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Comparison of vibration measurements of elastic and mechanically lossy (visco-elastic) materials, using fibre grating sensors

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ABSTRACT

The paper compares results when measuring oscillatory strain in elastic (Al alloy) and visco-elastic materials using in-fibre Bragg gratings. These show the effects of self-heating in the latter, when mechanical losses arise, and also show the effects of materials creeping at high strain levels. Results are also taken for highly-elastic metallic substrate materials when a visco-elastic damping medium is in close contact. The results show that care must be taken, not only when monitoring fast oscillatory perturbations in visco-elastic materials, but also when choosing fibre bonding cements or protective coatings for use with fibre gratings.

1. INTRODUCTION

The use of fibre gratings to monitor mechanical structures is becoming of increasing practical importance [1-4]. These structures may be metallic structures, having good elastic behaviour or, perhaps more frequently, carbon or glass-fibre composites, which again have reasonable elastic behaviour, provided the bonding resin is hard. So far, few structural measurements have been made in more plastic materials, such as un-filled polymers, which usually have a much greater degree of visco-elastic behaviour. This can lead to high mechanical losses, and even permanent creep, when cyclically strained. In addition, even if it is desired to monitor only elastic or near-elastic substrates, problems may still arise from the polymer bonding materials used to attach the fibre Bragg gratings or from any thicker plastic or rubbery outer coatings, that might be applied to protect surface-mounted gratings.

The most common method of bonding glass fibre sensors to structures is to use heat-cured epoxy resin, which, although quite hard, has, like most polymers, significant visco-elastic behaviour. In addition, for real-world applications, other thicker and more mechanically absorbing materials, such as soft rubbery coating materials, or thick bitumen layers, might often be used, to provide external protection to an, otherwise-fragile, surface-bonded grating. These bonding or surface-protection materials will generally have a much lower stiffness (Young's modulus Y) than the fibre sensor or the monitored substrates, so normally their influence on static strain measurements will be very small (the only stiffness requirement for the bonding material is to provide sufficient shear strength to transfer strain effectively). However, under circumstances where fibre Bragg gratings might be used to monitor high levels of structural vibration, particularly at high mechanical vibration frequencies, the mechanical hysteresis losses in these materials (usually expressed in terms of a tan δ figure, where δ is the phase angle between the applied stress and the resulting strain) can be a more significant problem. Firstly, in the extreme, the polymer or rubbery materials might even dampen the vibration to be monitored, but under less extreme conditions they might become noticeably heated by the mechanical hysteresis that can occur during cyclic straining, and hence affect the results by heating the grating. Even where the grating is thermally compensated, errors may still arise if the bonding material heats and causes thermal expansion in this material, as polymers usually have very high coefficients of linear expansion.

This paper will examine these critical aspects of monitoring visco-elastic substrate materials with Bragg grating sensors, and also take a preliminary look at the effects of placing layers of energy-absorbing materials in mechanical contact with otherwise elastic samples, as they are monitored under severe cyclical strain conditions. In order to assess these effects, we have conducted a series of experiments, as described below. Initially, we have chosen three substrate materials, having very different material properties. Values for these at room temperature are:

(a) Aluminium/magnesium alloy (AlMg3, also known as EN AW-5754), with good elastic properties, $Y = 70$ GPa, tensile strength ~ 230 MPa, tan $\delta < 0.0002$, a density of 2700 kg/m³ and high thermal conductivity of 135 W m^{-1} K^{-1}, coefficient of linear expansion ~ 33 10^{-6}/K,

(b) Polystyrene ("Hobbyglas" from Gutagliss GmbH), Y ~ 2.5 GPa, tensile strength ~ 50 MPa , a density of 1050 kg/m³, thermal conductivity ~ 0.19 W m^{-1} K^{-1}, coefficient of linear expansion ~ 67 10^{-6}/K, and

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(c) PVC, Y ~ 1.5 GPa, a density of 1380 kg/m^3, thermal conductivity ~ 0.2 W m^{-1} K^{-1}, coefficient of linear expansion ~75 10^{-6}/K.

It is well known that the mechanical loss factor of polymers can vary widely, not only with the basic chemical composition, but also because of the way it is formed. Its thermal and mechanical history, can, in particular, affect the polymer chain length and the degree of orientation, so is particularly important. The properties can vary widely with ambient temperature (typical tan δ mechanical loss values from the literature vary from 0.02 to 0.1 for polystyrene and 2 or three times greater for PVC). Because of this variability of polymers, we cannot precisely rely on published values, so we have constructed simple tuning forks from each of the actual materials used, in order to derive our own values for the relative mechanical loss factors for the actual sheets of the materials we have tested (Sect. 2). Following this, we have conducted tests of samples, taken from the same sheet as used for the tuning forks, in a simple tensile tester. This was capable of applying an initial tensile pre-strain (bias strain), plus an additional cyclical (sinusoidal) strain at frequencies up to 20Hz. We have measured each of the 3 above materials, with attached grating sensors (Sect. 3). In the case of the more elastic aluminium sample, we then made additional measurements after applying additional mechanical damping layers to it (Sect. 4). Details of the methods used and the results obtained are discussed below.

