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# Integrated stress measurement system in tower crane mast

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ABSTRACT

In the paper two methods for measuring changes in stress for slender steel structure are presented. The first method consists of surveying the inclination of the tower mast and jib by using a tacheometer to measure the coordinates of two prisms placed on the construction crane. The measurement of these deflections performed with a simple model of endurance allowed to calculate stresses in the base of the mast crane. The stresses resulted from changing load by transferring construction parts on its arm. The redundant measurement system which was used during measurements is called a Self-excited Acoustical System (SAS). Due to the self-oscillation effect it was possible to measure the changes in stress at the lift mast base. During the process of measurement two self-excited loops were used to allow stress monitoring in all corners of the truss crane construction. This article presents a comparison of the results obtained by two parallel measurement systems and analyzes the possibility of integrating them into a single, redundant system for measuring stress changes.

## 1. Introduction

The matter of the non-destructive testing and examination has a crucial meaning nowadays. The modern diagnostic methods of structural materials state examination have a large number of various physical methods. Most classical method uses the strain gauges in the field of strain measurement. Even now this very old method is still being improved, e.g. using nanofibers [1], fiber optic sensors [2] or even polymers [3]. In the field of magnetic diagnostics, there is on-going research to investigate the stress dependence of the magnetic characteristic under different applied stress [4,5].

The electrical methods are also well known in non-destructive strain and stress testing. The residual stress can be measured by electronic speckle pattern interferometry (ESPI) [6]. A very interesting method for stress measurement uses pulsed eddy current (PEC) [7,8]. This rapidly developing technique can be used, among others, in the defect characterization [9].

Among other groups of the non-destructive methods, like an X-ray stress determination [10,11], ultrasonic methods have a strong representation in diagnostics [12–15].

Stress measurement is of critical significance to user's security and the reliability of engineering components, so the methods of non-destructive testing and examination should be further improved to eliminate the disadvantages of today's methods. This paper presents an innovative ultrasonic non-destructive method called SAS (Self-excited Acoustic System), used for stress change determination. The second Section of this paper describes the measurement methodology for SAS system. The rest of the paper is organised as follows. Firstly, the model of the system and its quartz equivalent is presented in Section 3. The description of the reference measurement system is showed in Section 4. Next, the experimental studies are carried out in Sections 4–7. It presents as follows: the description, the study in stress changes and the measurement results. Finally, the conclusions are presented in Section 8.

## 2. Methodology

Self-excited oscillations in mechanics are created by nonlinearity of the exciting force. This force increases for small velocity and decreases for the large one. With such a behavior of the self-excited systems it is possible to achieve a stable solution – a series of self-excited vibration limits [16–19].

Self-excited systems are often found in many mechanical systems, where the oscillation circuit always absorbs energy from a constant external energy source, which causes the excitation of the periodic vibration [20]. These systems have become a topic of interest of many researchers at the beginning of the twentieth century. A pioneer of self-excited acoustic systems, who described

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continuous self-excited vibrations for the cello strings pulled by a bow, was Rayleigh [21].

Self-excited vibrations are usually undesirable. The most tragic incident was self-excitation of the bridge in Tacoma in 1940, where the construction was destroyed because of the constant wind. Similar problems may occur in the wings of aircrafts with suspended engines [22–24].

At the Department of Process Control the SAS – Self-excited Acoustical System was created to measure changes in elastic structures. It can be used to monitor the state of stress both in steel and concrete structures.

The first technically desirable use of self-excited systems occurred during improvement of old radio transmitters [25]. The use of autodyne lamps has significantly improved an increase in the amplitude of the waves at certain frequencies. Hence, the self-excited system is commonly called autodyne system or simply an autodyne.

Like any self-excited system, SAS consists of two subsystems coupled with each other, of which at least one must be non-linear [26]. In this case, a non-linear energy absorbing system is the tested object. The SAS system diagram is shown in Fig. 1. The system consists of electronic equipment, which core comprises two main components: an emitter (E) – a piezoelectric exciter and a receiver (R) – an accelerometer sensor. A conditioner and an amplifier are used for the suitable conditioning and gaining of a signal. The amplifier, the emitter (E) and the accelerometer sensor (R) form a feedback system. The energy delivery system is the emitter amplifier circuit, while the piezoelectric vibration sensor is responsible for the energy control. The general principle of the system is the fact that the change of stresses in the tested structure has an influence on the changes in the resonant frequency of the entire system. Measuring changes in the resonant frequency can thus determine the stress changes in the studied structure.

