Janusz KWAŚNIEWSKI[*], Ireneusz DOMINIK[*], Krzysztof LALIK[*]

A SELF-EXCITED ACOUSTICAL SYSTEM FOR STRESS MEASURMENT IN A CEMENT PLANT

SUMMARY

This paper presents the application of a Self-exited Acoustical System (SAS) for monitoring stress changes in the cement plant. The change in the speed of wave propagation, which is associated with a change in the resonance frequency in the system is caused by the deformation of the examined material. The SAS system is based on this phenomenon and can be used for the indirect measurement of the stress changes in the material.

Keywords: *stress measurement, monitoring systems, autodyne effect*

ZASTOSOWANIE SAMOWZBUDNEGO AKUSTYCZNEGO SYSTEMU DO MONITOROWANIA ZMIAN NAPRĘŻEŃ W FUNDAMENCIE SILOSU W CEMENTOWNI

W pracy przedstawiono zastosowanie samowzbudnego akustycznego systemu (SAS) w monitorowaniu zmian naprężeń w fundamencie silosu magazynującego cement. Zmiana prędkości rozchodzenia się fali, a co za tym idzie, zmiana częstości rezonansowej, jest związana z odkształceniami badanego obiektu. System SAS bazuje na tym zjawisku i pozwala na pośredni pomiar zmian naprężeń w badanym materiale.

Słowa kluczowe: *pomiar naprężeń, systemy monitorujące, efekt autodynowy*

1. INTRODUCTION

In the area of machine design and all creations of technology and nature, which are working in heavy conditions, monitoring the change in stress in different structures is one of the most important duties. It ensures the safety and reliability of these structures. Previous solutions of deformation measurement systems required us to use, for example the inconvenient strain gauges gluing or the very uncomfortable mechanical equivalent of strain gauge (Gordienko *et al.* 1996, Washer *et al.* 2002, Chen 2007).

The essence of the SAS system is to use a vibration exciter and vibration receiver placed at a distance, which are coupled with a proper power amplifier, and which operate in a closed loop with positive feedback. This causes the excitation of the system. It is similar to the excitation of a circuit consisting of autodyne lamps, which are used in old radio sets and can excite themselves. Hence, it is called the autodyne effect. This phenomenon can be used for the indirect measurement of stress changes in the material. For small deformations, the sensitivity of the self-exited systems is higher than the other measuring systems, especially in comparison with the open loop systems. Moreover, other solutions cause a lot of problems with the reflection and interference of the waves. SAS, for a well-chosen gain factor in the feedback loop, has only one impulse which is easily identifiable.

2. PRELIMINARY TEST STAND

During preliminary research in the Department of Process Control, AGH University of Science and Technology the Self-exited Acoustical System was developed. The system diagram is shown in Figure 1, where amplifier, shaker (*E*), and receiver (*R*) are formed in a feedback loop. Shaker (*E*) was fixed to a stone bar. The bar was put into a testing machine to create a load. On the beam's surface four accelerometers were fixed: three of them on the same surface as the shaker and the last one directly on the opposite site.

Preliminary tests taken on the sandstone bar proved that the SAS system is able to follow the changes of the load while changing its resonance frequency. Details are available in publications (Kwaśniewski *et al.* 2011a, 2011b).

The conducted preliminary tests highlighted two following facts: in the specific structures, such as continuous medium bar vibrations, the natural frequency of the bar decreases with increasing the compressive forces, so with the growth of the compressive stresses the frequency of the resonance of the bar should decrease – and in the case of the sandstone bar it is the opposite. The second fact is that the incipient natural frequencies of the bar are counted in hundreds of Hz, and the results of the measurement are given in kHz.

The dispersion equation, which describes the properties of transverse waves, can be determined using relation (1):

$$\omega = k^2 \cdot \sqrt{\frac{EJ}{\mu}} \sqrt{1 - \frac{F_0}{EJ} \frac{1}{k^2}} \tag{1}$$

where μ is the linear density of the bar, E is a Young's modulus, J is a cross-sectional moment of the inertia, k is a wavenumber, and F_0 is the force producing the compressive stress.

* AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Department of Process Control, al. A. Mickiewicza 30, 30-059 Krakow, Poland; kwa_j@agh.edu.pl, dominik@agh.edu.pl, klalik@agh.edu.pl
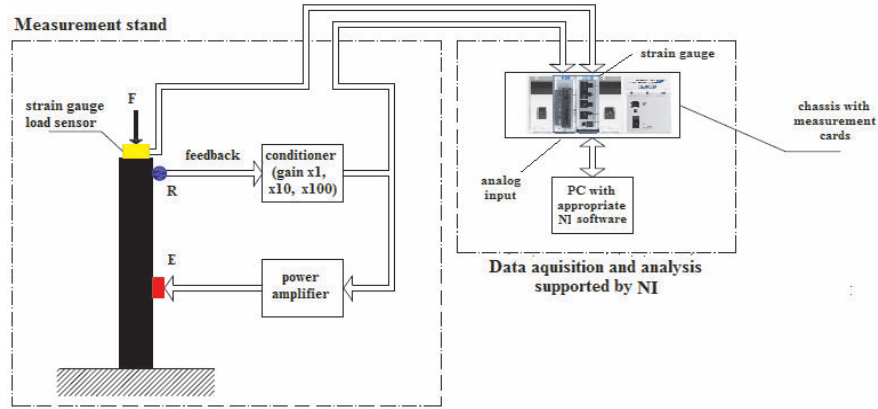
Fig. 1. Self-exited Acoustical System diagram,
where E – shaker and R – receiver

Assuming that on the bar length *l* occurs *n* waves, *k* can be determined from the relationship (2):

$$k = \frac{2\pi n}{l} \tag{2}$$

And the dispersion equation can be given by the formula (3):

$$\omega = \frac{4\pi^2 n^2}{l^2} \cdot \sqrt{\frac{\kappa}{\rho} E} \cdot \sqrt{1 - \frac{\sigma}{E} \frac{l^2}{4\pi^2 n^2 \kappa}} \tag{3}$$

where κ is the ratio of the moment of the inertia of the cross-section and the cross section field of the bar, ρ is the volume density and σ is the value of compressive stresses.

After the conversion of the formula (3) and the substitution of coefficient *b*, which depends on the dimensions of the bar, we get the following formula:

$$\omega = \frac{4\pi^2 n^2}{l^2} \cdot \sqrt{\frac{\kappa}{\rho}(E - b \cdot \sigma)} \tag{4}$$

Formula (4) shows that in material with crystal structure the natural frequency of vibrations decreases with the growth of the compressive stresses (σ). For the materials with grain structure, such as many kinds of stones and concrete, there is however some additional effect. According to Hertz's contact stress theory, the stiffness of the grains increases with the compressive forces. It is represented by an increase of the Young's modulus. According to formula (4) the growth of the resonance frequency with the compressive stresses can be explained. The change of the Young's modulus has greater impact on the change of the resonance frequency than the change of the compressive stresses.

The range of the measured resonance frequency should be also explained. The incipient natural frequencies of the bar are counted in hundreds of Hz, and the results of the measurement are given in kHz. As was shown in (Kwaśniewski *et al*. 2011a), there are electrical elements in the feedback loop. Every one of them has its own signal delay. For self -excited systems, these delays are an essential issue. Every auto-oscillator is very sensitive to active and passive

system elements and parameter changes. The system adjusts its frequency to the natural frequency of first form vibrations, but because of these delays, the system does not reach stability. The SAS system is an auto-oscillator with a nonlinear frequency shift (an auto-oscillator in which frequency depends on oscillation amplitude) and because of these signal delays usually reaches the frequency of the higher order forms. Control elements with smaller signal delays should eliminate the adjustment of the frequency to such a range. You can find more references about this effect in (Kwaśniewski *et al*. 2011a).

3. INDUSTRIAL TESTS

After successfully conducted preliminary tests an industrial plant was chosen. The industrial tests were conducted in the cement plant. The object under the study is shown in Figure 2. It can be treated like a continuous medium bar. It is a silo filled with cement. There are two types of actions, loading and unloading the silo. Almost every 15 minutes comes a mixer truck and takes a portion of concrete. Depending on the capacity of the mixer truck it is about 1.5 tons of cement to make the concrete, for a small mixer truck, and about 2.5 tons for a large mixer truck. Two times a day the silo is refilled with the thirty tons of cement, pumped to the silo. The silo is standing on four legs. The base of the leg is not made only of concrete but there is also metal for additional reinforcement.

