Effect of Amplitude and Phase Variations in Interferometer Signals on Dynamic Strain Estimation

Shamika Bachal[1], Dr. M. S. Panse[2], Anisha Acharya[3] & Nitin Kawade[4]

[1,2]*Veermata Jijabai Technological Institute, Mumbai, India.*
[3,4]*Bhabha Atomic Research Centre, Mumbai, India.*

Abstract

The recent developments in the field of Fiber optics Technology, has led to many successful implementations in structural health monitoring, intrusion detection systems, environment monitoring, physical and chemical sensing applications etc. The Mach-Zehnder Interferometer (MZI) is a fiber optic sensor, which has attracted great attention in these fields recently because of advantages like immunity to electromagnetic interference, resistance to erosion, high sensitivity, low propagation loss and high accuracy. For a Mach Zehnder Interferometer, many techniques exist for demodulation of signals. Derivative and cross multiply (DCM) algorithm is one of them. In this algorithm, the interferometer signals should ideally have equal amplitudes and phase difference of 120º. This paper presents an analysis of variation in amplitudes and phase of interferometer signals and the effect on the accuracy of the system. The main aim of this paper is to perform Error Analysis and to find the effect of this variation on the interferometer signals using virtual instrumentation.

Keywords: *Mach Zehnder Interferometer, Interferometer signals, Amplitude Variation, Phase Variation, Virtual Instrumentation.*

1. Introduction

Dynamic Strain Detection plays an important role in Perimeter Intrusion Detection Systems. The fiber optic cable is extremely sensitive, capable of detecting minute vibrations transmitted through the fence, soil or the surface. One can monitor the vibration signals along the length of the fiber optic cable based on the detection algorithm. Due to their small size and light weight, fiber optic sensors are appropriate for surface bonding or embedding structures. Unique aspects like immunity to electromagnetic interference and excellent multiplexing capabilities make it ideal for vibration detection for structural health monitoring. Fiber optics technology in these fields can be successfully used to eliminate the disadvantages of wired and electrical system. They are undetectable and light-weight. Hence, can be easily installed into floors, windows or walls. These fibers cannot be deactivated by the use of jammers due to the immunity against electromagnetic interference. Optical fibers are also environmentally rugged. [1][2]

Numerous fiber optic systems are reported in the literature as well as in practice. They are mainly based on either of these following principles. These are either Fiber Bragg Grating (FBG), Optical Time Domain Reflectometer (OTDR) or Interferometer based. Fiber optic interferometers are preferred because of following advantages like high sensitivity, aversion to electrostatic and electromagnetic interference, and the fact that they are relatively less affected by ageing components from which they are composed.[3][4]

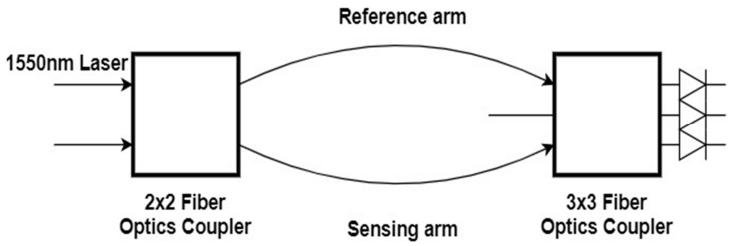

Figure: 1. MZI Configuration

Amongst different types of interferometers like Michelson Interferometer, Mach Zehnder Interferometer (MZI), Sagnac Interferometer and Fabry–Pérot Interferometer, MZI is used for strain detection. MZI comprises of 2 arms, the sensing arm and the reference arm, respectively (Refer Figure .1)

At the input end of the set-up, there is a 2x2 fiber optic coupler, which splits the incident laser beam into two parts. The split light is transmitted in both arms of the set-up, respectively. When strain signal is applied to the sensing arm, the elongation in the sensing arm would result into a phase shift of the light wave. The dynamic strain in the sensing arm, imparts a modulation in the phase of the output interferometer signal, which is given as:

$$\emptyset = \left(\frac{2\pi n \Delta L}{\lambda}\right) \qquad (i)$$

Where $\emptyset$ is the phase shift due to the difference in optical path length,

n is the refractive index,

$2\pi/\lambda$ is the wavenumber,

ΔL is the physical path difference due to elongation [5][6][8].

