New techniques and tools for efficient test setup and system verification

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Abstract

When performing vibration measurements, the setup time can be a significant part of the total test time. In particular, proper mounting of transducers on the test structure, connecting them to the measurement hardware and checking everything is working as expected can be quite time-consuming. Thus, to meet the ever-increasing demands for shorter test campaigns, addressing the test setup process is of paramount importance. This paper describes some of the challenges experienced by many experimentalists and presents new ways of overcoming them. It explains the technical background and the implementation of the Transducer Smart Setup tool, which can dramatically reduce the time required for the test setup and the Accelerometer Mounting Check procedure for checking the mounting state of transducers to ensure proper mounting conditions. The goal is to get data right first time and in the shortest possible time by providing robust algorithms and easy-to-use tools.

1 Introduction

The importance of simplifying the test setup preparation, reducing the measurement time and getting data right first time has been given increased focus in recent years to improve productivity and shorten time-to-market. Various techniques have been introduced and some of them are now considered standard in modern measurement systems. This includes TEDS support, PTP, PoE, Dyn-X and REq-X, all of which are briefly described below.

1.1 TEDS support

Transducers with TEDS (Transducer Electronic Data Sheet) contain information about their sensitivity, type number, serial number, manufacturer, calibration date, etc. When a transducer with TEDS is connected to an input module supporting TEDS, it is automatically detected and its data read into the measurement system. TEDS is specified in the IEEE 1451.4-2004 standard [1].

1.2 PTP and PoE

PTP (Precision Time Protocol) enables precise synchronisation of PTP devices on a network, for example, Ethernet. Synchronisation with sub microsecond accuracy can be achieved using hardware generated time stamps.

PoE (Power over Ethernet) is a technology that allows power to be transmitted on a standard CAT-6 LAN cable in an Ethernet network.

The combined use of PTP and PoE enables one-cable operation for data transfer, sample synchronisation between front ends and power supply [2], [3]. This makes it possible to drastically reduce the amount of cabling in distributed front-end setups by placing the front ends close to the measurement object. The length of the transducer cables can be significantly reduced and only a single standard LAN cable from each front end has to be connected to a LAN switch that again is connected to the measurement PC using a standard LAN cable.

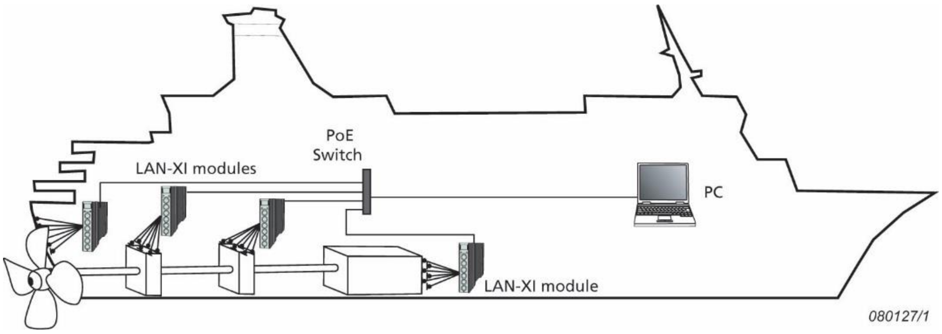


Figure 1: Using PTP and PoE, cabling can be drastically reduced for measurements on large structures.

The benefits are obvious and include reduced noise, low cable cost, faster setup and easier maintenance, less risk of setup and measurement errors, inexpensive LAN switches can replace expensive Patch Panels and there is no need for additional power outlets.

1.3 Dyn-X

With the introduction of Dyn-X (Dynamics eXtreme) technology, measurement systems, for the first time fully match or outperform the dynamic performance of high-quality transducers [4]. A Dyn-X input channel with a single input range has a useful analysis range of 160 dB narrowband and more than 125 dB broadband.

Dyn-X technology utilises a special analog input design to provide a very high dynamic range of the analog circuit, pre-conditioning the transducer signal before feeding it to the ADC.

A Dyn-X input channel has no input attenuators, but two input ranges: $10V_{peak}$ and $31.6V_{peak}$.

