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An Architecture for On-board Frequency Domain Analysis of Launch Vehicle Vibration Signals

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ABSTRACT

The dynamic properties of the airborne structures plays a crucial role in the stability of the vehicle during flight. Modal and spectral behaviour of the structures are simulated and analysed. Ground tests are carried out with environmental conditions close to the flight conditions, with some assumptions. Subsequently, based on the flight telemetered data, the on-board mission algorithm and the auto-pilot filter coefficients are fine tuned. An attempt is made in this paper to design a novel architecture for analysing the modal and spectral random vibration signals on-board the flight vehicle and to identify the dominant frequencies. Based on the analysed results, the mission mode algorithm and the filter coefficients can be fine tuned on-board for better effectiveness in control and providing more stability. Three types of windows viz. Hann, Hamming and Blackman-Harris are configured with a generalised equation using FIR filter structure. The overlapping of the input signal data for better inclusiveness of the real-time data is implemented with BRAM. The domain conversion of the data from time domain to frequency domain is carried out with FFT using Radix-2 BF architecture. The FFT output data are processed for calculating the power spectral density. The dominant frequency is identified using the array search method and Goldschmidt algorithm is utilised for the averaging of the PSDs for better precision. The proposed architecture is synthesised, implemented and tested with both Synthetic and doppler signal of 300 Hz spot frequency padded with Gaussian white noise. The results are highly satisfactory in identifying the spot frequency and generating the PSD array.

Keywords: Modal parameters; Spectral analysis; Windowing; Overlapping; FFT; PSD; Radix-2 BF; Block RAM

1. INTRODUCTION

The Natural Frequency and the Mode Shapes are the dynamic properties of the structures and are estimated by the Modal Analysis. The frequencies of different modes are generally low and the spectral values are completely random. The Modal and Spectral behaviour of the vehicle structure is an important factor for the stability of the vehicle and the control margins during the flight. The modal parameters are arrived at from the structural analysis and associated Ground Resonance Test of the flight article under simulated flight conditions. These parameters viz. the mode shapes, the first two modal frequencies and the Damping factor are utilised in the On-board autopilot algorithm from a look up table. Identifying the dominant frequencies, damping factor of the structure and avoiding the control-structure interaction by auto-pilot filters plays an important role in the controllability and stability of the flight vehicle.

2. METHODOLOGY

2.1 Structural Analysis

The Modal and Spectral behaviour of the flight structures are initially modelled and the structural analysis is carried out. Subsequently the ground tests are carried out, keeping the ground test setup close to the flight conditions. The natural frequencies of the structure and the dominant frequencies under dynamic conditions are evaluated in the ground tests. The accelerometer signals are processed and analysed in the frequency domain to identify the dominant modal frequencies of interest. The damping factor derived from the hammer test and the modal frequencies at different flight conditions are stored in the lookup table of the on-board computer for use in autopilot algorithm during the flight. The results of the ground resonance test and the random vibration tests are compared with the simulation results to fine tune either the model or the test conditions or both in many occasions. This is a recursive process as explained by the flow diagram shown in Fig. 1 till satisfactory results without major uncertainties are obtained. As a general rule, the stability studies are also carried out by perturbing the mode shape data within the expected bounds[1].

Also, these simulation and ground tests data are compared with the flight telemetered data for further fine tuning of the model. The recursive simulation and testing process on ground is a tedious one and always based on few assumptions on the flight trajectory conditions and the associated errors in the mathematical models. The flight vehicles for both space and defence applications are getting highly optimized to suit the

