Temperature Independent Vibrating Wire Displacement Transducers

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Abstract

Displacements sensors and transducers are often affected by temperature dependence. In this paper the vibrating wire displacement transducers behavior is inspected and its temperature dependency is analyzed. Moreover, an approach based on two wires transducers is proposed. It will be shown how these systems can exhibit temperature independent measurements without using other kind of temperature sensors.

1 Introduction

Displacement monitoring is an important issue in many applications such as movement along joints and geological faults, widening of fissures in concrete structures, monitoring of cracks in masonry brick walls, monitoring cracks at potential landslides, monitoring cracks in arch dams. It is a fundamental task the sudden perception of the gradual sinking of a structure in order to prevent cracks. A low cost and simple solution to this problem is the use of a vibrating wire as shown in fig. 1. Usually it consists of a wire in series with a tension spring which is used to suitably vary the wire tension. The physical principle that characterizes the behavior of the vibrating wire is that a strained wire vibrates at a certain resonant frequency which depends on the initial length of the wire L_0, on the strain τ, on the density of the wire ρ, and its section S by the following law

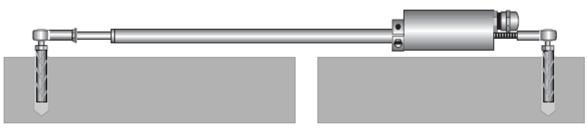

Figure 1: Crackmeter structure

$$f_0 = \frac{1}{2L_0}\sqrt{\frac{\tau_0}{\rho S}} \tag{1}$$

If the strain changes, owing to a displacement across two part of the monitored structures, thus provoking a change in the length of the vibrating wire, the frequency of the wire changes itself and the displacement can be identified. Many transducers, based on this principle are actually in commerce [1–7], embedded in displacement sensors called *crackmeters*. The principal drawback of these sensors is the necessity of embedding also a thermistor in order to suitable correct the effect of the temperature algorithmically. It is evident that the temperature effects are comparable to those of a displacement, thus producing a false, and unwanted, variation of the frequency of the wire. Since, in many application, the temperature can vary in a wide range (e.g -20°C ÷ 50°C), the output of the sensor could produce false alarms if not properly corrected. The necessity of the further calibration procedure makes this choice not suitable for application that need an immediate alarm. Moreover, the need of a periodic inquiring of the sensor, could represent a bothering task.

In this paper a new approach is presented that, through the redundancy in using two identical vibrating wires, allows to design a transducer which is independent from any temperature change.

Considering again (1) note that fixed the length, and the material, the frequency depends only on the

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section of the wire S and on the initial tension τ.

Let us suppose now that the wire is stretched of a ΔL that makes the new length be $L_f = L_0 + \Delta L$ or $(1+\delta_L)L_0$, where $\delta_L = \frac{\Delta L}{L}$. This effect is due to an additive tension $\Delta\tau$, so that the resulting tension, supposed to be parallel to the axle of the wire, is $\tau_f = \tau + \Delta\tau$ or analogously $(1+\delta_\tau)\tau$. By inserting these quantities in (1) we obtain

$$\begin{aligned} f_f &= \frac{1}{2(L_0+\Delta L)}\sqrt{\frac{(\tau_0+\Delta\tau)}{\rho S}} = \\ &= \frac{1}{2L_0(1+\delta_L)}\sqrt{\frac{\tau_0(1+\delta_\tau)}{\rho S}} \end{aligned} \tag{2}$$

under the assumption that the change in the section S is neglectable. So we get

$$f_f = f_0\frac{1}{1+\delta_L}\sqrt{1+\delta_\tau} \tag{3}$$

By Hooke's law, we can relate the change in the length of the wire and the change in the tension applied to the wire, through the modulus of elasticity (e.g. modulus of Young) E as follows

$$\delta_L = \frac{\Delta\tau}{ES}, \tag{4}$$

or equivalently

$$\frac{ES\delta_L}{\tau} = \delta_\tau$$

Consequently we obtain

$$f_f = f_0\frac{1}{1+\delta_L}\sqrt{1+\frac{\delta_L ES}{\tau}} \tag{5}$$

which provides an indirect way to measure the value δ_L by the measure of two resonant frequencies.

