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APPLICATION OF SELF-EXCITED ACOUSTICAL SYSTEM FOR STRESS CHANGES MEASUREMENT IN SANDSTONE BAR

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A self-excited acoustical system is suggested for monitoring of the change of stress in a sandstone bar. Stress changes manifest themselves in small but detectable variations of frequency in the self-excited system. The suggested system can be applied for the continuous stress changes monitoring in elastic constructions and rock masses. Tests on a single sample of sandstone were performed. They examined the impact on the stress measurement such parameters as: position of sensors and the actuator as well as the influence of geometrical shape and dimensions of the sample. A theoretical model whose parameters have been confirmed by performed experiments is also developed.

Key words: self-excited system, stress monitoring

1. SAS system in stress change measurement

1.1. Introduction to self-excited systems

By bringing a speaker closer to a microphone, the system is excited and it produces a hum. This effect also occurs in the radiotechnics. The autodyne lamps, which are used in the old radio sets, can excite themselves. This effect is called the autodyne effect. This effect consists in variation of such parameters of a self-excited system as: the amplitude, frequency and bias voltage.

Autonomous non-conservative systems are characterized by the fact that their vibrations are associated with a gain of energy. If at the time of 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-excited and its vibration – self-excited vibration (Votoropin *et al.*, 2008).

The most characteristic feature of self-excited systems is the way they charge the energy. It allows one to distinguish 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 (Nikolov *et al.*, 2008).

The time in self-excited systems occurs in equations not explicitly. The energy source is constant, not dependent on time. The energy flow is controlled by the oscillating system itself (which is why we call such a self-excited system). So considering these systems, we can distinguish the following elements:

a – constant source of energy,

b – oscillatory system,

c – control device supplying power to the vibrating system, controlling the flow of energy,

d – positive feedback between the system and the control device, through which the system directs the vibrating energy.

Elements **a** and **c** may be linear, part **b** is non-linear (Fig. 1). It results from dispersion equations. If any of the physical quantities (displacement, velocity or acceleration) occurs in these equations as non-linear, the oscillating system will also be non-linear (Bogusz *et al.*, 1974).

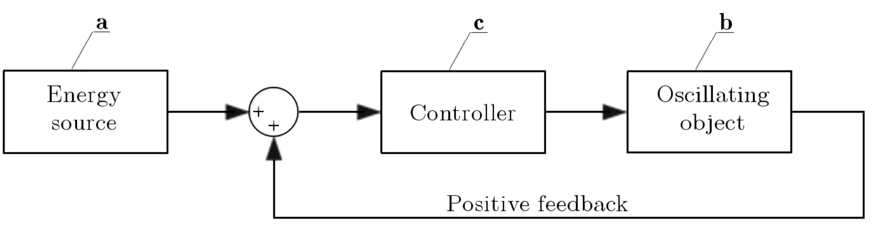

Fig. 1. Block diagram of a self-excited system (Bogusz *et al.*, 1974)

It can be assumed, according to a great number of tests conducted on several kinds of stones, that the dependence between the velocities of the wave and the change of the stresses in the sample is non-linear, in result the oscillating system as well. This non-linear dependence for the marble sample is shown in Fig. 2.

During the study on the acoustical systems for stress changes measurement, the authors did not find any solution working in the closed loop, neither in Polish nor foreign literature. However, there are a lot of open loop system

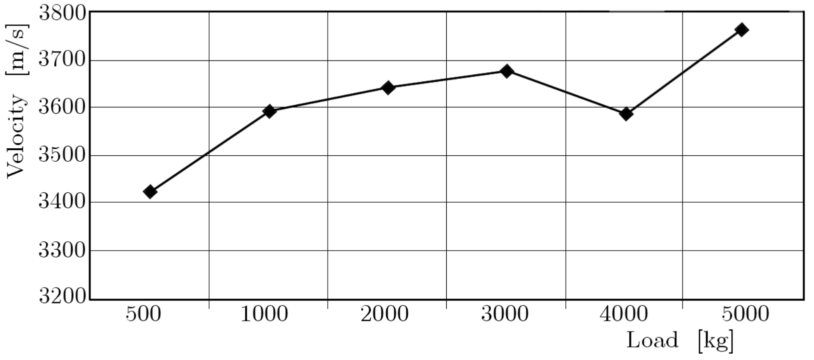

Fig. 2. Dependence between the wave propagating velocity in marble and the load

solutions. One of the most effective open loop system was patented in the USA [6]. The system presented in this patent works in an open loop and uses a critically refracted longitudinal ultrasonic technique. Every open loop system has a little resistance to disturbances (Deputat *et al.*, 2007) and worse sensitivity than in our closed loop system. In the paper the new, innovating method for stress changes measurement is presented together with experimental data.

