U.P.B. Sci. Bull., Series C, Vol. 81, Iss. 2, 2019 ISSN 2286-3540

SYSTEM FOR CONTROLLED VIBRATION STRESS RELIEF OF METAL PARTS WITH RESIDUAL INTERNAL STRESSES USING WAVELET FILTERING

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This article presents the implementation of a controlled vibration stress relief system for the dimensional stabilization of metal parts. The goal is to eliminate as much as possible of the unsteady internal stress, without affecting the steady stress condition. The time and frequency analysis is more suitable for non-stationary signals, since separate time or frequency specifications are not enough to provide comprehensive information about non-stationary signals. The wavelet transform based on LabVIEW programming was used to remove noise from picked up vibration signals and then to extract features from them. The equipment for the stress relief through vibrations is a complex system including a process computer, a frequency converter, an eccentric vibrator, a flexible shaft, an induction motor and an acceleration transducer. The system reduces the level of residual internal stresses in a certain metal part, following its own stress relief algorithm implemented in LabVIEW environment, achieve automatic reports, store the evolution in a database and sending the reports to default email addresses. There are presented results of the system presented after vibration stress relief of a work piece.

Keywords: stress relief, mechanical vibration, software application, LabVIEW, dimensional stability

1. Introduction

Residual stress may occur in metal components through welding, pressing, casting and many other machining processes. Residual stresses are introduced into the manufactured objects by all manufacturing and fabricating processes such as casting, welding, machining, molding, heat treatment, plastic deformation during bending, rolling or forging, which are caused by rapid, uneven cooling as opposed to the stresses caused by external loading and affect ageing duration and the dimensional stability of materials. In order to remove these unwanted residual

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stresses, various destructive and non-destructive techniques are used, such as the thermal stress relief method. Residual stresses are caused by such known factors as the increase of deformation gradients in various sections of the parts due to the increase of thermal gradients, volumetric changes arising during solidification or from solid state transformations, and from the differences in the coefficient of thermal expansion in parts made from different materials [1-7].

With the development of the mechanic manufacturing industry, the VSR (Vibratory Stress Relief) system has been used in many applications. Various stress relieving methods are used in order to reduce residual stresses, including vibratory stress relief techniques, shot peening and mechanical tumbling. The unstable residual stress influences the dimensional stability, and lead to cracking and dimensional changes in metal parts. The goal is to eliminate as much as possible of the unsteady internal stress, without affecting the steady stress condition. The part undergoes vibration at resonant frequencies for a given period depending on certain mechanical characteristics of the part. The internal energy caused by internal stress is activated by vibrations, thus accelerating the rearrangement process of atomic planes (the systematic displacement) and the internal energy dissipation in the material. It can be said that the material will undergo an accelerated or artificial ageing [8-12].

Dimensional stabilization through vibration is achieved by using controlled vibration to reduce the residual stress in metal parts or structures. This method doesn’t entirely replace the method of stress relief by thermal cycle, but it is an efficient alternative to dimensional stabilization and stress relief of parts in any production stage; the mechanical properties and fatigue strength in the material will not be affected and there will be no structural changes as a result of using this method. It is carried out by applying low frequency mechanical vibration, with controlled amplitude, in the part undergoing treatment. The positions of unstable atoms which move on very short distances will change as a result of the application of vibration, so that each crystal and the whole structure will be stabilized at the same time. Both to ferrous and non-ferrous parts can undergo this treatment, which can also be used during the welding process, in order to avoid cracking. This method can virtually be applied regardless of the weight of the part undergoing treatment [13-17].

The traditional VSR technique for frequency scanning and finding the work piece’s inherent frequency works in the time-domain, which has many disadvantages. For an efficient implementation of the system, the aim of many scientists and engineers is to solve the problems in the frequency-domain. Fast Fourier Transform (FFT) is widely used in stationary signal analysis, which is not often achieved in practice. Therefore, time and frequency analysis is more suitable for non-stationary signals, since separate time or frequency specifications are not enough to provide comprehensive information about non-stationary signals. The wavelet transform is a tool that divides the signal into different frequency components, and then analyzes each component with a resolution which matches its scale. It has a fast algorithm based on the FFT and its inverse transform (IFFT). The algorithm is characterized by faster speed and higher precision. LabVIEW becomes increasingly popular as a graphical programming language, especially for data measurement. Preparation modification and debugging becomes easier by using LabVIEW as a software application program control system for the VSR [18-22].

The wavelet transform based on LabVIEW programming was used to remove noise from picked up vibration signals and then to extract features from them. Wavelets are small localized waves based on mathematical functions. Wavelets are used to remove noise from a signal by identifying the components which contain the noise, and then reconstructing the signal after removing those components. The wavelet analysis is used for many modern applications for various purposes, such as condition monitoring and signal and image processing [23-28].

The system presented in this paper consists in the verification of the degree of vibratory stress relief in metal parts, and this process is carried out by primarily checking the stability of resonance peaks within the frequency range of the parts, both as amplitude and displacement. In other words, the vibration determines the shift and changes in the amplitude of the resonance peaks within the frequency range of the parts. The part is considered as dimensionally stabilized as soon as these changes stop.

The vibration method is based on an algorithm for adaptive vibration, influenced by the behavior of the metal parts. The main components of the equipment for the stress relief through vibrations include a process computer, a frequency converter, an eccentric vibrator, a flexible shaft, an induction motor and an acceleration transducer. The basic function of the system is to reduce the level of residual internal stresses in a certain metal part, based on its own stress relief algorithm implemented in LabVIEW environment.

The paper is an extension of work of [29] and is organized as follows: Section 2 describes the main components of the system for the stress relief through vibrations who is a complex process system including a process computer, a frequency converter, an eccentric vibrator, a flexible shaft, an induction motor and an acceleration transducer.

Section 3 presents the implemented main software modules which achieve data acquisition and wavelet filtering of acquired signal in order to reduce the noise, show the instant evolution of the acquired values, achieve automatic reports, store the evolution in a database and sending the reports to default email addresses. There are presented results of the system presented after vibration stress relief of a work piece. The paper ends with a section of conclusions describing the main aspects and advantages of the developed system.

