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Characterisation of an Optical Strain Gauge for Pantograph Applications

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An optical strain gauge is developed and characterised for an active pantograph for high-speed electrical trains applications. Indeed, the pantograph is subjected to a continuous impact forces when it makes contact with the 25 kV overhead ac line. To detect load behaviour experienced, by the electrical pick-up on the pantograph, tests were carried out. The results show that the strain gauge responded linearly to static load over the range 0 to 80 Newton. Also, a high repeatability was achieved and acceptable amount of hysterisis was experienced. The influence of the electromagnetic field on the optical strain gauge was sufficiently weak to be neglected. Beside that the optical strain gauge has proved a high resistance to time varying forces.

Keywords: Optical strain gauge, Load behaviour, Electromagnetic field, Repeatability.

1. INTRODUCTION

An optical strain gauge is developed and characterised for an active pantograph for high-speed electrical trains applications. Indeed, the pantograph is subjected to continuous impact forces, when it makes contact with the 25 kV overhead ac line placed on the roof of the vehicle, which provides current collection. Indeed, this arrangement has been generally satisfactory, and the margins of acceptable current collection have been reduced as the operational speed of vehicles has increased over the years.

Moreover, based on the consideration of the capital cost, lighter overhead equipment on the high voltage AC system has been widely used that adds to the problem. With the increase of speed and the use of the lightweight overhead equipment, dynamic impacts, which are directly applied to the carbon material of the pantograph head, has increased dramatically. As a result, crack damage may occur more often on the carbon material, where there are more and larger impacts. The crack, in serious cases, may trap or pull down the overhead line, which has serious consequences for the reliability of the electric train service and the operational costs.

To detect the load behaviour experienced by the electrical pick-ups on the pantograph; an optical strain gauge has been developed. This optical means of

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quantification of forces provide a complete immunity to electrical interference and isolation. In the current application chromatic modulation producing a spectral change through variable birefrengent material subject to the force monitored is exploited. Using distimulus linear measurement technique, as described by Bevan, the spectral change is quantified [1].

2. THEORY

An optical strain gauge based on the photo-elastic effect has been developed to monitor on line the contact force applied to the pantograph. The sensing system exploits the concept of chromatic modulation that can be produced by spectral changes induced by a controlled birefringence.

Many optically isotropic materials can become anisotropic, when subjected to a stress or induced strain through an elastoptic interaction known as photoelasticity; therefore display an optical characteristic similar to those of birefrengent crystal [2]. The propagation of linearly polarised light through a photoelastic plate subjected to unidirectional strain result in the split up, of the light wave, in two mutually orthogonal polarised components propagating to the photoelastic plate Fig.1 [3].

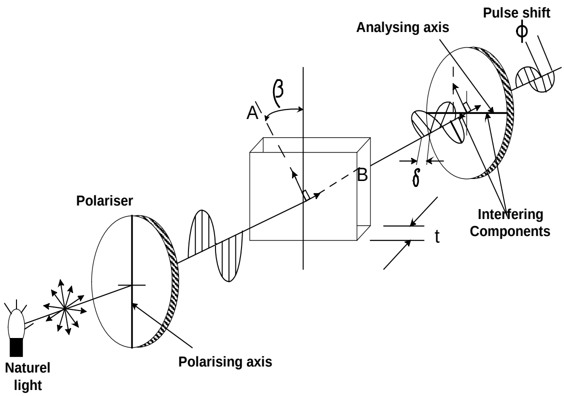

Figure 1. Polarised Light Propagating through Stressed Plastics

Since the indices of refraction in the direction of propagation of the light waves are different, the two components will travel with different velocities. Thus, they emerge from the photoelastic medium out of phase or with a relative retardation δ given by the following equation [4]:

$$\delta = (n_1 - n_2)\, d = \varepsilon k d \tag{1}$$

Where n_1 and n_2 are the refractive indices parallel and orthogonal to the direction of the strain respectively, d is the thickness of the photoelastic plate, k is the strain optic coefficient.

