OPTIMIZING PCM BANDWIDTH USAGE IN FLIGHT TEST BY REAL-TIME DATA ANALYSIS DURING FLIGHT

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ABSTRACT

There is an ever-increasing demand for more data to be captured during flight test applications, placing more demand on the limited bandwidth available for PCM data transmission. Some strategies can help, such as performing analysis on the platform itself. For example, by performing Fast Fourier Transform (FFT) analysis in the air and sending just the results down over PCM in real-time, the PCM bandwidth usage can be optimized, saving the users time and reducing the overall cost of ownership.

This paper discusses data analysis methods, specifically FFT analysis on accelerometer data in real-time during flight, that can be used without additional flight test instrumentation hardware onboard the aircraft.

Keywords: Big Data, real-time data analyses, Data Reduction, Bandwidth Optimisation

INTRODUCTION

During flight test applications, it is critical to understand and quantify the vibration frequencies experienced by the airframe during an actual flight. The vibration data is compared to flight qualification random vibration test standards and are typically substantially lower than the random vibration test curves.

Traditionally, the vibration measurements are taken using ICP type accelerometers positioned on the aircraft's control surfaces, sampled at a high rate, and transmitted to the ground over PCM for real-time FFT processing. However, as many FTI engineers will attest, PCM is not impervious to drop-outs and interference, and high sample rate accelerometer measurements can take up huge amounts of the available PCM bandwidth.

There has been a trend to attempt to move the analysis to onboard the aircraft and send only the FFT results over the PCM stream. This should speed up the data analysis and free up the PCM bandwidth for other data, thereby reducing the number of flights required for the test campaign and the program's overall cost. This approach, up to now, has required separate data analysis computers to be onboard the aircraft, increasing the complexity and size of the FTI installation.

This paper discusses some of the issues, challenges and trade-offs that must be made when considering performing FFT analysis in real-time onboard the aircraft. It proposes an approach where data acquisition units conduct the FFT analysis in real-time, and both the raw data and FFT results are available to the user, with the raw data recorded onboard and the FFT results sent over PCM, highlighting the bandwidth savings that are possible.

2. Considerations for Measuring Vibration in Flight Test

One of the first steps when measuring vibration is to calculate the expected vibration frequency range of the control surface under test during all stages of flight and then ensure your sensor has the bandwidth to measure the expected vibration.

Following that, data acquisition units must be selected that meet the required bandwidth, taking into account the filtering applied by the data acquisition modules to ensure all the signal frequencies are captured. Then, as part of the full FTI system architecture, especially the telemetry bandwidth available on the test range, a PCM frame structure is selected that allows sampling of all the required data sources at the required rates. This PCM frame structure usually defines the limits of available sampling rates for the accelerometer channels.

3. FFT Analysis, the Balancing Act

There are multiple factors to consider and trade-offs to be made when performing FFT analysis; these will be discussed in detail below:

For this discussion, we will consider the example of the NASA F-15B/ Flight Test fixture II Test Bed. On this airframe, the power spectral density (PSD) of accelerometer flight data was required to be analyzed to quantify the in-flight vibration environment from a frequency of 15 Hz to 1,325 Hz[1].

3.1 Channel Sample Rate and Filter Cut-off

To meet the above bandwidth requirements, the accelerometer modules in the data acquisition units must have a bandwidth available greater than 1325 Hz after filtering is applied. Considering this, sampling at 8,192 Hz with FC set to FS/4 gives us a bandwidth of 2,048 Hz, easily meeting the bandwidth requirements of the program.

3.2 Max detectable FFT Frequency

FFT maths tells us that the maximum detectable frequency in an FFT analysis is driven by the number of FFT points or BINs and the resolution of the FFT. The number of FFT points or BINs of intestest is half the FFT block size due to the Nyquist theorem:

FFT BINs = No of FFT Samples / 2

The resolution of the FFT points is driven by the sample rate of the raw samples and the number of FFT samples:

FFT Resolution = Sample Rate / # FFT Samples

The Maximum detectable FFT frequency is the frequency contained in the final FFT BIN of your FFT analysis. It is important to ensure that the number of FFT samples and the sample rate of the channels results in a Maximum detectable FFT frequency that is greater than the expected frequency range required to be analyzed.

Relating this back to the NASA F-15B example:
For a sample rate of 4,986 Hz and an FFT block size of 16,384, there would be 8,192 frequency BINs, and the maximum detectable frequency would be 2,047.75 Hz.

For a sample rate of 8,192 Hz and an FFT block size of 32,768, there would be 16,384 frequency BINs, and the maximum detectable frequency would be 4,095.75 Hz.

3.3 Number of FFT Samples

Following on from the previous section, the number of FFT samples must be large enough to give both the resolution required and cover the frequency range required.

3.4 FFT Resolution

FFT resolution is a critical consideration; if the frequencies required to be analyzed are all close together, the highest possible resolution is required; lower resolutions may be acceptable if spaced apart.

Relating this back to the NASA F-15B example:
An FFT Block size of 16,384 at a sample rate of 4,096 Hz will result in an FFT resolution of 0.25Hz. Doubling the sample rate to 8,192 Hz decreases the resolution to 0.5 Hz.