2. Description of the system

A PC based measurement or control application consists in the conversion of real-world analog signals into digital formats and the transfer of digitized data to the PC. A data acquisition system performing the conversion of analog signals to digital data and of the digital data to analog signals is interfaced to a PC to implement the functions of measurement and control instrumentation applications.

The hardware architecture of the stress relief system is shown in Fig. 1. The hardware components of the stress relief system are the following: process computer; control and monitoring module which includes DAQ NI USB-6009, signal conditioning system Model CA2 Honeywell, frequency inverter Model D700-SC Mitsubishi; acceleration transducer Model MAQ14 Honeywell; three-phase asynchronous motor; eccentric vibrator; rubber buffers.

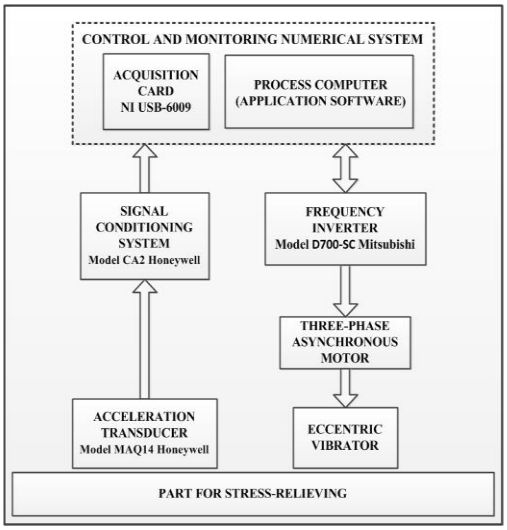

Fig. 1. The hardware architecture of the stress relief system

The DAQ NI USB-6009 has the following specifications: 8 analog inputs (14-bit, 48 kS/s); 2 static analog outputs (12-bit); 12 digital I/O; 32-bit counter; bus-powered for high mobility; built-in signal connectivity; compatible with LabVIEW, LabWindows™/CVI, and Measurement Studio for Visual Studio .NET.

Charge-mode piezoelectric transducers require charge amplifiers to convert their output to useful levels. Honeywell in-line charge amplifiers are versatile and convenient solutions for the use of charge-mode piezoelectric transducers (see Fig. 2). The charge Amplifier Honeywell Model CA2 has the following specifications: input voltage ±15 V dc or 24 V dc to 32 V dc; input current 20 mA; sensitivity programmable from 0.05 mV/pc to 6.4 mV/pc; input range from 780 pc to 100000 pc; output ±5 V RMS; frequency response from 3 Hz to 30 kHz (-3 db); time constant 50 ms.

The MAQ14 is a self-generating piezoelectric transducer which has no internal electronics and requires no external power for operation. The accelerometer Model MAQ14 has the following specifications: dynamic range 1000 G; sensitivity 50 pC/G; transverse sensitivity less than 5 %; temperature sensitivity 0.145/°F; frequency range from 1 Hz to 10 kHz; amplitude linearity better than 1 % linearity; mounted base resonance 18 kHz.

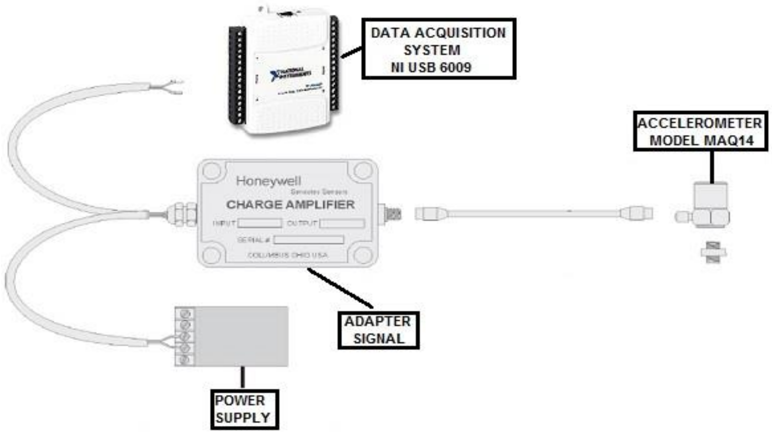

Fig. 2. The charge Amplifier Honeywell Model CA2 in connection with accelerometer and DAQ board NI USB 6009

The developed system presented in this paper is shown in Fig. 3, and it is a monitoring and control system for the resonance peaks within the frequency range of the metallic parts, carried out by the process computer.

The three-phase asynchronous electric motors are simple, reliable and low-priced, for this reason the choice for these motors for industrial application will be highly prevalent. Since the power supply frequency is usually constant at 50Hz, the motor speed is constant and can be modified for various applications by changing the structure of the winding. After choosing the speed, the motor always operates at constant speed, for example approximately 3000 rpm or 1500 rpm.

The solution for this problem consists in using a frequency converter, which is a device converting the constant voltage and the power supply frequency into variable voltage with variable frequency. This converter is installed between the power supply and the motor, and allows the continuous adjustment of the speed, turning a standard single winding motor into a flexible, variable speed actuator mechanism. The speed of the connected motor can be modified continuously by changing the converter frequency and the output voltage.