The component propagating parallel to strain direction would travel slower than the component propagating orthogonal to strain direction. Using a second linear polariser as analyser crossed to the first one, an interfering field of the two components is observed. So, the intensity of the transmitted polychromatic light is given by [5]:

$$I = \sum_{\lambda} I_{\lambda} \sin^2(2\beta)\sin^2\left(\frac{\pi\delta}{\lambda}\right) \tag{2}$$

Where I_{λ} is the optical intensity at a given wavelength, β is the angle between the polariser axis and the principal strain, and λ is the optical wavelength.

It is clear from the above equation that there are two conditions under which extinction of light may take place. The first condition is when the principal strain direction is set at 0 or $\pi/2$ with respect to the polariser-analyser axis; variation of β with respect to unidirectional strain field has been proved to be critical in optical strain gauge design, and to achieve a maximum sensitivity β is set to $\pi/4$. The second condition for light extinction is obtained when the relative retardation is equal to an integer number of wavelengths (equation 3), i.e. ($n = 0, 1, 2, 3...$).

$$\delta = n\lambda \tag{3}$$

If the light source used is monochromatic, for example sodium yellow, when this condition is satisfied the resulting spectrum of the fringe pattern appears as a series of distinct black lines on a uniform yellow background [4]. However in case of polychromatic light the retardation that causes the extinction of one wavelength does not generally causes the extinction of other wavelength. Thus the gradual increase of strain magnitude results in the extinction of each wavelength in sequential manner.

3. DISTIMULUS DETECTION

In order to monitor on-line the contact force applied to the pan head, an optical fibre sensor system based upon photo-elastic effect is proposed. The modulation technique consists of producing spectral change that can be induced by a controlled birefringence material subject to the force monitored. To detect the output signal, distimulus detection using two photodiodes having different but overlapping spectral response sensitivities, $R_{PD1}(\lambda)$ and $R_{PD2}(\lambda)$ as shown in Fig.2, is proposed. Indeed, the analysis of the spectral sequence provides the dominant wavelength.

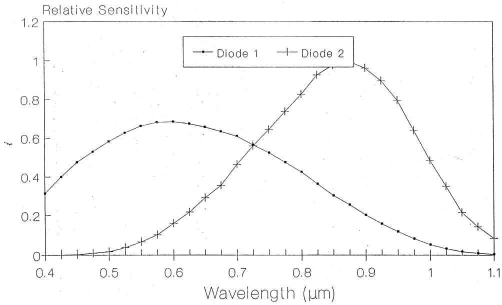

Figure 2. The spectral sensitivities of the overlapping photodiodes

The ratio of the outputs from the two photodiodes varies with the spectral signature of the returned optical signal. This ratio would be a function of the induced strain and the wavelength, and it is given by:

$$\lambda_e = \frac{\text{output from PD1}}{\text{output from PD2}} = \frac{I_{PD1}}{I_{PD2}} \tag{4}$$

Where I_{PD1} and I_{PD2} are the photocurrents output from PD1 and PD2 respectively.

$$\lambda_e = \frac{K_1 \int P(\lambda) R_{PD1}(\lambda) \partial\lambda}{K_2 \int P(\lambda) R_{PD2}(\lambda) \partial\lambda} \tag{5}$$

Where $P(\lambda)$ is the spectral power density, $R_{PD1}(\lambda)$ and $R_{PD2}(\lambda)$ are the spectral sensitivities of the two overlapping photodetectors; K_1 and K_2 are constants of proportionality of photodiodes PD1 and PD2 respectively.