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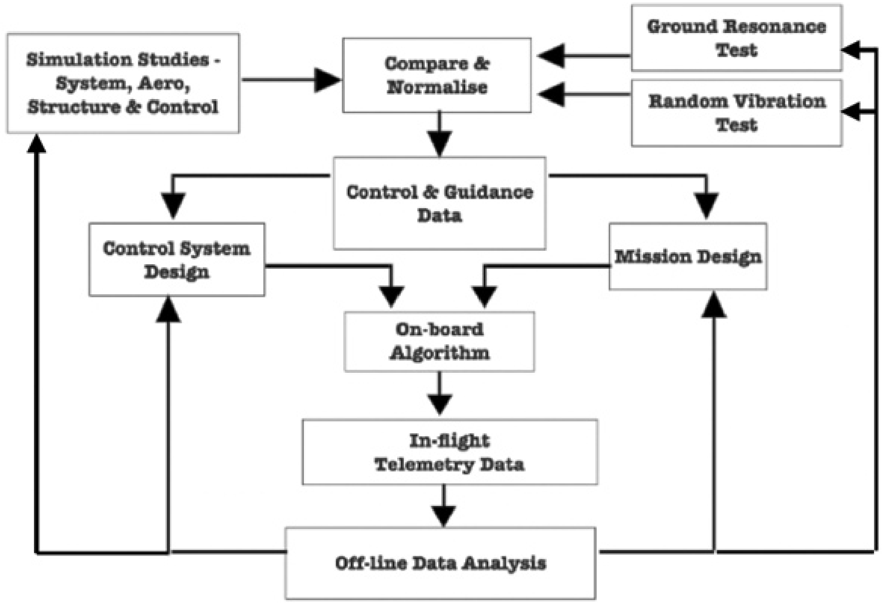


Figure 1. Simulation & analysis flow.

operational requirements. And so the need for on-board analysis of the vibration signals, to have better controllability. The best method is the adaptive tuning of the auto-pilot parameters in real time during the flight of the vehicle. This calls for spatially separated sensors along the structure and the associated signal processing electronics to identify the dominant frequencies which are immune to failures and has relatively fast update rate, with in-flight updation of the control and auto-pilot filter coefficients.

2.2 SPECTRAL ANALYSIS

To carry out the spectral and modal analysis assuming the periodicity of infinite time, these signals has to obey the Drichlet condition[2]. The random vibration signals are time varying. In the Fourier Transform, the signal under analysis is expanded as signal of single frequencies those exist all over the time. Hence, the variation in the instantaneous frequency cannot be obtained by simple Fourier transformation[3]. During the initial days, Fourier transformation and Chirp-Z transformation were used to analyse the flight flutter data and spectral data[4]]. Hilbert Transform analysis in time-domain is suited to extract the instantaneous undamped frequency and the real non-linear elastic force characteristics[5.] This method involves intense numerical calculations for non-linear frequency response function. Hence, may not be suitable for real-time on-board applications.

Estimation of the modal parameters using the wavelet transformation as proposed by M.Ruzzene, *et al.*[6] is an effective method for Time-Frequency analysis of random vibration signals. Fundamental frequency estimation using the Complex Continuous Wavelet Transformation[7] and Maximum likelihood Estimator using auto correlation methods[8] are viable alternatives to process the real valued signals. With varying methods proposed for multiple applications, different architectures for domain conversion are proposed in literatures viz. Pipelined, Parallel-pipelined, Multiplierless, Serial & Interleaved and Serial Commutator catering for different applications, namely, Real Valued FFT, OFDM signal processing, processing of word sequential data, Video motion compensation, etc.[9-17]. Many of these methods and the transformations are generally applicable in the off-line analysis of the vibration signals. Generally, Wavelet Transformation and Fourier transformation are widely used by the vibration experts for the time-frequency and frequency domain analysis of random vibration signals, respectively[18]. It may be noted that the closeness to the correct value, update rate and the resource requirements are the important factors for on-board application. It may also be noted that the most suitable method for use in on-board analysis is the Fast Fourier Transformation with necessary Windowing and Overlapping functions to calculate the Power spectral density and thus closely identifying the dominant frequencies, based on the range of interest[19]. These identified dominant frequencies and their variations with time during the time of flight can well be used to fine tune the control and autopilot parameters in real time. The adaptive tuning of the filter coefficients will enable better controllability and optimum mission design. The generalised block diagram of the spectral analysis for the analysis of flight vibration signals is shown in Fig. 2.