3.5 Time to gather FFT Samples

Considering the sampling rate and the number of FFT samples required, the FFT results can only update once the required number of samples have been gathered. Large FFT sample blocks at lower sample rates can take considerable time to gather the samples. Higher sample rates obviously gather faster, but at the trade-off of resolution.

Looking at all of the above and considering the NASA F-15B example:

- Sample rate of 8,192Hz, max required frequency 1,325Hz.
- An FFT block size of 8,192 samples will give us a resolution of 1Hz, and 4,096 FFT Points, with a max detectable frequency of 4,095 Hz, and will take 1 second to gather the samples.
- Changing this to a block size of 16,384, improves the resolution to 0.5 Hz per BIN and will take 2 seconds to gather the data.
- Doubling the block size to 32K samples improves the resolution to 0.25 Hz per BIN, but will take 4 seconds to gather the samples.

3.6 FFT Windowing Function

FFT transforms of a pure sinewave signal assumes that the data is one period of a periodic signal. For the FFT, both the time domain and the frequency domain are circular topologies, so the two endpoints of the time waveform are interpreted as though they were connected. When the measured signal is periodic and an integer number of periods fill the acquisition time interval, the FFT turns out fine as it matches this assumption. However, in reality, the measured signal is not an integer number of periods, not a pure sinewave, and this introduces discontinuities in the signal that appear as spectrum leakage, visible in the FFT results as magnitude spread both sides of the main peak.. These can be reduced by applying "windowing" functions to the FFT analysis.
Many windowing functions are available in FFT analysis, but Hann and rectangular windows are most common.
Hann windows are better for detecting frequencies that are closer together, where higher spectral resolution is required. Rectangular windows are better where the amplitude accuracy is the important factor.

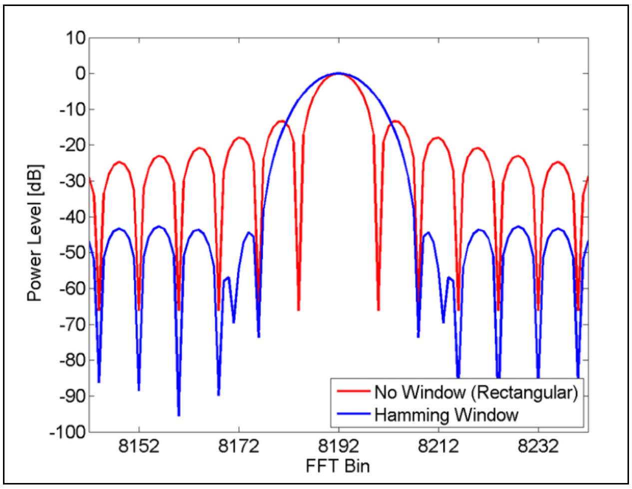

Figure 1: Rectangular vs Hann Window[2]

3.7 FFT Frequency Spread

Typically, vibration signals are not pure sinewave signals, where all the signal's power is concentrated into a single frequency point in the spectrum. It is more common that the true power of a specific frequency is spread across a number of points, all close together.
To this end, reading the power at a single frequency BIN may not accurately reflect the power seen. It may be more beneficial to read the power across several sequential BINs and average the reading across those points.
Breaking the FFT results into clusters or groups and calculating the power seen on that group can give a more accurate result, provided that the members of said group are close together. Groups of 3 or 4 give good average power readings.

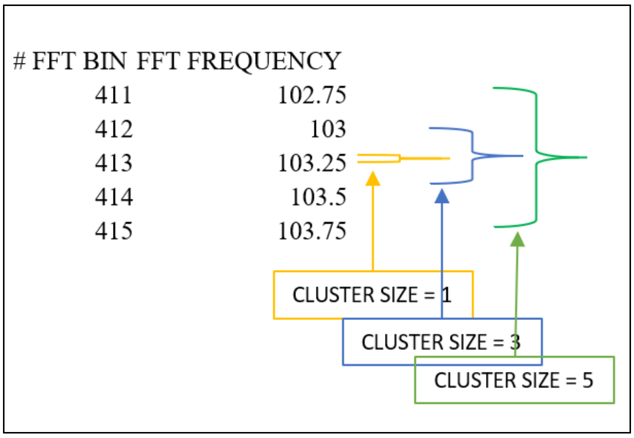

Figure 2: Cluster Sizes

3.8 Challenges of Designing in FFT analysis into Data Acquisition Modules

As stated at the outset of this paper, we will discuss an approach whereby the FFT analysis is done as part of the normal data acquisition, not in a separate box on board the aircraft. To that end, some of the challenges in achieving this are discussed below.

3.8.1 Raw Sample Storage / Buffering

ICP modules typically sample at high rates. Balancing this alongside channel density can be a challenge. For multiple channels at high rates, large buffers are required to store the data prior to processing; not only that, but the buffer also needs to store the next set of samples while the 1st set is being processed.