Indeed λ_e may be rewritten in terms of strain (ε), wavelength (λ), and spectral distribution ($I(\lambda)$) generated by a Tungsten Halogen Lamp:

$$\lambda_e(\varepsilon, \lambda) = \frac{K' \int_{400}^{1100} I(\lambda) R_{PD1}(\lambda) \sin^2(2\beta) \sin^2\left\{\frac{\pi\delta}{\lambda}\right\} d\lambda}{K' \int_{400}^{1100} I(\lambda) R_{PD2}(\lambda) \sin^2(2\beta) \sin^2\left\{\frac{\pi\delta}{\lambda}\right\} d\lambda} \tag{6}$$

Because the photodiodes are identical, then K_1 and K_2 the photodiodes constants of proportionality are equal and are designated by K'. As the polarisers used in this application have an operating bandwidth that varies from 400 nm to 800 nm, equation 6 can be rearranged such that:

$$\lambda_e(\varepsilon) = \frac{K'\left[\int_{400}^{800} I(\lambda)R_{PD1}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda + \int_{800}^{1100} I(\lambda)R_{PD1}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda\right]}{K'\left[\int_{400}^{800} I(\lambda)R_{PD2}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda + \int_{800}^{1100} I(\lambda)R_{PD2}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda\right]} \quad \textbf{(7)}$$

However for $800 \le \lambda \le 1100$ nm, we have:

$$\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\} = 1 \quad (8)$$

Rewriting equation 7, gives:

$$\lambda_e(\varepsilon) = \frac{\int_{400}^{800} I(\lambda)R_{PD1}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda + A}{\int_{400}^{800} I(\lambda)R_{PD2}(\lambda)\sin^2(2\beta)\sin^2\left\{\frac{\pi\delta}{\lambda}\right\}d\lambda + B} \quad (9)$$

where

$$A = \int_{800}^{1100} I(\lambda)R_{PD1}(\lambda)\,d\lambda \quad (10)$$

and

$$B = \int_{800}^{1100} I(\lambda)R_{PD2}(\lambda)\,d\lambda \quad (11)$$

The theoretical chromatic transfer function, given by equation 7, is plotted in a Cartesian coordinate as a function of retardation (Fig.3).

It can be seen from Fig.3 that the chromatic transfer function $\lambda_e(\varepsilon)$ is a symmetric and a periodic function irrespective of the sign of the retardation (δ). Therefore, if the strain magnitude were determined from retardation it would be multivalued. Consequently the zero point needs to be displaced to Π. To achieve this result quarter wavelength is introduced in the optical arrangement.

4. GAUGE CONSTRUCTION AND DESIGN CRITERIA

The optical strain gauge considered in the current application was constructed from a thermosetting optical epoxy through a casting process. This process allows the overcoming of problems associated with initial birefringence that can be induced during other manufacturing process such as machining technique. Moreover, casting process does not require skilled intensive labour. Having a suitable Young's modulus and optical strain coefficient the optical strain gauge allows unidirectional strain in point to be made with a negligible Poisson effect. The size and form of the optical strain gauge constitutes an integrated unit with the linear and circular (providing the retardation offset) polarising filters bonded to the optical fibre tips (Fig.4.b). These tips are embedded into the thermosetting epoxy as shown in Fig.4.a.

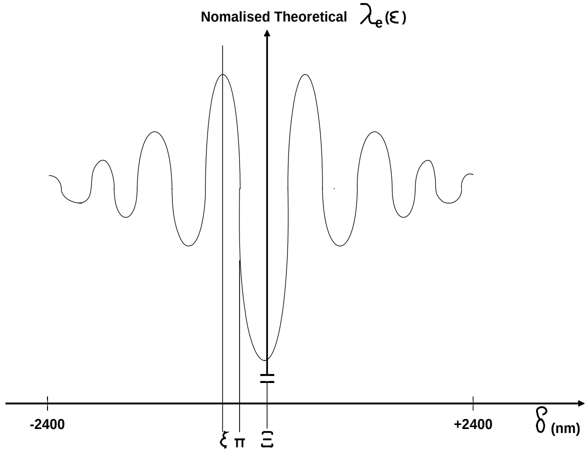

Figure 3. Photodetectors Ratio (Normalised Theoretical $\lambda_e(\varepsilon)$)