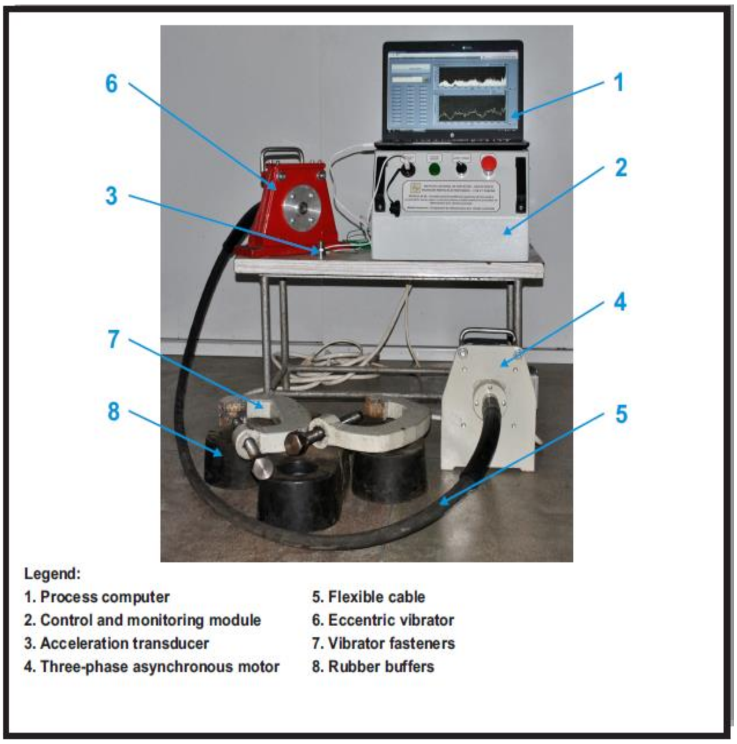

Fig. 3. System for controlled vibration stress relief

The eccentric vibrator has a welded, robust frame, with a fastening lug, providing increased operating safety. The fastening of the vibrator on the part undergoing treatment is achieved by using bulky catches. The rubber buffers isolate the part mechanically, enabling its vibration at maximum amplitude.

The vibratory stress relief process is achieved by means of the computer by using the software application developed with LabVIEW programming based on the algorithm shown in Fig. 4.

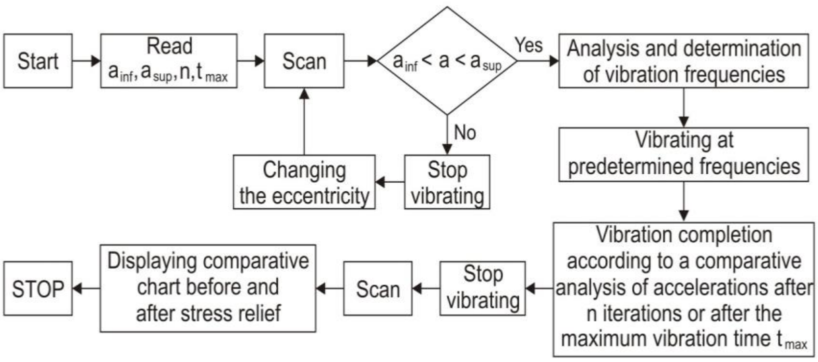

Fig. 4. The algorithm used for the developed software application

3. Description of the software application

The application's development software is LabVIEW, which is a powerful programming graphical environment, widely used for signal acquisition, measurement analysis and data presentation, providing flexibility to traditional programming languages and at the same time a user-friendly interface. LabVIEW works on a data flow model in which information within a LabVIEW program, called a virtual instrument (VI), flows from data sources to data sinks connected by wires [30].

The application software is based on state machines. A state machine is programming architecture that can be used to implement any algorithm that can be explicitly described by a state diagram or flowchart. Fig. 5 shows the software architecture of the vibratory stress relief system. The applications running on the dedicated computer have been developed using the LabVIEW graphical programming environment and are based on the operation of a dedicated function using MySQL Server and Gmail Server [31].

The main software modules of the application perform the data acquisition and filtering of the acquired signal in order to reduce noise (Wavelet Filtering, Peak Detection and Power Evolution), and the filtered data are written in the MySQL Server using the Database Write Module. The following modules are used to view the instant evolution of the acquired values, to achieve automatic reports, to store the evolution as TDMS-type files and Send Mail Module: VSR Software Module, Automatic Report and Automatic Send Mail Software Module.

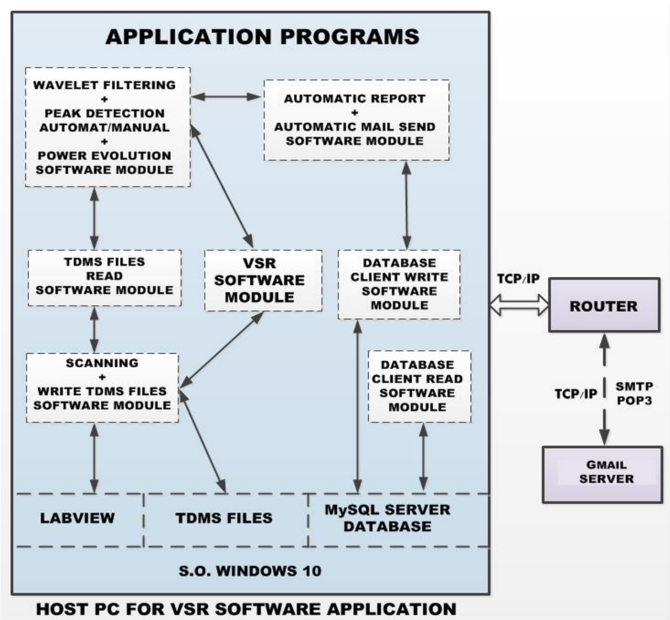

Fig. 5. Basic model structure of a fuzzy logic control system

3.1. Wavelet filtering

The vibration signals have a non-stationary nature. However, by calculating the frequency component of non-stationary signals based on the Fourier transform, the result will consist in the frequency composition averaged over the duration of the signal. Hence, the Fourier transform cannot be used to describe the characteristics of the transient signal adequately. Thus, time-frequency analysis has been studied because it can provide signal representation in both the frequency and time domains. Due to this unique feature, the time-frequency analysis techniques are suitable for non-stationary signals. Another benefit of time-frequency methods is the interesting information they provide on energy distribution over frequency bands. Several time-frequency analysis techniques have been used for fault detection and diagnosis, including the short time Fourier transform and wavelet transform [21-22].

To improve the Fourier transform, was introduced a windowing technique as the short time Fourier transform (STFT). A localized analysis is possible by passing the signal through a time window to get a time-dependent spectrum [26]:

$$X_{WFT}(u,\xi) = \int_{-\infty}^{\infty} x(t) g(t-u) e^{-j\xi t} dt \ , \tag{1}$$

where: $x(t) \in L^2(R)$ is a finite energy signals, u is time-shift, ξ is modulation frequency.

The windowed Fourier transform (WFT) (1) can be interpreted as cross-correlation of x(t) with window function $g_{u,\xi}(t) = g(t-u)e^{-j\xi t}$ which resemble a modulated and time-shifted lowpass signal g(t).

