718. Application of self-oscillating system for stress measurement in metal

Janusz Kwaśniewki[1], **Ireneusz Dominik**[2], **Krzysztof Lalik**[3]
Department of Process Control, AGH - University of Science and Technology
al. Mickiewicza 30, 30-059 Cracow, Poland
E-mail: [1]*kwa_j@agh.edu.pl*, [2]*dominik@agh.edu.pl*, [3]*klalik@agh.edu.pl*

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Abstract. Within the article the applicability of the Self-oscillating Acoustical System (SAS) in order to continuously monitor changes in strain was examined. The essence of SAS is to use a vibration exciter and vibration receiver placed in a distance, which is coupled by an amplifier operating in a positive feedback loop. Changing the speed of wave propagation, which is associated with the change of frequency in the system, can be measure of deformation of the material. The study confirmed the existence of the phenomenon of self-oscillating which can be used to assess the state of metal frame deformation.

Keywords: vibrations, autodyne, stress measurement, monitoring systems.

Introduction

By bringing a speaker closer to a microphone the system is excited and produces a hum. With an appropriately high ratio of the amplifier gain it causes the excitation of the circuit microphone - speaker. The autodyne phenomenon in these systems is undesirable, however, this effect also occurs in the radio-technique. In the second half of the 20's of the last century the autodyne lamps (generators which used positive feedback) were used in old radio sets [1, 2].

This phenomenon of autodyne effect may also be applied for the other research, where the increase of the rock mass deformation can be easily evaluated. If in the feedback circuit, apart from the amplifier, a test material under the influence of external forces was located, the change of stress in the material would cause change the speed of wave propagation and, as a result, a generator retuning.

Autonomous non-conservative systems are characterized by the fact that their vibrations are associated with a gain of energy. If, at the time of a vibration of an autonomic system, the flow of energy from the outside appears causing a gain of the amplitude of these vibrations or compensating the loss of energy and supporting periodic oscillation, then the system is called self-oscillating and its vibration – self-oscillating vibrations [1, 3]. The most characteristic feature of self-oscillating systems is the way they charge the energy. It allows distinguishing between autonomous self-excited systems and non-autonomous systems. Energy flow occurs in non-autonomous systems by the action of external, explicitly time-dependent forces [6].

The paper presents the application of the autonomous non-conservative Self-oscillating Acoustical System (SAS) for monitoring the change of the stresses in the metal frame test stand.

The Basis of the Self-excitation Phenomenon

It can be assumed, according to great number of tests conducted on several kinds of stones and metals [4, 5], that dependence between the velocities of the wave and the change of the stresses in the samples is non-linear and in result the oscillating system as well. This non-linear dependence for the metal sample is showed in Fig. 1.

The first laboratory tests were conducted on sandstone and marble samples [5, 7] The SAS system diagram which was used is shown in Fig. 2, where the receiving head is a piezoelectric sensor and the emitting head (shaker) is a piezoelectric actuator. The power amplifier, emitter (*E*) and receiver (R_1) are formed in the positive feedback loop.

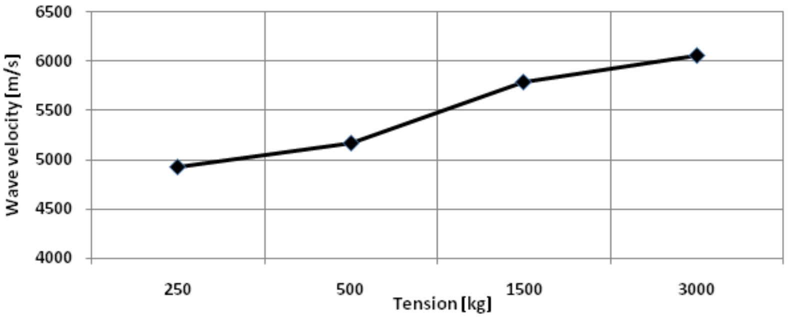

Fig. 1. Dependence between the wave propagating velocity in a metal and the tension