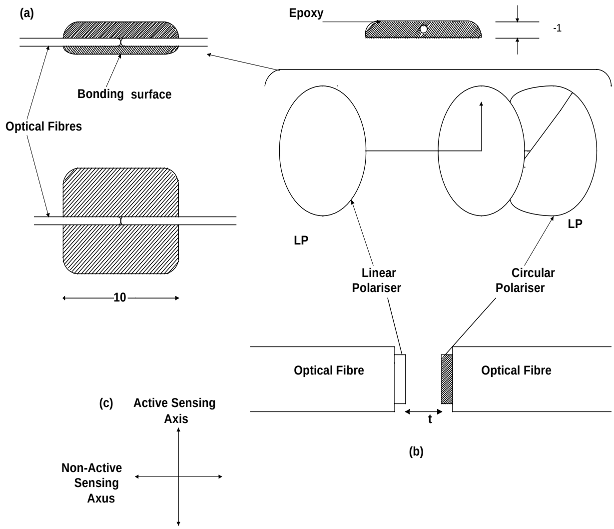

Figure 4. Configuration of: (a) casting unit (b) active element detail (c) sensing axes.

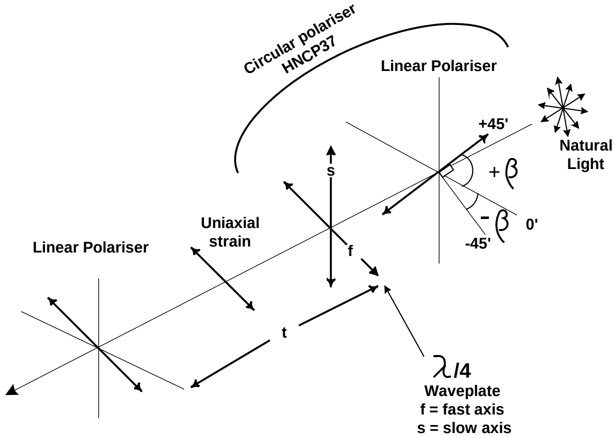

Figure 5. Optical Arrangement showing the Angle β for Crossed Linear / Circular Polariser Arrangement.

The alignment of polariser transmission axis with respect to the direction of principal strain has been proved to be critical for optical strain gauge. In order to achieve a maximum strain gauge sensitivity and great modulation depth, the transmission axis needs to be set at $\pi/4$ to the direction of principal strain (Fig.5).

As it can be seen from Fig.5, the fast axis of the quarter-wave plate is parallel to the direction of uniaxial strain; when this component reaches the optical strain gauge it become delayed under the influence of the stress. The slow axis, which is orthogonal to the fast axis, is not under stress and the polarisation component propagating along this axis, experiences no change in velocity when entering to the optical strain gauge. However, the first component i.e. along the fast axis initially leads that parallel to the slow axis by $\pi/2$, and the increase of the strain results in the reduction of the global delay between these two polarisation components. As the strain is further increased, a point where, the overall delay will be zero is reached and the linear polarisation state will be perpendicular to the analyser-transmitting axis. Consequently, no optical disturbance is transmitted giving the dark field condition.

5. LINEAR DISTIMULUS MEASUREMENT SYSTEM

Practically the photocurrents are obtained using the sharp PD150 double diode with a common cathode (Fig.6) [7].

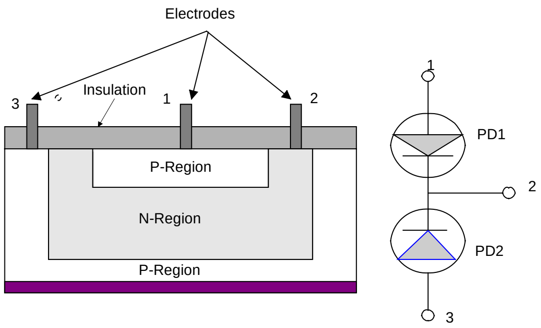

Figure 6. Sharp PD150 sequential photodiode

These two photocurrents are converted into two voltages using two operational amplifiers. An operational amplifier with a fixed gain factor is used to invert the sign of V_1 to positive value. A proportion, α of V_1 is obtained from the potential divider V_{R1}. This voltage is added to $-V_2$ and the subsequent result is multiplied by a gain factor $-\gamma$, so that the final voltage will be described by the equation $\gamma(V_2 - \alpha V_1)$. And then the two voltages V_1 and G $(V_2 - \alpha V_1)$ are fed to the 12-bits AD574AJN, to obtain the ratio of these voltages in digital format (Fig.7) [8].