The light in the reference arm and sensing arm is directed towards another 3*3 fiber optic coupler. The two lights again recombine at the input of 3*3 fiber optic coupler and the interference patterns generated are measured using photo-detectors. At the output end of the interferometer, this 3*3 coupler splits the light signal into 3 signals with equal amplitudes. This splitting is such that there is a phase difference of 120º between the 3 arms of the 3*3 coupler. But the amplitude remains the same in all the 3 channels [6][8].

A 3 x 3 coupler is used to derive signals so that phase demodulation can be performed and direction ambiguity of the dynamic strain can be resolved. The strain signal is dynamically detected and demodulated by using a demodulation algorithm, called Derivative and Cross Multiplication (DCM). It was implemented by a simulation code through Virtual Instrumentation. Thus, the demodulated signal is recovered in terms of frequency and amplitude [7].

1.1 Problem Definition:

To introduce a software-based approach to vary the amplitudes and phase of the interferometer signals similar to that obtained from a MZI setup. Also to obtain the demodulated signal with varying amplitude and phase of the input signals and to perform an Error Analysis to find out the parameter variation effects on the DCM algorithm.

1.2 Proposed System:

This paper introduces a software-based approach of simulating signals with varying amplitude and phase. This technique utilizes virtual instrumentation. Simulation code of the DCM algorithm is developed for varying amplitude and phase of the interferometer signal and its effect on the demodulated signal is analyzed. Interferometer signals from MZI are demodulated using DCM algorithm for dynamic strain detection. The error analysis of DCM algorithm is performed by varying its amplitude and phase. The amplitude of interferometer signals is varied in terms of percentage of the original amplitude. The simulated phase is varied in terms of (+/-) degrees with respect to 120º .The simulated phase difference corresponds to the phase difference between the signals obtained from the 3 arms of the 3*3 coupler, of the MZI.

2. Methodology

The main objective of the proposed system is, to study and analyze the effects observed on the demodulated signal using a DCM demodulation scheme, with introduction of amplitude and phase variation in interferometer signals. For this purpose, a schematic is designed, which comprises of Amplitude and Phase variation block, Derivative Cross Multiplier Algorithm, FFT blocks and, Cross correlation block.

The Interferometer signals from the 3 channels of the interferometer are defined as follows:

$$A = A1 * \cos(s(t) + P1) + b \quad \text{(ii)}$$

$$B = A2 * \cos(s(t) + 120º + P2) + b \quad \text{(iii)}$$

$$C = A3 * \cos(s(t) - 120º + P3) + b \quad \text{(iv)}$$

Where *A1, A2* and *A3* are amplitudes of signals A,B and C respectively and *P1, P2* and *P3* are offset phase of signals A,B and C respectively, b is the DC offset [7]

Ideally amplitudes of signals A, B and C = 1 (i.e. A1 = A2 = A3 =1),

phase difference between A, B and, C = 120º i.e. P1 = P2 = P3 = 0

Also, s(t) is phase variation due to strain signal S in sensing arm and can be expressed as:

$$S = \frac{2*\pi*n*a*(m*\cos(\omega t))}{\lambda} \quad \text{(v)}$$

where, a = phase amplitude = $\frac{2\pi n}{\lambda}$, w = $2\pi f$ = frequency of strain and m = amplitude of strain

The amplitude and Phase variation block allows us to vary the amplitudes between +/- 25% of its original amplitude with a step change of 5%. Thus the total range of variation of A1, A2 and A3 is from 1.25 to 0.75. Phase is varied up to +/-10º of the original phase i.e. between 110º to 130º.