1.2. Structure of SAS system

During our research conducted at The Department of Processes Control at The University of Science and Technology, the Self-excited Acoustical System (SAS) has been developed. It is an assembly of devices which similarly to the speaker-microphone system or autodyne lamps exploit the phenomenon of self-excitation.

The SAS system diagram is shown in Fig. 3, where the receiving head is a piezoelectric sensor and the emitting head (shaker) is a piezoelectric actuator. The power amplifier, emitter (E) and receiver (R1) are formed in the feedback loop.

As a result of positive feedback, there is a bilateral interaction between the control device and the vibrating system, which allows the self-excited system to control its own energy balance. As a result of that, despite the fact of losses of energy occurring in the system, there are non-fading periodic oscillations.

Many applications of the self-excited phenomenon are known. These are: vibrations of cutting tools, turbine blade vibration, vibration of aircraft wings, vibration of bridge suspension which may cause destruction of the bridge (as happened to the Tacoma Narrows bridge), etc. In such systems, we try to eliminate these vibrations.

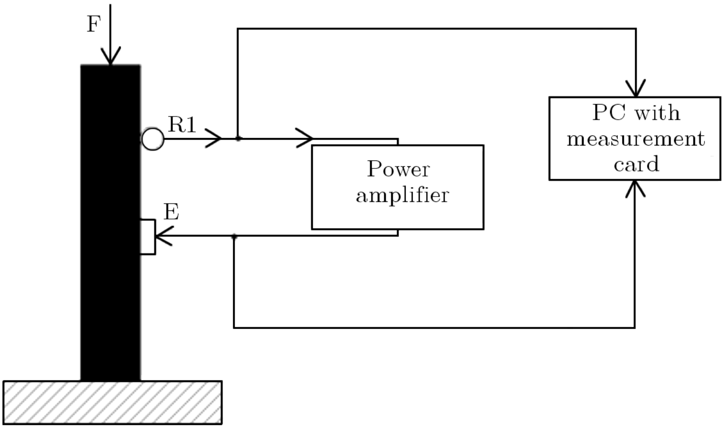

Fig. 3. The SAS diagram, where R1 is the receiver and E is the emitter, F – load

The system was intended to measure a change of stress in elastic mechanical structures, constructions and rock masses. The purpose of this study is to determine the possibilities of using this system for real objects such as bridges, dams, buildings, mines, etc. The sensitivity of this system, for small and large deformation, is higher than the sensitivity of other measurement systems (especially open systems).

Tests on a single sample of sandstone were performed. They examined the impact on the stress measurement such parameters as: position of sensors, position of actuator, and the influence of geometrical shape and dimensions of the sample.

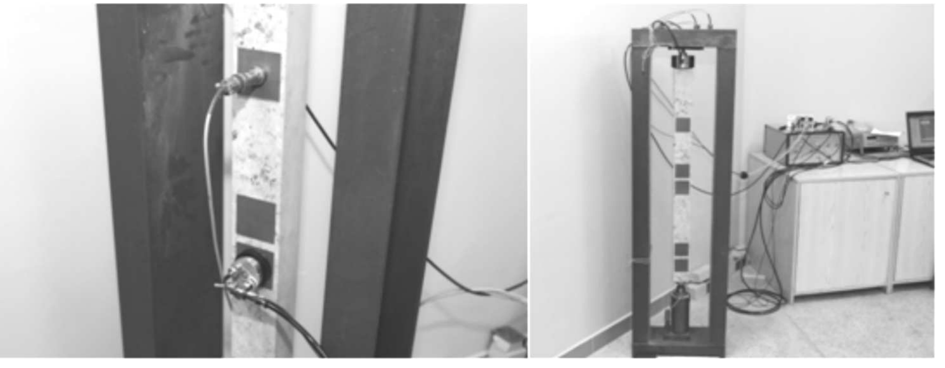

Fig. 4. The test stand for endurance tests using the SAS System

In the study a sample of sandstone compressed in the frame by a hydraulic press (Fig. 4) was used. In addition, the system was equipped with a force sensor to calculate the compressive stress in the beam in real time. Accelerations were measured by three accelerometers for three reasons:

- to determine what impact the distance from the emitter to the receivers has on the results and the position of resonances,
- to avoid a situation where the sensor is located in the resonance node, which would result in incorrect test results,
- to determine the velocity of wave propagation in the material with correlation methods.