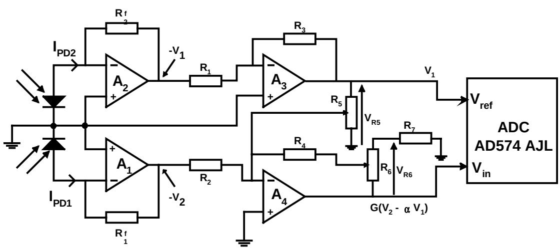

Figure 7. Schematic of the Processing Circuit.

6. EXPERIMENTAL RESULTS

The developed optical strain gauge was assessed to evaluate its performance and to find the range of operation. Static, hysterisis, dynamic, repeatability and electromagnetic susceptibility tests were carried out and the results compared to the theory when applicable.

6.1 Effects of Static Forces

The optical strain gauge was subjected to an applied static force increasingly varied from 0 to 150 Newton. To determine the hysterisis that could be exhibited by the optical strain gauge, the force was decreasingly varied from 150 to 0 Newton. It has been found that the dominant wavelength increases when the load is increased, but when the load reaches 80 Newton the dominant wavelength decreases as the force is further increased. Consequently, the measurement range of the force should be limited in the range of 0 to 80 Newton (Fig.8).

The amount of hysterisis exhibited by the strain gauge may result from the non-perfect positioning of the hanger on the active region of the photoelastic material. It is thought that the major factor contributing to such effect remains the physical nature of the material constituting the strain gauge. The response of the optical strain gauge was found to depart slightly from linearity. Among the factors that could have contributed to such effect are, additional stresses induced during clamping which may pre-strain the optical strain gauge, the connectors used and the positioning of the optical source relative to the tip end of the optical fibre may also contribute to such effect.

Indeed, the considered optical strain gauge has demonstrated a quit good repeatability (Fig.9). And the small variation between the two curves may have as origin the fluctuation of the temperature or may be systematic errors.

6.2 Effect of Dynamics Forces

In this second experiment, the optical strain gauge has been subjected to dynamic forces as the overhead lines make contact with the pantograph. Therefore, the optical strain gauge must be tested for resistance to these dynamic forces. Using a hounsfield machine the optical strain gauge has been firstly subjected to a dynamic force for a maximum value of 200 Newton (Fig.10.), then subjected to more rapidly time varying force for a maximum value of 300 Newton (Fig.11). The optical strain gauge has demonstrated a large resistance to such dynamic forces.

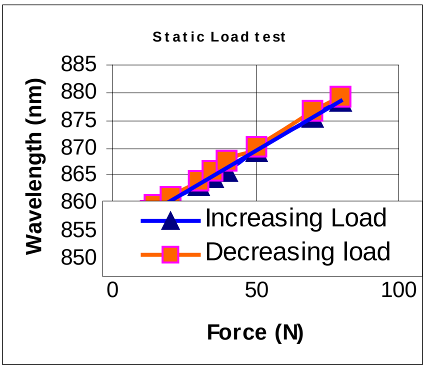

Figure 8. Response of the Strain Gauge to a static Load.

