Digital Adaptative Filters for Interrogating Fiber Optic Sensors

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ABSTRACT

The use of digital adaptative filters for the processing of signals coming from fiber optic sensors is discussed. An insight into the theoretical operating principle and the experimental parameters that affect their performance is given.

1. INTRODUCTION

During the processing of the information measured by photonic sensors [1] it is quite usual to come across the problem of decomposing a measurement into its constitutors. This problem can arise in pattern recognition problems (images should be decomposed in known geometrical figures), in food inspection (defects are classified into known-types) [2], or in chemical analysis (a spectrum is decomposed in the spectral signatures of known basic elements) among others. Most of the times these problems are reduced to the recognition of a combination of elements, patterns or signatures stored in a database (this is the case of the identification of elements in a chemical compound-analysis). The kind of problems cited above is often solved by the use of neural networks. However, there are situations (when the set of patterns stored does not change with time, for example) in which a much simpler and straightforward approach can be used: a digital adaptative filter [3]. These filters are able to modify their characteristics with time as a response to changing input conditions. Therefore, they are ideally suited for modeling functions that indicate the time-changing proportions of constituents present in a measurement or sample under analysis.

The authors have very recently used an adaptative filter as the key element of the processing carried out by a multi-transducer interrogation unit [4-5]. In this paper the specifics of this application will be reported. Although the application discussed in this paper is quite unusual, the kind of filters presented here can be very useful for easily solving multiple problems that arise in the photonic sensing field. This paper covers both the theoretical principle of operation (second section) and the practical issues to be addressed to obtain the maximum performance from the filter (third section). At the end several conclusions are extracted that can be used as guidelines for obtaining the best results when dealing with digital adaptative filters applied to the interrogation of photonic sensors.

2. THEORETICAL OUTLINE

A measurement known to be composed of basic constituents can be modeled in the way sketched in Fig.1. There, the measurement (a recorded image in this case) is formed as a result of the superposition of several patterns of a set stored in a database (left side of the image). The database has been represented as a gray-encoded map (the lighter the color the higher the amplitude) containing individual images (horizontal lines) that can be part of the final recorded image (basic constituents). The amount of each of these basic constituents present in the measurement under analysis is governed by a discreet transfer function. This transfer function has as many elements as basic constituents stored in the database. Since the measurement comes from a photonic sensor, it is expected to vary with time, and so will do the transfer function. This change of the transfer function is required to account for the variation in the proportions of the constituents that form the new measurement. As has been previously said, it is because of the time-dependent nature of the transfer function that it is well modeled by a digital adaptative filter. These filters comprise a number of weighted taps. It is the value of these weights the parameter that changes with time in the adaptative filters. And it is also this

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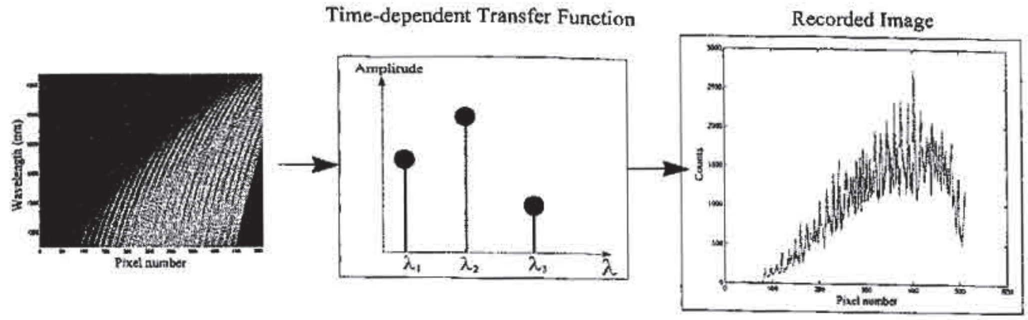


Fig.1. Model for the formation of measurements composed of basic constituents: some of them are picked up from a set of them (image on the left) and scaled and superposed (transfer function) to form the measurement (recorded image).