The STFT algorithm consists in dividing the signal into small sections, which are assumed to be stationary. Then, a window function is located at the start of the signal and multiplied together. Subsequently, the result of this product will be the Fourier transform, followed by shifting this window function to a new section of the signal and repeating the above-mentioned process. Thus, by repeating this procedure until reaching the end of the signal, the STFT turns the signal into a two-dimensional, frequency - time function, as shown in the Fig. 6.

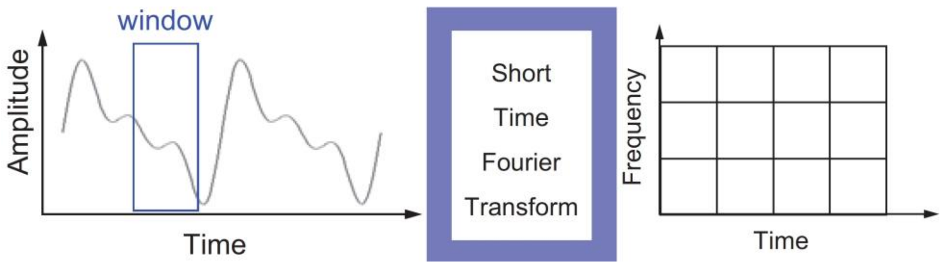

Fig. 6. Signal analysis by STFT [27]

The STFT is used to obtain both the frequency spectrum and the time evolution of the signal. However, the major constraint of the STFT is that it has a fixed resolution in relation to the size of the time window for all frequencies. This can be explained by the fact that when using the FFT there is no time resolution, but the frequency resolution is very high. This high resolution is due to the fact that the window function used covers the entire time interval from minus infinity to plus infinity.

Since the window function has a finite length and hence only a small segment of the signal will be covered, the frequency resolution becomes less good when implementing the STFT, as compared to the resolution obtained based on the FFT.

However, the frequency resolution will increase if the window function is wide enough, but that entails missing the time information as well as violating the stationarity assumption which requires the window to be very small. Consequently, there is a compromise relationship between time and frequency in the STFT. In case of a wide window, good frequency resolution but poorer time resolution is obtained and vice versa.

The wavelet transform was introduced to overcome the resolution limitation of the STFT. In order to show the principles of signal representation with wavelets, we consider time-continuous signal first. We obtain a local analysis of finite energy signals $x(t) \in L^2(R)$ by signal decomposition with a set of dilated and translated wavelets [19]:

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right), \quad u \in R, s \in R^+ \tag{2}$$

The wavelet $\psi(t) \in L^2(R)$ has a zero average $\int_{-\infty}^{\infty} \psi(t)dt = 0$ is normalized $\|\psi(t)\| = 1$ and centered on t = 0. At large scale s, the wavelets in (2) are expanded and cover a large support. On the other hand, small scales s yield compressed wavelets which are used to unveil finer signal details.

The Continuous wavelet transform (CWT) at time shift u and scale s of x(t) is [26]:

$$X_{WFT}(u,s) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{s}} \psi^*\left(\frac{t-u}{s}\right) dt \tag{3}$$

Equation (3) can be interpreted as cross-correlation operation on signal x(t), and dilated and translated wavelets. It can be written as convolution [26]:

$$X_{WFT}(u,s) = (f * \overline{\psi}_s)(u), \tag{4}$$

With:

$$\overline{\psi}_s(t) = \frac{1}{\sqrt{s}}\psi^*\left(\frac{-t}{s}\right) \tag{5}$$

As opposed to the short time Fourier transform, the wavelet transform has varying window lengths and represents the signal as a sum of wavelets at different scales.

The concept of the discrete wavelet transform refers to filters with different cut-off frequencies used to analyze the signal at different scales. High frequencies are analyzed first, by passing the signal through a high-pass filter, and then low frequencies are analyzed by passing it through a low-pass filter.

Therefore, the first step of the analytical process is the de-noising of such signals, which consists in removing noise while maintaining and not distorting the quality of the processed signal.

The process starts by decomposing the signal, transforming it into the time-scale plane by using a suitable wavelet family to analyze it at a number of levels (N). The next step consists in wavelet detail coefficient thresholding, which is required for the removal of small coefficients associated with noise from the wavelet coefficients resulting from the decomposition step. Since it is typically considered that noise has high frequency coefficients, these small coefficients are generally removed after the decomposition process with the detail coefficients.

The wavelet coefficients represent a measure of similarity in the frequency content between signal and a chosen wavelet function. These coefficients are computed as a convolution of the signal and the scaled wavelet function, which can be interpreted as a dilated band-pass filter because of its band-pass like spectrum. The scale is inversely proportional to radian frequency. Consequently, low frequencies correspond to high scales and a dilated wavelet function.

By wavelet analysis at high scales, global information called approximations is extracted from a signal, while at low scales, fine information called details is extracted from a signal.

The signal denoising qualities of the wavelet transform are tested by the signal estimation technique known as wavelet thresholding. A result close to the input, but which may still be noisy can be obtained by using a small threshold, whereas a large threshold yields a signal with a large number of zero coefficients, resulting in a smooth signal.

Minimax threshold is also used for fixed threshold and it yields minimax performance for Mean Square Error (MSE) against an ideal procedure. Because the signal required for the denoising can be seen similar to the estimation of unknown regression function, this extreme value estimator can realize minimized of maximum mean square error for a given function. In this method, the threshold value will be selected by obtaining a minimum error between wavelet coefficient of noise signal and original signal.

Generally, different values of the analyzed signal will be obtained when a different wavelet basis is used, and there are still no general theoretical criteria specifying how to select the optimum wavelet family.

For this reason, selection is mostly done by trial and error. A compromise has to be made especially between noise reduction and signal degradation and a parameter called the percentage root mean square difference (PRMSD) is calculated based on the following equation [23-25]:

$$PRMSD = 100 \cdot \sqrt{\frac{\sum_{i=1}^{n}\left[x(i)_{raw\ signal} - x(i)_{denoised\ signal}\right]^2}{\sum_{i=1}^{n}\left[x(i)_{raw\ signal}\right]^2}} \qquad (6)$$

Where n is the number of samples, $x(i)_{raw\ signal}$ and $x(i)_{denoised\ signal}$ are the amplitudes of the noisy and de-noised signals respectively.