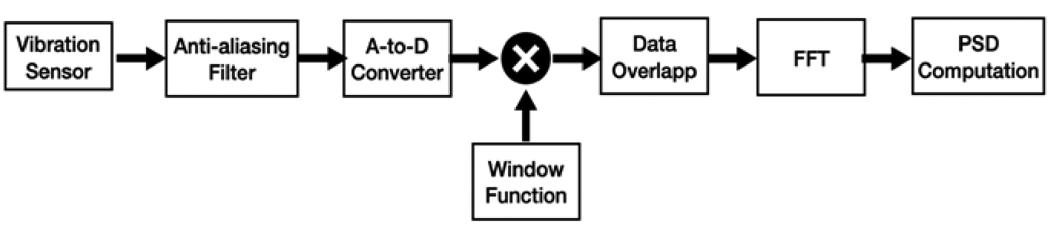


Figure 2. Generalised block diagram for spectral analysis.

Based on the throughput requirement of the system, overlapping of the sensor data is carried out to have more accurate and realistic output. The power spectral density at each analysed frequency will provide vital information about the dominant frequencies and the associated energy content. The flight performance and behaviour are evaluated even today by off-line analysis of the telemetered data. with the time proven iterative method described in Fig. 1. With repeated analysis and tests, the on-board algorithm is optimised. But with changing scenario of optimized rocket motors, requirement for high maneuverability and mission control requirements, it is proposed to analyse the vibration signals on-board in realtime. In this work, we propose the architecture for the implementation of window functions, overlapping, FFT and the calculation of PSD for on-board applications in flight vehicles.

3. PROPOSED SYSTEM ARCHITECTURE

The proposed memory-based architecture shown in Fig. 3 is designed to integrate into the on-board-computer (OBC) system of flight to perform the real-time frequency domain analysis of the Spectral and Modal vibration signals, so as to optimise the auto-pilot filter coefficients and Active Vibration Control coefficients for avoiding the tedious and time-consuming off-line iterative process.