The digitising is performed synchronously in two specially selected, high-quality, 24-bit delta-sigma ADCs, and both data streams are fed to the DSP environment where dedicated algorithms merge the signals in real time while obtaining an extremely high accuracy match in gain, offset and phase.

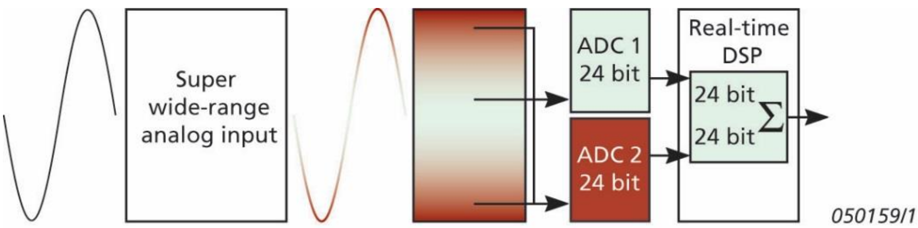


Figure 2: A simplified block diagram of the Dyn-X technology.

With no setting of input ranges, and with no need to be concerned about overloads, under-ranged situations and the accuracy of the measurements made, the ease and safety of measuring are dramatically increased using Dyn-X technology. In addition, with no need for trial runs to ensure correct input ranges for the various input channels, the certainty of getting the measurements right the first time is also significantly increased.

1.4 REq-X

REq-X (Response Equalization eXtreme) is a technique that allows you to flatten and stretch the frequency response of accelerometers, microphones and couplers in real time by correcting the time signal of a transducer by the inverse of its calibrated frequency response. Both amplitude and phase are corrected [5].

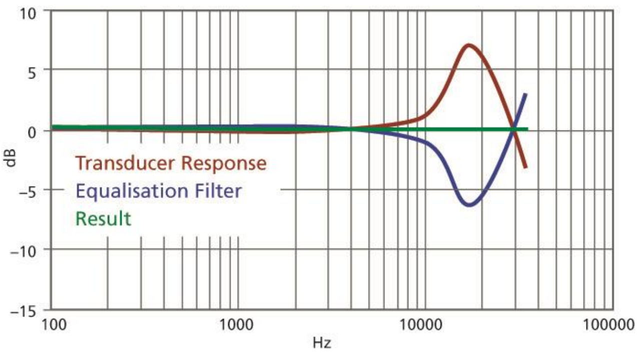


Figure 3: Basic principle of REq-X. Upper red curve shows transducer response before equalization.

This extends the useful frequency range of the transducers, improves the accuracy of the measurements and expands the use of existing transducers. As an example, for a correctly mounted accelerometer REq-X will increase the usable frequency range from 1/3 of the accelerometer's resonance frequency to 1/2 - an increase of 50%. Consequently, an accelerometer optimised for low-frequency measurements can now be used for more general purpose tasks.

1.5 A step further – Smart Setup and Mounting Check

All of the above techniques have, for some years, been implemented in Brüel & Kjær's measurement systems using LAN-XI hardware and PULSE software [2], [3]. However, transferring transducer DOF and component information to the measurement system – or checking that the information corresponds to what has been defined in the measurement system's DOF Setup – still had to be done manually and was therefore both time-consuming and error-prone. In addition, procedures for checking that the transducers were properly mounted during the measurements were not implemented.

Consequently, the Transducer Smart Setup app was introduced in 2015 to make transducer setup as simple and automated as possible and, in addition, give the user instant access to specifications, documentation and calibration data. In 2016, a procedure called Accelerometer Mounting Check was introduced to check changes in the mounting state of transducers to ensure proper mounting conditions. They are both described in [6], in particular the Accelerometer Mounting Check procedure.

The following chapters give a more detailed description of the Transducer Smart Setup app, go through the main elements in the Accelerometer Mounting Check procedure and explain new functionality added. Used in combination with the above-mentioned techniques, this provides a fully integrated concept for simplifying the test setup preparation, reducing measurement time and getting the data right first time.

2 Transducer Smart Setup

Apps downloaded on smart mobile devices such as smartphones and tablets are increasingly being used within sound and vibration as they are generally popular, relatively inexpensive and give access to useful functionality such as camera, GPS, wide range of apps and not least Internet and cloud services – all useful within the field of sound and vibration [7].

While their use as serious measurement instruments are probably still a long way away, they offer great value as supplementary tools for measurements. Typical examples include measurement setup, measurement control, data analysis, results viewing and reporting.

2.1 Challenges and purpose

When performing vibration measurements, the setup time can be a significant part of the total test time. Obviously, large scale testing such as modal surveys with hundreds of channels, but also smaller scaled tests, can benefit greatly from clever setup tools.

To keep track of your setup, when performing structural measurements, it is commonplace to:

- Attach labels to the transducer cables
- Make notes about DOF information (component, node ID, directions)
- Make notes about transducer information (type and serial number, sensitivity, etc.)
- Have printed documentation available (for example, product data sheets)
- Have calibration data available

The purpose of the Transducer Smart Setup is to eliminate these manual tasks and thereby optimize the workflow by using a tool that automatically handles this.

The app is available for iOS 8.0 or newer devices (iPhone®, iPad® and iPod touch®) and is available free of charge from the App Store.

2.2 Implementation

The Transducer Smart Setup scans data matrix codes engraved on transducers containing information about the transducer type, serial number and the surface side of the transducer being scanned. In addition, when scanning the data matrix code, the app uses a patented algorithm to determine the orientation of the transducer relative to a predefined reference coordinate system. When all transducers in the test setup have been scanned, transducer information and orientations are seamlessly transferred to the PULSE Reflex™ Measurement software for fast and safe setup.

Moreover, the data matrix code contains a link giving you instant access to specifications, documentation and calibration data stored in the cloud.

Laser engraving is used to obtain very high resistance to scratching and denting from regular use of the accelerometers. In addition, the data matrix codes use Reed-Solomon error correction codes for reliable scanning.

Only one data matrix code needs to be scanned, even when using triaxial accelerometers, but the accelerometers have codes on multiple surfaces (sides) to ease scanning in confined spaces.

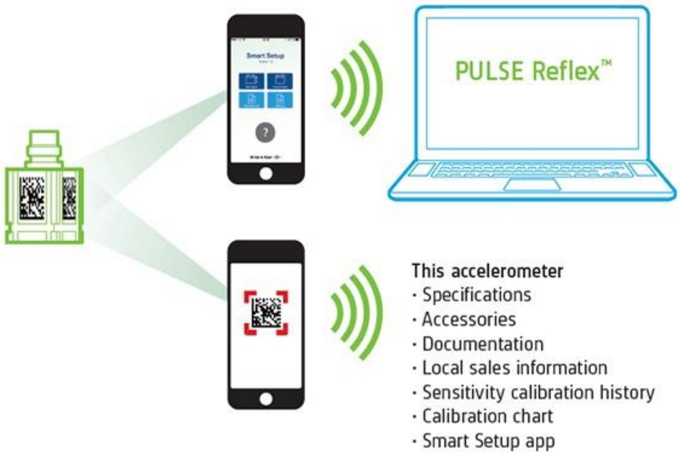


Figure 4: The Transducer Smart Setup workflow.

In addition, you can scan customized 2D labels attached next to the transducers to read transducer position (component) and node ID. These labels can be generated in different ways by:

1. Using one of the several data matrix code generators available on the web
2. Purchasing a label printer and associated software that support data matrix codes
3. Using Microsoft® Excel and a dedicated data matrix code generator add-in

Figure 5: Accelerometer with data matrix codes (left). Example of 2D label (right).

Figure 6: Scanning the data matrix code of an accelerometer and its associated 2D label.

