Temperature Compensation of Fiber Bragg Gratings Manometry Catheter Using Kalman Filter

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***Abstract*—This paper presents a method for temperature compensation of fiber Bragg grating based manometry. The catheter used in manometry contains two fibers, one is used for pressure measurements and the other one is used to sense only temperature changes. Therefore, two signals are obtained from the system, and the aim of this paper is to process the two signals to compensate for temperature variations in the pressure signal. An algorithm is developed to compensate for the temperature variations using an autoregressive (AR) model and a Kalman filter. The algorithm fits an AR model to the difference between the two signals and the corresponding coefficients are estimated using Kalman filter. When a pressure signal is detected, the difference signal during the pressure period is considered missing and the previously determined AR model is used to estimate that signal. The estimated signal is then added to the temperature signal and the compensated difference is estimated. The developed algorithm performance is evaluated in this paper using both simulated and measured datasets.**

***Index Terms*—FBGs, temperature compensation, manometry, Kalman filter, AR model**

I. Introduction

Manometry is a diagnostic technique used to measure and record the peristaltic pressure within the esophageal lumen and sphincters [1]. High resolution manometry was introduced into clinical practice as a result of developments of sensors technology, software, and resolution of the display [2], [3]. The most common hardware designs of the catheter are based on either solid state pressure transducers or water-perfused catheter. Solid state based catheter has pressure transducers placed inside the catheter itself while water-perfused based catheter has volume displacement transducers placed outside the patient [4], [5]. Recently, fiber Bragg grating is used as the basis for pressure sensing elements [6]-[9] in the catheter. Consequently, allowing the designers to add more sensors without the need to scale the catheter diameter [6] as a result of adding more connections, in addition to its flexibility, and noise immunity.

Fiber Bragg grating is formed by periodic perturbation of the refractive index of the fiber core. These perturbation results in combined mode of the fiber, the forward propagation mode and backward propagation mode at a wavelength (λ_B) satisfying Bragg condition [10]:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the core, and Λ is the grating period. Therefore, any change in the grating period or in the refractive index in response to the local environment such as pressure or temperature gives the corresponding change in the Bragg wavelength. The combined effect of temperature and strain is given by ([11]):

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\epsilon + (\alpha + \eta)\Delta T, \tag{2}$$

where P_e is the effective photoelastic coefficient of the glass. For a typical fused-silica fiber P_e= 0.22. α is the thermal expansion of silica, and η is the thermo-optic coefficient representing the temperature dependence of the refractive index. The temperature dependency of the Bragg wavelength shift can be seen in Equation (2). Hence, temperature compensation must be considered when stress measurements are required in variable temperature environment. Different techniques for

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temperature compensation have been developed recently. In general, these techniques can be grouped into two groups according to their basic principle of compensation: (i) a group that depends on reducing the temperature sensitivity of the fiber itself [12]-[16], and (ii) a group which depends on adding another strain protected temperature sensitive FBG to the configuration and then applying signal processing techniques to compensate for the temperature effect [17], [18].

In case of manometry, the catheter is constructed using two FBGs, one is used for pressure sensing and the other one is strain protected and used for temperature compensation. The mechanical configuration of the catheter is described in [9], [19] and shown in Fig. 1. The temperature FBG is protected against sensing pressure by a substrate, while the pressure FBG is affixed to the substrate only at the edges [9], [19].

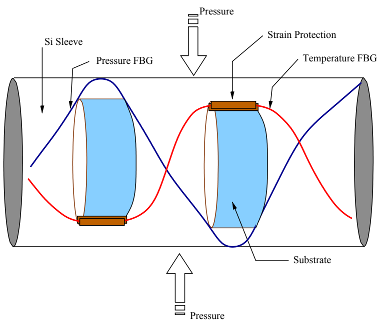

Figure 1. Catheter Construction showing only two gratings.