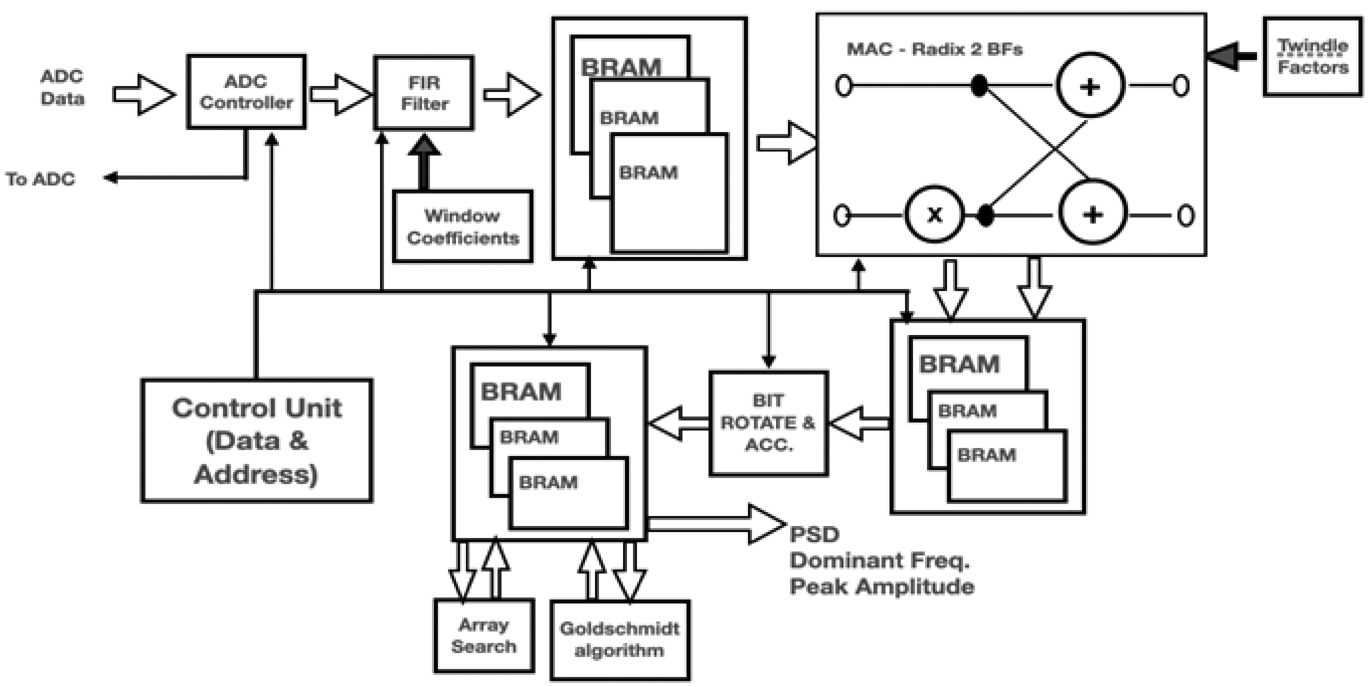


Figure 3. Proposed architecture for on-board frequency domain analysis.

3.1 Windowing

To minimise the picket fence effect and the spectral leakage during domain conversion using Fourier Transformation, many window functions are derived over the time and applied on the input signals[20-25]. Windowing is the process of smoothening the signal end points by multiplying the time data by finite length spectrum with smoothly varying amplitude that zeros out at the edges. The loss in the total signal power induced by this type of weighing can be avoided by applying a correction factor. For the given signal x(t), applying a window w(t) results in the signal x'(t) as

$$x'(t) = x(t) * w(t) \tag{1}$$

Though many types of windowing techniques are available to control the signal leakage, only a few are used in vibration signal analysis by the practitioners, because of suitability and efficiency. The three windowing techniques proposed in the literature[17] to analyse the spectral data of the flight mechanical structures are:

- Hann Window
- Hamming Window and
- Blackman - Harris Window.

The generalised equation for the above three window functions can be expressed as,

$$w(n) = a_0 - a_1 \cos\frac{2\pi n}{N-1} + a_2 \cos\frac{4\pi n}{N-1} - a_3 \cos\frac{6\pi n}{N-1} \tag{2}$$

where, a_0, a_1, a_2 and a_3 are coefficients which takes specific values depending on the type of window as presented in Table 1.

The Eqn. 2 can be realised in hardware by employing parallel-pipelined architecture for implementing the window functions. Here, these windows are basically designed using the FIR filters with coefficients derived from the mathematical model simulation and further optimised for the lowest possible Mean Squared Error (MSE) using the Simulated Annealing algorithm. The derived optimised coefficients are stored in the Block RAM of FPGA. The filter architecture is based on

Table 1. Window type and co-efficient values

Window type	a_0	a_1	a_2	a_3
Hann	0.5	0.5	0	0
Hamming	0.54	0.46	0	0
Blackman-Harris	0.35875	0.48829	0.14128	0.01168

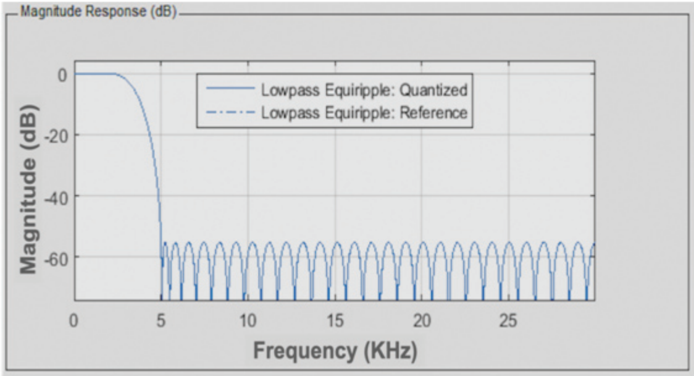


Figure 4. Magnitude response of equiripple filter.

