ABSTRACT

This paper demonstrates the use of the Hilbert-Huang Transform (HHT) to analyze and eliminate error in bridge sensor data. The use of HHT is an attempt to improve data analysis, and subsequently improve prediction modeling in Bridge Management Systems. HHT combines two major analytical theories: Empirical Mode Decomposition (EMD) and the Hilbert Transform. HHT can be used to decompose natural data into independent Intrinsic Mode Functions (IMF) using the theories of EMD. Furthermore, HHT employs Hilbert Transform to determine instantaneous frequency and amplitude, and therefore can be used to accurately describe the local behavior of signals. HHT was used to analyze and filter disturbances caused by sensor noise and vibrations in data collected from the Ashland Bridge in Delaware.

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I. INRODUCTION

Currently, 40% of the nation's 600,000 bridges are classified as deficient and replaceable [8]. The combination of the need to rehabilitate and rebuild the nation's deficient bridges and the Intermodal Transportation Efficiency Act of 1991, has focused the nation's Departments of Transportation (DOT) on ways to improve their Bridge Management Systems (BMS) [4]. Previously many DOT had no BMS, and therefore there is a great need for development. Bridge management much like other management systems consist of three major steps: planning, control, and monitoring.

The first step of bridge management, *planning*, is broken into two levels: the network level, which includes non-technical standard setting and budgeting, and the project level, which includes more technical work such as design. The next step is *control,* which in many cases is provided by Quality Control/ Quality Assurance (QC/QA) testing preformed by the contractor and owner. The final post-construction step, *monitoring,* includes data collection and analysis [2]. This by far is the longest and most intensive step of BMS given that it involves the entire 50-75 design life of a bridge. Moreover monitoring is a significant step when considering the future preservation or rehabilitation of the bridges, in which case the cycle begins again.

Recently, many methods such as the Health Index (HI), which ranks bridge members based on previous inspections, have been used to monitor and have made improvements in the rating and inspection of bridges [4]. Unfortunately, visual inspection can be subjective and labor-intensive, and its infrequency fails to provide immediate notification of structural problems. For these reasons there has been a shift towards automated inspections using sensors and analysis software such as Pontis and BRIDGIT. Sensors have proven to be valuable resources due to the large amounts of data created to describe the "complexity of the structural response of a bridge in service and in predicting potential problems [8]."

As the use of sensors for structural data collection has become more prevalent, there has been a larger need for reliable analysis tools. Although extremely beneficial, because of their sensitive nature, sensor data many times can be distorted by things such as noise, vibrations, and other non-loading occurrences. One such case occurred with the Newburgh Beacon Bridge in New York, where in less than two months sensors recorded

nearly a thousand stress peaks of up to 40 ksi in critical members. It was later determined that the peaks were not due to extreme loading or residual stresses as thought, but to electromagnetic interference occurring around the bridge. In this case inaccuracies in the sensor data collected could have caused unnecessary expenses to the NYSDOT [9].

II. HILBERT -HUANG TRANSFORM (HHT)

There have been two prominent methods applied to the analysis of bridge data: the Hilbert Transform and Empirical Mode Decomposition. All of these methods have has an effect on the development of a new analysis tool, the Hilbert- Huang Transform.

Hilbert Transform

The Hilbert method can be used to transform a solely time-dependant function, X(t), into a time-frequency function, Y(t). Y(t) is simply a shift of X(t), and therefore has the same amplitude A(t). Both the amplitude and new phase, Φ(t), are dependant on time and so can be described in terms of X(t) and its transform:

$$A(t) = \sqrt{X^2(t) + Y^2(t)}$$

$$\Phi(t) = \tan^{-1}\left(\frac{Y(t)}{X(t)}\right)$$

The derivative of the phase describes the instantaneous frequency of Y(t), f(t) [7]. This frequency, unlike the Fourier Series, can be used to describe the local behavior of data.

$$f(t) = \left(\frac{1}{2\pi}\right)\frac{d\Phi(t)}{dt}$$

The Hilbert method also makes it possible be display the data in a time, energy (microstrain), frequency diagram or spectrogram [6]. This can be used to better understand the energy flow in a bridge and at what frequency events occur.

Empirical Mode Decomposition (EMD)

Also unlike the Fourier method, Empirical Mode Decomposition can be used to analyze data which is neither linear nor stationary. EMD decomposes complicated functions into independent polynomial and sinusoidal components referred to as modes, or intrinsic mode function (IMF). There are two major properties that all IMF have "(a)

the number of extrema is and zero-crossings must be either equal or differ at most by one; (b)… the mean value of the envelope defined by the local maxima… and minima is zero [5]." The IMFs of a function are determined by a process called shifting. Shifting involves the enveloping and repeated subtraction of the local mean, m_n (where *n* is the number of shifts), from the original data, X(t), until the new local mean of residual, r_n, is inconsequential in comparison to the original data. After shifting, the summation of all of the IMF and the residual should return the original data.

Step 1. Envelope the original data, X(t). The envelope is determined by the maximum and minimum of X(t).

Step 2. Determine the local mean, m_0.

Step 3. Subtract the mean from the data to determine the first IMF, h_{1n}. Then determine the first residual value, r_1.

$$h_{1k} = X(t) - m_0$$

$$r_1 = X(t) - h_{1n}$$

Step 4. Repeat until final IMF, h_{nk}, is found. The summation of the IMF and residual should return the original data.

$$X(t) = \sum h_{1\text{-}nk} + r_n$$

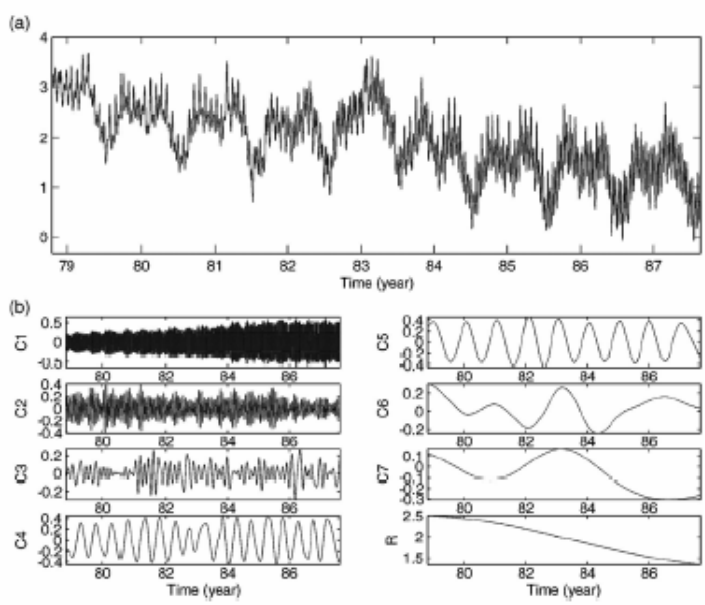

Figure 1. MF Decomposition (Vatchev, 2002)

Hilbert- Huang Transform (HHT)

In 2000, a new analysis tool was patented through NASA. This new method, called the Hilbert- Huang Transform (HHT), combined the theories of both of EMD and the Hilbert method [3]. It was found that this combination could be used to filter disturbances from non-stationary signal data and has been applied successful in aeronautics, biology, physics, and many other fields. This method was beneficial because it not only can find the varying components of the data using the theories of Empirical Mode Decomposition, but could be used to create Hilbert spectrograms. With collaborations with NASA, HHT software was developed as a "Computer Implemented Empirical Mode Decomposition."

III. DATA ACQUISITION AND ANALYSIS

In-Field Testing

June 24, 2003 microstrain data was collected from through girder bridge number 119 on State Route 82 over Red Clay Creek in Delaware using the self contained Structural Testing System by Bridge Diagnostic Inc (BDI-STS). The system consists of foil strain transducers to be mounted and adhered to the bridge, a power supply, and a PC for data recording [1]. Twenty sensors were placed in varying locations along on the girders and floor beams to collect microstrain data during the six tests performed using two loaded trucks. This research analyzed the data from Tests 3-6. Tests 3 and 6 involved two trucks following each other at 5 and 35 mph respectively. Tests 4 and 5 entailed the two trucks simultaneously driving down both lanes at 5 mph.

Figure 2. Bridge Diagnostic Inc Structural Testing System (BDI-STS)

Description of Trucks

Truck #	Weight (lbs)
2750	58,110
2873	58,470

Description of Test

	Run	Speed(mph)
Test 3	2 trucks, center, one at a time	5
Test 4	2 trucks, both lanes, simultaneously	5
Test 5	2 trucks, both lanes, simultaneously	5
Test 6	2 trucks, center, one at a time	35

Figure 3. Description of Trucks and Tests 3-6

Data Analysis Using HHT Software

After testing, the microstrain readings collected from the sensors were converted into text files to be inputted into the HHT software, WinHhtP. According to specifications set by the operator, WinHhtP then performed a series of extrema shifts. The program's output displayed the number of IMF components needed for the shift process and the numerical interpretation of these components. This output file was then be used to plot the separate components using MATLAB 6.5. The spectrum data is also plotted using MATLAB and HHT code.

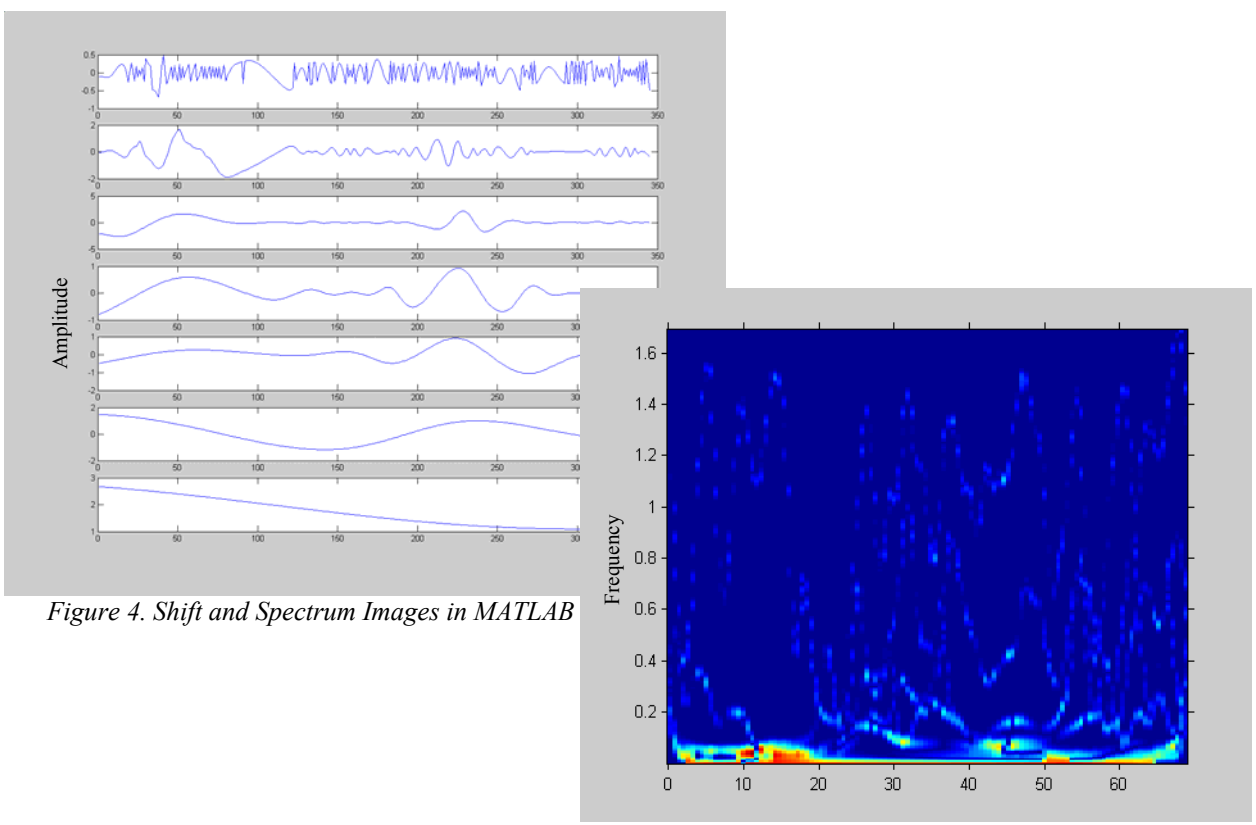

Figure 4. Shift and Spectrum Images in MATLAB

Discussion of Results

Test 3, Sensor 306

Figure 5 displays data collected during Test 3 from the bottom girder Sensor 306. There are two distinct stress peaks as expected, but a large amount of fluctuation along and between the peaks, and after the trucks have passed. During these times it is assumed that the stress is negligible. Due to the magnitude of the trucks and their weights it is understandable that large amounts of disturbance in the form of vibrations are caused within the bridge. There is also a large amount of noised cased in the sensor as it tries to adjust its reading during the passes. Both of these disturbances can be removed using HHT analysis.

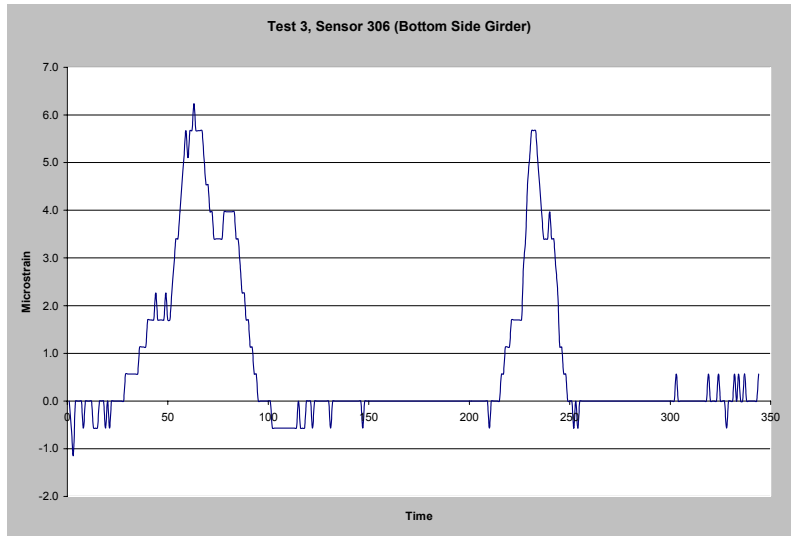

Figure 5. Test 3, Sensor 306

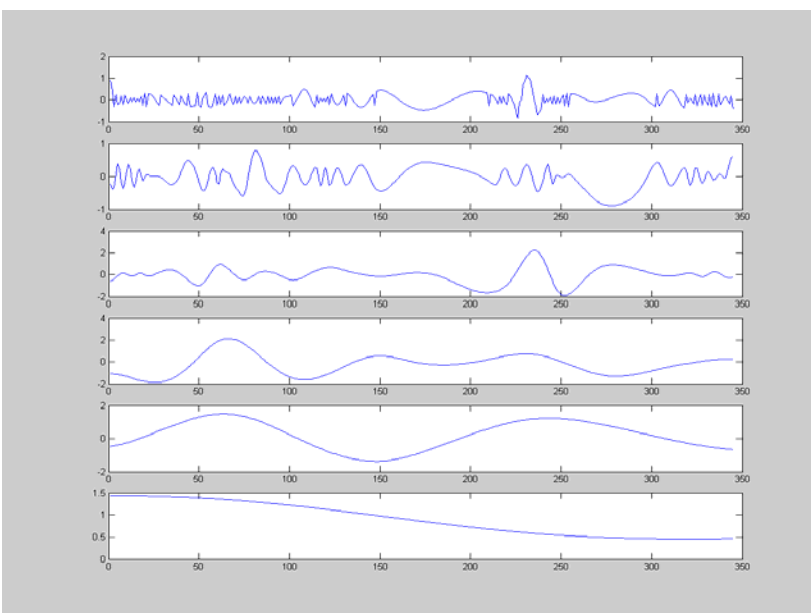

Figure 6. IMF components of Test 3, Sensor 306

Upon viewing the six IMF (Figure 6) components of the original data it appears that IMF 3-6 have a better correspondence with the overall microstrain data collected. From observing the behavior if IMF 1 and 2 it can be concluded that these components are due to a

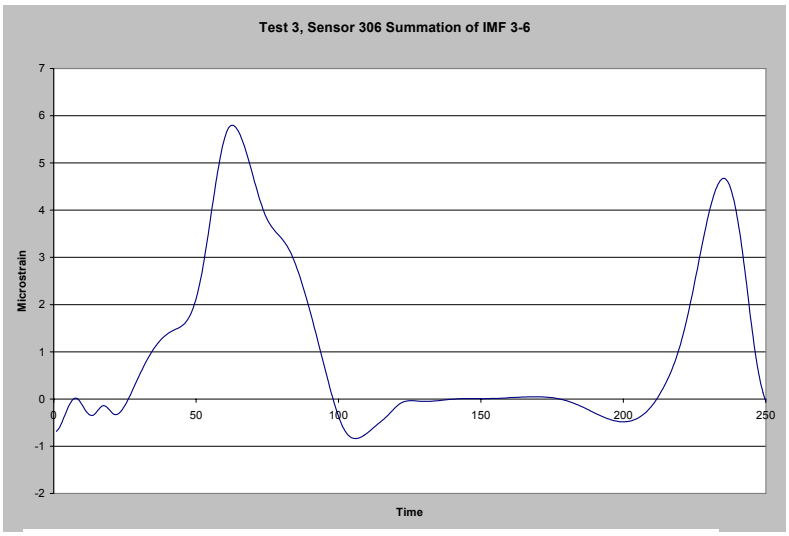

Figure 7. Test 3, Sensor 306 Summation of IMF 3-6

constant disturbance that exists in the testing environment and not due to any loads applied to the bridge. From this knowledge it would be acceptable to assume that IMF 3 through 6 are the true components of stress collected by the sensor.

Figure 7 displays the summation of IMF 3 through 6. Eliminating IMF 1 and 2, has drastically decreased the disturbance in the data. Comparing the maximum stress found in the raw data (6.2 με) and the summation of IMF 3 through 6 (5.8 με), an error of approximately 6.5% was determined.

Test 6, Sensor 350

Comparing the original data in Figure 8, to its seven IMF components (Figure 9), it becomes apparent that the disturbance in the sensor data was captured in IMF 1 and 2. From observing its behavior, it can be deduced that IMF 1 depicts the vibrations in the bridge. As the trucks pass over the bridge the signal's magnitude and frequency both increase, and after the trucks pass slight damping can also be seen. This is

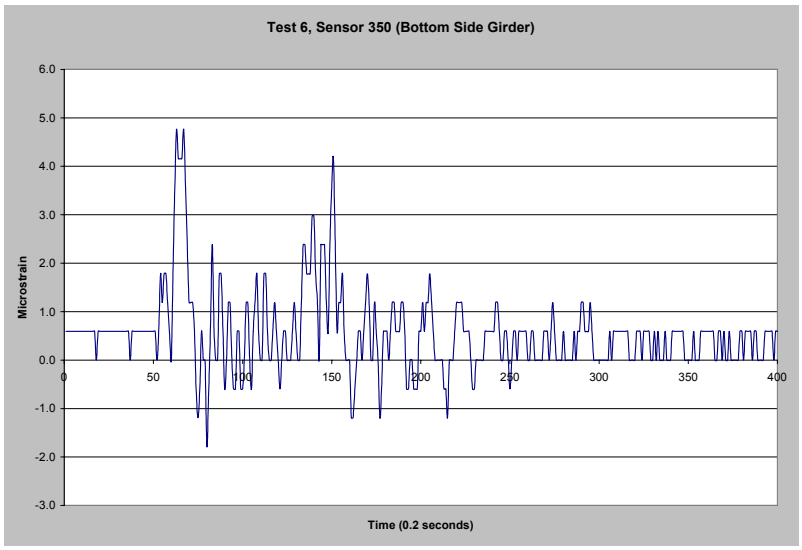

Figure 8. Test 6, Sensor 350

understandable when considering the speed (35 mph) at which the trucks were driving. In this case, large amounts of noise (captured in IMF 2) and vibrations would be caused in the bridge. Vibrations can cause strains in the bridge, but with the use of HHT, the user can eliminate the components of strain due to vibration and observe the bridge's reaction solely to live loading.

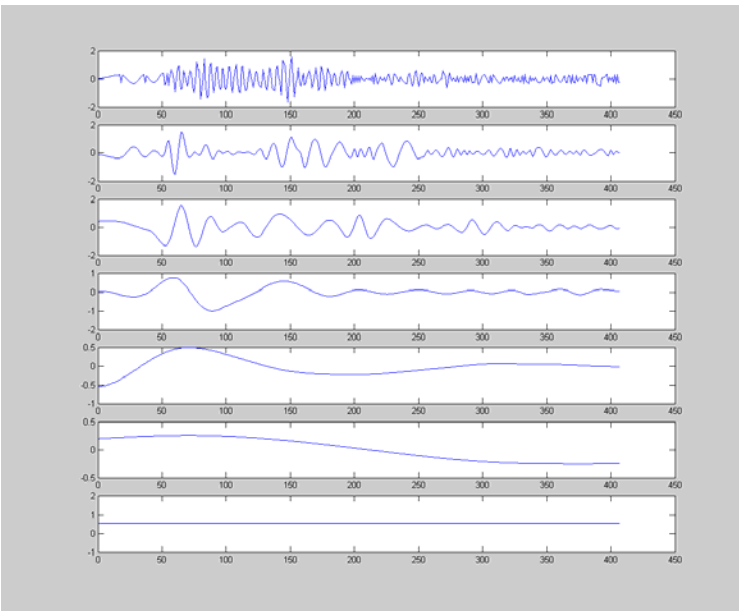

Figure 9. IMF Components of Test 6, Sensor 350

Figure 10 depicts the summation of IMF 3 through 6. The new summation shows a dramatic decrease in disturbance, and the stress peaks are relatively more visible. The maximum strain determined from the original data was 4.7 με. The new summation of IMF 3-6 produced a maximum strain of 2.9 με. This yields an error of 38%. This large error is believed to be indicative of the error generated in sensor data during dynamic loading due to vibrations and noise.

Test 6, Sensor 316

The two previous examples displayed strains of low magnitudes, but HHT can also be applied to data of large magnitudes. During Test 6, Sensor 316 (center bottom girder) recorded stains up to 90 με. Larger magnitude data, unlike the previous examples, have peaks far out of the

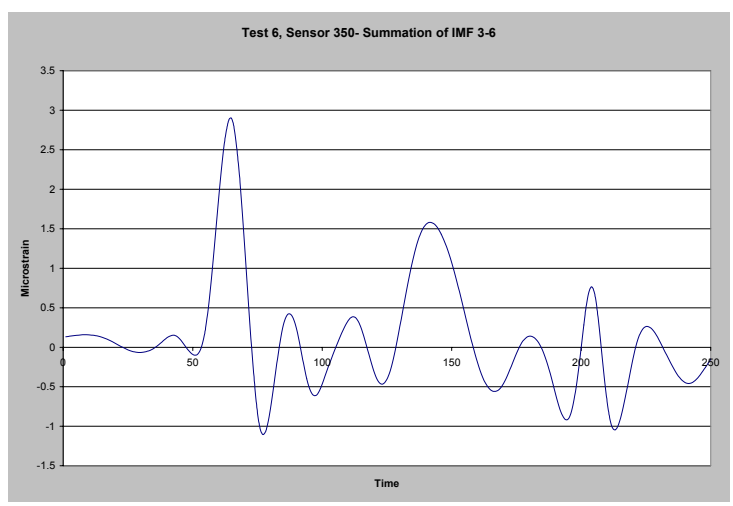

Figure 10. Test 6, Sensor 350- Summation of IMF 3-7

noise range, and therefore it is interesting to observe the effects of subtracting disturbance IMF. The magnitude of this data allows for more variability by allowing the user through trial and error to decide which components to eliminate. Figure 11 shows the data collected

by Sensor 316, and two summation options. The summation of IMF 2-7 returns a curve very close to the original data. On the other hand, the summation of 3-7 returns a much different option. In this case, much of the disturbance between the stress peaks are eliminated, but there is also, as experienced with the previous data, (Sensor 350) a significant decrease in the peak stress found.

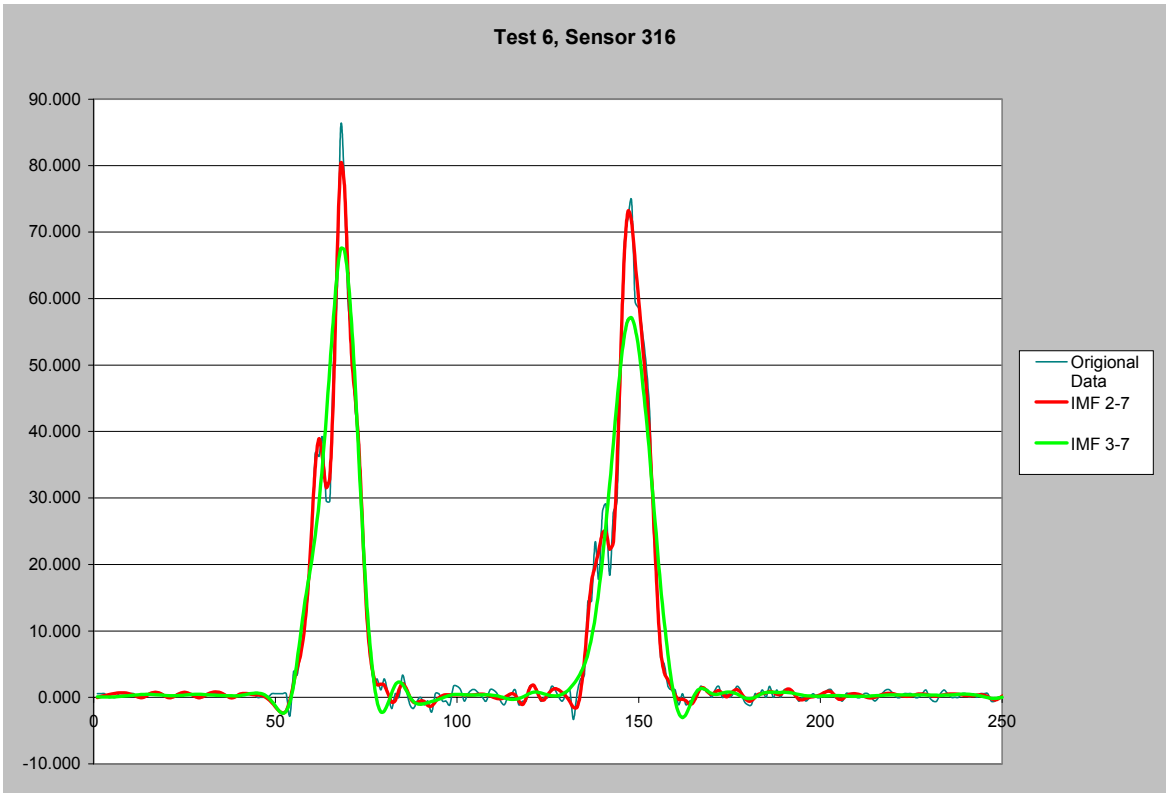

Figure 11. Test 6, Sensor 316- Comparison of Various Summations

IV. CONCLUSION

One of the Hilbert-Huang Transform most useful tools is its flexibility. It can be used to remove noise caused by sensor fluctuations, vibrations caused during dynamic testing, or data picked up from outside frequencies. It can also be used to analyze vibrations in the bridge that can cause strain, and distinguish this from the bridges direct response to live load. The Hilbert-Huang Transform has proven a useful analytical tool in a variety of fields and can now be applied to the analysis of bridge sensor data. Its decomposition tools can be used to produce more accurate data, enabling users to make more informed decisions regarding the future of bridges.

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