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Correlating Spectral Measurements

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ABSTRACT
In a recent paper [3], we introduced a new metric for comparing two operating .deflection shapes called the ***Shape Difference Indicator (SDI)***. In another previous paper [4], we used SDI to measure the difference in modal frequencies resulting from a joint stiffness change in a mechanical structure.

In this paper we use SDI in two new ways. In the first application, SDI is used to ensure that a repeatable impact is applied to a structure during a Roving Response ODS or Modal test. In the second application, SDI is used to measure the difference between ***currently acquired and Baseline*** Auto spectrum measurements over prescribed frequency bands.

We have implemented SDI together with a search method for ranking ***currently acquired and archived data*** based upon their numerical differences. We call this new method Fault Correlation Tools (FaCTs™). FaCTs™ is useful in multiple applications, including route-based machine condition monitoring, structural health monitoring, production qualification testing, machinery recertification following scheduled maintenance, and noise & vibration monitoring in public places such as building construction sites to comply with local ordinances.

KEY WORDS
Fourier spectrum (FFT)
Auto power spectrum (APS)
Cross power spectrum (XPS)
Frequency Response Function (FRF)
Operating Deflection Shape (ODS)
Modal Assurance Criterion (MAC)
Shape Difference Indicator (SDI)

INTRODUCTION
SDI has been previously used for correlating two complex shapes, either ODS's or mode shapes [2],[3] It was also used for correlating shapes with modal frequencies as their shape components to detect and quantify joint stiffness changes [4]. In this paper, SDI will again be used to measure the difference between two shapes, but in a different sense. SDI will be used to measure the difference between multiple FRFs, and also to measure the difference between multiple Auto spectra in several frequency bands.

In its first application, SDI will be used to compare three reference FRF measurements with three **Baseline FRFs**. This comparison is done at the same frequency in the two blocks of measurements. An ODS is defined as structural deflection at a single frequency sample. Therefore, we have named this comparison of two blocks of data **ODS Correlation**,

ODS Correlation can be used throughout a Roving Response Impact test to ensure that the structure is impacted at the same impact location & direction, (degree-of-freedom or DOF). ODS Correlation can also be used to ensure that removable sensors are attached at the correct DOFs during a route-based condition-monitoring program.

In its second application, SDI is used to measure the difference between pairs of Auto spectra in multiple prescribed frequency bands. We call this comparison **Measurement Pairs Correlation**. Rather than use the conventional approach of comparing peak spectrum values with handbook values, Measurement Pairs Correlation numerically compares the ***"shape"*** of an Auto spectrum in a frequency band with the ***"shape"*** of another Auto spectrum with a matching DOF in the same frequency band.

Measurement Pairs Correlation will be used to correlate a block of **Baseline Auto spectra** with blocks of currently acquired Auto spectra thus creating a table of SDI values. FaCTs™ will then be applied to the archived SDI values to indicate a change in the operating condition of a rotating machine, and to identify a pre-defined unbalance condition in the machine.

REVIEW OF MAC AND SDI
SDI is similar to MAC, which was originally developed to provide a numerical comparison between two mode shapes [5]. Like MAC, SDI is a ***correlation coefficient*** with values that range between 0 & 1. A value ***equal to 1*** indicates no difference between two shapes. A value ***less than 1*** indicates that two shapes are different.

The mathematical formulas utilized by these two metrics were presented in a previous paper [3]. Both are briefly reviewed here to point out their differences.

MAC was developed as a metric for correlating two mode shapes [5]. SDI was developed for a similar purpose, but it has different properties.

1. MAC indicates the ***co-linearity*** of two shapes. If two shapes lie on the same straight line, MAC=1
2. MAC cannot measure the difference between two numbers. MAC=1 if two shapes have only one component

Summarizing the MAC properties, if **MAC=1,** then two shapes lie on the same straight line. If **MAC<1,** then two shapes do not lie on the same straight line

In contrast to MAC, if **SDI=1,** then two shapes have ***identical shape components***. If **SDI<1,** then two shapes have ***different shape components***. Several examples illustrate typical SDI values between two shapes **{A}** & **{B}**.