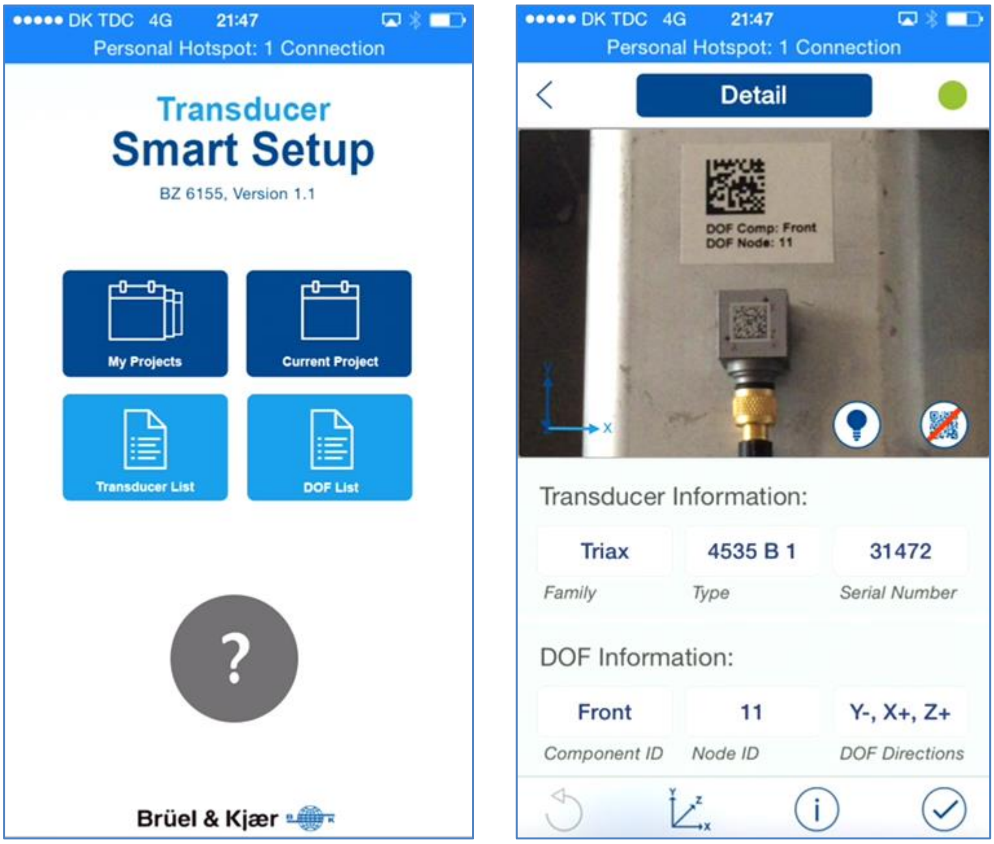


Figure 7: The app's user interface. Home Screen showing the main elements of the app (left). Scanning a data matrix code on an accelerometer and 2D label (right). If no label is used, the Component ID and Node ID can be selected from a list of entries or can simply be typed in.

2.3 Scanning transducers without data matrix codes

For transducers without data matrix codes, the app needs to be told the transducer family, type and serial number, which can be selected from a transducer list or entered directly.

For most Brüel & Kjær accelerometers without data matrix codes, the app contains detailed accelerometer drawings. By rotating and aligning the drawing of the accelerometer with the actual one, you obtain the DOF directions.

For legacy Brüel & Kjær transducers – or third party transducers – the same principle applies, now however, with a more generic drawing depending on transducer family, for example, uniaxial or triaxial accelerometers.

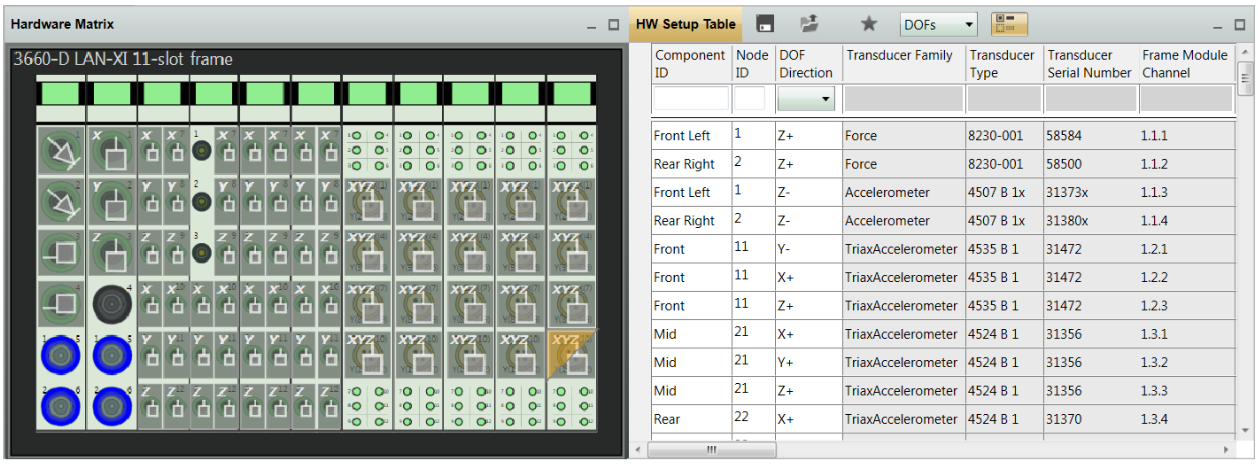
2.4 Scanning procedure

The scanning procedure consists of a few simple and intuitive steps:

1. Create a new project or open an existing project in the app
2. Align your smart device to a reference coordinate system by:
    a. Placing the smart device in the xy-plane with the screen facing in the positive z direction
    b. Aligning the device so the short side is parallel to the x-axis and the long side parallel to the y-axis
3. Locate an accelerometer on the test structure
    a. For accelerometers containing data matrix codes
        i. Scan one of them. This gives you the transducer family, type, serial number and DOF directions
        ii. If a 2D label exists, scan it to get Component ID and Node ID. Otherwise, select them from a list of entries or simply type them in
    b. For accelerometers not containing data matrix codes
        i. Select the transducer family, type and serial number from your transducer list
        ii. Rotate and align the accelerometer drawing to the actual one to obtain the DOF directions
        iii. If a 2D label exists, scan it to get Component ID and Node ID. Otherwise, select them from a list of entries or simply type them in
4. Repeat step 3 until all accelerometers in the test are included in the project
5. Export the project to PULSE Reflex™ using either:
    a. A cloud device such as iCloud, DropBox, Google Drive or OneDrive
    b. Email
    c. iTunes through a wired connection

Once the project is exported, it can be imported into the PULSE Reflex™ HW Setup Table.

Note that random cable connections or changes to the cabling are automatically aligned. If changes to the cable configuration have appeared, just re-import the project into the PULSE Reflex™ HW Setup Table.



Component ID	Node ID	DOF Direction	Transducer Family	Transducer Type	Transducer Serial Number	Frame Module Channel
Front Left	1	Z+	Force	8230-001	58584	1.1.1
Rear Right	2	Z+	Force	8230-001	58500	1.1.2
Front Left	1	Z-	Accelerometer	4507 B 1x	31373x	1.1.3
Rear Right	2	Z-	Accelerometer	4507 B 1x	31380x	1.1.4
Front	11	Y-	TriaxAccelerometer	4535 B 1	31472	1.2.1
Front	11	X+	TriaxAccelerometer	4535 B 1	31472	1.2.2
Front	11	Z+	TriaxAccelerometer	4535 B 1	31472	1.2.3
Mid	21	X+	TriaxAccelerometer	4524 B 1	31356	1.3.1
Mid	21	Y+	TriaxAccelerometer	4524 B 1	31356	1.3.2
Mid	21	Z+	TriaxAccelerometer	4524 B 1	31356	1.3.3
Rear	22	X+	TriaxAccelerometer	4524 B 1	31370	1.3.4

Figure 8: Transducer and DOF information appearing in the HW Setup Table in PULSE Reflex™.

2.5 Additional information

In addition to using the Transducer Smart Setup for fast and safe transducer setup, the app contains powerful supplementary features such as instant access to transducer specifications, documentation (for example, Product Data Sheets in various languages) and calibration data (history and charts) stored in the cloud.

The use of the Transducer Smart Setup app is not limited to accelerometers. Shakers, impact hammers, force transducers and microphones are also supported. In the future, other transducers could be included as well.

Even without the app, you can scan a transducer's data matrix code with any data matrix 2D barcode scanner and get immediate access to detailed transducer information, including calibration data.

Further description and videos of the Transducer Smart Setup can be found on Brüel & Kjær's website [8].

3 Accelerometer Mounting Check

Whereas the Transducer Smart Setup tool works in principle with all kinds of transducers, the Accelerometer Mounting Check procedure is dedicated to accelerometers as the name implies. When the accelerometer setup (project) is transferred to PULSE Reflex™ from the Transducer Smart Setup, the Accelerometer Mounting Check can be used to ensure that the accelerometers are properly mounted by detecting changes in their mounting state.