Let us consider now the effect of a change in temperature. It is well known that, under the assumption that the change in temperature ΔT does not produce phase transitions in a solid or chemical alterations, the following linear thermal dilatation law holds

$$L_T = L_0(1+\alpha(T)\Delta T) \tag{6}$$

where $\alpha(T)$, called *thermal linear coefficient*, is in general temperature dependent, but usually a mean value on a certain range of temperature is considered. When the solid is anchored so that it cannot expand when temperature increases of ΔT, as in the vibrating wire application, then its relative length keeps the same value and an equivalent reduction of tension occurs $\Delta\tau_T$. So, from (6) and (4) we have

$$\frac{\Delta\tau_T}{ES} = -\alpha\Delta T$$

and consequently

$$\delta_{\tau T} = -\frac{ES\alpha\Delta T}{\tau}$$

So, a change in temperature produces a change in the resonant frequency of the wire, thus obtaining

$$f_{fT} = f_0\frac{1}{1+\delta_L}\sqrt{1+\delta_\tau-\frac{ES\alpha\Delta T}{\tau}}$$

So a change in the resonant frequency, due to a temperature variation, may cause an erroneous alarm, if not properly verified.

2 Two-wires framework

Let us consider now two wires, with different sections S_1 and S_2, with the same length L_0, with same E, α_T, and ρ. Arguing as above we obtain

$$\begin{aligned} f_{f1T} &= f_{01}\frac{1}{1+\delta_L}\sqrt{1+\delta_{\tau_1}-\frac{ES_1\alpha\Delta T}{\tau_1}}, \\ f_{f2T} &= f_{02}\frac{1}{1+\delta_L}\sqrt{1+\delta_{\tau_2}-\frac{ES_2\alpha\Delta T}{\tau_2}} \end{aligned}$$

By the nonlinear relation between the temperature and the resonant frequency, a nonlinear combination must be considered in order to avoid temperature dependency. In particular, by evaluating $f_{f2T}^2 - f_{f1T}^2$ we

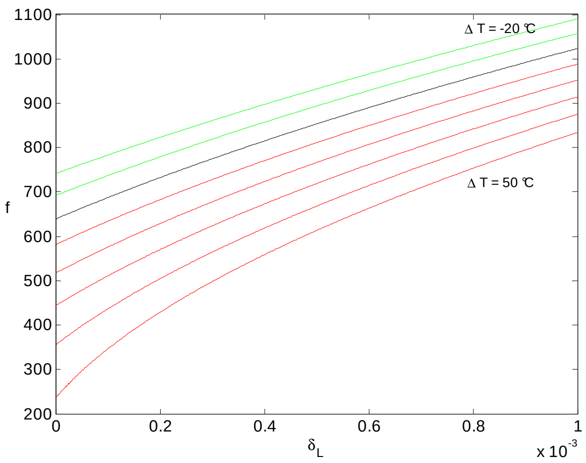

Figure 2: One-wire transducer characteristics vs. T variation

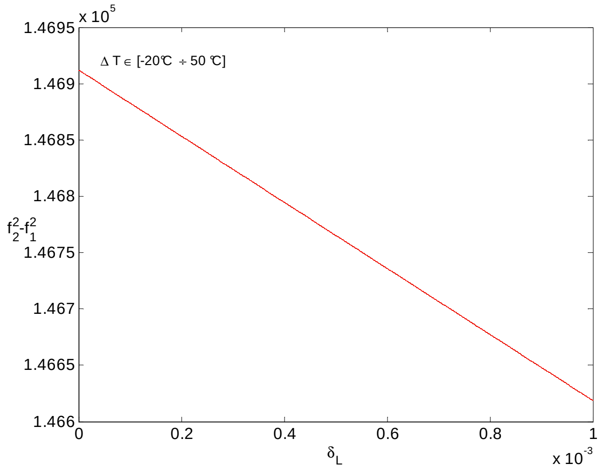

Figure 3: Two-wires transducer characteristics vs. T variation

have

$$\Delta f_T = f_{f2T}^2 - f_{f1T}^2 =$$
$$= \frac{1}{(1+\delta_L)^2}\left[f_{02}^2 \cdot \left(1 + \delta_L E S_2 - \frac{ES_2\alpha\Delta T}{\tau_2}\right) - f_{01}^2 \cdot \left(1 + \delta_L E S_1 - \frac{ES_1\alpha\Delta T}{\tau_1}\right)\right] =$$
$$= \frac{1}{4L_0^2(1+\delta_L)^2\rho}\left[\cdot\left(\frac{\tau_2}{S_2} + \delta_L E - E\alpha\Delta T\right) - \left(\frac{\tau_1}{S_1} + \delta_L E - E\alpha\Delta T\right)\right] =$$
$$= \frac{\frac{\tau_2}{S_2} - \frac{\tau_1}{S_1}}{4L_0^2(1+\delta_L)^2\rho}$$

Note that the above quantity dos not depend anymore on T. For simplicity we can set $S_2 = S_1 = S$ and we obtain a transducer sensitivity that depends on only ρ, L_0, S, τ_1 and τ_2.