Table 2. Performance parameters of standard FIR and SA-FIR filters

Noise - SNR (in dB)	Filter type	MSE	SNR (in dB)
3	Standard Hann	12.2510	24.1775
	FIR - optimised with SA	1.1101	24.8416
5	Standard Hann	12.1203	26.2847
	FIR - optimised with SA	0.941835	27.0779
10	Standard Hann	11.9976	31.3157
	FIR - optimised with SA	0.749809	31.9743

the equi-ripple FIR filter for optimum response both interns of magnitude and phase. The FIR filter of order 8 is designed to be used in the proposed architecture with a cut-off frequency of 2 KHz and a Stop band of 5 KHz. The magnitude response of this filter is obtained using the Matlab tool and the plot is presented in Fig. 4.

The performance of these filters is measured using indices such as MSE and SNR. Table 2 shows the values of MSE and SNR for inputs with different noise levels. Standard Hann represents the Hanning window-based FIR filter and SA – FIR represents the FIR filter optimised with Simulated Annealing Algorithm. It is observed that the optimised filter using SA algorithm produces better MSE and SNR than the standard filters in all the three cases.

3.2 Overlapping

Overlapping is used to include more original data in the PSD and to generate more DoF within a period of time. As the overlapping percentage increases, that much data points are reused in the next frame forming the number of data points.

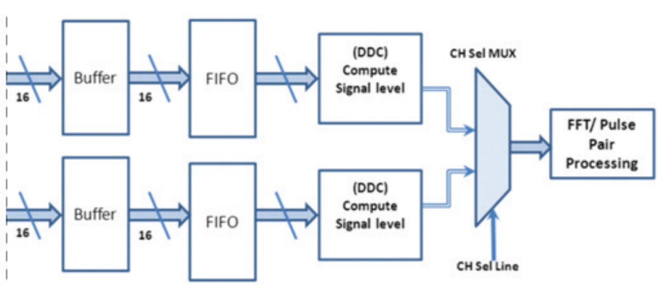


Figure 5. Data flow architecture for overlapping.

This overlapping procedure can be applied at any point of the process after digitisation. Each frame of data is stored in the memory for use in the next frame to overlap. Thus, the memory requirements are based on the overlapping options needed for the particular application. The proposed scheme for implementing the overlapping function is as in Fig 5.

In the proposed architecture, the overlapping percentage is selectable and/or hardcodable among 0 %, 25 % and 50 %. Hardware-in-Loop-Simulation test results show that 25 % overlapping of the data provides better results with the proposed windowing techniques[16]. The same to be hardcoded for ground experimental results of the proposed architecture.

3.3 Discrete Fourier Transformation

For a given sequence 'x' of N terms x_0, x_1,..., x_{N-1} the Discrete Fourier Transform can be defined as

$$X(p) = \sum_{n=0}^{(N-1)} x(n)\, e^{-j2\pi\frac{np}{N}} \quad (3)$$

N samples of the analog signal: $x_n = x\,(n/fs)$, are the N terms of the signal x(n), where fs is the sampling frequency and N point frequency approximation of the Fourier transformed signal is expressed by the N terms of X(p). The above equation can be written as

$$X(p) = \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n} e^{-j\frac{2\pi}{N}(2n)p} + \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n+1}\, e^{-j\frac{2\pi}{N}(2n+1)p} \quad (4)$$

$$= \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n} e^{-j\frac{\frac{2\pi}{N}(np)}{2}} + e^{-j\frac{2\pi}{N}(p)} \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n+1}\, e^{-j\frac{\frac{2\pi}{N}(np)}{2}}$$

$$X(p) = A_p + W_N^p * B_p \quad (5)$$

Where Ap , W_N^p and Bp are respectively,

$$A_p = \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n} e^{-j\frac{\frac{2\pi}{N}(np)}{2}} \quad (6)$$

$$B_p = \sum_{n=0}^{(\frac{N}{2}-1)} x_{2n+1} e^{-j\frac{\frac{2\pi}{N}(np)}{2}} \quad (7)$$