The study was conducted in three configurations of the position of emitter (E). For a sandstone sample with rectangular cross-section of 60×70 mm, the emitting and receiving devices were mounted in the configuration shown in Fig. 5.

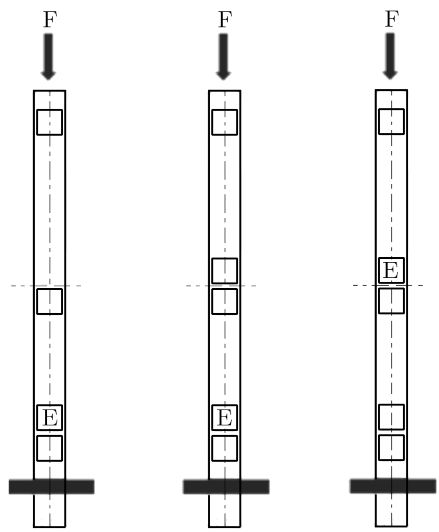

Fig. 5. Diagram of deployment of emitters on sandstone, E is the emitter and F is load

2. Test results

The SAS System is designed for use in real objects such as bridges, dams, buildings, mines, etc. Therefore it is necessary to create a universal procedure to detect the change in the strain in these structures. The designers decided to use first the system to conduct tests in the open loop (Kwaśniewski *et al.*, 2009). To the sample charged with various compressive forces, the chirp signal emitted in the frequency range of 100 Hz-20 kHz was initially given. This allowed one to obtain the amplitude-frequency characteristics (Fig. 6) of the structure with visible resonances (Fig. 7).

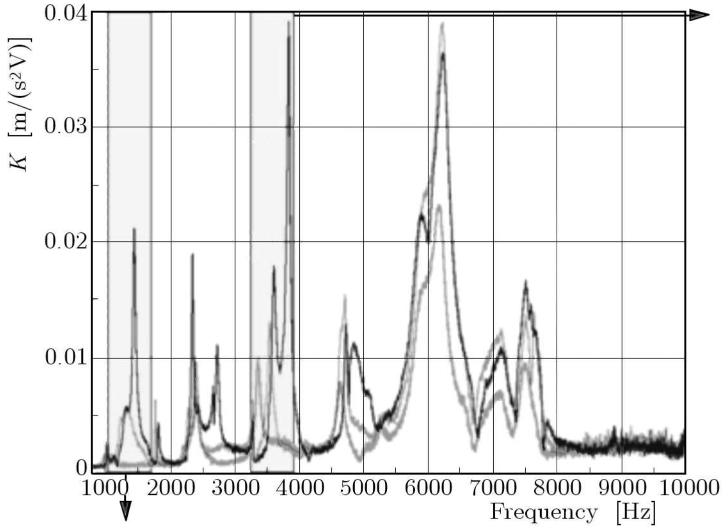

Fig. 6. Comparison of vibration transmissibility functions for different sample loads in the open loop system