For the purpose of this research, various wavelet functions are used and the best results (including the maximizing of PRMSD) was obtain with the Daubechies of the order 7 (Db7) and level 7. The order of the Daubechies functions denotes the number of vanishing moments, or the number of zero moments of the wavelet function. This is weakly related to the number of oscillations of the wavelet function. The software block diagram, the specifications of the wavelet algorithm for implementation in LabVIEW and the scalogram and detail coefficients of Db7 filter are presented in Fig. 7, 8 and 9 respectively.

Fig. 7. Specifications of the wavelet algorithm in LabVIEW

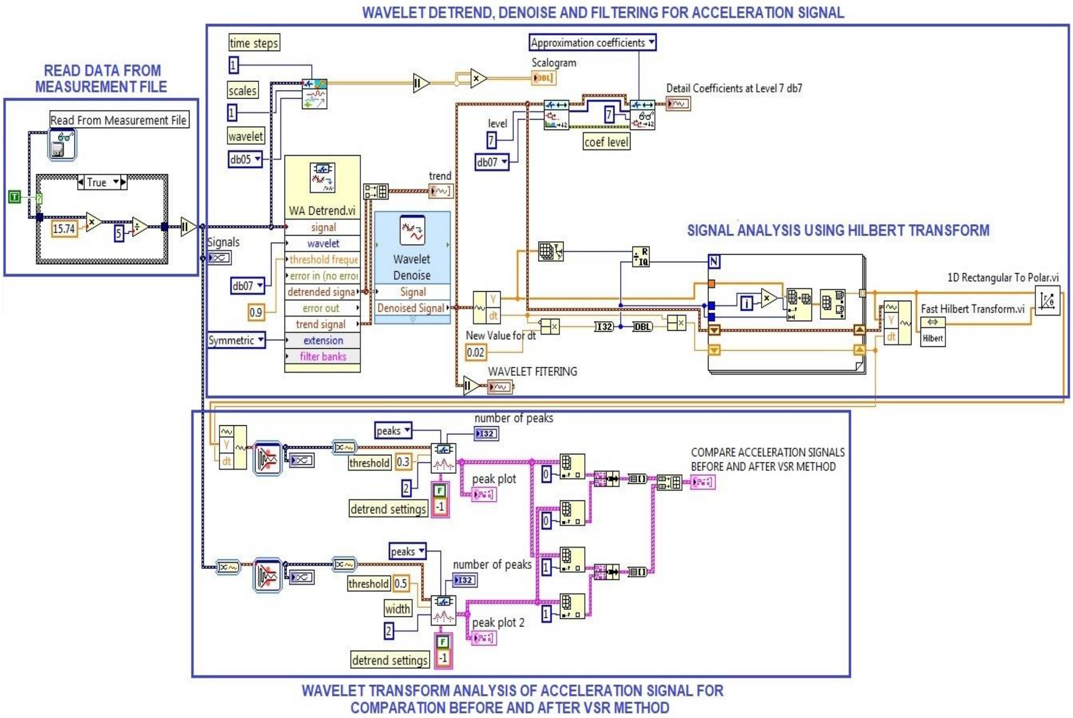

Fig. 8. Software bloc diagram for signal denoising

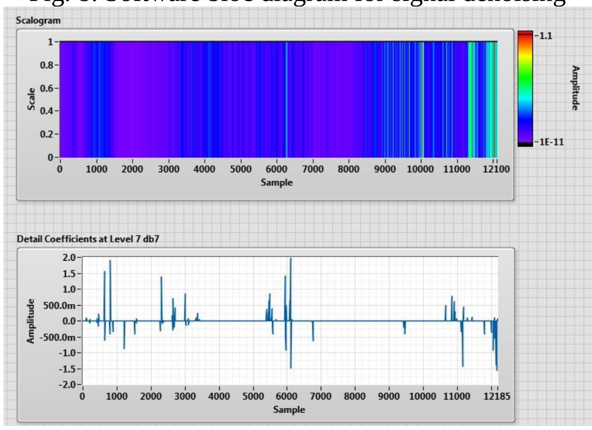

Fig. 9. Scalogram and detail coefficients for Db7 filter

Fig. 10 shows the time evolution and processing of the acceleration signal.

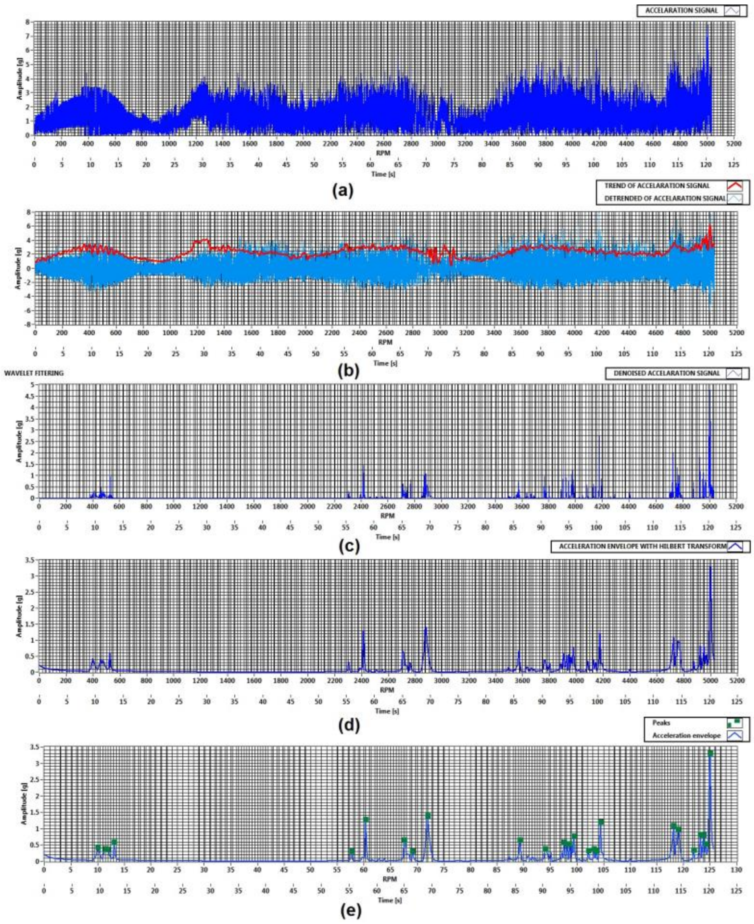

Fig. 10. Time evolution and processing of the acceleration signal: (a) Raw signal; (b) Trend and detrended signals; (c) Denoised signal; (d) Acceleration envelope with Hilbert transform; (e) Peaks and acceleration envelope

For denoising of the raw signal are used a Db7 wavelet filtering and for obtain an envelope of the signal are used the Hilbert transform implemented in LabVIEW.