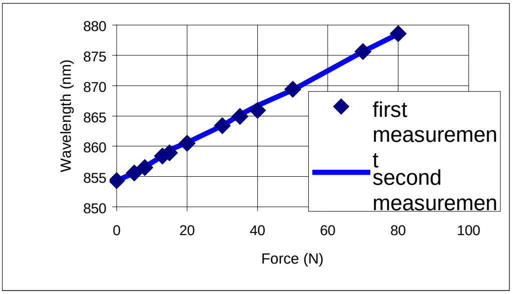

Figure 9. Results of the Repeatability Test

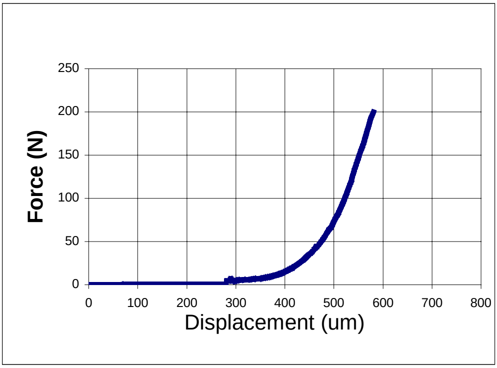

Figure 10. A Maximum Dynamic Force of 200 N

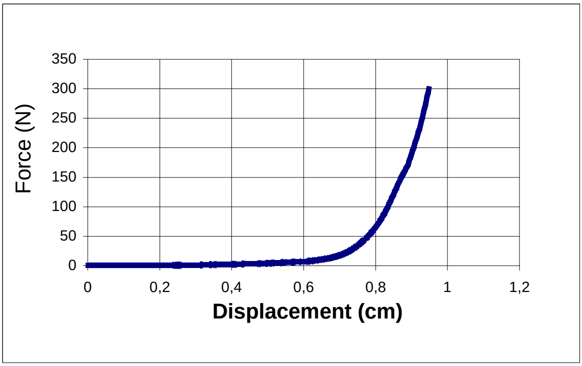

Figure 11. A Maximum Dynamic Force of 300 Newton

6.3. Electromagnetic susceptibility

Electromagnetic interference immunity of optical sensors was stated as one of their attractions for use in sensing system. However, many problems may arise when dealing with polarised light. Indeed, when an optically isotropic material is introduced into an electromagnetic field, the state of polarisation of the propagating light could be altered, which in turn can modulate the chromaticity. Since the considered optical strain gauge is intended to measure force in a potentially hazardous electromagnetic environment, its susceptibility to such effects has been considered. Other authors have found, when conducting measurement on photoelastic polymers, that susceptibility of the optical strain gauge to electric fields has been sufficiently weak to be neglected.

7. CONCLUSION

An optical strain gauge is developed and characterised for an active pantograph for high-speed electrical trains applications. Indeed, the pantograph is subjected to a continuous impact forces when it makes contact with the 25 kV overhead ac line placed on the roof of the vehicle, which provides current collection.

In order to monitor on-line the contact force applied to the pan head, an optical fibre sensor system based upon photo-elastic effect is proposed. The modulation technique consists of producing spectral change that can be induced by a controlled birefringence material subject to the force monitored. To detect the output signal, distimulus detection using two photodiodes having different but overlapping spectral response sensitivities is proposed. Indeed, the analysis of the spectral sequence provides the dominant wavelength.

The developed optical strain gauge was assessed to evaluate its performance and to find the range of operation. Static, hysterisis, repeatability and dynamic tests were carried out and the results compared to the theory when applicable. Through the static test it has been found that the response of the dominant wavelength to an applied force is linear over the range 0 to 80 Newton, after which the response ceases to be linear. This limits the range of the applied force.

Also, one of paramount parameter of interest is the ability of the strain gauge to satisfy the repeatability criteria. Extensive tests over a long period of time have been carried out and it has been found that, the optical strain gauge has a high degree of repeatability, and the influence of electromagnetic interference was negligible as several authors have certify.

The strain gauge proved to be resistant to the impact forces that can be applied in the real pantograph application, where these forces are applied every time the overhead line comes in contact with pantograph head.

The proposed optical strain gauge for pantograph applications is potentially viable and its principle may be used in other industrial applications where conventional transducers cannot be used due to the severe working environment.

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