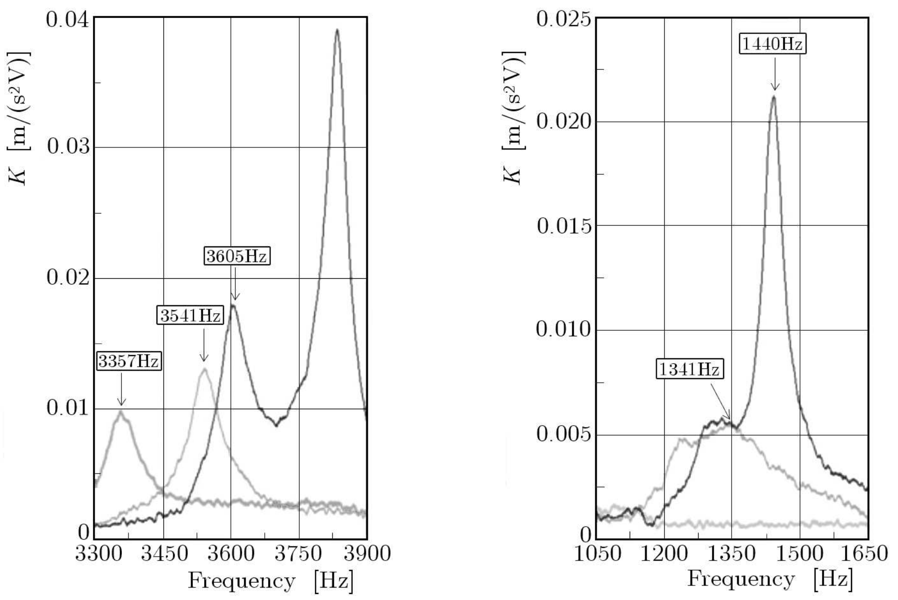

Fig. 7. Selected and expanded resonance peaks believed to be related with the change of stress in the open loop system

Figure 7b presents the movement of the first resonance peak believed to be related with the change of stress in the sample. Figure 7a – the third resonance peak. The damage of frequency respectively amounts to 150-250 Hz. In Fig. 7a, the fourth peak with the highest amplitude is also shown. It has been omitted, because it comes from the own resonance of the emitter, so this 4th peak is out of consideration. For the closed loop system, which is shown in Fig. 8, the frequency change at the same load variation is approximately 450 Hz. In addition, the amplitude of vibration is 20-30 times greater than in the open loop system, which makes them more visible and easier to identify.

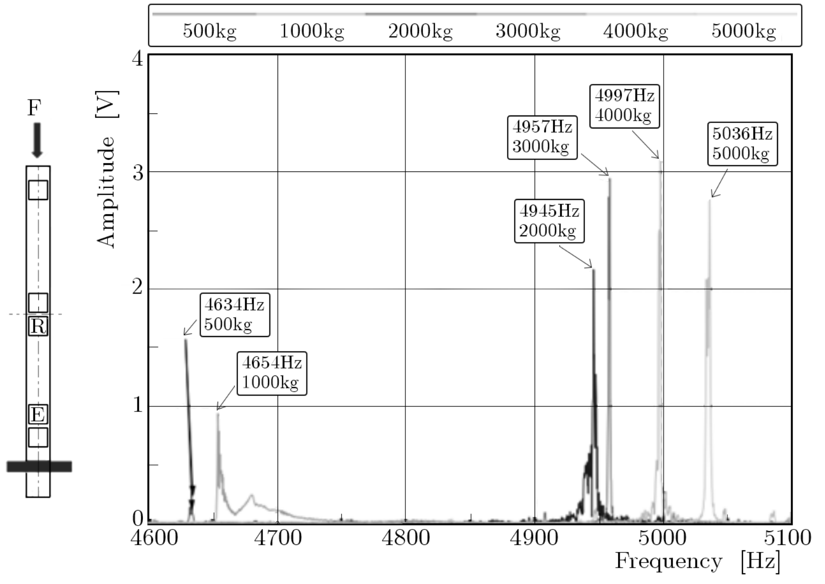

Fig. 8. Selected and expanded resonance peaks of the closed loop system believed to be related with the change of stress, where E is a position of the emitter and R is the position of the receiver

A theoretical model needs still additional adjustment in order to confirm the model data with the experimental ones. The mathematical formulas which were used in the model are described in the following (Bobrowski *et al.*, 2004). The emitted signal reaches the receiver with a time delay $\tau = l/V$, where V is the velocity of the elastic wave. The delayed signal, registered by the receiver R1, returns to the power amplifier by means of a positive feedback system. The frequency of oscillations in such a system ω follows the phase balance equation

$$\omega\tau = 2\pi m \tag{2.1}$$

where m is a integer number, which is estimated as the number of wavelengths λ on the distance l: $m \approx \lambda$. It follows from (2.1), that the m -th frequency of self oscillations is equal to

$$\omega_m = \frac{2\pi m}{\tau} = \frac{2\pi m V}{l} \tag{2.2}$$

Then the frequency shift $\Delta\omega_m$, caused by a small variation ΔV of sound velocity, equals

$$\Delta\omega_m = \frac{2\pi m}{l}\Delta V \tag{2.3}$$

The changes in stress in rocks cause variations in the sound velocity V, and thereby in the frequency of oscillations in the feedback system.