2. TUNING FORK MEASUREMENTS

Simple tuning forks were constructed from sheets of the 3 materials (sheet thickness was 1 mm for the aluminium, and 2 mm for the polymer samples), each with vibrating tines of 6.5 mm width and 65 mm length, as measured from the junction of the fork. Note that, because of the in-plane nature of the vibrations of the tines, the thickness of the material used for the forks is not important, as it should not significantly affect the resonant frequency or the material damping factors of the forks, provided air damping is insignificant. In order to monitor the displacement, without bonding relatively expensive Bragg grating sensors to each fork, a very simple method was used. In each case, a miniature 5 mm diameter coil of ultra-thin (100 μm diameter) enamel-insulated copper wire was bonded to one tine of the fork to be tested (in the same position for each, at a distance 20 mm from where the tines are joined) and a magnet was positioned close to the coil to produce a simple moving-coil displacement sensor when the output voltage from the coil is recorded. A scheme of the design of the fork, and oscillatory results after the tines were pressed closer together and then released, are shown in Fig 1, a-d.

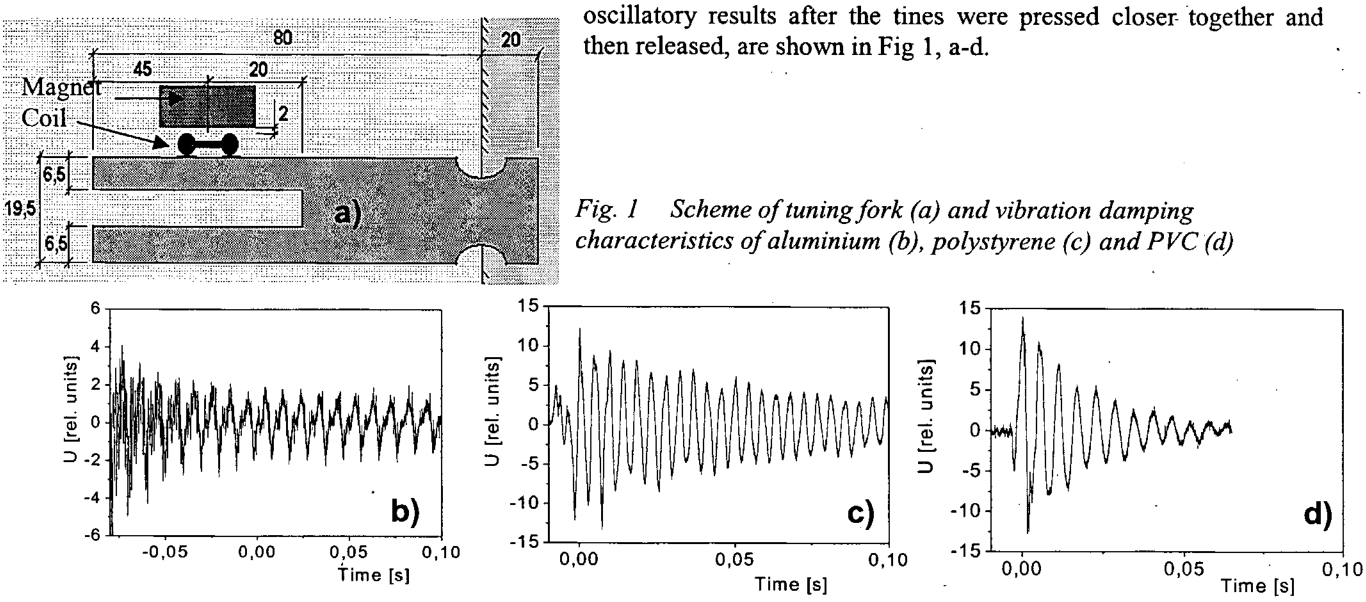

Fig. 1 Scheme of tuning fork (a) and vibration damping characteristics of aluminium (b), polystyrene (c) and PVC (d)

It can be seen that the 3 materials have markedly different mechanical behaviour, with the aluminium having, as expected, very little damping (probably, in this case, more damping occurs from the viscosity of the surrounding air and from the coupling of energy to the thin wire leads of the sensing coil and to the mechanical mounting). The polymers, however, clearly have very strong damping behaviour. This is particularly strong for the case of the PVC sample, where the material clearly absorbs 50% of its stored strain energy in only 3 to 4 cycles of oscillation. The polystyrene fork requires approximately 12 complete cycles to absorb the same 50% of its strain energy (Note: Since performing our own measurements, we found that similar mechanical relaxation behaviour to this has been observed for pure polystyrene samples, when subjected to a steel ball impact [5]. There, damping to 50% amplitude was found to take around 14 oscillations, a similar value to that which we observed).