II. Method of Temperature Compensation

In general, two concerns should be considered when designing temperature compensation schemes in FBG manometry. The first concern is the dynamic behavior of the swallow process itself. That is during swallow, when a bolus material passes the gratings, transient temperature change occurs due to the difference in temperature between bolus and body. This temperature perturbation due to bolus material is transient followed directly by peristaltic contractions which will affect the pressure fiber. The second concern is the variations in the thermal conduction properties of the various parts of the catheter. The two FBGs are connected to different materials, specifically, the temperature FBG is essentially part of the thermal mass of the substrate, and it expands and contracts at the same rate as the substrate. Whereas the pressure fiber is independent of the substrate. This means that the pressure sensor responds to bolus temperature more rapidly than the temperature FBG. A simplified response of the FBG due to temperature changes can be written exactly in the same manner as that for the chemical sensor [20] as:

$$y_t\,(t) = y_t\,(t_0) \pm A_T\left(1 - e^{-\frac{(t-t_0)}{\tau_s}}\right)u(t - t_0\,), \quad (3)$$

where A_T is a combined temperature dependent variable that represents the amount of heat dissipated or absorbed by the mechanical structure attached to the fiber. τ_s is the time constant of the complete configuration of the catheter which is composed of the fiber itself and the attached materials. $u(t)$ is the unit step function and t_0 is the time at which temperature change is applied. The two fibers in the catheter differ both in A_T and τ_s as explained earlier. This effect is simulated as shown in the first panel of Fig. 2 where the grey region corresponds to temperature effect on the pressure fiber. An algorithm is developed to cancel out the temperature effect on the pressure fiber using AR modeling and a Kalman filter as shown in Fig. 3. The algorithm monitors both signals coming from the temperature and pressure fibers to obtain the difference signal $(x_p(k) - x_t(k))$ shown in second panel of Fig. 2. This difference signal represents the deviation in response between the temperature FBG and the pressure FBG. When there is no pressure effect, an AR process is used to model the difference signal and the AR coefficients are estimated via Kalman filter [21], [22]. If a pressure signal is detected, the difference signal is considered missing data and the model previously determined by Kalman filter is used to predict the signal. In this case we can estimate the temperature effect on the pressure fiber all the time. Hence, the direct subtraction compensation is then modified as follows:

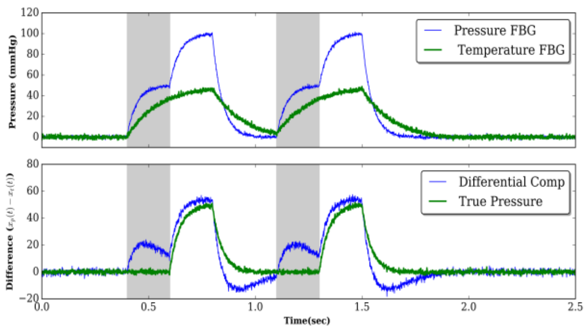

Figure 2. Simulation of typical catheter response due to normal swallow.

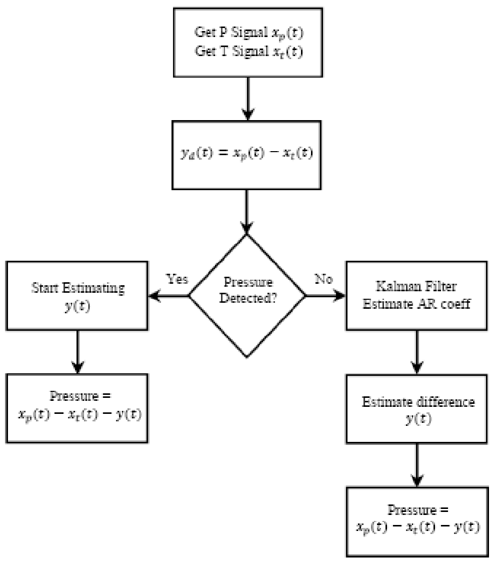

Figure 3. Catheter Construction showing only two gratings.