$$W_N^P = e^{-j\frac{2\pi}{N}p} \quad (8)$$

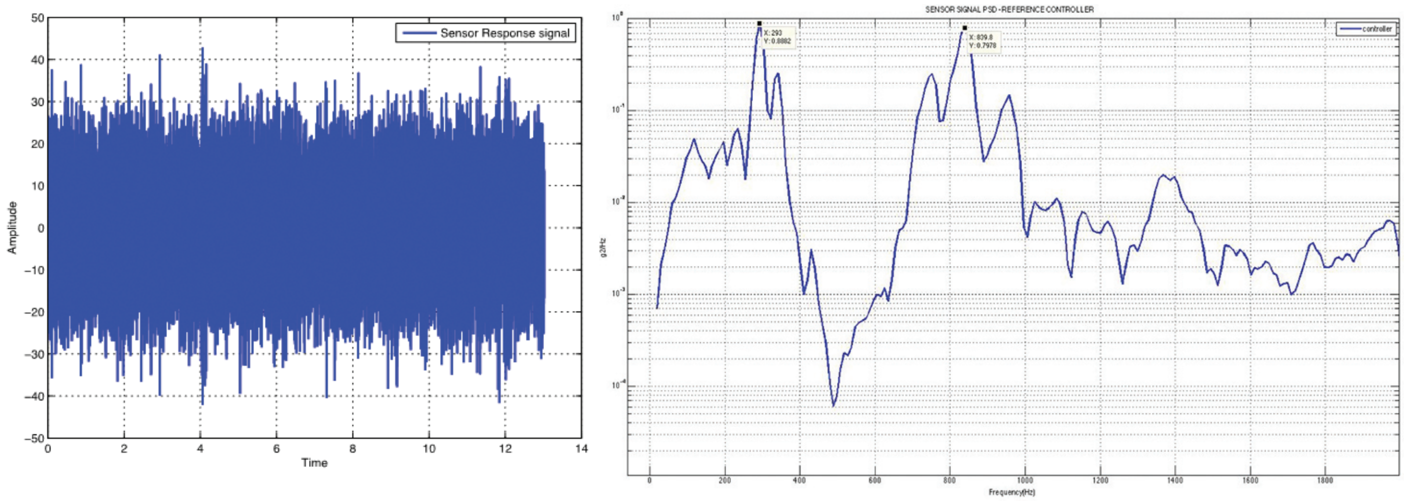
Since the DFT is considered as periodic,

$$X\left(p + \frac{N}{2}\right) = A_p - W_N^P * B_p \quad (9)$$

The above equations define the structure of the FFT algorithm in the butterfly form and the same is configured with Radix-2 BFs. The output of this transformation is complex numbers as the FFT operates over complex numbers. Many regular designs for computation of Complex FFT (CFFT) are well presented in the literature[26-28].

3.4 Power Spectral Density

The time history of the random vibration signal measured by an accelerometer and the frequency domain distribution of the spectral power are illustrated in Fig. 6. The spectral



(a) (b)

Figure 6. (a) Time history and (b) Power spectral density.