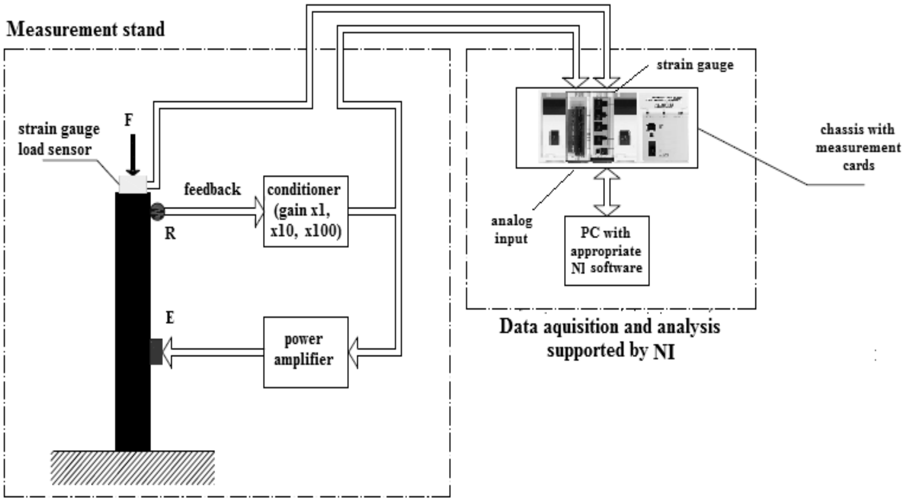

Fig. 2. Self-oscillating Acoustical System diagram for stone samples, where *E* – shaker and *R* – receiver

The research conducted on several kinds of stones proved that SAS system can be used for the stress changes measurement. The results for the marble compressed with different loads, shown in Fig. 3, can be present as an example. The frequency of the resonance strictly depends on the stress level.

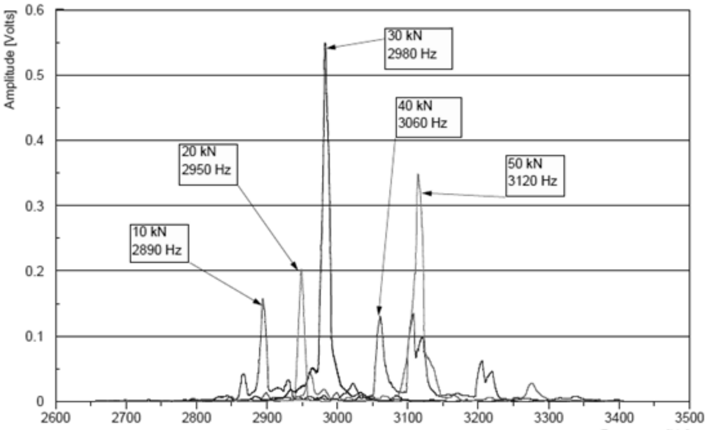

Fig. 3. The resonance frequency for a marble as a result of the measurement

There are many different methods and systems for the stress change measurement (e.g. strain gauges) and several acoustic methods (string method, open loop systems) [3, 8, 9], but comparing to SAS system, these methods are more difficult to apply in practice. As frequency measurement is one of the most precise method of the measurement it was used for the stress changes measurement as well. The second reason for using this method is that a measurement of the wave propagation causes many difficulties. The measurement routine is troubleshooting, because of a large velocity of the wave and small distance between the sensors, which is determined by the dimensions of the material. The main advantage of the SAS system is its applicability. It can be used for almost every type of stones, including the concrete, without a distinction between any kind of reinforcement or lack of it.

SAS System for the Measurement the Stress Change in Metal

After research on the stone samples the SAS system was used for the metal. The material under the study was the frame made of metal (E295) C-profiles shown in Fig. 4. Two forces in range 5 kN to 50 kN were applied between the transoms, causing tension for the vertical frame legs. During the research a troublesome effect was discovered. For the measurements in different kinds of stone, the measured signal has always the amplitude in a range of the measurement card +/– 10V. The gain for this signal can be set up by conditioner used in the feedback loop (see Fig. 2). Too small gain causes lack of self-excitation. On the other hand too high gain causes magnification of the signal out of the measurement cards range. The used conditioner had only 3 values of gain: ×1, ×10, ×100. Neither of it was appropriate for metal. First gain caused lack of excitation effect and the others two brought on the saturation effect. According to the signal frequency analysis theory any saturation reveals on the frequency characteristics as a series of harmonic peaks [2]. The effect appeared during tests, as it is shown in Fig. 5, were several peaks on the spectrum characteristics are visible. It caused difficulties in interpretation of the results. To avoid this problem, there it was necessary to rebuild the structure of the SAS system. Instead of the previously used conditioner (see Fig. 2) the digital gaining system was placed in the feedback loop. It consists of the hardware generating module and of the appropriate software. Unlike the preliminary structure of the system, the analog input card is not separate part of the system, which was used additionally for data acquisition. In the metal frame case the analog input card is an integral and vital part of the feedback loop. The measured signal in the input card is gained by software and sent to generate module and further to the emitter. In this way, there is possibility to choose manually any gain between ×1 and ×100 and in that way avoid saturation.

As it was mentioned, the frame was stretched with the force in range 5 to 50 kN. It means change of the stresses between 0,7 and 7.5 MPa for the vertical frame leg which was made of C200 profile. Results of working SAS system applied to the metal frame are presented Fig. 6. The frequency of the resonance growing up with the tension is clearly visible. For the lowest tension the frequency equaled 3889 Hz and for the highest tension its value was 3905 Hz. It means that for every 1 Hz there is 0,44 MPa change.

It seems to be not wide enough range of the signal changes for detection with reference to the classical methods, but by applying the self-oscillating SAS system the signal changes are satisfying. Furthermore it may be noticed that the change of frequency is nonlinear and additionally the result proved that the system is even more sensitive with smaller loads. The upper chart shown in Fig. 6 shows one more thing – there is only one dominating peak for one load and there is no difficulty to write algorithm for monitoring it.

It can be noticed comparing the results from Fig. 3 and Fig. 6 that in stones the resonance is growing up with compression in the same way like in metals with tension. The explanation for it may be that the standing waves are observed in the bars having the strains at the ends. Both waves: the longitudinal and the transverse are associated with the stress and the axial deformation. Therefore the bar is the spreading medium for both waves: longitudinal and transverse at the same time.

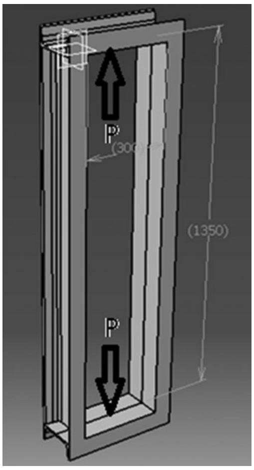

Fig. 4. Tested object

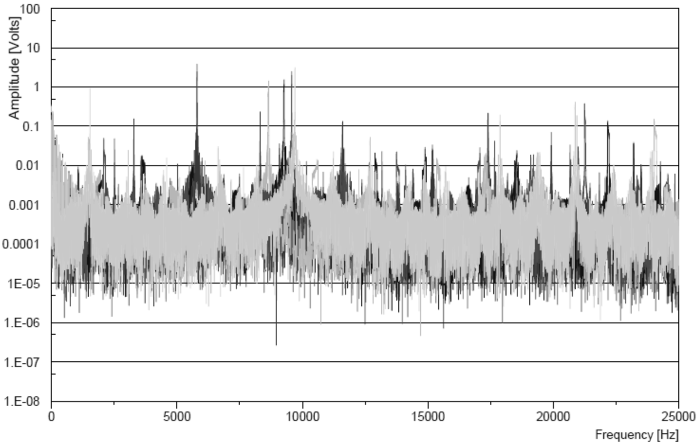

Fig. 5. FFT characteristic for the SAS signal with the saturation

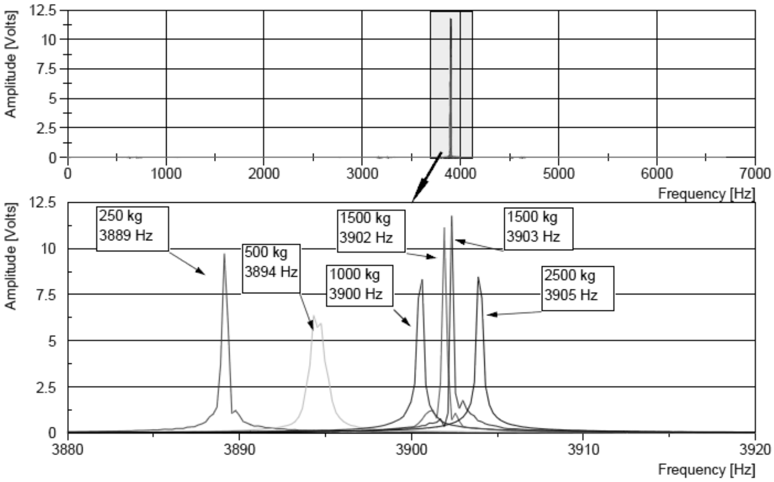

Fig. 6. The resonance frequency for a metal as a result of the measurement

Dispersion equations for both types of waves are different. In the simplest case the equation of wave motion has the form:

$$\begin{aligned} &\mu \frac{\partial^2 u}{\partial t^2} - EA\frac{\partial^2 u}{\partial x^2} = 0 \\ &\mu \frac{\partial^2 w}{\partial t^2} + P_0 \frac{\partial^2 w}{\partial x^2} + EJ \frac{\partial^4 w}{\partial x^4} = 0 \end{aligned} \tag{1}$$

where μ is the linear density of the bar, E is a Young's modulus, A is a field of the cross-sectional area, J is a cross-sectional moment of the inertia and P_0 is the force producing the initial compressive stress. The function $u(x, t)$ describes the longitudinal wave, and $w(x, t)$ - transverse wave. Wave equations, in this simple model are not correlated with each other; therefore the movement of longitudinal and transverse waves can be analyzed independently.

The running monochromatic waves are considered in order to calculate dispersion relations. It can be described by the equations:

$$\begin{aligned} u(x,t) &= U_0 \sin(\omega t - kx) \\ w(x,t) &= W_0 \sin(\omega t - kx) \end{aligned} \tag{2}$$