The distance between the emitter and the receiver is not determined parametrically and thus, there is no optimal setting. However, it can be determined empirically. The only limit for the system is when the acoustic wave doesn't deliver enough energy. It comes when the emitter is not strong enough or/and the distance is too long. In this case, the distance should be shortened, till the excitation would start. This distance is the maximum one, where the heads may be placed.

The power of the emitter is also the crucial issue in the case of the large cross section member, as well as in case of the corrosion. If the emitter delivers too small amount of energy to the receiver, the self-excitation does not start. That is why one of ours goals was to determine parametrically the dependence between those two quantities.

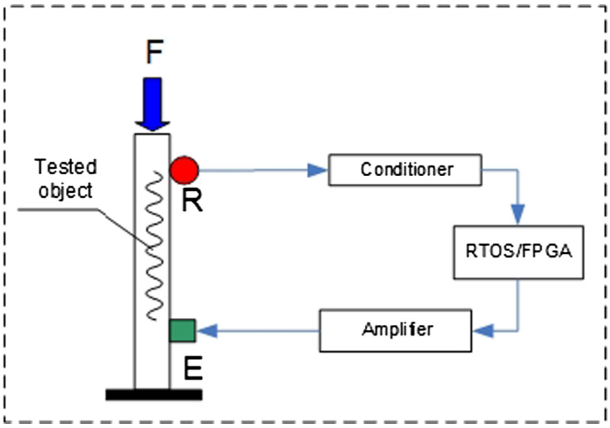

**Fig. 1.** SAS diagram where E-emitter and R-receiver.

Although the corrosion is not usually a problem in the case in tower crane mast, because of the strict safety and maintenance/-conservation norms, it is very interesting to investigate its influence on the measurements results. If the corrosion is shallow, and the propagation wave is not a Rayleigh wave, then it has no influence on the SAS system frequency. In the case of the deep corrosion petting it occurs in the system frequency. The velocity of the acoustic wave changes during propagation through the rust, so it can unintentionally disturb the results. In this case the placing of the heads should be changed.

## 3. Modeling

The principle of operations of the SAS system can be easily represented as a simple crystal resonator. The simplified schema of such a device was presented in Fig. 2a. The quartz resonator stabilizes the resonance frequency of the electrical circuit through mechanical vibrations [27,28]. It is a parallel resonance, and the crystal is effectively a bandpass filter. This quartz, coupled with the electrical circuit, is dosing a small amount of energy in the feedback loop via piezoelectric effect [29,30]. This phenomenon is stabilizing the resonance frequency. The electrical equivalent of such a system was shown in Fig. 2b, where $C_1$ is a motional capacitance, $L_1$ is a motional inductance, $R_1$ is a motional resistance and $C_o$ is a shunt capacitance of the crystal, and $C_L$ is a load capacitance.

Fig. 3 shows the functional equivalent for the Self-excited Acoustical System. In this case, the piezoelectric transducer has a function of the quartz crystal. The acoustical wave, which is propagated in material between the emitter and receiver heads is represented as a variable load capacitance $C_L$. Although, the load capacitance is usually a constant parameter of the piezoelectric transducer, the material under examination can be treated as additional parallel capacitance. For simplification it was represented as a variable capacitance $C_L$, because the parallel capacitances are cumulative.

As it is shown in [31], the parallel resonance frequency $f_l$ of such a crystal can be represented by Eq. (1).

$$f_l = \frac{1}{2\pi\sqrt{L_1 C_1}}\left(\frac{C_1}{2(C_0 + C_L)} + 1\right) \tag{1}$$

The SAS system is using also the elastoacoustical phenomenon This effect determines the change of the velocity of the acoustic wave propagation caused by the change of the stress in material under examination, which is given by (2).

$$\frac{\Delta V}{V_0} = \beta\sigma \tag{2}$$

where $V_0$ is a acoustic wave propagation velocity in non-stressed state, $\beta$ is an elastoacoustic coefficient and $\sigma$ is the stress.

Assuming the constant distance between the emitter and receiver, the time of acoustic wave propagation in material under the load is given by (3).

$$t_\beta = \frac{t_0}{\beta\sigma + 1} \tag{3}$$

where $t_0$ is an initial acoustic wave propagation time, and $t_\beta$ is an acoustic wave propagation time for $\sigma$ stress.

In order to get the accurate representation of the SAS system model, the dependence between the load capacitance $C_L$ and the time of wave propagation $t_\beta$ is necessary to determine. It can be concluded by analyzing the scheme in Fig. 2b, a low-pass filter with a transfer function given by (4) is present in the electrical circuit.