the optimization of the estimation of the noise level.

The methodology exposed in this paper, should concur in determining the diagnose of some anomalies useful for a reliable maintenance [7].

The DWT is able to perform such an assessment. At the same time, wavelets have proven extremely useful in solving problems of data compression. If we consider that an other important step, will be the diagnosis of anomalies inducted by wear, it is clear the importance of compressing the images captured in order to create a wide database in which we can storage the templates of the main anomalies.

To summarize, there are five main answers to the question “Why wavelets?":

1. Signal processing
2. Image analysis
3. Denoising
4. Fast algorithms
5. Data compression.

Wavelets transforms can model irregular data patterns such as sharp changes, better than the Fourier transforms and standard statistical procedures and provide a multi resolution approximation.

References: