Signal Magnitude Analysis of Vibration Test Data of Satellites

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ABSTRACT
Signal analysis techniques are categorized into three types. They are signal magnitude analysis, time domain analysis, and frequency domain analysis. Each type has its advantages and disadvantages. In the present work, signal magnitude analysis parameters are analyzed for response signals monitored during various types of vibration tests on satellites. Considering the fact that the efficiency of compression techniques depends on the characteristics of the data being compressed, results of this analysis will be used to choose a suitable approach to compress the satellite vibration test data.

General Terms
Signal Analysis, Vibration Test Data, Statistical Parameters.

Keywords
Signal magnitude analysis, vibration signal, random signal, sine signal, shock signal.

1. INTRODUCTION

Vibration testing of satellites involves subjecting the satellites to random vibration, sine vibration, and high frequency shock. During these tests, to understand the behavior of the satellite, large numbers of responses (typically about 200 responses) are monitored. The number of responses monitored depends upon the size and complexity of the satellite. Considering the sampling rate of about 50K samples/sec, a recording duration of about 5 minutes, and 4-byte representation for storing the data, the storage requirement will be about 15GB per test. As 12-15 tests are conducted on a satellite, with 4 satellites per year, about 900GB of data is generated and stored in the data acquisition system. Apart from this, vibration tests on different subsystems of satellite would result in additional 2160GB of data per year. Thus a minimum of about 3TB of data is generated every year, which has to be archived for analysis and for future reference.

With the increase in the number of satellites being realized and increase in size and complexity of satellites, the storage requirement is bound to increase exponentially. This calls for application of a suitable compression algorithm for efficient archival and dissemination of the data. The compression algorithm should make use of the unique characteristics of the vibration test data for improved efficiency. To choose a suitable algorithm from the existing array of compression techniques or to develop a new algorithm for efficient compression of the vibration test data, the characteristics of the vibration test data has to be properly understood. Precisely for this purpose, the present work focuses on characterizing the data for signal magnitude analysis parameters and identifies the unique features of the vibration data.

Signal analysis is an important process to characterize any signal, which plays important role in variety of applications such as to infer about the correctness of the signal, extracting information from the signal, and for developing a suitable compression technique. The types of signal analysis techniques are signal magnitude analysis, time domain analysis and frequency domain analysis. Signal magnitude analysis and time domain analysis provides basic information about the signal such as statistical parameters whereas frequency domain analysis provides detailed information about the signal including frequency components of the signal.

Signal magnitude analysis involves analysis of magnitude related parameters such as peak value, extreme value, range, mean value, mean square value, root mean square value, variance, standard deviation, skewness and kurtosis. Further, it is required to obtain additional parameters of the signal in order to establish the relative frequency of occurrences, which include probability density function and the probability distribution function of the signals.

1. DESCRIPTION OF PARAMETERS
Different signal magnitude analysis parameters are studied as part of this work. The parameters chosen are based on their relevance to the objective of the present work. The methodology of estimating their values and the significance of these parameters are explained in the following paragraphs.

In vibration data analysis, peak value is the value that corresponds to maximum acceleration level that the specimen has undergone during vibration test. Extreme values are used to decide on DC level shifting, if required, during of compression of the data. DC level shifting is an initial process in most of the compression algorithms. This will reduce the maximum value of the output coefficients of the transformation used in the further stages of compression algorithm.

Summarization of the data is a necessary function of any statistical analysis. As a first step in this direction, a measure of central tendency is a mean value or average value, which is very essential and an important summary measure in statistical analysis. Mean square value is also referred to as the second statistical moment and it provides information about energy content in the signal. In most of the vibration measurements, instead of mean, root mean square value is used to represent the data set as it represents the energy content of the data.

The positive square root of the arithmetic mean of sum of squares of the deviations about the mean is taken as a measure of dispersion. This measure of dispersion is known as standard deviation or root-mean square deviation. Standard deviation gives a numerical value to the clustering tendency of the data. A large standard deviation is an indication that the vibration data values are widely distributed, with some relatively extreme values possibly observed. If the standard deviation is small, the vibration data points will be more closely clustered around the center of the data. It is not very much affected by the fluctuations of sampling.

Skewness of the data set refers to asymmetry in the vibration test data. The symmetry of a data distribution implies that for a given deviation from a central value, there is equal number of samples on either side of it. If the distribution is asymmetrical or skewed, its frequency curve would have a prolonged tail either towards its left or towards its right hand side. Kurtosis is a measure of the shape of a frequency curve. This parameter provides information about transient nature of the vibration data. The analysis of skewness and kurtosis of vibration test data are very useful in making conclusion about the nature of frequency distributions of the vibration data.

Probability density function, f(x) is the ratio of frequency of each variable to the total number of samples. If X is a discrete Random Variable (RV) representing the value of the vibration test data, assuming the values x_1, x_2, ... x_n and $f(x_i)$ is a number associated with each x_i. Then, the function $f(x_i)$ is called the probability density function of the vibration data, where, $f(x_i) = P(X = x_i)$ is the probability of RV, $X=x_i$. The collection of all pairs of x_i and $f(x_i)$ i.e., {x, $f(x_i)$} is called the probability distribution of RV, X. A Probability density function is either a listing of probability values or a mathematical relation, which describes how probability is distributed over the different values of the variable. The word "density" is appropriate since it gives the weighting of probability for each value. As mentioned earlier, vibration test signals are categorized into three major types of signals. They are stationary random signals for random test data, sinusoidal signals for swept sine test data and a finite amplitude and finite duration impulse signal for the shock test signal. Probability density function of stationary random signal is generally Gaussian in nature and hence it is given by:

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}} e^{-(x-\mu)^2/2\sigma^2}$$

Probability density function of sinusoidal signal is given by:

$$f(x) = \frac{1}{\pi\{(X^2 - x^2)\}^2}$$

Cumulative Distribution Function, F(x) accumulates the probability over the range of the random variable. The vibration test data ranges from -100 to +100 and about 10^6 samples are acquired during a typical vibration test. As mentioned earlier, the data is sampled at very high sampling rate of 50 K Samples/sec and the samples are stored using 4 byte representation. Hence, the resolution of the sampled data values is very high with 16 decimal places. The challenging task of estimating probability density function of this high resolution and huge amount of data was carried out by implementing the algorithm given below:

Algorithm to estimate Probability Density Function (PDF) of vibration test data, $x_i(t)$:

1. Let "X" is a Random Variable(RV), which represent the values of the vibration test data
2. "fr_X" is the frequency of each value of the random variable
3. Find minimum and maximum of data values, x_{min} and x_{max} (having only two decimal places) amongst all data samples
4. Minimum and maximum of RV, X is
   a. X_{min}=floor((x_{min})*100)/100
   b. X_{max}=ceil((x_{max})*100)/100
   This ensures that if data has 4 decimal places, and takes the values from -3.5603 to 2.8324, minimum and maximum values are -3.56 and 2.84
5. Let the RV, X takes values from X_{min} to X_{max} with an increment of 0.01
6. No. of values that RV, X takes is X_{count} = [(X_{max} - X_{min})*100 + 1]
7. Frequency of each value of the random variable, X_i is denoted as fr_X_i
8. Consider each value of the RV, and find out how many data samples can be assigned to this RV value. For e.g. all the data samples from -3.5600 to -3.5599 are assigned to the RV value {-3.56}. Number of such data samples is the frequency of the RV, X_i=-3.56
9. PDF, $f(x_i)$ is defined as the probability of the RV, X taking the value, x_i, is given by: $f(x_i)=P(X=x_i)$ = fr_X_i / X_{count}. i.e. for each value of RV, PDF, $f(x_i)$ is frequency of occurrence of the RV, X_i divided by sum of frequencies of all values of random variable.

2. EXPERIMENTAL RESULTS

Three different sets of vibration data viz. swept sine test data, random test data and shock test data of a typical satellite are analyzed in the present work. Vibration data acquisition system used is capable of acquiring data of about 250 responses with the sampling rate of 50 KHz for each response. The raw time domain data acquired during the vibration test by this data acquisition system is stored in the throughput disks. This raw time domain data is available for storage and archival in MATLAB binary format. The present work uses this data for carrying out analysis of satellite test vibration signal.

Swept sine test data contains the samples which represents the signal starting from initial frequency and sweeps till the final frequency, whose amplitude varies as per the response at the monitored location on the satellite. Random test data represents a stationary random signal, whose statistical parameters do not vary with time. Shock test data contains samples of high frequency transient responses of the monitored location during a shock test. At any instant of the data set, sine data has only one frequency component, random has all the frequency components from initial test frequency to the final test frequency and shock also has many frequency components. Hence, each data set is unique by itself and the analysis is carried out on all three sets of data.

Table 1. Table captions should be placed above the table

Sl No	Parameter	Sine Test Data	Random Test Data	Shock Test Data
1	peak value	-6.58	-52.75	530.42
2	extreme value - x_{min}	-6.58	-52.75	-214.34
3	extreme value - x_{max}	6.37	52.24	530.42
4	range	12.95	104.99	744.76
5	mean value	-0.01	-0.01	-2.58
6	mean square value	0.08	48.25	9.47
7	root mean square value	0.29	6.94	3.07
8	variance	0.08	48.25	2.76
9	standard deviation	0.29	6.94	1.66
10	skewness	-0.01	0.01	167.70
11	kurtosis	72.08	5.99	50536.75

Table 1 shows comparison of values of all parameters of these three different data sets. The plots of original sampled time domain data of the dynamic tests viz. random, sine and shock tests are shown in Figure 1. They represent the raw time domain data acquired and recorded during these three different tests. Probability Density Function and Cumulative Distribution Function for these three data sets are computed and plotted and are shown in Figure 2 and Figure 3 respectively. It may be noted that the data indicated in Table 1 and plots shown in Figures 1, 2 and 3 are obtained from response data monitored during the vibration tests of one particular satellite. The same analysis was carried out on sine, random and shock test data of three different satellites. It was observed that the values of various parameters and the graphs of Probability Density Function and Cumulative Distribution Function possess similar range of values and behavior for all the three satellites. Hence, the present data sets and values illustrated in this paper are generic in nature and represent the data of any typical satellite vibration test data.