3.8.2 DC Offset Removal

One of the highest frequency components of any signal is a zero frequency component of a DC signal. This can have the undesirable effect of making it look like the largest frequency component is 0 Hz, washing out the actual frequencies of interest. Correcting this can be done by either applying a high pass filter to the signal or subtracting the mean from the original signal. However, applying a high pass filter increases filter delay; therefore, subtracting the mean is better.

3.8.3 Timestamping of the FFT Blocks

It can often be critical to know when the block of interest started and ended to correlate the FFT results back to the raw data. To this end, the timestamp at the start of the block must be tracked and available to the user.

3.8.4 FFT Windowing & Processing

The windowing function must be applied to the raw buffered FFT samples before passing them to the FFT IP for FFT processing.
The FFT processing itself must be balanced against the time taken to process multiple channels as the buffering requirements of storing the data while the FFT is being processed.
The cluster size selected must also be applied to the results to calculate a siding average of the power seen at each frequency BIN.

3.8.5 Power Consumption

All of the above can increase power consumption and, therefore, the overall temperature of the data acquisition unit. Care must be taken to ensure the processing time and data buffering is not so high that larger buffers are required and, therefore, excessive power is used.

3.9 How to Present the Results to the User

As can be deduced from the above, running an FFT creates a massive amount of possible data results that may be of interest to the user. An FFT block size of 32,768 results in 16,384 frequency measurements with 16,384 corresponding RMS Voltage measurements, per channel.
From the point of view of PCM bandwidth saving, presenting all 16K frequency and 16K corresponding power measurements per channel would easily defeat the purpose of saving space in your PCM frame.
To this end, there are two possible approaches discussed here:

3.9.1 Peak Detect

Based on the idea that the user wants to know the most significant frequencies being seen in the FFT, the results, after DC offset removal, can be sorted into a list ordered by most significant power first and then offered as a fixed list of frequency and power pairs. Typically, the top 32 frequency and power pair results will cover most of the required data as after that, the powers seen are so low those frequency components are insignificant.

3.9.1 User Defined Frequencies of Interest

Based on the idea that the user knows which specific frequencies they expect to see in the results, the ability to define a set of user-defined frequencies of interest (FOI) and only get the RMS voltages seen at those specific points is sufficient.

4. PCM Bandwidth Saving Examples

At this point, we have discussed the challenges and trade-offs that must be made when considering performing an FFT in real-time during flight test; now we will highlight the potential bandwidth savings in real-time telemetry that is possible by taking such an approach, whereby, instead of flooding the entire PCM bandwidth with the raw samples, the FFT results are transmitted instead.
Taking an extreme example, based on the IRIG-106 Chapter 4 PCM rules.[3]

IRIG-106 2020, Chapter 4 Section 4.3.2 a.1 allows for 16,384 bits per minor frame (Class II), and section b.1 allows for a max of 256 minor frames per major frame.
At 16 bits per word, this gives us a major frame that is 1,024 words wide and 256 minor frames deep.
In such a frame, after accounting for Sync words and Subframe ID there would be 261,376 sample locations in the PCM frame

Sampling 16-bit ICP channels into such a frame at 8,192 Hz, in keeping with the NASA F-15B example above, each channel would require 1,024 PCM sample locations, assuming an 8 Hz major frame rate.
This allows us to have 253 ICP channels, each with 4:1 commutation.

This would take up 99.12% of the available PCM bandwidth for 253 ICP channels.

Now, using an FFT block size of 32K and a sample rate of 8,192 Hz and in peak detect mode, using the top 32 frequency and power pairs, that is 64 parameters per channel, each updating at 8 Hz rate, we would have a resolution of 0.25 Hz and only require 16,192 of the available sample locations in that frame for the same 253 channels, that is a total bandwidth usage of 6.19%, a 92.93% saving. Switching this to user defined frequencies, and defining 8 specific FOI, and just transmitting 8 RMS voltage readings per channel, we would require only 0.77% of the available PCM sample locations.

Under a more realistic example, 12 ICP channels sampled at 8,192Hz inside a 100-word wide minor frame with 256 minor frames per 16 Hz major frame takes up 12.18% of the available PCM frame.

Figure 3: 12 ICP Channels Sampled Raw at 8192Hz

Changing that to just the top 32 FFT frequencies and respective powers per channel takes up only 1.52% of the available PCM space.

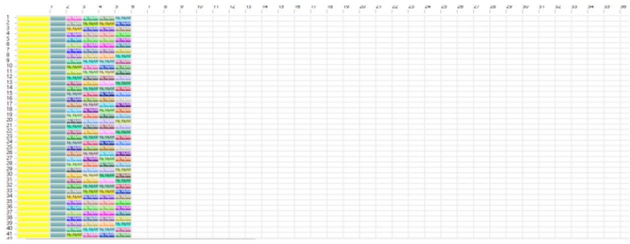

Figure 4: 12 ICP FFT Results Only

5. Conclusions

This paper has discussed the increasing demand for more data in flight test applications and the associated problems for transmission? bandwidth. It has been shown that by conducting FFT analysis in real-time in the relevant data acquisition modules, significant bandwidth savings can be achieved.

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[3] IRIG-106 2020, Chapter 4, Section 4.3.2, Sections a.1 & b.1