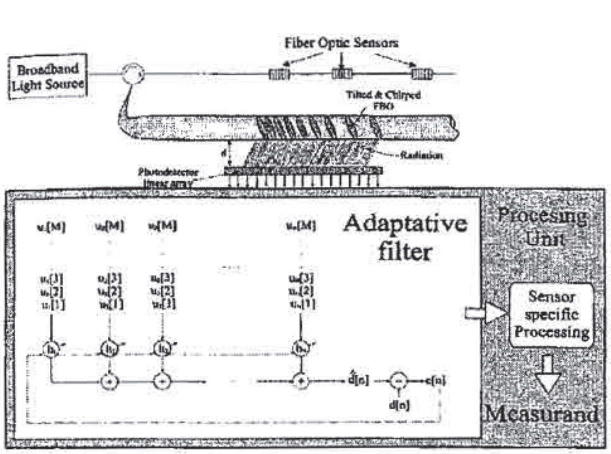
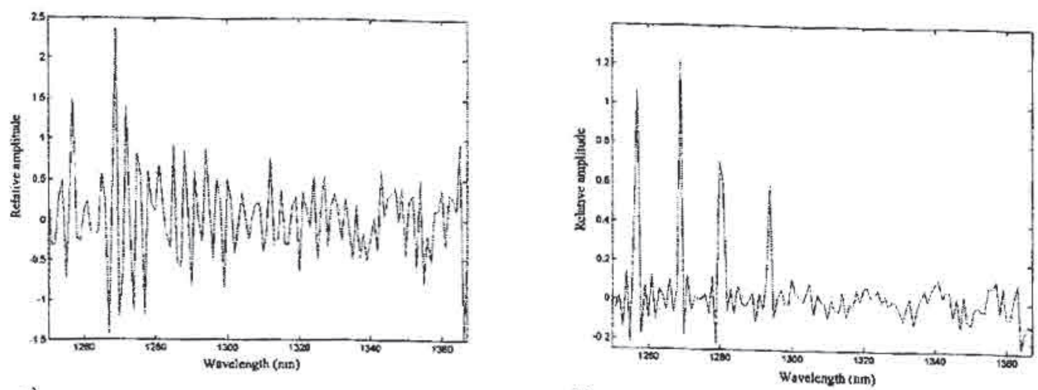


Fig.2. Diagram of the multi-transducer interrogation unit that uses an adaptative filter for the processing of the images recorded by the photodetector linear array. The filter gives a representation of the spectrum of the light reflected by the sensors that has to be further processed (with sensor specific algorithms) to extract the measurand.

weight distribution what is considered as the useful output of the filter, i.e. the decomposition of the measurement in its basic constituents. Ideally, the number of taps should match the number of possible constituents of the measurement. However, as will be shown in a moment in the frame of the application discussed in this paper, this is not always possible. Therefore, the results presented in this paper will serve as a demonstration that adaptative filters are apt to solve complex decomposition and identification problems.

As has been previously said, the authors employed a digital adaptative filter as the key processing element of an interrogation unit for fiber optic sensors. As can be seen in Fig.2, this unit comprised a tilted and chirped fiber Bragg grating (TCFBG) placed in front of a photodetector linear array. Thus, the light expelled by the grating was captured as an image by the array. Therefore, the measurement under analysis is, in this case, an image. On the other hand, the basic constituents of this measurement are the images recorded when the tilted grating is illuminated under monochromatic light. This way, sweeping the wavelength of this monochromatic light, a whole set of basic images can be recorded and stored. This set is shown in Fig.1 under the form of the gray-encoded map.

In this case the mission of the adaptative filter is to provide the combination of basic images that best fits the recorded one. Since the basic constituents are images indexed by wavelength, the output of the filter will be a representation of the spectrum of the incoming light. Although inaccurate (as will be seen in next section), this representation preserves certain characteristics of the original spectrum (like the wavelengths of the peaks or its periodicity) that allows for the interrogation of many fiber optic sensors (namely those based on fiber Bragg gratings and on interferometers). Therefore, this technique performs poorly as spectrometer but good as interrogation unit. The reason for the inaccurate spectral representation obtained as the output of the adaptative filter has to do with the fact that wavelength is an analog variable. This means that the number of possible contributors for the recorded image is infinite. However, it is not possible to record and store an infinite number of images in the set of constituents. This way, the problem is clearly underdetermined. There is a great probability of not having the basic image corresponding to the wavelengths of the light reflected by the fiber sensors. This implies that the filter will have to somehow guess which the exact wavelengths are, in spite of them not being part of the set of constituents. Due to the fact that the adaptative filter does not look for a perfect match of the recorded image, but for a best fit instead, it can efficiently cope with this difficult problem.



a) b)

Fig.3. Set of filter tap weights, i.e. estimate of the spectrum of the light, when the interrogation unit is connected to a fiber containing four multiplexed FBGs. a) The TCFBG is dipped in index-matching gel, b) the TFBG is surrounded by air.

The adaptative filter used in this work is a modified parallel version of the Kalman filter [3]. As can be seen in Fig.2, it is formed by N identical taps that accept as input the basic images ($u_i[n]$). These images are M-pixels long, being M the number of pixels of the linear array. The whole set of basic images (constituents) is commonly referred to as *data matrix*. Each of these images is weighted by its corresponding tap weight (h_i) to form a new composite image ($\hat{d}[n]$). This new image is compared with the recorded one coming from the tilted grating ($d[n]$). From this comparison an error signal is obtained ($e[n]$) that serves to modify the tap weights in a way that this error is minimized. Mathematically this problem can be efficiently solved, i.e. the optimum tap weights values obtained, by the following matrix equation:

$$\hat{\boldsymbol{H}} = \left(\boldsymbol{A}^{\boldsymbol{H}} \cdot \boldsymbol{A}\right)^{-1} \cdot \boldsymbol{A}^{\boldsymbol{H}} \cdot \boldsymbol{d} \qquad (1)$$

In this expression the operator H stands for Hermitian transpose. On the other hand, $\boldsymbol{A}$ is the data matrix defined in a way that each of its columns is one of the basic images corresponding to a single wavelength. Besides, $\boldsymbol{d}$ is a column vector that contains the composite image captured by the linear array; and $\hat{\boldsymbol{H}}$ is another column vector containing the set of optimum tap weights.