To demodulate the signals, DCM technique is adopted. The Derivative and Cross Multiplication (DCM) Algorithm comprises of 4 blocks i.e. DC Removal, Derivative Cross Multiplier, Adder and Integrator. The operations intended for each block of the algorithm are performed in virtual Instrumentation. The simulated interferometer signals A, B and C are provided to the input of Derivative Cross Multiplier Algorithm i.e.to the input DC removal block. This leads to the removal of DC components i.e. 'b' we have expressed in the equation. The Derivative Cross Multiplier block generates signal which

is proportional to the time derivative form of the demodulated signal. The Adder block eliminates cosine squared term. This result is then integrated in time in the integrator block is used to provide the demodulated signal. [7]

The FFT blocks are used to obtain spectrum of excitation signal and demodulated signal, to check whether the frequencies of the demodulated signals match that of excitation signals. The FFT of the signals provides a better result, when the excitation frequency is more for a fixed acquisition time and a high sampling rate as the number of cycles increase with increased excitation frequency.

The Cross Correlation block provides a correlation factor between excitation signal and the demodulated signal i.e. to know how much resemblance exists between the excitation signal and the demodulated signal. The block diagram of the algorithm is shown in Figure.2.

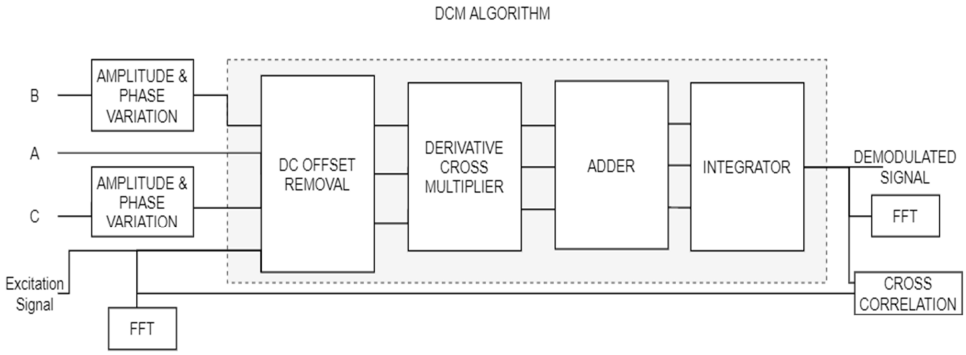

Figure 2: Schematic diagram of the proposed system

For developing the simulation code, following parameters are considered. The Strain signal (excitation) is set to an amplitude = 3µm. Under the default conditions, amplitudes of interferometer signals A, B and C is 1(i.e. A1 = A2 = A3 = 1). The phase of A is 0º, B is 120º (2.094 radians) and C is -120º (-2.094 radians) i.e. P1 = P2 = P3 = 0. For different frequencies, the interferometer signal amplitude is varied for every 5% change up to +/- 25% of the original amplitude. The phase is varied for every 2º up to +/-10º i.e. from 110º to 130º.

3. Experimental Results and Analysis:

- For excitation frequency of **5Hz:**

Here, all the default conditions are maintained. Under the standard conditions, the waveforms obtained are as follows:

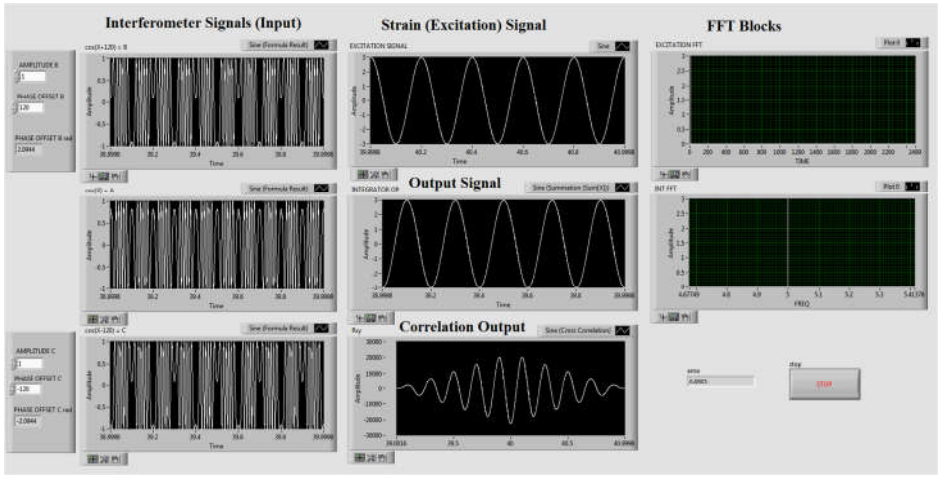

Figure 3: Waveforms under default conditions for 5Hz excitation frequency and amplitude 3μm