3.2. Application programs

The software block diagram based on stacked sequence structure which implements the vibratory stress relief process presented in Fig. 4 is shown in Fig. 11. In Fig. 11 (a) it is shown the way how the raw data of the acceleration signal are written in TDMS type files to achieve the data logging, the command for frequency converter and motor block to achieve the scanning procedure. The command sequence for stopping of motor is presented in Fig. 11 (b).

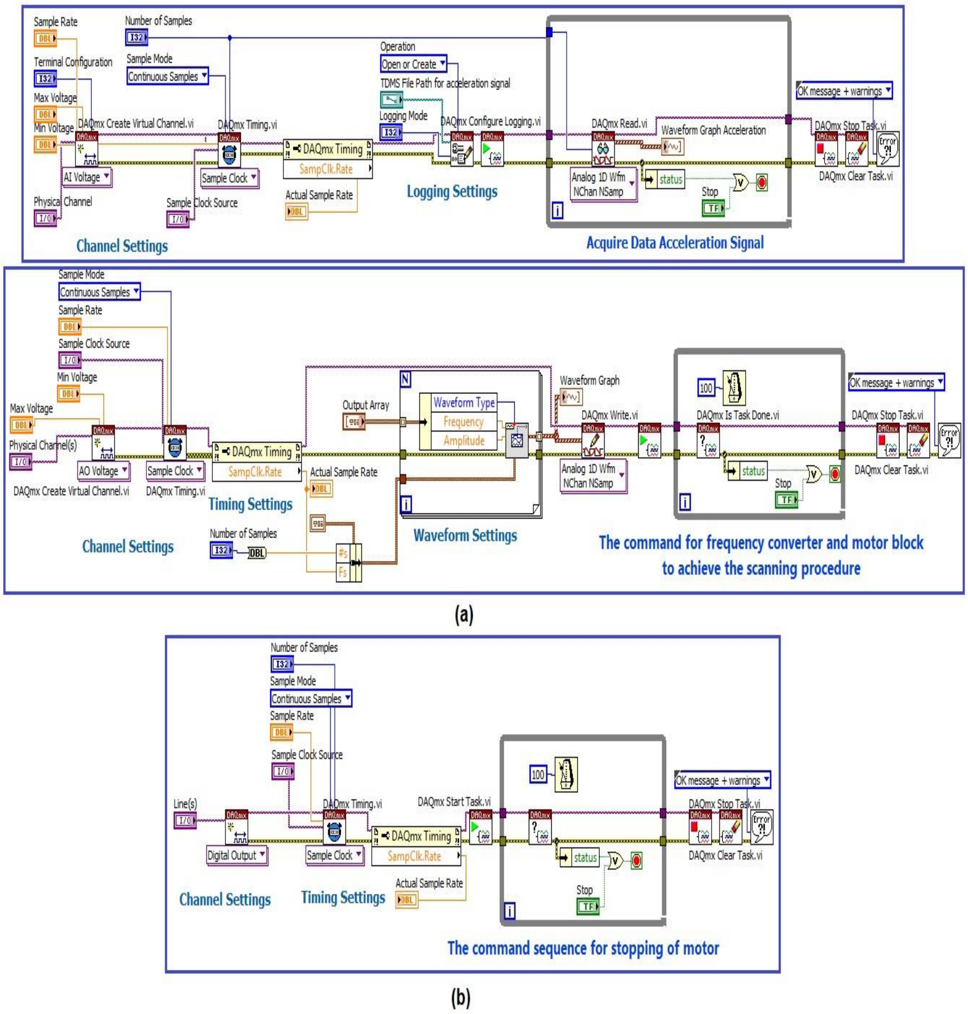

Fig. 11. The software block diagram for the VSR algorithm: (a) Data logging and scanning procedure, (b) Sequence for stopping of motor

The developed application software generates a report which is an essential part of a professional application. Reports must contain all the information that the user wants. In addition, reports must look professional and be carefully formatted. The LabVIEW Report Generation Toolkit for Microsoft Office is a library of flexible, easy-to-use VIs for programmatically creating and editing Microsoft Word and Excel reports from LabVIEW. The software block diagram for automatic reports is shown in Fig. 12.

Based on the fact that LabVIEW offers support for ActiveX automation as a server as well as support for ActiveX Containers, and ActiveX Events (ActiveX is an extension of a previous technology called OLE) the application program automatically generates emails with the previously presented report, to default email addresses and the software block diagram is shown in Fig. 13.