As an example of this approach let us consider the following settings. Given two steel wires, with circular section, with diameter $d = 0.5$ mm, modulus of elasticity $E = 200 \cdot 10^9$ N/m^2, $\alpha = 11 \cdot 10^{-6}$ K^{-1} and density $\rho = 8000$ kg m^{-3}. Let us suppose an initial tension $\tau_1 = 100$ N and $\tau_2 = 10\tau_1$, and an initial length $L_0 = 0.1$ m. Under these hypotheses we have the two resonant frequencies $f_{01} \simeq 1261$ Hz and $f_{02} \simeq 3990$ Hz.

Figures 2 and 3 show respectively the one-wire and the two-wires transducer output responses for a temperature variation ΔT in the range [-20°C ÷ 50°C]. It is evident that the redundancy, as expected, produces an independency from the temperature change, avoiding the use of a thermistor to correct the measure of the frequencies.

Figures 4 and 5 compare the sensitivity of the one-wire transducer and two-wires transducer.

3 Conclusions

This paper presents a displacement transducer based on the use of two vibrating wires. The proposed approach allows to have measurements independent from temperature variation. The characteristics and sensitivity of this system have been analyzed in detail.

References

[1] Slope Indicator. VW Crackmeter 52636099. [Online]. Available: www.slopeindicator.com.

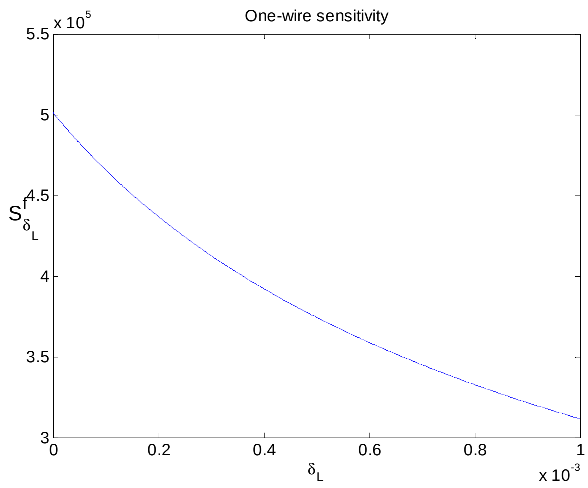

Figure 4: One-wire sensitivity

[2] Geosystems. Manual Crackmeter Model 3215-GS-MCM Series. [Online]. Available: www.geosystems.com.au.

[3] Geokon. Vibrating Wire Displacement Transducers 4400 Series. [Online]. Available: www.geokon.com.

[4] Boart Longyear Interfels GmbH. Crackmeter. [Online]. Available: www.interfels.com.

[5] Encardio-Rite Electronics PVT. LTD. Crackmeter Model EDJ-40M/P. [Online]. Available: www.encardio.com.

[6] Bell Lane. Cable-FreeCrackmeter J2CF. [Online]. Available: www.soil.co.uk.

[7] Roctest. Surface Jointmeter. Model RTF 1D-3D [Online]. Available: www.roctest.com.

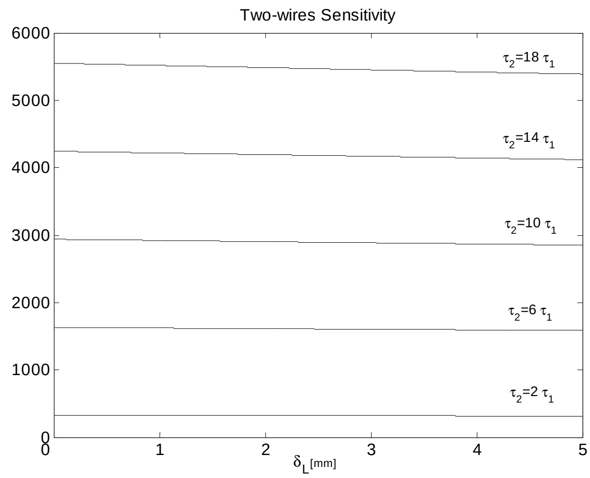

Figure 5: Two-wires sensitivity vs. ratio of tensions