3.1 Challenges and purpose

Bad measurements due to improperly mounted accelerometers are, unfortunately, quite common. A non-optimal mounting technique might have been chosen resulting in bad measurements from the beginning, or the accelerometers might simply have become loose over time. In addition, changes to the cable connections might have appeared.

Often these imperfections are difficult to spot with the naked eye. Obviously, large scale testing such as modal surveys with hundreds of accelerometers mounted, but also smaller scaled tests, can benefit greatly from a robust verification tool. The need obviously becomes even more apparent when the accelerometers are located in remote areas or areas with limited or no access.

The purpose of Accelerometer Mounting Check is to provide a simple and robust procedure to check changes in the mounting state of the attached accelerometers to ensure that they are properly mounted. Accelerometer Mounting Check is a patented procedure implemented in the Brüel & Kjær's measurement systems using LAN-XI hardware and PULSE Reflex™ software. It works with all charge accelerometers and with newer Brüel & Kjær CCLD accelerometers with modified built-in preamplifiers.

3.2 Implementation

3.2.1 Basic idea

The mechanical system of an accelerometer, the mount and the test structure can be modelled as a three degree-of-freedom system [9]. When applying an electric excitation to the piezoelectric element of the accelerometer, the accelerometer output significantly depends on its mounting state. Three limit cases can be defined:

1. The accelerometer is perfectly mounted on an infinite heavy structure
2. The accelerometer is freely hanging
3. The accelerometer is mounted on a light structure

