Development of DSP Based Signal Acquisition and Processing System for Extrinsic Fabry-Perot Interferometric (EFPI) Fiber Optic Sensors

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Introduction
The advent of fiber optic sensors has brought numerous potential advantages over conventional electrical signal based sensors, such as small size and weight, immunity to electromagnetic interference, lack of sparking hazard, larger bandwidth, easy interface with data communication system, higher accuracy and resolution, and high multiplexing potentials. Along with this, the low optical loss of the fibers makes it possible to locate sensors far from the signal processing electronics. Their ability to withstand high level of radiation, temperature and pressure makes them ideal for applications in harsh environments. The optical fiber sensing proves to be a remarkably versatile approach in the field of measurement.

Indigenous development of Fiber Optic Sensors based on EFPI principle has been carried out for Pressure (Gauge), Temperature and Low Pressure (Absolute) transducers. The article presents the development of a DSP based signal acquisition and processing system for Extrinsic Fabry-Perot Interferometric (EFPI) sensors, jointly by Precision Engineering Division and Control Instrumentation Division. It describes the basic concepts of EFPI sensors and the algorithm used to estimate its cavity length. The hardware configuration and the implementation issues are covered in detail. The experimental results of an EFPI temperature sensor interfaced with this hardware have also been presented.

Fiber Optic Sensing
In an EFPI sensor, two mirrors (either or both mirrors could be ends of fibers, separated by an air cavity or any dielectric material other than fiber) form the interferometer. The distance between the two mirrors is called the cavity length or gap length. Fiber optic white-light interferometry (WLI) has been widely used to measure the cavity length of an EFPI. This technique allows absolute and unambiguous measurements over a wide range and is insensitive to the light source instability. WLI uses a broad band light source to illuminate the sensor and a spectrometer senses the optical signal. A change in the physical parameter, to be measured, causes a calibrated change in the cavity length of the EFPI. Hence the primary objective is to get an accurate and reliable measure (calibration) of cavity length. By using different transduction principles, different type of EFPI sensors can be developed.

Fig. 1: EFPI configuration formed using a fiber end and a diaphragm.
Fig. 1 shows an EFPI pressure sensor. The diaphragm indicated has its inner surface polished using nano finishing, forming one of the EFPI mirrors, while the fiber end face forms the second. Increase in pressure causes the diaphragm to deflect, changing the cavity length of the EFPI. By measuring the cavity length the pressure can be determined. On similar lines thermal expansion of an element can be used to cause transduction in an EFPI temperature sensor.

Cavity length Measurement

The interference spectrum acquired from the spectrometer needs to be demodulated to compute the cavity length (or gap length) of the EFPI sensor. As the physical parameter to be measured cause a direct change in the cavity length, the measurement of cavity length gives the estimation of the measurand as shown in Fig. 2. Such a system is not unique to one type of sensing. They remain generic to all EFPI sensors measuring any physical parameter. The basic principle is to be able to let the physical parameter, to be measured, bring about a change in the cavity length that can be calibrated in terms of the physical parameters.

The spectrum signal of an EFPI can be expressed as

$$x(\lambda) = a(\lambda) + b(\lambda) + \cos\left(\frac{4\pi}{\lambda} I + \pi\right) + c(\lambda)$$

where \(I\) is the cavity length, \(2\xi\) is the total optical path difference; \(a(\lambda)\) is the low frequency envelope present predominantly due to a combination of responses on various components of the system viz., light source, splitter, grating, CCD array; \(b(\lambda)\) is the contrast which is influenced by the cavity length and the reflection of fiber ends and \(c(\lambda)\) is noise. The constant phase \(\pi\) is added due to the reflection occurring on the second surface of the interferometer. Fig. 4 shows a typical optical spectrum signal acquired from an EFPI. In this particular experimental set up, the EFPI sensor has been formed using a single mode fiber (SMF) facing
an Aluminium mirror. The Aluminium mirror surface has been finished using Diamond Turn Machining (DTM) having a surface finish of 10nm (peak to valley) approximately.