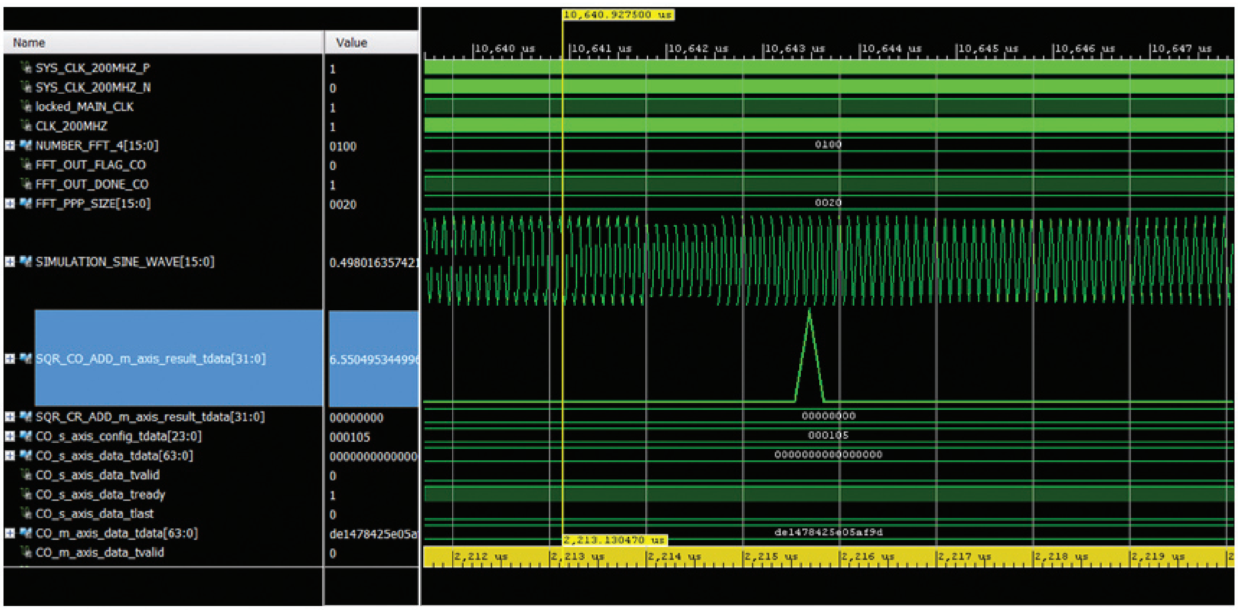


Figure 7. Functional simulation result for 300 Hz spot frequency.

resolution of the measurement sensitivity and the quantisation resolution normalizes the scale of frequency in the X-axis and the PSD in the Y axis.

- Autocorrelation function
- Filtering of the signal with Δf wide filters and
- Calculation of the RMS Value of the filtered signal using Fourier Transformation are the main three methods to calculate the Power Spectral Density (PSD) for an excitation between -T and +T. In view of the simple mathematical functions and easiness in processing the data in digital mode after domain conversion, method using the RMS value is widely used to calculate the PSD. The PSD is defined from the Fourier transform of the random vibration $\ddot{x}(t)$ sample with 2T durations

$$G(f) = \lim_{T\to\infty} \frac{1}{T}\left|\ddot{X}(f)\right|^2 \quad (10)$$

But for the finite duration samples in real time,

$$G(f) = \frac{1}{T}\left|\ddot{X}(f)\right|^2 \text{ G} \quad (11)$$

During the period T, the Fourier transform gives the highest peak amplitude of the output signal from a filter (f, Δf). Hence, to improve precision of the output value, it is desirable to carry out averaging of several Fourier transforms. An averaging module using Goldschmidt algorithm is introduced in the PSD core for storing the calculated PSD data into the block RAM and averaging based on the throughput rate and array search method for finding the Instant Maxima from the PSD data.

4. RESULTS AND ANALYSIS

The proposed architecture is modelled using Verilog HDL and synthesised with Vivado v.2015.4 with a target of Kintex-7 hardware. XC7K410T. The device utilisation is presented in Table 3.

Table 3. Device utilisation

Resource	Estimation	Available	Utilisation %
LUT	8653	254200	3.40
LUTRAM	4986	90600	5.50
FF	10761	508400	2.12
BRAM	496	795	62.39
DSP	170	1540	11.04
IO	21	400	5.25
BUFG	6	32	18.75
MMCM	1	10	10.00

The proposed architecture is simulated with a synthetic signal of 300 Hz frequency padded with Gaussian white noise. The number of FFT points is set at 1024 and the overlapping percentage selected as 25 %. The level of input sinusoidal signal is varied in range from -10 dBm up to -40 dBm with a step of -5 dBm. The performance of the proposed architecture is verified based on the results of the post-synthesis functional simulation. One of the results is presented in Fig. 7.

It is evident from the simulation results that the dominant frequency of the input noisy signal is clearly identified by the proposed architecture at 300 Hz. Further, the proposed architecture is validated with the real time signal from the field sensor input added with predefined noise levels. Bench level test setup is prepared with the proposed architecture ported onto the hardware by feeding a real time signal with varying noise levels. The proposed architecture is also validated by performing multiple simulation runs with Hardware-in-loop, while varying the no. of FFT points between 256 and 2048 with same input signals.