3. OSCILLATORY STRAIN MEASUREMENTS USING SURFACE-BONDED BRAGG GRATING SENSORS

We shall now describe our measurements using Bragg grating sensors, inscribed in $125\mu m$ diameter silica fibre, that were bonded to the surface of our samples at a curing temperature of 80^0C, using Epotec 353 ND epoxy adhesive. The gratings were read out at a rate of 500 meas./s using a sensor system basing on SLD broadband light source and CCD spectrometer, which has been described in more detail in [6]. The wavelength repeatability of the measurement system was 0.6 pm (1σ value), with an equivalent strain resolution of 1 $\mu\varepsilon$ and a temperature resolution on Al substrate of 0.05 K.

The samples were AlMg3 alloy, with a strained cross section of 1 mm × 1.5 mm, PVC sheet 10 mm × 2 mm and Polystyrene sheet also 10 mm × 2 mm. The polymer samples were wider and thicker because of their much lower Young's modulus (tensional stiffness). All these samples were first pre-stressed in tension, and then peak-peak longitudinal oscillatory stresses of up to ± XXX N were applied. The oscillatory-stress was applied for several different time periods, firstly at a low frequency, then at a higher frequency, with quiescent periods between these, when only the fixed pre-stress, was applied. In each case, the response of the Bragg grating wavelength was observed. It was expected from knowledge of material properties, that several types of material behaviour might occur:

(a) A purely elastic response, with rapid recovery to the initial Bragg wavelength when the stress returns to the initial value. (The aluminium sample might be expected to show this).

(b) Visco-elastic behaviour at low strain levels, with internal heating of samples, which might cause Bragg wavelength changes during the period of oscillatory excitation. Such wavelength changes might occur firstly through temperature changes of the grating and secondly through thermal expansion of the substrate, followed by eventual recovery as the material cools. (The aluminium sample is expected to show relatively weak effects if measured in this way, firstly because the mechanical loss is low, secondly because it's thermal conductivity is high (resulting in rapid conduction of heat from the strained region into the more massive end clamps) and thirdly because its coefficient of thermal expansion is much lower than that of polymers. The polymer samples are expected to show strong effects here, because their mechanical loss is much higher, their thermal conductivity is nearly two orders of magnitude lower, and their thermal expansion coefficient is much higher).

(c) Significant irreversible behaviour (i.e. "creep") after straining, with permanent elongation. (All materials are likely to show this after the elastic limit is reached, but the polymers are likely to show more marked changes at the same stress level. This is most likely to occur at the higher levels of stress).

We shall now present our results (Fig. 2, a-c) for the 3 materials. In these, the measurement cycle included the following periods of static stress, or static plus additional cyclic stresses, all at ambient temperature of 23 °C:

(a) A static stress only, of 50 N steady amplitude.
(b) Application of additional cyclic stress of 100 N peak-to-peak, at 3 Hz, starting at t = 0, for 4 min.
(c) Same static stress only as in (a), for 4 min.
(d) Application of additional cyclic stress of 100 N peak-to-peak, now at the higher frequency of 16 Hz, 4 min.
(e) Same static stress only, for 10 min, to allow cooling and possible relaxation.