The load from the weight of the metal silo and from the weight of the cement inside it is distributed equally among the four legs. To determine the sensitivity of the SAS system the real object test stand had several positions to mount emitter and sensors. Figure 2 is shows these positions, where the letter *E* refers to the position of the emitter, and *R* refers to the position of the receiver (accelerometer). The tests were split in three different groups: the closed loop system, the open loop system, and the velocity measurement system. The tests in the open and closed loop were done in four configurations *E*1, *R*1 or *E*1, *R*2 and *E*2, *R*1 or *E*2, *R*2. It has been proved during the tests, especially for
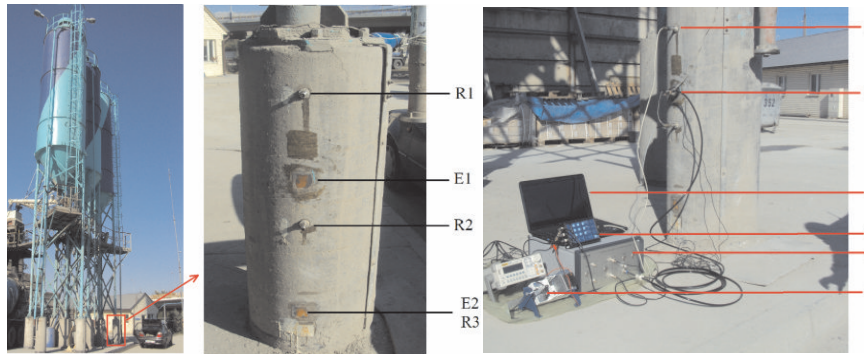
Fig. 2. View of the measurement test stand: *E* – positions of the emitter, *R* – positions of the receiver, *a* – fixed receiver, *b* – fixed emitter (shaker), *c* – laptop with appropriate LabView software, *d* – conditioner, *e* – compact measurement cards, *f* – power amplifier

the closed loop, that regardless of the configuration, the results were exactly the same. This paper shows the measurement results for the closed loop in the example of the configuration $E1$, $R1$.

The tests for measuring the velocities were conducted in configuration $R1$, $R2$, and $R1$, $R3$. They were caused by different ways of connection between the sensors and the concrete. The $R1$ and $R2$ sensors were connected by the thread, while the $R3$ has a magnetic connection with metal plate glued to the concrete.

3.1. MEASURING THE WAVE PROPAGATION VELOCITIES

As was mentioned the tests for measuring wave propagation velocities were conducted in two configurations of the sensors $R1$, $R3$ and $R1$, $R2$. Each configuration placed the first sensor in the $R1$ position with the thread connection. The second sensor was in position $R2$ with the thread connection in the first configuration. In the second configuration the sensor has a magnetic connection and position $R3$ (Fig. 2). An analyses of the results showed that magnetic connection is not suitable to determine the velocity of the wave. It is

caused by unstuck connections between the magnetic sensor and the rounded surface of the metal plate. The tests were conducted on a two-phase system object. The silo leg was made of concrete reinforced with metal bars, so the first phase was concrete (B30), and the second was construction steel (E295). For a better understanding, several tests were made in the laboratory with the one phase system separately: for concrete and for steel.

The distance between the sensors was $l = 1$ m. The measuring card was sampled with the frequency of 600 kHz. Above the upper sensor several mechanical knocks were applied. Created impulse can be treated like a Dirac delta function. Figure 3 shows the impulse response of the tested material and one zoomed impulse for signals from both sensors. By analysis of the distance between the first maximums for both signals, the time delay was determined. Because of the wave reflection and interference phenomena, the other maxima of signals were abandoned. This measurement routine was troubleshooting because of the requirement of the choosing only the first maximums. A large velocity of the wave and small distance between the sensors, which is determined by the dimensions of the material was the main reason for the difficulties.
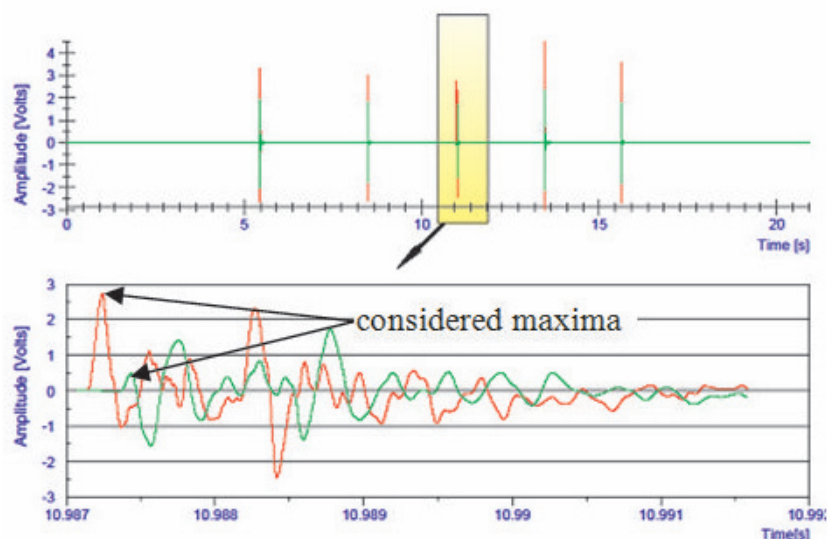

Fig. 3. The impulse response

3.2. STATIC TESTS

The first group of tests was conducted when there were no loads or unloads in the silo. The relative value of the weight of the cement in the silo was known. This group of tests can be treated as a static test.