- If {A}={B}, SDI=1

- If {A}={0} *or* {B}={0}, SDI=0
- If {A}=2{B}, SDI=0.64
- If {A}=10{B}, SDI=0.04

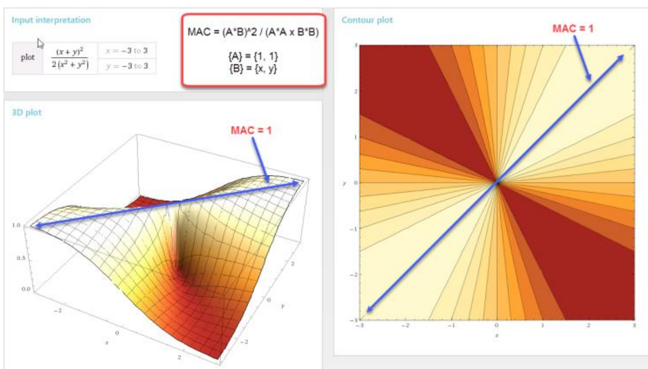
Figure 1 is a plot of MAC for two shapes **{A}** & **{B}**. It shows that if vector **{B}** has values that ***lie anywhere along the line*** defined by vector **{A}={1, 1}**, then MAC has a value of **"1"**.

Figure 2 is a plot of SDI for the same two shapes **{A}** & **{B}.** It shows that there are ***only two values*** of vector **{B}** where SDI has a value of **"1"**; **{B}={1, 1}** and **{B}={-1, -1}.**

SDI has two unique properties, which make it more useful for measuring the difference between two vectors.

1. SDI=1 under only two conditions, when B= +-A
2. SDI can measure the difference between ***two scalars (two numbers)***

For these reasons, we will use SDI as the preferred metric for quantifying the ***difference between two "shapes"*** (or ***vectors***) of spectral data.



It Figure 1. MAC plot of Shape {A} vs. Shape {B}

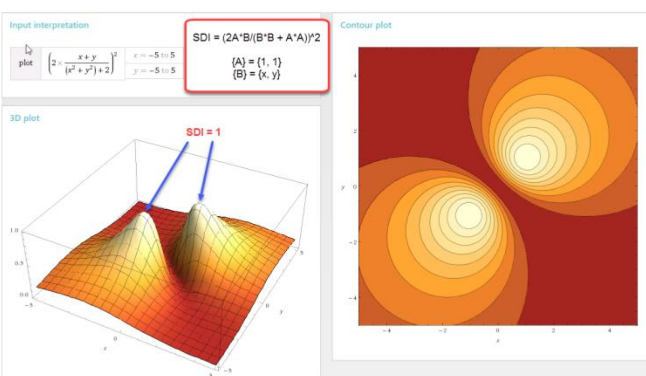


Figure 2. SDI plot of Shape {A} vs. Shape {B}

TWO TYPES OF MEASUREMENT CORRELATION

SDI can be used to measure the difference between two sets of spectrum measurements at ***a single frequency,*** or it can be used to measure the difference between a pair of spectra over a band of frequencies. We call the first type of correlation **ODS Correlation**, and the second type **Measurement Pairs Correlation**.

ODS Correlation

Two (or more) spectral measurements can be correlated by measuring the difference between their values, ***sample by sample***. We call this type of correlation **ODS Correlation** because the values at any frequency sample in a set of experimental Cross spectra, FRFs, or ODS FRFs can be displayed on a model of the test article as an ODS, (or deformation shape) of the structure at that frequency.

In **ODS Correlation**, an SDI value is calculated ***for each frequency sample*** in the band over which two blocks of measurements are compared. An example is shown in Figure 4.

Measurement Pairs Correlation

In Measurement Pairs Correlation, SDI is used to measure the difference between a pair of spectral measurements ***over a band of frequencies.*** The pair of spectra is assumed to have been calculated from data taken at the same DOF on the machine or structure.

- If two spectra have the ***same value*** at each sample in a band of frequencies, then SDI=1
- If two spectra have ***different values*** at each sample in a band of frequencies, then SDI<1

SDI measures the difference between the ***"shapes"*** of the two spectra, over the same band of frequencies.

MAC has also been used to measure the difference between two FRFs, and has therefore been called the **Frequency Response Assurance Criterion** (or **FRAC**),

If two blocks of spectral measurements with matching DOFs are correlated, a table of SDI values is created, with one SDI value for each matching pair. Each SDI value is a measure of the difference between the values of a spectrum in one block versus the values of the spectrum with a matching DOF in a second block, over the same band of frequencies.

REPEATABLE IMPACT

Like MAC and Coherence, SDI has values between 0 & 1. Like both of these other metrics, SDI can also be used as part of a testing procedure to insure that repeatable measurements are being made.

A popular way to perform an ODS or Modal test on a machine or structure is to test it using an instrumented impact hammer, a tri-axial accelerometer, and a 4-channel acquisition system. This is also called a ***"bump test"*** when it is done on an operating machine.

Impacting a structure is a good way to excite its resonances because the impact force will excite a broad band of frequencies. There are two ways to perform an impact test.

Roving Impact Test

This is the most popular type of impact test. In this test, the accelerometer is attached at a single point, and a different DOF is impacted with the hammer for each acquisition of data

Roving Response Test

In this test, the structure is ***impacted at the same DOF***, and the response sensor (for example, a tri-axial accelerometer) is moved to a new point prior to each acquisition of data.

The advantage of a Roving Response test is that if a tri-axial sensor is used, 3D ODS's and mode shapes can be obtained from the data. In other words, the ***3D deformation of the structure*** at each Roving Response point is obtained at each frequency.

To obtain a valid set of measurements from a Roving Response test, the structure ***must be impacted at the same DOF*** throughout the test.

Impact Repeatability Check

ODS Correlation can be used during a Roving Response test to insure that the structure is ***always impacted at or near same DOF***. Using another ***(fixed) reference*** accelerometer, an impact Repeatability Check involves the following steps;

1. Attach the **reference accelerometer** anywhere on the structure. The accelerometer can be uni-axial or tri-axial,
2. Impact the structure at the fixed DOF chosen for the Roving Response test, and calculate one or more **Baseline FRFs** between the impact DOF and the DOFs of the reference accelerometer.
3. During the Roving Response test, each time an FRF is calculated between the impact DOF and the Roving Sensor, also calculate one or more **Repeatable FRFs** between the impact DOF and the reference accelerometer.
4. Calculate and display the **ODS Correlation** between the **Repeatable FRFs** and the **Baseline FRFs**.

To illustrate a Repeatability Check, a tri-axial accelerometer was attached as a **reference accelerometer** to the beam structure shown in Figure 3. The beam was then impacted with an instrumented hammer at Point 1, and three **Baseline FRFs** were calculated between the impact force and the three responses of the **reference accelerometer**. These three **Baseline FRFs** were the result of impacting the structure at Point 1.

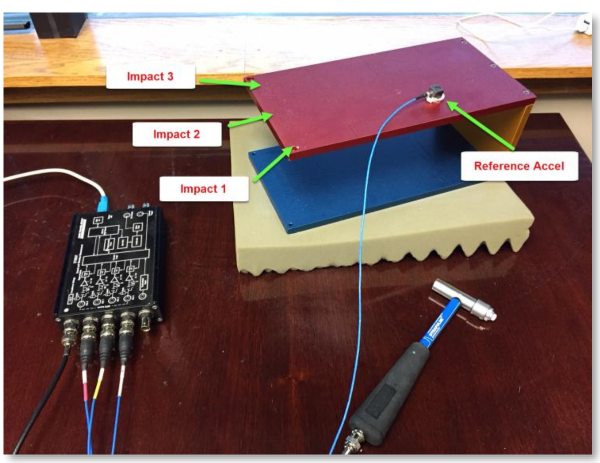


Figure 3. Repeatability Check

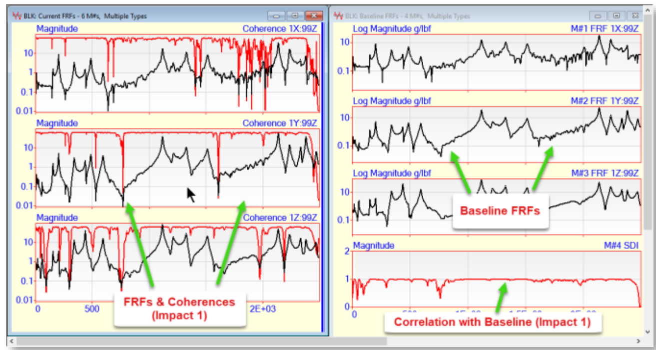


Figure 4. Impact 1

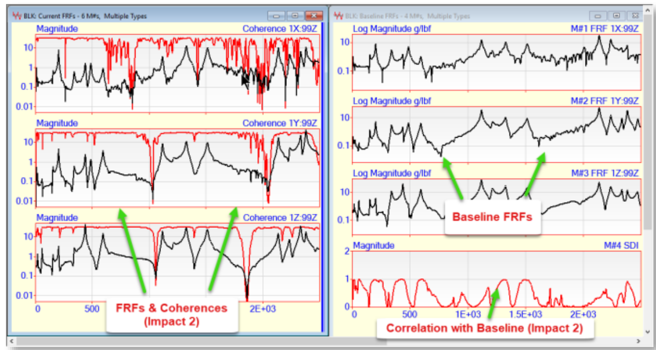


Figure 5. Impact 2

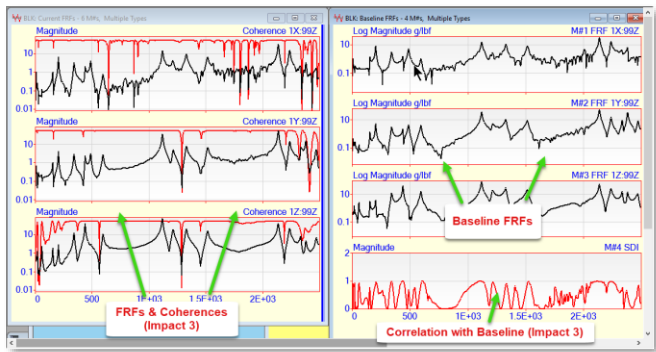


Figure 6. Impact 3

Figure 4 shows the results of impacting ***at or near*** Point 1 a second time. The FRFs and Coherences from the second impact measurement are shown on the left, and the Baseline FRFs and **ODS Correlation** are shown on the right.

In Figure 4, the **ODS Correlation** (SDI values) with the Baseline FRFs is ***close to "1"*** for most of the frequencies. This means that the second set of FRFs was calculated from data that resulted from an impact applied ***at or near*** Point 1.

The results of impacting at Points 2 & 3 are shown in Figures 5 & 6 respectively. Notice that in both cases, the ODS Correlation is ***less that "1"*** for many frequencies. Those FRF measurements ***did not correlate well*** with the Baseline FRFs at the frequencies with low SDI values. Of course this is expected since those impacts were not applied ***at or near*** Point 1.

Notice however that some ODS Correlation values are ***close to "1"*** for some frequencies in Figures 5 & 6. This means that the FRFs calculated from impacting at Points 2 & 3 ***did correlate well*** with the Baseline FRFs at some frequencies. At those frequencies where the ODS Correlation values are ***close to "1"***, it can be assumed that the structural response is ***dominated by resonances*** that have mode shape components similar in value to the mode shape components in the Baseline FRFs.

CORRELATING AUTO SPECTRA

In this second application, Measurement Pairs Correlation is combined with the FaCTs™ search method to indicate both a change in the operating condition of a rotating machine, and to identify a know unbalance condition in the machine.

To illustrate the combined use of **Measurement Pairs Correlation** and FaCTs™, ***four Auto spectra*** were calculated from two tri-axial accelerometers mounted on the bearing blocks of the rotating machine trainer shown in Figure 7.

Figure 7. Rotating Machine Simulator

A 4-channel acquisition system was used to acquire the accelerometer data, and only the horizontal (X) and vertical (Z) vibration signals were acquired from the machine. The axial (Y) direction was not acquired. The model in Figure 8 shows the horizontal (X) and vertical (Z) measurement directions of the two accelerometers attached with magnets to the two bearing blocks.

Baseline Auto Spectra

A Baseline set of Auto spectra was calculated from data that was acquired while the machine was operating in a balanced condition. In a machine condition mentoring program, these Baseline measurements would be archived in a database.

The four Baseline Auto spectra are shown in Figure 9. Several order-related peaks are evident in the spectra.

The large peak at 1984 RPM is the first-order peak, or rotor speed of the machine. This peak ***is dominant*** in the horizontal (X) direction on both bearing blocks. The second large peak is ***close to*** a third-order peak, but is actually the

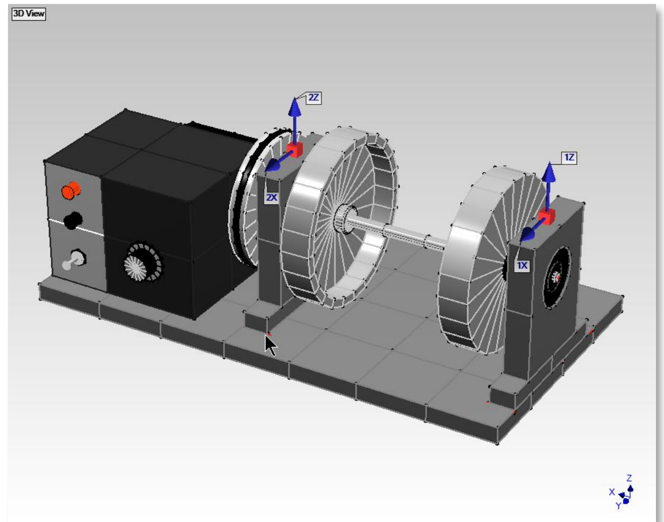


Figure 8. Model Showing Four Measurement Directions

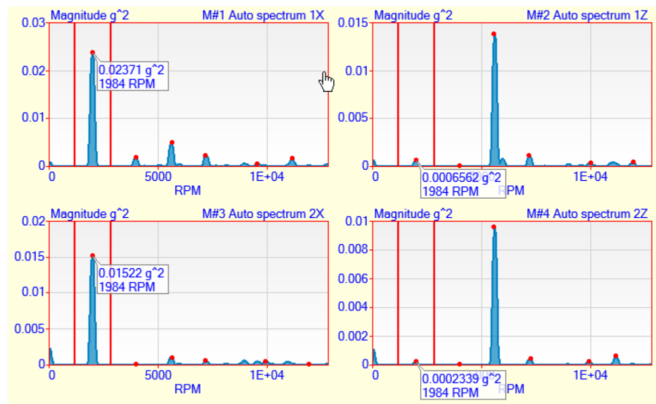


Figure 9 Baseline Auto Spectra

motor speed, which is ***2.85 times*** the rotor speed. This peak ***is dominant*** in the vertical (Z) direction on both blocks.

Measurement Pairs Correlation was used to measure the difference between the four Baseline Auto spectra and a ***current set*** of Auto spectra over three different frequency bands***, each band enclosing an order peak.*** Each band was ***1000 RPM*** wide.

Applying Measurement Pairs Correlation over three frequency bands of spectrum data would typically be used to identify machine faults that manifest more quickly as changes in and around the frequencies of higher machine orders.

Measurement Pairs Correlation yields a table of SDI values, one for ***each frequency band***, and ***each pair of Auto spectra with matching DOFs***. Each time a new set of data was acquired from the rotating machine and post-processed, another table of SDI values was archived in an archival database.

FaCTs™ was used to correlate ***current tables of SDI values*** with a ***Baseline set of SDI values***. Two different examples will illustrate the combined use of Measurement Pairs Correlation and FaCTs™.

Example 1. Machine Warm Up

In this example, the machine was started and a Baseline set of Auto spectra was calculated. The machine was allowed to run for a while and SDI tables measuring the difference between the current and Baseline Auto spectra were stored into the archival database. The results are shown in Figure 10.

The trend plot shows the SDI values decreasing as new data is acquired, indication that the four Auto spectra are changing relative to the Baseline Auto spectra. Each time new data is acquired, a new set of SDI values appears on the right side of the trend plot.

For this case a ***Baseline table of SDI values*** was also saved in the database when the machine was started. As the machine warms up, the FaCTs™ bars in Figure 10 have all dropped below a ***value of "1"***, indicating that the SDI values for all three frequency bands of Auto spectrum data have undergone a change relative to the Baseline Auto spectra.