1) Amplitude Variation:

By varying the amplitude, A2, of the interferometer signal B, we get the following waveforms for maximum and minimum values i.e. amplitude of signals A and C maintained at 1, and amplitude of B, i.e. A2, is varied from 1.25 to 0.75. Starting with the default conditions, amplitude of B is increased by 5% for each iteration, until it reaches the maximum amplitude of 1.25 i.e. 25% of the default amplitude. Similarly again starting from default conditions, amplitude of B is decreased by 5% for each iteration, until it reaches the minimum amplitude of 0.75 i.e. -25% of the default amplitude. The waveforms of the same are shown in figure 4 and figure 5.

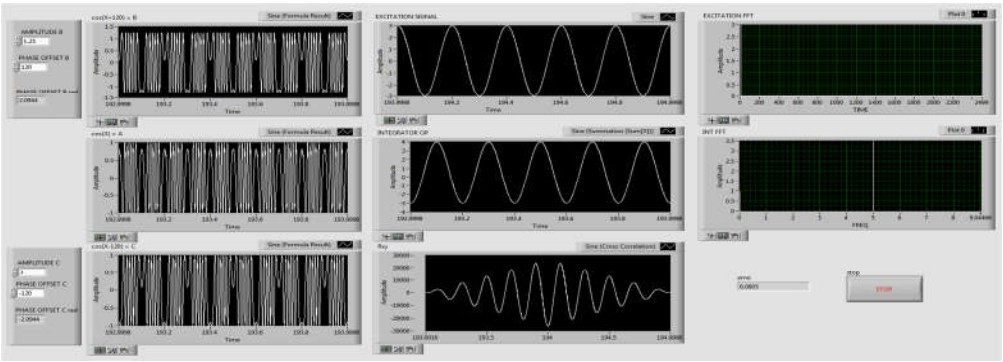

Figure 4: Waveforms obtained with amplitude variation of B (amplitude 'B' = 1.25)

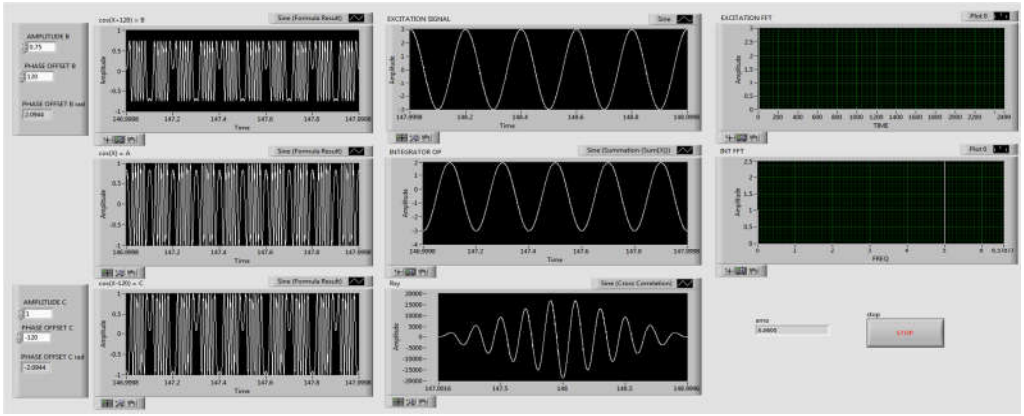

Figure 5: Waveforms obtained with amplitude variation of B (amplitude 'B' = 0.75)

Based on the above waveforms, an error analysis of DCM algorithm is performed. The error percentage is calculated for each iteration for the specified range. The result of varying amplitude, in each iteration is computed from the peaks of both FFT blocks. Thus the error percentage is computed from the given formula:

$$\% \text{ error } = \frac{(varied\ value) - (original\ value)}{(original\ value)} \text{x}100 \qquad \text{(vi)}$$