3. EXPERIMENTAL ISSUES

From the previous section it can be deduced that the data matrix is the key element for the good performance of the filter. However, it still remains a problem associated with the definition of the data matrix. There are two questions to be addressed: the first one deals with whether the shape of the images obtained by the linear array (that from now on will be called radiation images) affect the effectiveness of the filter; and the second one has to do with the number of radiation images that have to be stored in the matrix (i.e. determining the best wavelength sampling period). The topic of whether the radiation images itself contribute to the properly working of the filter is an important fact. Since this is an inherent characteristic of the grating, the solution of this problem would be quite complicate. In order to explore this subject, the authors used two different tilted gratings: one dipped in index-matching gel and the other completely surrounded by air. The reason for using the first grating is double: on one hand this is a common practice when making spectrometers employing tilted gratings (they are usually dipped in index matching gel or embedded in index-matching prisms); on the other hand by means of this dipping the radiation images recorded are completely different (they become very smooth) and, therefore, a new data matrix is obtained. Fig.3 shows the results obtained after the adaptative filter when a set of four multiplexed gratings were interrogated using those two tilted gratings. The photodetector linear array had 512 pixels (Hamamatsu G8161-512S). On the other hand the four sensing FBGs were centered at the following Bragg wavelengths: 1256.6nm, 1268.8nm, 1280.45nm and 1293.7nm. The last grating had a reflectivity of 60% while the rest were close to the 100%. Both data matrixes were defined from 1250nm to 1370nm with 1nm steps. With just a glimpse to Fig.3 it becomes apparent that there is a strong dependence of the final result (spectrum) on the characteristics of the radiation images. Meanwhile in the first case (index-matching gel dipped TCFBG) the spectral signatures of the sensing FBGs are hardly distinguishable, in the other one the four gratings are clearly visible. That is the same to say that the characteristics of the radiation images greatly affect the final Signal to Noise Ratio (SNR) of the spectral representation obtained as the output of the filter. The reason for this behaviour has to do with the decision-making process of the filter. The smoother the radiation images the harder to decide which one contributes to the recorded image, since they all are pretty much alike. So the secret for a good SNR is to have a set of radiation images in the data matrix that are as different as possible one from the other. That is, the radiation images should have enough singular marks (spikes, valleys, etc) to be distinguished one from another. This is exactly what the images of the air-surrounded TCFBG provide.

There is another point worth to be noted: the inaccuracy of the amplitude information in the calculated spectrum. As can be seen in Fig.3b, the recovered amplitude of the third FBG is around 0.6. However its actual reflectivity is near 100%. Moreover, its spectral signature is also wider than the rest. The reason for these two distortions can be found in the Bragg wavelength of the grating: 1280.45nm. This value lies in the middle of two of the wavelengths used for the data matrix (1280nm and 1281nm). This means that the filter, when determining which image of the data matrix forms part of the recorded image, decides that both wavelengths contribute equally (more or less half the total amplitude each). That is the way in which the filter indicates that the actual wavelength is in between these two values.

The problem of the amplitude distortion is, at the end, caused by the poor wavelength resolution of the filter. This resolution is equal to the wavelength step with which the data matrix was defined (1nm in this example). So, in order to improve the quality of the calculated spectrum, it seems reasonable trying to increase this resolution simply by decreasing the wavelength step. However, as shows Fig.4, this approach has a limit. There a group of four sensing FBGs (Bragg wavelengths: 1250.55nm, 1256.03nm, 1280.15nm, 1327.3nm) was interrogated. The graph that can be seen in Fig.4 corresponds to a wavelength step of 200pm. It shows a very poor result. The reason for this behaviour is that as the wavelength step decreases, the adjacent radiation images of the data matrix become more and more alike. This, as was explained before, has a great impact on the SNR of the calculated spectrum. Nevertheless, the authors have found that the interpolation of the spectrum obtained with the filter can cast excellent results for increasing the wavelength resolution of the filter when interrogating FBGs.

4. CONCLUSIONS

This paper demonstrates the feasibility of using digital adaptative filters to solve complex decomposition and identification problems. These structures are simpler than neural networks and still deliver an excellent performance. However, special attention has to be paid to the configuration of the data matrix. The possible constituents of the measurement should be as different as possible one from the other. Provided this requirement is met, these structures can be very useful in a wide range of applications.

ACKNOWLEDGEMENTS

This work has been co-supported by the Spanish CICYT TIC'2001-0877-C02-01 and the TIC-2001-4503-E projects.

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