The three FaCTs bars clearly indicate that the operating condition of the machine has changed. The change can be attributed to a warming of the belt between the motor and the rotor causing belt slippage. The warm up caused the order peaks (rotor vibration caused by the motor) to ***migrate in their frequency bands***. When correlated with its matching Baseline Auto spectrum, the peak migration in each current Auto spectrum caused a drop in the SDI value for each frequency band.

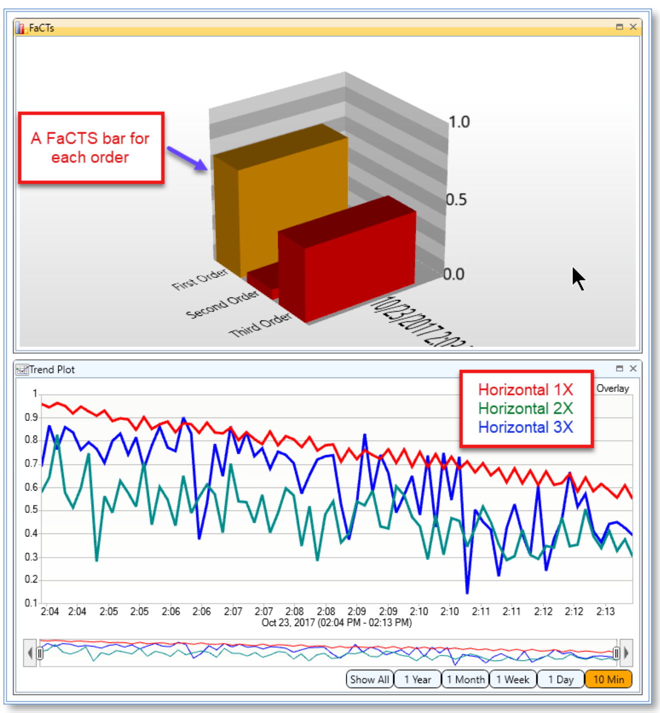


Figure 10 FaCTs and SDI Trend During Warm up.

Figure 11 shows the FaCTs™ bars and SDI trend plot ***after new Baseline spectra*** and ***new Baseline SDI values*** have been calculated. With new Baselines, the FaCTs™ bars return to values that are ***close to "1".***

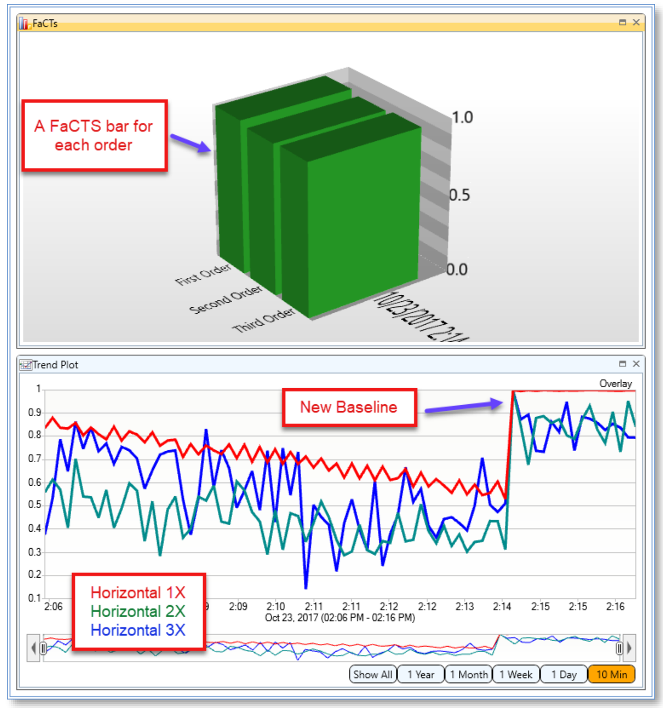


Figure 11 FaCTs and SDI Trend After a New Baselines

Example 2 Unbalance

In this second example, a small unbalance weight was added to the outboard rotor, and Auto spectra were again calculated from the vertical & horizontal acceleration data acquired from the two bearing blocks. Measurement Pairs Correlation was used to correlate the Auto spectra ***after the unbalance weight was added*** with Baseline Auto spectra from ***before the weight was added***.