where ω is the wave frequency and k is a wave number. Symbols $U_{0,}$ W_0 describe the amplitude of the waves. The dispersion equations, which are describing properties of longitudinal and transverse waves, can be determined using relations (3):

$$\begin{aligned} \omega &= k \cdot \sqrt{\frac{EA}{\mu}} \\ \omega &= k^2 \cdot \sqrt{\frac{EJ}{\mu}} \sqrt{1 \pm \frac{P_0}{EJ} \frac{1}{k^2}} \end{aligned} \tag{3}$$

The sign in Eq. (3) depends on the kind of stresses. For tension it is positive and for compression is negative. The interaction between the grains and the filling fraction is linear, because the contact surfaces do not decrease significantly during deformation of the bar elements. Therefore, the final constitutive relation, which takes into consideration the granular structure of the stone bar, can be offered in the form:

$$\sigma = E_w \varepsilon + \frac{4\sqrt{2}}{3\pi\left(1-\nu^2\right)} E_z \varepsilon^{3/2} \tag{4}$$

Fig. 7. The dependence between the resonance frequency and the tension in metal

Equation (4) is a non-linear equation describing a stiffening of the grains with increasing strain, where E_w is the initial Young modulus, is ν is Poisson ratio and E_z is a substitute Young modulus comes from a grain dispersion strengthening. So, in the material with grain structure there are two competitive effects, the first – stiffening of the grains induces increase of the resonance frequency and the second – dispersion of the energy - decrease of the resonance frequency. The first effect is stronger, so in stones the frequency of the resonance is growing up with compression (Fig. 3) just like in metals with tension (Fig. 7).

To check the repeatability of measurements of applied SAS system to the metal frame the series of tests were conducted. The results are plotted in Fig. 7.

Conclusions

The paper presents the application of the Self-oscillating Acoustical System SAS for measuring the change of stresses in metals. Conducted tests proved the theory that for materials with the crystal lattice the frequency of the resonance is growing up with the tension, in the same way as for the materials with grain structure, where the frequencies are growing up with the compression. This effect in stones is induced by a grain dispersion strengthening.

The new conception of the SAS system with adding digital gaining system allowed to eliminate the saturation troubleshot and the results obtained from the measurement were easier to interpret. The results gathered in Tab. 1 and plot in Fig. 7 clearly indicates that SAS system is very reliable and accurate.

The SAS system was developed for better, faster and more accurate determining the state of constructions. Thanks to SAS system structure and its principle of operation it can be quickly adapted to the new measurement conditions.

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