2) Phase Variation:

By varying the phase, P2, of interferometer signal B, we get the following waveforms (refer Figure 6) when the phase of A and C is maintained at 0º and -120º, respectively. The phase of B, i.e. P2, is varied between 110º to 130º. Starting with the default conditions, phase of B is increased by 2º for each iteration, until it reaches the maximum phase variation of 10º i.e. 130º. Similarly again starting from default conditions, phase of B is decreased by -2º for each iteration, until it reaches the minimum phase variation of -10º i.e. 110º. The waveforms obtained of the same are shown in figure 6:

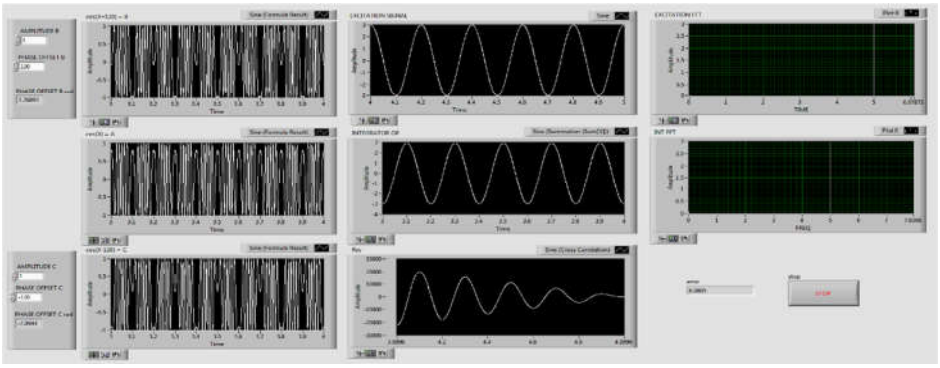

Figure 6: Waveforms obtained with phase variation of B (phase 'B'= 130º)

It is observed that, the value of FFT peak for a particular degree of phase variation, is of same amplitude, irrespective of its sign. This indicates that the sign of degree of varied phase does not have any effect on the value of FFT peak. Hence the phase is only

incremented in the simulation, as phase increments and decrements of same magnitude yield same errors in the output.

Based on the above waveforms (figure 6), an error analysis of DCM algorithm is performed. The error percentage is calculated for each iteration for the specified range (as per equation (vi)). The result of varying phase, in each iteration is computed from the peaks of both FFT blocks.

From the recorded data, the graphs of Amplitude variation percentage versus error percentage and phase variation versus error percentage are plotted (Figure 7) as shown below:

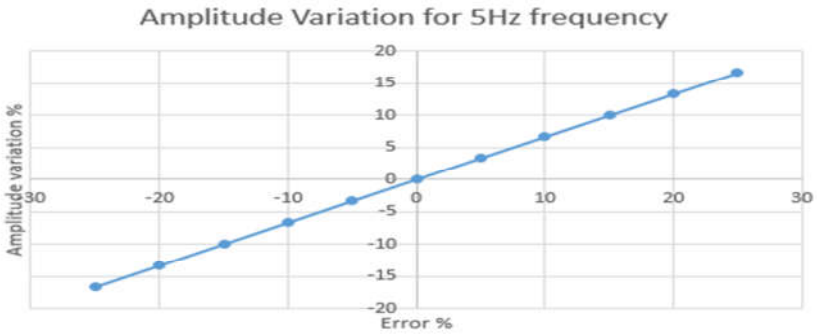

Figure 7: Amplitude Variation (5Hz)

It is observed that, for every 5% step change in Amplitude, 3.33% error is induced. Thus, from error analysis of DCM algorithm, it is observed that, when the maximum and minimum values of amplitude variation are applied to the input interferometer signals i.e. for amplitude 1.25 i.e. 25% variation in amplitude, 16.6% error is introduced. Similarly when the minimum value of amplitude variation are applied to the input interferometer signals i.e. for amplitude 0.75 i.e. -25% variation in amplitude,-16.6% error is generated.