By using Discrete Wavelet Transform (DWT) the frequency content (measurement is in wavelength of the spectrum) of the signal could be analyzed at multiple resolutions or scales. The decomposition is carried out by passing the signal through a half band low pass filter at each scale followed by a half band high pass filter. The output of the low pass filter is called the approximate coefficient and the output of the high pass filter is called the detailed coefficient. Subsequently, each low pass filter output is down-sampled, obeying Nyquists rate, as each of these signals is band limited ideally to half the frequency range. The above procedure, referred to as sub-band coding is repeated for the approximate coefficients to obtain further levels of decomposition. By appropriately thresholding the approximate and detailed coefficients and then combining them by the process of reconstruction (using inverse Wavelet Transform), the envelope and high frequency noise can be eliminated from the spectrum signal. In the present case, 8 level wavelet decomposition has been implemented for pre processing of spectrum signal.

Instantaneous phase of the denoised spectrum signal can be obtained using Hilbert Transform.

\[ \phi(\lambda) = \left( \frac{4\pi}{\lambda} \right) \]  \hspace{1cm} (2)

Hilbert Transform is numerically implemented using Fast Fourier Transforms (FFT). The method involves transforming the signal in the frequency domain using FFT. Coefficients at positive frequency are doubled and those at negative frequency are reduced to zero. An inverse FFT of the modified frequency domain signal gives the analytic representation (an array of complex numbers) of the signal. The argument or the phase of the complex number gives the instantaneous phase. \( \phi(\lambda) \) thus computed is wrapped around \(-\pi\) to \(\pi\). An unwrapping algorithm is used to unwrap the phase. This unwrapped phase bears a linear relation with \(1/\lambda\) as seen in (2), the absolute value of the slope of the line being equal to \(4\pi\) times the cavity length.

In order to process a spectrum having a frame length of 1024 points, a total of 286,600 flops are needed for the present algorithm. The pixels of the CCD are currently read in a linear fashion imposing a restriction on the minimum time of 7.2 ms, required to digitize one full frame of spectrum data. DSP based dedicated hardware simultaneously manages 1) all house-keeping activities and 2) transfer of data to a permanent storage in 3.2 ms. Hence, time available for processing EFPI signal is only 4.0 ms. Sampling frequency however is decided by real time process requirements and may need to be increased, thereby reducing available processing time further. The DSP processor selected for the application is capable of executing 1.2 Giga flops and takes 0.25 ms to perform the total number of 286,600 floating point operations. It is evident that in order to meet the processing requirements in the stipulated time a dedicated DSP processor based hardware is essential for the application.

**Signal Processing Hardware**

As explained earlier the sensor system includes a light source, an EFPI sensor and a spectrometer connected using an optical splitter. The signal acquisition and processing system acquires the CCD output of the spectrometer, subsequently processing
it to compute the cavity length. Fig. 5 shows the block diagram of the EFPI sensor signal processing system.

The spectrometer shown, an original equipment manufacturer (OEM) device is a symmetrical Czerny-Turner design with a fiber optic entrance connector, collimating and focusing mirror, diffractional grating and linear CCD sensor. The signal acquisition and processing hardware consists of a floating point Digital Signal Processor (DSP) along with an FPGA. The FPGA generates control signals for CCD sensor in spectrometer and to the peripherals on board. The DSP processor acquires the spectrum frame, processes it online for the estimation of EFPI cavity length as per the cavity length estimation algorithm and transfers the processed results to the host computer for display of parameters.

The signal acquisition and processing tasks are made to run in parallel by implementing a FIFO on the FPGA. The analog signal from spectrometer is digitized on board by a 16 bit ADC and the output is stored in FIFO. After acquisition and storage of one full frame of signal in FIFO, an interrupt is generated for the DSP processor by the FPGA. DSP copies the data from FIFO and stores it in its internal RAM for further processing. As the FPGA controls the acquisition and fills the FIFO with next frame, the DSP processor processes an earlier frame. A flash memory provided on board is used to store important calibration data. An ethernet module communicates the computed cavity length along with raw and filtered spectrum to the host computer.