The frequency of normal mode f is given by the equation of balance of the phase

$$2\pi f\tau + \varphi_E(f - f_E) = 2\pi m \qquad m = 1, 2, 3, \dots \tag{2.4}$$

which requires that the phase difference in the feedback loop is a multiplication of 2π. Expression $\varphi_E(f - f_E)$ is the phase difference from the emitter. Assuming that the difference Δf_E between the frequency of normal mode f and the frequency of the emitter f_E is relatively small, the expression $\varphi_E(f - f_E)$ can be linearized as

$$\varphi_E(f - f_E) \approx 2\pi\tau_E(f - f_E) \tag{2.5}$$

where τ_E is the delay in the emitter, defined by the formula

$$\tau_E = \frac{1}{2\pi}\frac{d\varphi_E}{df} \tag{2.6}$$

The time of transition of the wave through the stone sample τ is much longer than the time of the conversion of the voltage signal to mechanical vibrations in the shaker τ_E, so it can be assumed that the delay from (2.6) is small compared with the time of flight of the wave τ

$$\tau_E \ll \tau \tag{2.7}$$

where $\tau = l/v$ and v is the velocity of the wave.

Substituting equation (2.5) with equation (2.4) and dividing both sides by 2π, we obtain

$$f\tau + \tau_E\Delta f_E = m \tag{2.8}$$

According to inequality (2.7), and solving equation (2.8) in line with the theory of disorders, it is assumed that

$$f = f_0 + \Delta f \qquad \tau = \tau_0 + \Delta\tau \tag{2.9}$$

where f_0, τ_0 corresponds to the initial stress, and Δf and $\Delta\tau$ correspond to the change of the stresses. According to formula (2.9), we have approximately

$$f_0 = \frac{m}{\tau_0} \tag{2.10}$$

then the first disorder is

$$\frac{\Delta f}{f_0} = -\frac{\Delta\tau}{\tau_0} - \frac{\tau_E}{\tau_0}\frac{\Delta f_E^0}{f_0} \tag{2.11}$$

and Δf_E^0 describes the differences between the frequency f_0 and the resonance frequency of the emitter. The indicator m in formulas (2.9) and (2.11) approximately shows the number of lengths of waves over the distance l between the emitter and receiver R

$$m \approx \frac{l}{\lambda} \tag{2.12}$$

3. Conclusions

During the work on the SAS system, the researchers conducted a great number of tests, which will facilitate the implementation of the system to real objects. The following algorithm was developed:

- one header system works initially in the open loop system,
- it will allow one to select the frequency range in which the resonance peak will be responsible for the change in stress – this is going to be the identification step,
- secondly, the system operates with two headers, which will allow one to determine the speed of propagation of the acoustic wave in the investigated material.

Using this algorithm for creation of a compact measuring apparatus and carrying out research on industrial constructions will be the priority in the development of the current project.

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Zastosowanie samowzbudnego akustycznego systemu do pomiaru zmian naprężeń

Streszczenie

W artykule przedstawiono koncepcję i wyniki badań nad samowzbudnym akustycznym systemem, który jest proponowany jako nowy sposób monitorowania zmian naprężeń w belce z piaskowca. W badanym rozwiązaniu zmiana naprężeń objawiała się małymi, aczkolwiek mierzalnymi, zmianami częstotliwości. Proponowany system pomiarowy może znaleźć zastosowanie do ciągłego monitorowania zmian naprężeń w konstrukcjach sprężystych oraz masach skalnych.

W artykule opisano przeprowadzone badania doświadczalne z zastosowaniem próbki wykonanej z piaskowca. Podczas badań sprawdzono wpływ umiejscowienia nadajnika i odbiornika oraz wymiary geometryczne i kształt próbki na uzyskiwane wyniki. Dodatkowo został zbudowany model teoretyczny, którego parametry zostały pozyskane i potwierdzone na drodze eksperymentalnej.

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