$$y_p(k) = x_p(k) - \big(x_t(k) + y(k)\big), \qquad (4)$$

where $x_p(k)$, and $x_t(k)$ are the pressure and temperature fibers signals, respectively, both after calibration. $y(k)$ is the estimated difference signal using Kalman filter. The difference signal $\big((x_p(k) - x_t(k)\big)$, is modeled as an AR process with order p:

$$y(k) = \sum_{i=1}^{p} a_i y(k-i) + \gamma(k), \qquad (5)$$

where γ is white Gaussian noise. The model will be used to predict the difference signal during the pressure event. Kalman filter is used to estimate the model coefficients when there is no pressure detected. Therefore, the state variables, $\boldsymbol{x}_k$, to be estimated by Kalman filter are the AR coefficients

$$\boldsymbol{x}_k = [a_{1k}\ a_{2k}\ a_{3k} \cdots a_{pk}]. \qquad (6)$$

The coefficients are evolving according to the random walk equation:

$$\boldsymbol{x}_k = \boldsymbol{x}_{k-1} + \boldsymbol{w}_k, \qquad (7)$$

where $\boldsymbol{w}_k$ is the state uncertainty which is assumed to be white Gaussian with zero mean and variance of σ_w^2. The measurement equation is given by

$$y_k = [y_{k-1}\ y_{k-2} \cdots y_{k-p}] \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_p \end{bmatrix} + v_k, \qquad (8)$$

where v_k is white Gaussian noise with zero mean and variance of σ_v^2. The measurement equation can be written in compact form as:

$$y_k = \boldsymbol{H}_k \boldsymbol{x}_k + v_k, \qquad (9)$$

where $\boldsymbol{H}_k$ is the transformation matrix given by

$$\boldsymbol{H}_k = [y_{k-1}\ y_{k-2} \cdots y_{k-p}]. \qquad (10)$$

The Kalman filter is then used to estimate the AR Coefficients according to the equations [23]:

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + \boldsymbol{K}_k(y_k - \boldsymbol{H}_k \boldsymbol{x}_k), \qquad (11)$$

where $\boldsymbol{K}_k$ is the Kalman filter gain given by

$$\boldsymbol{K}_k = \boldsymbol{P}_{k-1}\boldsymbol{H}_k^t(\boldsymbol{H}_k\boldsymbol{P}_{k-1}\boldsymbol{H}_k^t + \boldsymbol{I}\sigma_v^2)^{-1}, \qquad (12)$$

$$\boldsymbol{P}_k = (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k)\boldsymbol{P}_{k-1} + \boldsymbol{I}\sigma_w^2. \qquad (13)$$

III. Results

The performance of the algorithm is evaluated using simulated and measured data. The measures of performance are visual inspection and mean squared error. Figs. 4, and 5 show examples of simulated signals using the model presented in Equation (3) and the corresponding outputs of the developed algorithm for two cases: Case 1 (Fig. 4) is when only the change in temperature is affecting the catheter, while case 2 (Fig. 5) represents the occurrence of two pressure events. Both cases have signal to noise ratio (SNR) of 25dB. Table I shows the mean squared error of case 2 compared to that of the direct subtraction technique for different SNRs. It can be seen that the proposed technique is better than the direct subtraction technique in terms of MSE. Figs. 6 and 7 show examples of applying the presented compensation technique for real measured signals during two swallow events.

IV. Discussion

A method to compensate for transient temperature changes in FBG based manometry is presented in this paper. The results obtained show that the algorithm performs very well in eliminating the transient temperature effect. Since the algorithm is based on Kalman filter to estimate the AR model coefficients it can be used for real time processing given that the two signals are sampled at 50Hz. Accurate detection of the onset of pressure occurrence is a very important step and can affect the performance greatly. However, more research on this topic needs to be undertaken to compare the results with those obtained using solid state manometry for normal cases and under different pathological conditions.

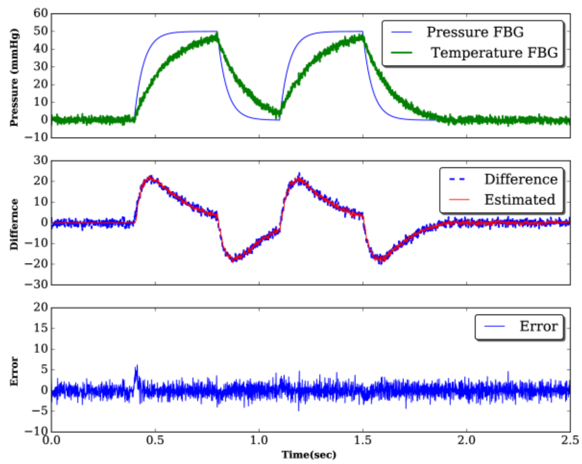

Figure 4. Simulation of a typical catheter response and the corresponding signals and compensation obtained. Case 1 where only temperature changes is affecting the catheter.

