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Origin of frequency difference between damped and sustained modes in vibrating wire sensors

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ABSTRACT

Vibrating wire sensors can operate in two modes, damped mode and sustained mode. In practice, the resonant frequency measured in sustained mode is higher than the one measured in damped mode. In this paper, the theoretical analysis indicates that average magnetic force and coil coupling are responsible for the frequency difference. This prediction is experimentally confirmed by measuring the resonant frequencies for different values of the two parameters. It is shown how to correct measurements in order to obtain the same results for the two modes.

1. Introduction

Vibrating wire sensors are widely used to monitor deformations of large civil structures such as dams, bridges and nuclear power plants [1]. This type of sensors is based on a stainless steel wire which is set into vibration by an excitation coil and this vibration is detected by the same coil or an additional coil depending on the measurement mode [2]. The wire is tightly stretched between two anchors installed in the monitored structure, as shown in Fig. 1. Small relative movements of the two anchors alter the mechanical tension of the wire and hence its resonant frequency [3]. Therefore the deformation of the structure can be determined by measuring the resulting change in the resonant frequency of the wire [4].

There are two modes of operation: damped mode that corresponds to a measurement when the wire is freely vibrating after a pulsed excitation, and sustained mode that corresponds to a measurement when the wire is continuously excited at its resonant frequency. Historically, the sensors operating in damped mode have been in use since about 1930 [5], and those operating in sustained mode have been adopted around 1960 [6]. It is commonly considered that the resonant frequency of the vibrating wire depends primarily on the wire properties (length, density and tension), and very little on the operation mode of the sensors. However, this is not exactly true. According to various experimental tests [7,8], the resonant frequency measured in damped mode differs from the one measured in sustained mode by 0.1–0.3%. Since the vibrating wire sensors are expected to be accurate at 0.1%, this frequency difference is far from being negligible. Moreover this makes it difficult to compare the measurements obtained in one mode and another. To properly interpret the measurements, one needs to fully understand the sensor signals, thus finding out what causes the frequency difference and how to correct it. In the case of two-coil sensors, if one of the coils fails, it is necessary to switch from sustained mode to damped mode [9]. In that case, it is very important to compensate the frequency difference.

In this paper, firstly the sensor operation in damped and sustained modes is analyzed in order to find the possible parameters that may affect the resonant frequency. Secondly, the influence of the relevant parameters on the resonant frequency is experimentally investigated in the two operating modes.

2. Relevant parameters of resonant frequency

The operation of vibrating wire sensors relies on the wire excitation and frequency measurement. Both can be accomplished using magneto-mechanical coupling. There are two modes of operation

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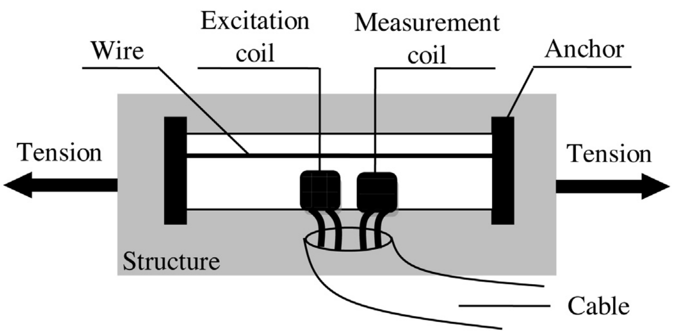

Fig. 1. Vibrating wire sensor installed in the monitored structure.

commonly used today: damped mode corresponding to pulsed excitation and sustained mode corresponding to continuous excitation [10].

2.1. Damped mode

The damped mode consists in giving the wire an initial displacement and then measuring the frequency of the damped free vibration [11]. The operating procedure in damped mode is illustrated in Fig. 2. Initially a single pulse or a burst is applied to the excitation coil [12], thereby creating a magnetic field that excites the wire during a short period of time (Fig. 2a). Then the wire vibrates until the vibration is completely damped, within seconds. The damped vibration induces, due to the remaining magnetic field, for instance due to the magnetization of the coil core produced by the excitation, a voltage in the same coil or a second coil (Fig. 2b). The frequency and the temporal evolution of this voltage are identical to those of the wire vibration.