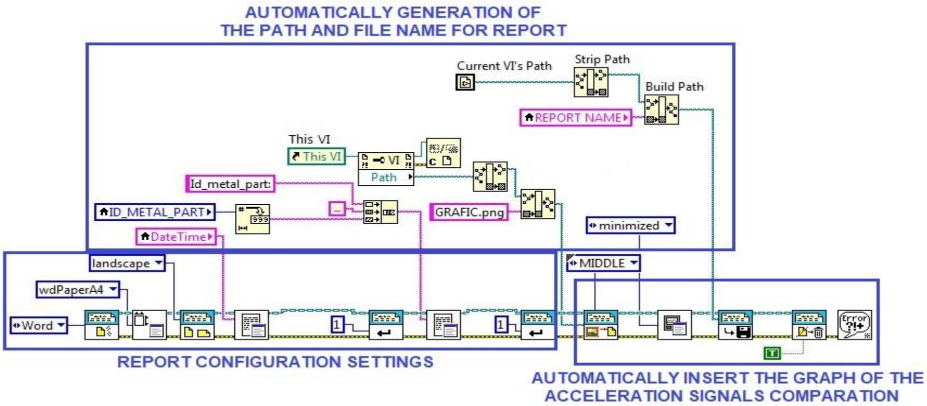

Fig. 12. The software block diagram for the automatic report

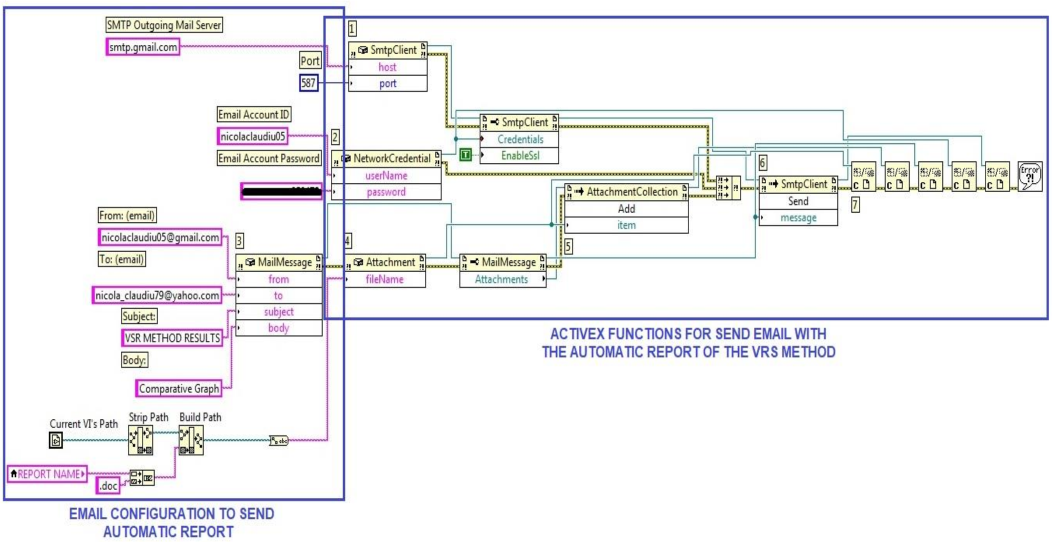

Fig. 13. The software block diagram for the automatic mail sends

A DataSources (ODBC) type connection, through which the application program performs the writing and querying of the MySQL Server type database will be used to store the image of the acceleration signals before and after the VSR method is recorded in the database in order to recreate the logging and create automatic reports.

The interface for database structure for database connection is shown in Fig. 14. The software block diagram for database Write and Read Module are presented in Fig. 15 and Fig. 16 respectively.