It is observed that the noise floor levels are improving approximately by -3 dBm as the number of FFT points are doubled. Also this architecture can provide better isolation upto -70 dBm of the input signal. The output of the unit under test with 1024 point FFT for varying input sinusoidal signal levels is presented in Fig. 8.

5. CONCLUSION

In this paper, we have presented the architecture proposed for the frequency domain analysis of the random signal to identify the dominant frequency for in-flight real time applications. The performance of the proposed architecture is evaluated with a known signal added with Gaussian white noise. The General System Specification requirement for the handling of random vibration signals during flight is limited to -40 dBm isolation of the signal noises. It can be seen from the field test output plots that the spot of frequency of 300 Hz is clearly identified. Also, the isolation is provided upto -70dBm in the worst case. The update rate of the output PSD data array is at about 1.77 msec with 25 % overlapping of the input data. Further testing of the proposed architecture with random signals with different and multiple frequency peaks are to be carried out to prove the consistency. The same can be fully utilised for on-board applications for the identification of the dominant frequency of the random vibration signals for further utilisation in finetuning the filter coefficients in real time.

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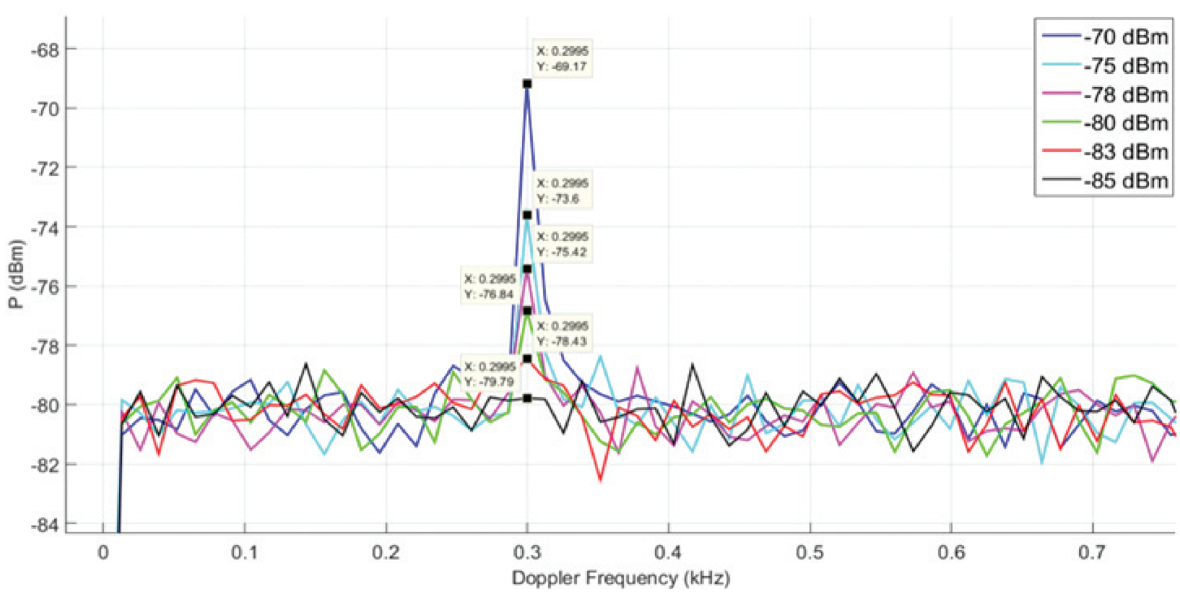

Figure 8. Field test signal with 1024 point FFT and 25 % overlapping.

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In the current study, she has extended supervision to the main author for the analysis, outline of the research work, synthesis procedure, analysis of the results, literature survey and final scrutiny of the paper.

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In the current study, she has contributed in guiding through the need aspects, implementation bottlenecks, test configuration and data validation.