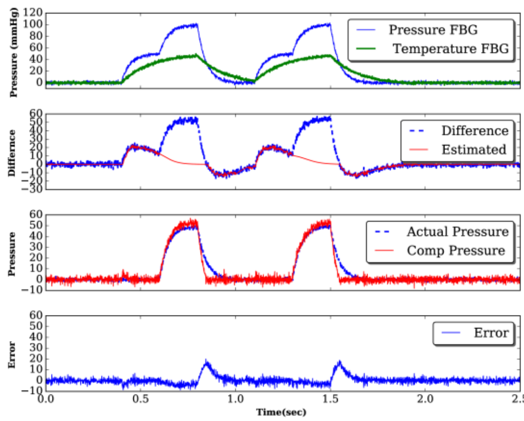

Figure 5. Simulation of a typical catheter response and the corresponding signals and compensation obtained. Case 2 where temperature and pressure changes are affecting the catheter.

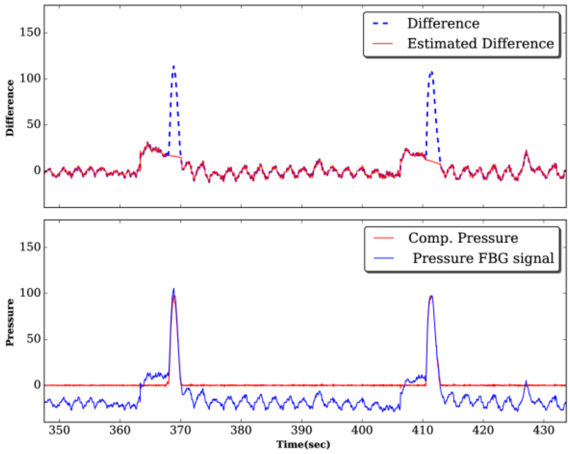

Figure 6. Examples of normal swallow events: example 1.

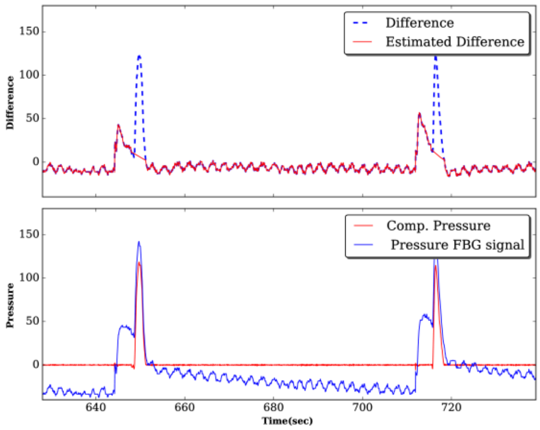

Figure 7. Examples of normal swallow events: example 2.

TABLE I. TYPE SIZES FOR CAMERA-READY PAPERS

SNR (dB)	Mean Squared Error (MSE)	
	AR model	Direct method
15	0.0175	0.0234
20	0.0073	0.0139
30	0.00288	0.0096
40	0.0036	0.0093

V. CONCLUSION

Given that the limited mechanical design options of the catheter, the two FBGs have different responses to temperature variations due to variations in the thermal conduction paths. In addition, transient change in temperature is present due to heat transfer from bolus material, therefore, effective temperature compensation of the pressure FBG has to be implemented. The paper presented an implementation of an algorithm to compensate for the abrupt change in temperature due to swallow event. The algorithm is based on modeling the direct difference signal with an AR model. The coefficients of the AR model are estimated between swallow events using Kalman filter, and then the AR model is used to estimate the difference signal during swallow event. The algorithm showed minimum mean squared error compared to direct subtraction compensation. Since the algorithm is based on estimating the difference signal, it can also be used to eliminate any drifts in response. In addition, it can be used to remove false pressure signals resulting from blood pressure.

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