The trend plot of SDI values in Figure 12 has much lower values in it, indicating that the unbalance caused the Auto spectra in all three frequency bands to be substantially different than the Baseline spectra of the balanced machine.

Three events are marked with vertical lines in the trend plot. They were marked when the ***machine was in an unbalanced condition***. Three FaCTs™ bars were defined to correlate current SDI values with the three unbalanced machine events. The most current SDI values are displayed on the right side of the trend plot.

All three FaCTs™ bars are ***close to "1***" in value, clearly showing that the data currently acquired from the unbalanced machine ***strongly correlates*** with the three prior unbalance events.

CONCLUSION

Two new uses of the SDI metric were demonstrated in this paper. In the first application, it was shown how **ODS Correlation** can be used during a Roving Response Impact test to indicate that a repeatable impact is applied to the structure during the test. ODS Correlation values between three reference FRFs and three Baseline FRFs were used to indicate repeatability.

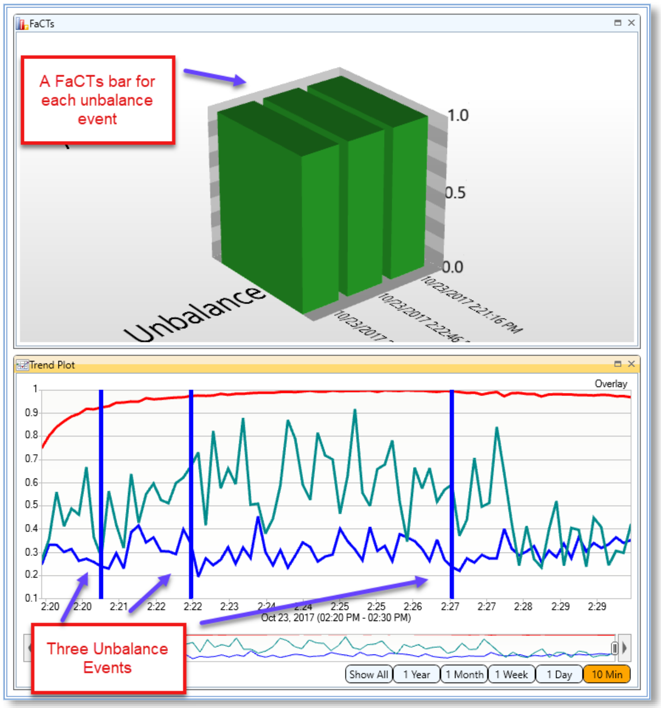


Figure 12. FaCTs Bars Identifying Unbalance.

The ODS Correlation calculation can be applied between any two sets of spectral measurements, containing any number of spectra.

In the second application, it was shown how **Measurement Pairs Correlation** was combined with the FaCTs™ database search method to indicate a changing operating condition in a rotating machine, and also to identify a previously defined unbalance condition in the machine.

Measurement Pairs Correlation was applied to four Auto spectra calculated from accelerometer data acquired from a rotating machine. Current Auto spectra where correlated with Baseline spectra in three different frequency bands. This correlation resulted in a table of 12 SDI values, one for each pair of spectra and each frequency band. Tables of SDI values were stored in an archival data base as the machine ran.

Three FaCTs™ bars were defined for correlating Baseline SDI values with current SDI values, for each frequency band. It was shown how the FaCTs bars indicated a slowly changing belt slippage condition due to warm up of the machine.

In the second example, three FaCTs™ bars were defined for correlating three marked unbalance events with current SDI data. In this example, FaCTs™ strongly correlated the current data from the unbalanced machine with the three prior unbalance events.

Measurement Pairs Correlation combined with FaCTs™ can be used in a number of route-based or continuous monitoring applications,

1. To indicate ***slowly occurring changes*** in the spectra of a machine or structure from monitored data
2. To ***identify specific mechanical faults*** which have been previously associated with data already stored in an archived database
3. In ***qualification testing*** were spectral measurements made on a test article are correlated with Baseline measurements to determine its ***pass-fail*** condition

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