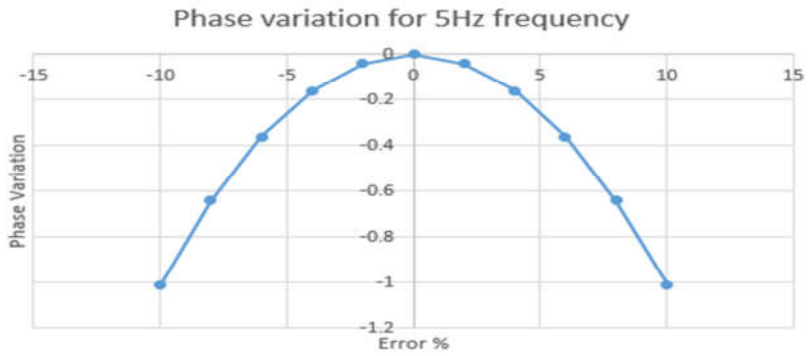

Figure 8: Phase Variation (5Hz)

Similarly, it is observed that, for every 2º step change in phase, an error is induced. Induced error is same for a particular degree, irrespective of its sign. Thus, from error analysis of DCM algorithm, it is observed that when phase variation is applied to the input interferometer signals, the error percentage increases with an increase in the degrees of phase variation. The errors percentages for 2º, 4º, 6º and 8º are -0.04%, -0.16%, -0.36% and -0.64%, respectively. The phase variation plot for 5Hz excitation is shown in Figure 8.For the maximum phase variation of 10º, the error percentage calculated is -1.01%.

To check the effect of excitation frequency on error analysis, various frequencies were considered. Similarly, the waveforms of Amplitude variations and Phase variations for the excitation frequencies of 60Hz, 400Hz and 1000Hz were also analyzed. Based on it, following graphs are plotted for both types of variations:

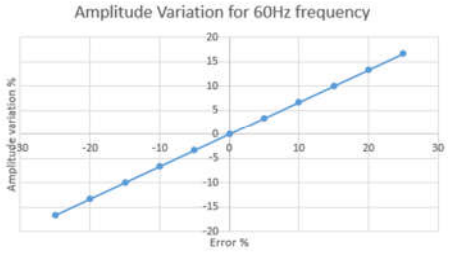

Figure 9: Amplitude Variation (60Hz)

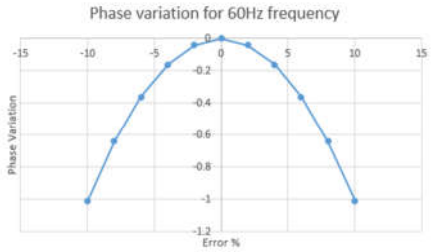

Figure 10: Phase Variation (60 Hz)

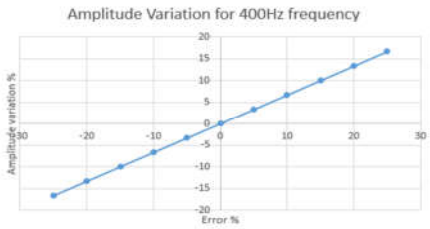

Figure 11: Amplitude Variation (400Hz)

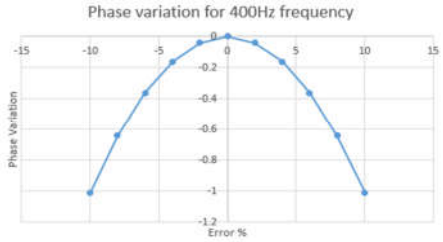

Figure 12: Phase Variation (400 Hz)

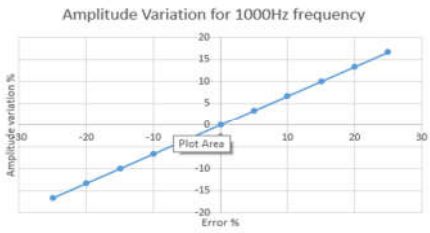

Figure 13: Amplitude Variation (1000Hz)