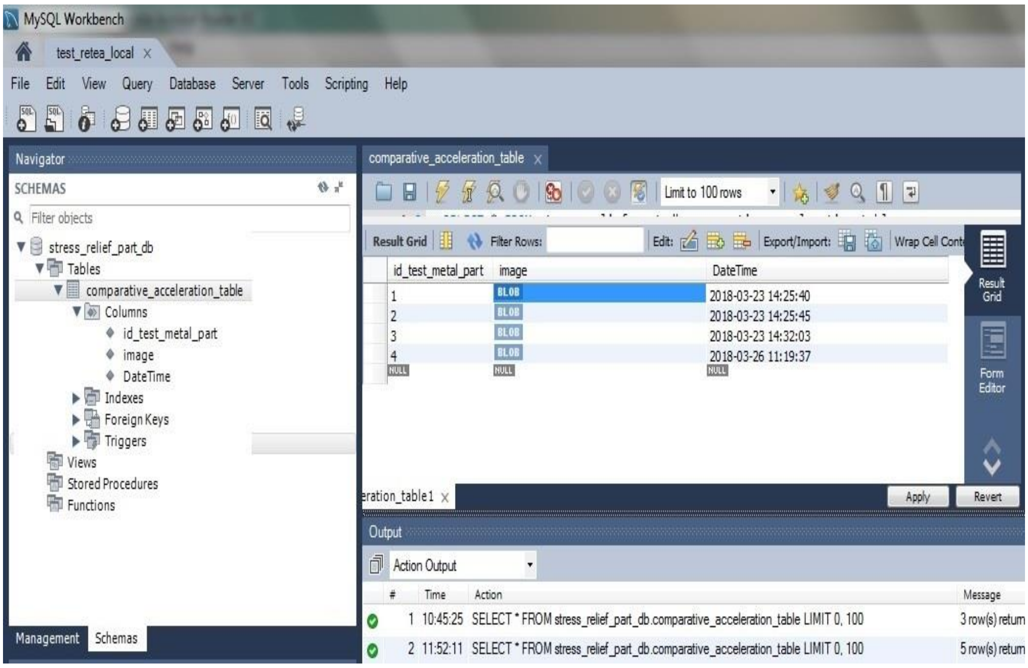

Fig. 14. The interface for database structure

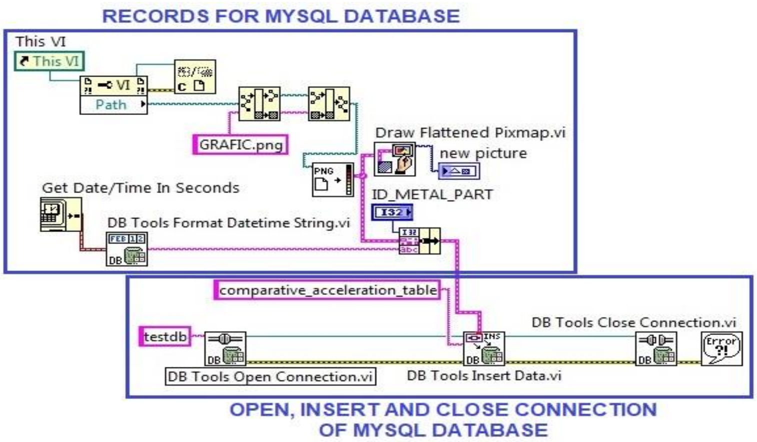

Fig. 15. The software block diagram for database Write Module

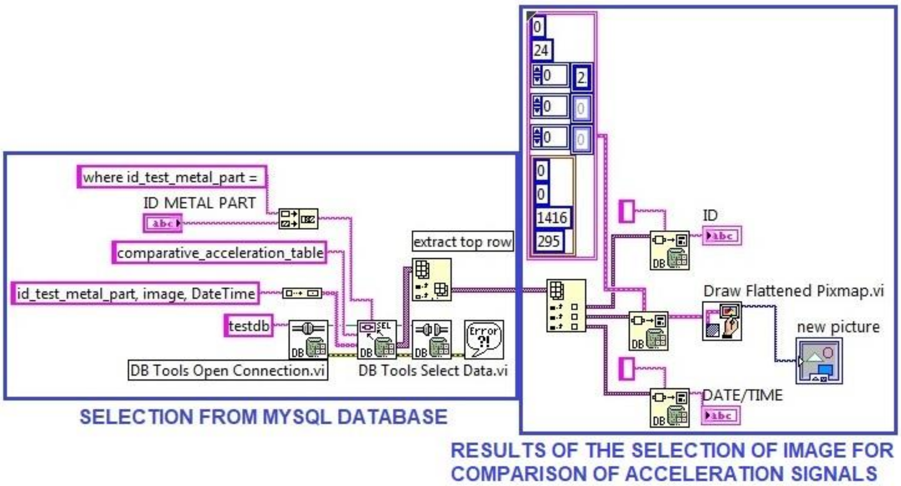

Fig. 16. The software block diagram for database Read Module

In the case of a work piece (see Fig. 17), following the presented algorithm from previous sections, in Fig. 18 it is shown the evolution of the vibration treatment which can be monitored by following the increase in the amplitude of the resonance peaks and the transition of the resonance phenomenon at smaller frequencies. This modification requires the adjustment of the vibrator speed so that the vibration frequency remains within the range of the resonance frequency.

Fig. 17. Image of the work piece

The scanning of the frequency response of the work piece in the presented frequency range was carried out in the same conditions: the vibrator remained fastened at the same position, the vibrator's eccentricity was not altered, the accelerometer position was not changed, the position of the dampers for the insulation of the work piece to the ground was not modified, the scanning speed was the same.

As presented in the literature, the vibration stress relief process is considered effective for the intended purpose and is considered to be completed if the resonant frequency value changes after the application of the process, as opposed to the resonant frequency of the work piece before vibration. Under these conditions, the only quantity which determines this frequency change is the elasticity of the work piece, which means that the residual stress has been reduced. The change in the resonance peak towards the lower frequency is caused by an increase in the elasticity of the structure. This increase occurs as a result of the actual stress relief [18].

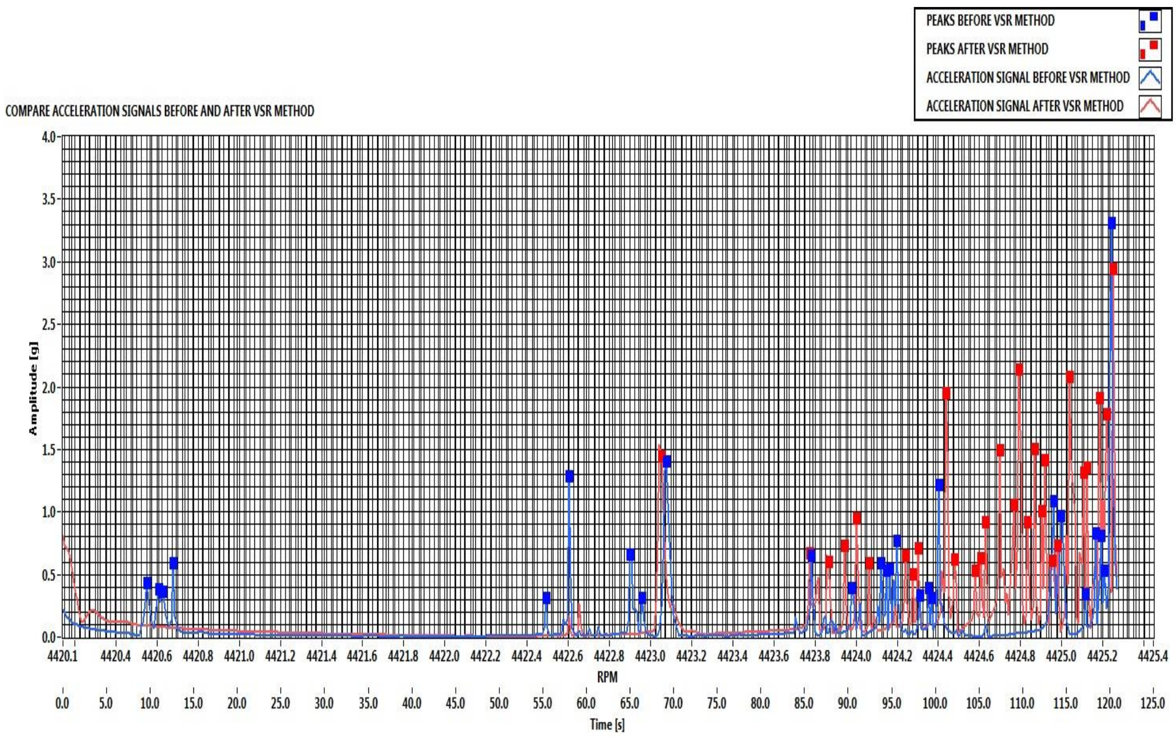

Fig. 18. Comparison of acceleration signals before and after the VSR method

4. Conclusions

This article presents the implementation of a controlled vibration stress relief system. To reduce the noise a wavelet filtering is performed, and a MySQL Server Database is used for data logging. The system is portable, and can be used for parts in any size, shape or weight achieved through welding or casting. Small parts can be treated by fastening to a vibration plate. This method is ideal for the applications requiring critical size parts, which would require very large ovens for thermal stress relief. The main advantage of the developed system consist in reducing of the level of residual internal stresses in a certain metal part, following its own stress relief algorithm implemented in LabVIEW environment.

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