When we started the tests, the weight of the silo was about 48 tons. When there was no loading and unloading, the measurement was done. As a result we obtained a resonance peak on FFT characteristics at frequency about 15 kHz – highlighted area on upper chart showed in Figure 4. To show the detailed frequency, we extended this highlighted area and showed it in the lower chart in the same figure. The first peak from the right site represents the resonance frequency of SAS system when the cement in the silo weighted 48 tons. This load has to be distributed into the four legs of the silo. So, each leg was compressed with 12 tons plus the weight of the silo, which is constant. The changes of the stresses are determined only by the variations of the weight of the cement inside the silo.

After this measurement, the process of unloading has begun. The cement from the silo was unloaded to the small mixer truck, which holds about 1.5 tons of cement. After the operation, again when there was no loading or unloading, the measurement was conducted. On an extended chart in Figure 3 the result is visible as an "46.5 tons" peak. The cement that was sent to a small mixer truck caused a decrease in the load for one leg, about 400 kg, and also decreased the stresses. The peak moved left for about 5 Hz from the starting position. Then, the process of unloading was continued, but this time the mixer truck was bigger; its capacity was about 2.5 tons. Again in static conditions (no loading or unloading) the test was done. The peak responsible for new resonance is shown in figure 4 with a 44 ton label. It moved to the left for about 33 Hz from its previous position and 38 Hz from the starting position. It was caused by a decre-

ase of the load of about 625 kg for one leg (2.5 tons goes to the large mixer truck divided by four).

On the next day, the measurements were carried out. The weight of the cement in the silo was about 38 tons – during the night some unloading was done. The test was conducted also in static conditions. The first peak from the left site presented in Figure 3 is responsible for the resonance of the concrete leg by this load. This peak has moved about 322 Hz from the last position and 355 Hz from the starting position. The decrease of the load between the start condition and end condition was about 2.5 tons per leg. The static tests clearly prove that the Self-exited System, which uses the autodyne effect, can be adapted for the changes in the stress measurements of real objects.

3.3. CONTINUOUS MONITORING OF THE CONSTRUCTION

The second group of tests was conducted when the silo was loading (it takes cement from the truck) and unloading (sending the cement to the mixers). The cement comes from truck. This truck is equipped with a special pump system, which pushed the cement through the pipe to the silo. In one loading cycle, it gives about 30 tons of cement. The process takes about one hour. Assuming the constant efficiency of the pumps we can calculate the rate of the flow. It is about half a ton per minute, which means, that the load for one leg grew about 125 kg every minute. The SAS system was continually monitoring the real object during the process of loading.

What is interesting is that during the loading process the silo did not stop working. It means that from time to time mixer trucks took portions of cement. After the process of loading started, the FFT peak went to the frequency value which was around 15 kHz, as is shown in Figure 5.
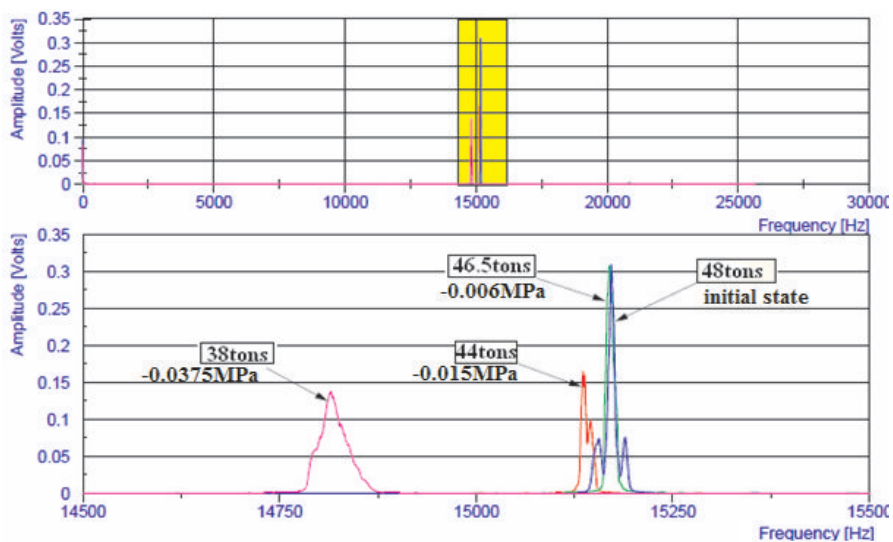