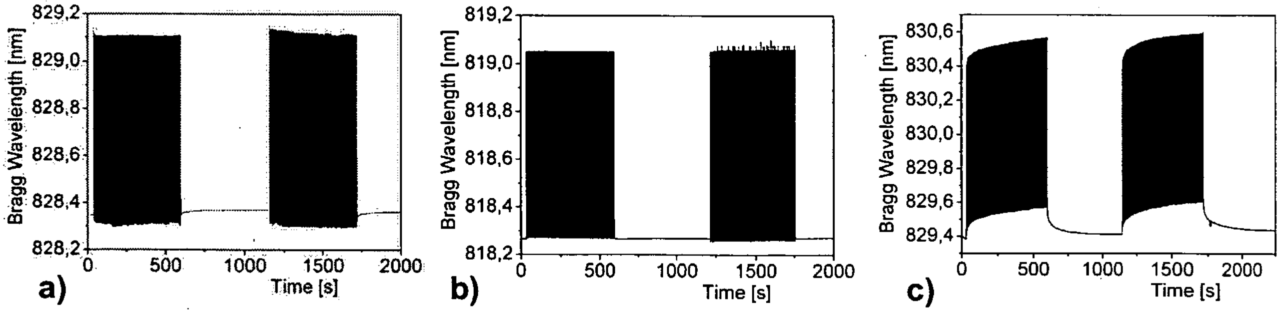

Fig. 2 Time characteristics of FBG sensor wavelengths during application of fast cyclic and static stresses, resp., on materials with different elastic properties: a) aluminium, b) polystyrene, c) PVC

The temporal characteristics above show that pronounced self-heating can occur during cyclic stress periods, particularly in the most mechanically lossy sheet, that of PVC (Fig. 2c).

4. MEASUREMENTS OF ALUMINIUM ALLOY WHEN ADDITIONAL POLYMERIC DAMPING MATERIALS WERE APPLIED TO ITS SURFACE

The aluminium alloy strip had a relatively low mechanical loss, and the effects of cyclic strain on this showed negligible heating or creep effects. However, as we discussed above, elastic materials might be measured with protective coatings over the fragile fibre grating. To investigate this, mechanically-damping coatings were applied in two ways. In the first method, an energy absorbing nitryl rubber layer (type NG150 from Hottinger-Baldwin-Messtechnik), approximately 0.3 mm thick, was filled with high density tungsten powder (specific gravity of approximately 19 g/cm^3) and applied. The second method was to apply an additional dual-layer fluoro-polymer heat-shrink tubing (outer layer of thermo-setting PTFE, the inner layer of thermo-plastic FEP) and shrinking this onto the Al/nitryl/tungsten sample. Both these coatings will cause far more mechanical loss, the shrink tube will also reduce heat loss, but will not, of course, avoid the heat conduction along the Al to the clamps. The slightly enhanced heating of the Al is seen in Fig. 3.

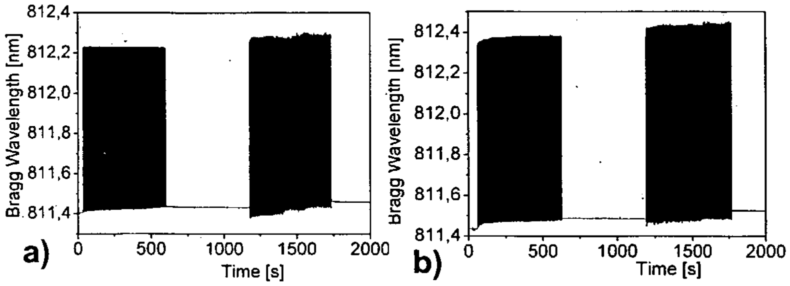

Fig. 3 Time characteristics of FBG sensor wavelengths on an elastic aluminium alloy substrate, which was coated with one of the following acoustically damping polymer materials:-

a) nitryl rubber filled with tungsten
b) additional FEP/PTFE dual heat-

5. CONCLUSIONS

We have shown how considerable care must be taken when measuring visco-elastic materials or composites with strain gauges, whenever strong vibrations are present. Soft polymer materials of high mechanical tanδ mechanical loss factor are particularly likely to exhibit self-heating errors and/or mechanical creep. We have found these effects can even be seen with otherwise elastic materials when visco-elastic coatings may be present. As gratings are often protected with soft protection layers, care must be taken when strong vibrations are expected.

6. REFERENCES

[1] W W Morey, J R Dunphy, G Meltz "Multiplexing fiber Bragg grating sensors" Proc SPIE 1586 pp216-224 (1991)

[2] Proceedings of OFS 15 Int conf, Portland, Orogon, 6th-10th May 2002. sessions TuA,TuB,TuC and TuP. ISBN 0-7803-7289-1

[3] Proceedings of OFS 16 Int conf, Nara, Japan, Oct 13th-17th 2003. sessions Tu2, Tu 4 and We3. ISBN 4-89114-036-4

[4] W. Ecke, R. Willsch "Field Trial Experience with Fiber Bragg Grating Health Monitoring Systems and Optochemical Sensor Concepts Basing on Polychromator Signal Processing", Proc. of 16th International Conference on Optical Fiber Sensors, IEICE Japan, ISBN 4-89114-036-4, pp. 500-505 (2003)

[5] http://www.septon.info/en/hybar/list/bpd.html, data for material from Kurray Co. Ltd, dated 8/12/2004