After the pulsed excitation, the absence of external force (magnetic force) allows the wire to undergo damped free vibration due to the mechanical tension in the wire. Consider a uniform stretched wire of mass density ρ, cross sectional area A, under constant tension T. For the sake of simplicity, the gravity and the bending stiffness of the wire are always ignored. The equation of motion of the wire undergoing free vibration can be written as

$$\rho A \frac{\partial^2 u_y}{\partial t^2} = T \frac{\partial^2 u_y}{\partial x^2} \tag{1}$$

where $u_y(x, t)$ is the transverse vibration of the wire at position x at time t, Assuming that the ends of the wire of length L are fixed at $x = 0$ and $x = L$, one has to impose the boundary conditions: $u_y(0, t) = u_y(L, t) = 0$. Applying the boundary conditions to Eq. (1) leads to the expression of the fundamental natural frequency [13]:

$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{\rho A}} \tag{2}$$

In the damped vibration, the actual frequency measured by the coil is slightly lower than the natural frequency f_0 because of damping influence. The apparent damped frequency f_a related to the damping ratio ζ is given by

$$f_a = f_0\sqrt{1-\zeta^2} \tag{3}$$

2.2. Sustained mode

The sustained mode consists in maintaining the wire at resonance and meanwhile measuring the resonant frequency [14]. In this mode, it is necessary to use two coils, one to continuously excite the wire and the other to simultaneously measure the frequency of the vibration. The operating procedure in sustained mode is illustrated in Fig. 3. The first coil is supplied by a sinusoidal voltage at the resonant frequency of the wire. The continuous excitation generates a sinusoidally varying magnetic field which maintains the wire in resonant vibration. The wire displacement induces an alternating voltage in the second coil. This induced voltage has the same frequency as the wire vibration.

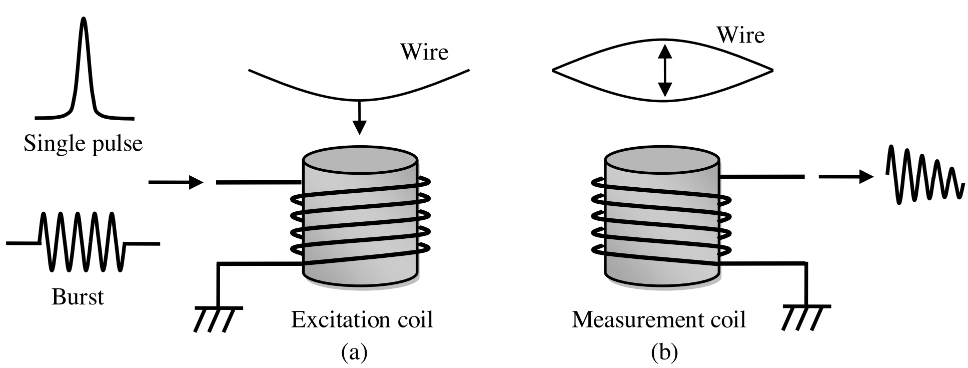

Fig. 2. Damped mode. (a) Pulsed excitation. (b) Measurement of the damped vibration.

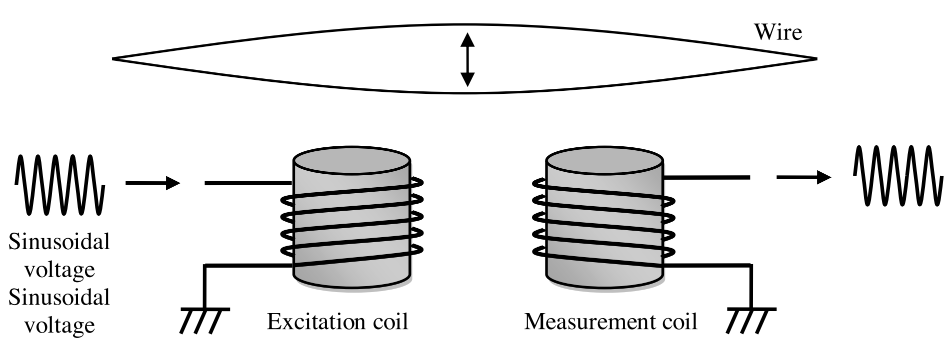

Fig. 3. Sustained mode. Excitation and measurement are continuous and simultaneous.