Fig. 4. The SAS system FFT characteristic of cement silo during unloading
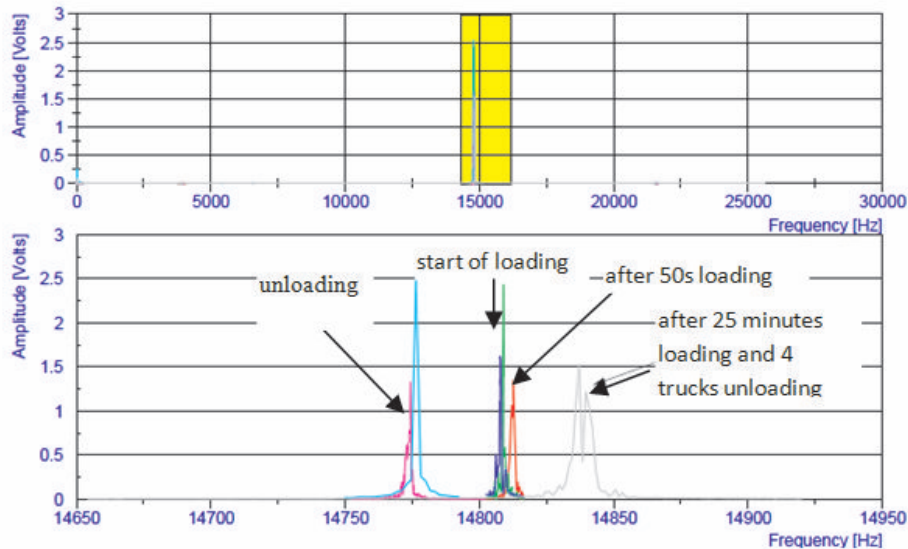
Fig 5. The FFT characteristics after 25 minutes of SAS monitoring

The chart in the same figure shows the exact value of the frequency 14807 Hz. With the time the load increasing, so after 50 seconds, which means 100 kg per leg more (+0.0015 MPa from the initial state), the peak moved to the right 4 Hz more. After a couple of minutes the mixer trucks came and took cement portions from the silo. After a rapid loss of weight caused by the mixer trucks, the resonance frequency had changed. This was noticed by the SAS system: the resonance frequency after rapid unloading moved to the left about 33 Hz from the start position (–0.0375 MPa from the previous state).

The loading process was still continuing so, after the end of rapid unloading, the weight of the cement in the silo was still increasing. The SAS system was monitoring the construction for the next 25 minutes. In this time there were 4 large mixer trucks, which took about 10 tons of the cement. We could also notice that in 25 minutes there were 12 tons of cement pumped into the silo. So, from the beginning of the monitoring process there was 12 tons of the cement loaded into the silo; 10 tons were taken by the four truck mixers. This means that after 25 minutes there were 2 tons of cement more in the silo than at the beginning (+0.03 MPa from the initial state). In figure 5 it appears as the frequency peak movement from the starting position to the right with 32 Hz difference, up to 14839 Hz value.

4. SUMMARY

The main thesis shown in this article is that a self-exited acoustical system with positive feedback permits monitoring of the changes of stress in construction. The usefulness of this phenomenon for different states of strain and various dimensions of test samples of sandstone, marble, and concrete was examined to prove this argument. The study confirmed the existence of the self-excitation phenomenon, which can be used to recognize the state of rock mass deformation. After performing experiments in the laboratory and analyzing the results from the simulation, real object tests were conducted. In the cement plant, the research was conducted on one of the legs of the silo.

The obtained results clearly indicates the apllicability of the SAS system which operates very well in both periodical and continuous measurements. It detected both the decrease and increase of the stresses caused by the change of the load in the cement silo.

From the same reason as in the static tests, we cannot give the exact value of the load change. There are a few reasons for it. The first one is that the irregular and vertical level of the cement could change the displacement of the mass center causing different and unequal loads for each leg. Additionally, in case of continuous measurements, we have to mention that the efficency of the pumps was not constant, so the assumed flow rate was not constant as well. Additionally, there are some variable reactions, because the cement is falling from the top of the silo creating the variable force, which has an influence on the load of the single leg.

In spite of it the system had very good sensitivity – the researchers marked even a 20 kg change in the weight of the cement in the silo, which is a very good result in comparison with the overall weight of the silo, which equals 60 tons.

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