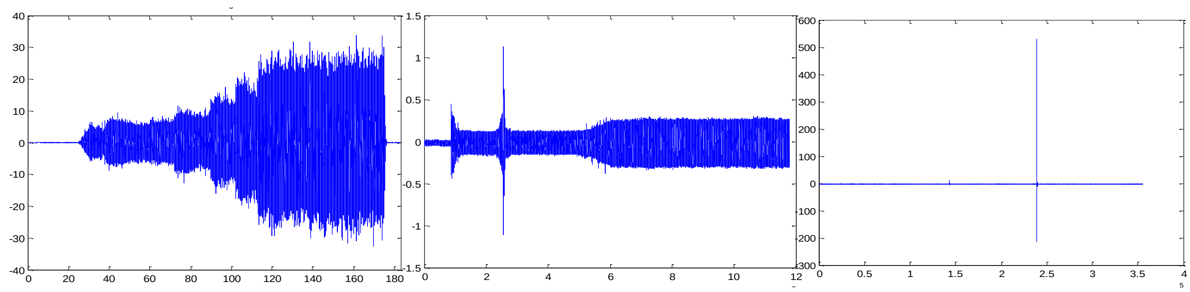

Figure 1: Time domain data of random, sine and shock tests

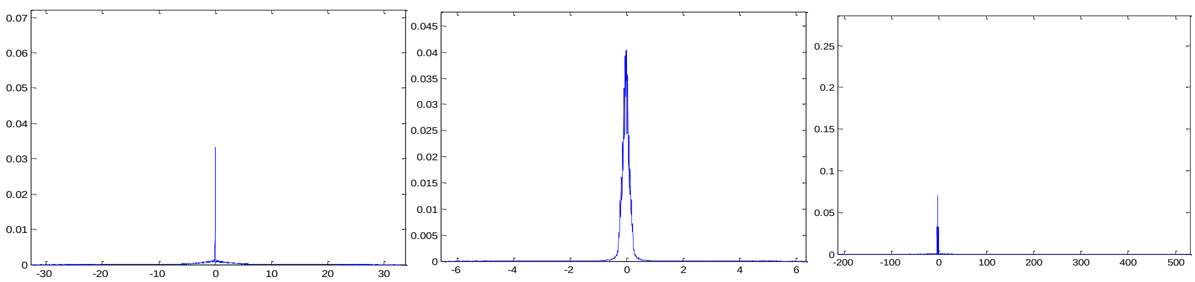

Figure 2: PDF plots of random, sine and shock tests

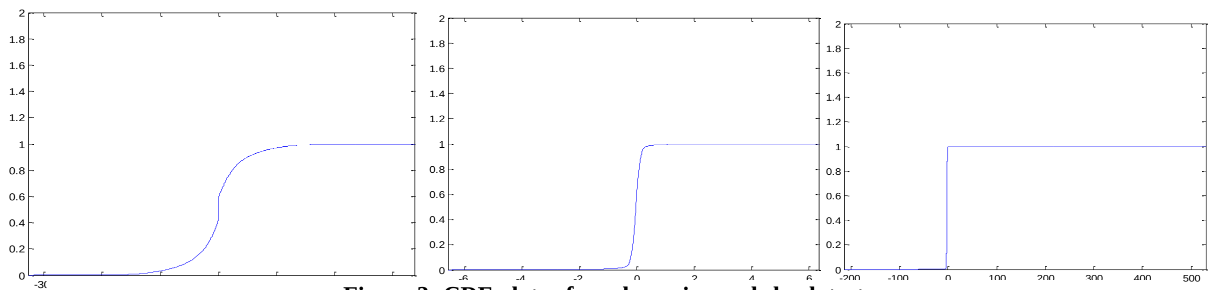

Figure 3: CDF plots of random, sine and shock tests

3. OBSERVATIONS

The analysis of satellite vibration test data signals provides wealth of information about the data. It indicates nature of the data, dispersions, variations, distributions, etc. From the experimental results, following observations are made about satellite vibration test data.

- The range of values for random test data is one order above that of sine test data and is one order below that of shock test data.
- The mean of the acquired data of sine and random tests are about -0.01 and that of shock is -2.58. This is because the distribution of the data values for sine and random about 'zero' is almost symmetrical and it is not so in case of shock data.
- Mean square values and root mean square values indicate that the degree of variation is high in the case of random data and is low in case of sine data compared to that of shock test data.
- The dispersion of data values about the mean, indicated by standard deviation is high in case of random and low in case of sine data compared to that of shock test data.
- The skewness of random and sine test data is almost zero i.e. the data values are evenly distributed on both sides of the mean. But, shock test data has very high skewness value of about 167, which indicates that most of the values lie to the right of the mean.
- Shock test data has the transient behavior because of its nature and hence has very high value of kurtosis (about 50000), where as random and sine test data have nominal values of kurtosis.
- Frequency distribution, PDF and CDF plots of random, sine and shock test data indicates that majority of the values lie in the vicinity of zero. This is due to the fact that though the test duration of random and sine test is one or two minutes and few milliseconds in case of shock test, data is acquired before the start of test and continues after the completion of the test. Hence significant number of samples represents noise which has the value about zero.

4. INFERENCES

Form the observations made in the previous section, following inferences are made.

- Each of the test data is unique. It is proposed to look for suitable algorithm for compression of each of these data sets independently.
- It is also proposed to discard the data samples that are stored before actual start of the test and after the the end of test, as they do not carry any information about the test. This will improve the efficiency of the compression algorithms to a large extent.
- As the mean of the sine and random data is almost zero, and the original plots of the data indicates that the samples are normally distributed, it should be ensured that the transformation used in compression algorithm is suitable for normally distributed data.
- The values of random and sine test data is found to oscillating above and below the zero value throughout the test duration and hence Fourier transform based compression algorithm is more suitable. Shock data is transient in nature and the efficient compression can be obtained by adopting wavelet based compression algorithms.
- As each of the three data sets has unique characteristics, it is also proposed to incorporate algorithms such as using Karhunen–Loève transform which results in data based compression techniques.

5. CONCLUSION

From the observations and inferences made in this work, it can be concluded that each of the three sets of satellite vibration data is unique. Therefore, it is essential to choose/develop a suitable algorithm for compression of each these data sets independently. It is also proposed to discard the data samples that are stored before actual start of the test and after the the end of test, as they do not carry any information about the test. This will improve the efficiency of the compression algorithms developed for satellite vibration test data..

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