As shown in the detailed block diagram, the FPGA generates necessary control signals required to run the CCD sensor present in the spectrometer. The analog CCD output is shifted serially, pixel wise, and is digitized using the ADC at a rate of 500 kHz. The ADC works in sync with the CCD sensor using control signals also generated using the FPGA. The entire digitized spectrum frame is stored in a FIFO created within the FPGA.

The 200MHz DSP processor core used has the capability of single cycle execution of an instruction. The single instruction and multiple data (SIMD) structure of the DSP processor is used efficiently for faster implementation of processing algorithms. Floating point DSP processor features an enhanced Harvard architecture. With its separate program and data memory buses and on chip instruction cache, the processor can simultaneously fetch two operands and an instruction (from the cache), all in a single cycle. Processor core contains three independent, parallel computation units i.e. the arithmetic/logic unit (ALU), multiplier and shifter for maximizing the computational throughput. Wavelet filtering of spectrum signal uses large number of convolution operations. There are three basic operations in a convolution namely shift, multiply and accumulate. The multiply and accumulate (MAC) operation requires filter coefficients and signal samples to be stored in program data memory and data memory respectively or vice versa which would allow the operation to execute in a single cycle. The efficient utilization of DSP hardware for in-situ computation in MAC minimizes the execution time of the wavelet de-noising algorithm.

Prototype Development of Signal Processing System

Fig. 5: Block diagram of EFPI signal processing system

Prototype development of the system includes the development of data acquisition and signal processing hardware and power supply card, implementation of signal processing algorithm on
DSP-FPGA hardware, building a graphical user interface on host computer and system integration. Fig. 6 shows the experimental setup which includes optical setup, DSP based signal acquisition and processing electronics, power supply, and necessary debugging emulator.

Fig. 7 shows the Graphical User Interface (GUI) displaying the cavity length of the EFPI, and raw and filtered spectrum on separate charts. The interface also allows the user to set the parameters needed by spectrometer. As seen in the figure, the left side of the GUI allows the setting of IP and Port.
address for communication with DSP hardware via the ethernet module. The integration time can be set from 1 ms to 10000 ms. The cavity length is displayed in microns. The right side of the GUI shows the spectrum signal. The top chart show the raw spectrum signal from the spectrometer in red and the bottom chart shows the wavelet denoised signal with the pixel number on the X-Axis and the amplitude on the Y axis.

**EFPI Application**

A prototype extrinsic EFPI temperature sensor developed and fabricated at PED, BARC was interfaced with the acquisition and processing system. The thermal expansion of a metallic object placed in front of a fiber causes a change in the cavity length of the EFPI. Thus by estimating the cavity length, using processing hardware, the temperature could be computed. The sensor was tested and compared with conventional temperature sensors (thermocouple and RTD). The cavity length estimation algorithm was implemented on prototype DSP hardware for computation of cavity length. Fig. 8 shows the variation of the cavity length of the prototype EFPI temperature sensor as compared to the temperature measured by thermocouple and RTD.

These temperature sensors can prove to be extremely useful in providing real time temperature monitoring of transformer winding temperature, owing to their immunity to EMI/RFI. Similarly they can be effective in temperature monitoring of generator winding, microwave and induction heating and various biomedical equipments involving harsh RF-environments such MRI and NMR.

**Conclusion**

This article reports in-house implementation of EFPI sensor cavity length estimation on a DSP hardware. The DSP based processing hardware is not specific to any one type of sensor. It could be used to measure any external measurand by using the right transduction principle. This would prove to be a huge advantage while multiplexing sensors. Such systems would not be constrained to multiplexing different types of sensors in one unit. For example, temperature, pressure and accelerations sensors could be multiplexed in one acquisition and processing system. Development of the systems for actual deployment is in progress.

**References**