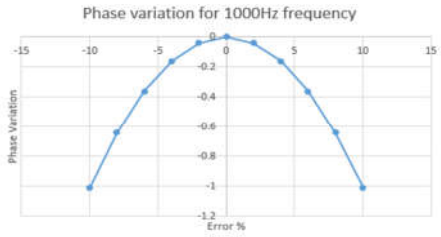

Figure 14: Phase Variation (1000 Hz)

From the error analysis of DCM algorithm with excitation frequency of 5 Hz,60 Hz,400 Hz and 1000 Hz, it is observed that, at the input end, when amplitude of interferometer signals is varied from 1.25 to 0.75 i.e. (+/-) 25% variation in amplitude, (+/-) 16.6% error is induced respectively. Similarly, when phase of interferometer signals is varied up to (+/-) 10º with every 2º step change the maximum error percentage calculated is -1.01%. Thus the excitation frequency of the strain signal does not contribute any error.

3) Combinational variations:

When both amplitude and phase are varied together, i.e. when the maximum variation in terms of both phase and amplitude are applied simultaneously for excitation frequency of 5Hz, the following results were obtained (Figure 15):

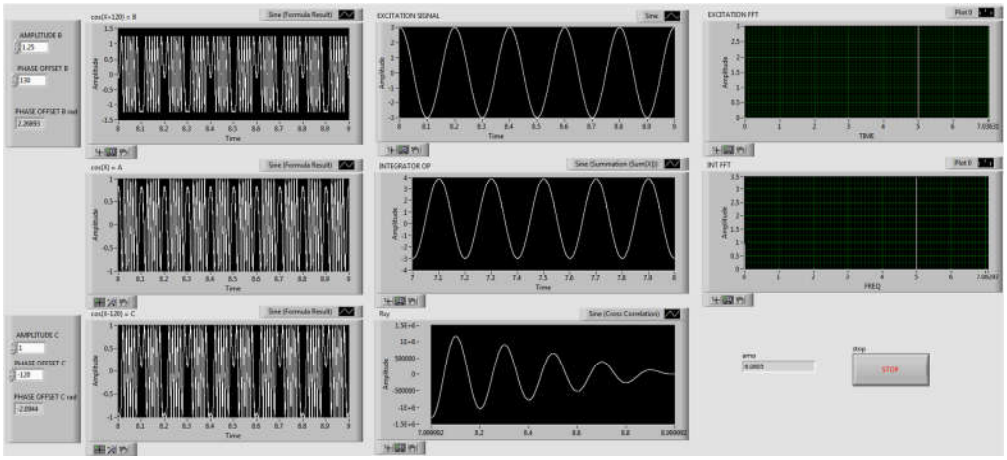

Figure 15: Waveforms obtained for simultaneous amplitude and phase variation for 5Hz excitation (amplitude B=1.25, phase=130º)

When the amplitude and phase of B are varied simultaneously, with maximum values of amplitude, phase i.e. 1.25 and 130º, the value of peak of integrator FFT block, changes from 3 to 3.461. This leads to an error percentage of 15.40.

Similarly, when the amplitude and phase of B are varied simultaneously, for the remaining frequencies like 60Hz, 400Hz and 1000Hz, the value of peak of integrator FFT block, changes from 3 to 3.461. This leads to the same error percentage of 15.40, as with the 5Hz frequency.

4. Conclusion:

This project studies an experimental approach in error analysis of Derivative and cross multiply algorithm i.e. for analyzing the effects of amplitude and phase variation, by successfully implementing the simulation code. From the results obtained above, it can be interpreted that, for every 5% change in amplitude, 3.33% error is induced. Amplitude variations induced a maximum of 16.6% error in the results, when amplitude was varied up to 25%. Also when phase is varied up to (+/-) 10º with every 2º step change the maximum error is -1.01%. The amplitude variation has more impact on the results, as compared to the phase variation, irrespective of the frequency of the excitation signal. When both maximum amplitude and phase variations are induced simultaneously, the error percentage is 15.40% which is slightly less than that of only maximum amplitude variation (16.6%) and more than that of maximum phase variation (-1.01%).We also conclude that the excitation frequencies do not contribute to the overall error of the system.

Acknowledgement:

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