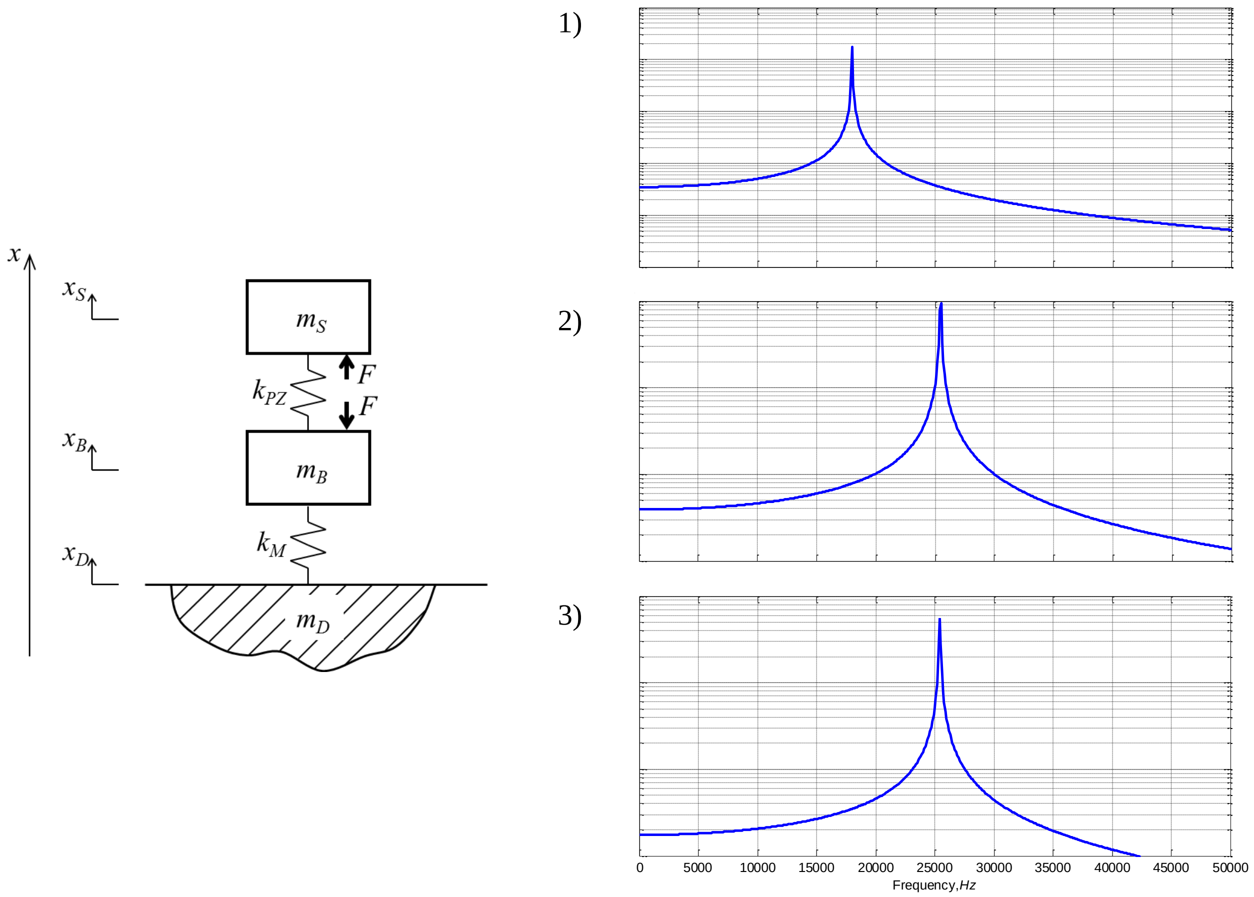


Figure 9: Simplified model of mounted accelerometer (left).
Typical analytical FRFs of the model: 1) Perfectly mounted on an infinite heavy structure;
2) Freely hanging; 3) Mounted on a light structure (right).

The Accelerometer Mounting Check procedure is based on the above-mentioned idea. An electrical excitation signal is sent to the accelerometer's piezoelectric element and the response is measured simultaneously. Based on the Frequency Response Functions (FRFs) and Coherence functions estimated in the range between the mounted resonance frequency and the resonance frequency in free hanging position, it is possible to determine if an accelerometer is properly mounted or not.

For real-life structures and accelerometers, the combined accelerometer-mount-structure model is typically much more complex than a simple three degree-of-freedom system. However, the idea can still be applied. In Figure 10, FRFs are shown for different structures and mounting conditions. In Figure 11, an example using a car frame is shown with the accelerometer properly mounted and freely hanging (fallen off). External noise is added to test the robustness of the algorithm. The freely hanging accelerometer also picks up some of the noise. Hence, the curves are different for the noise free and noisy cases.

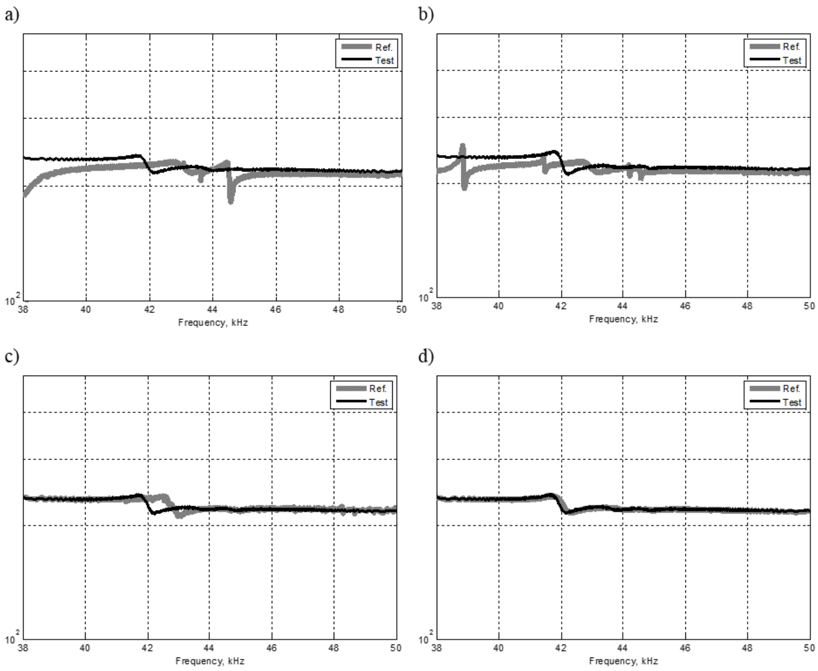


Figure 10: FRFs for different structures and mounting conditions.
Proper mount (thick grey). Accelerometer freely hanging (thin black).
a) Heavy steel block, steel stub; b) Heavy steel block, beeswax; c) 1.5 mm steel plate, beeswax;
d) Composite structure (thickness 20 mm), beeswax.

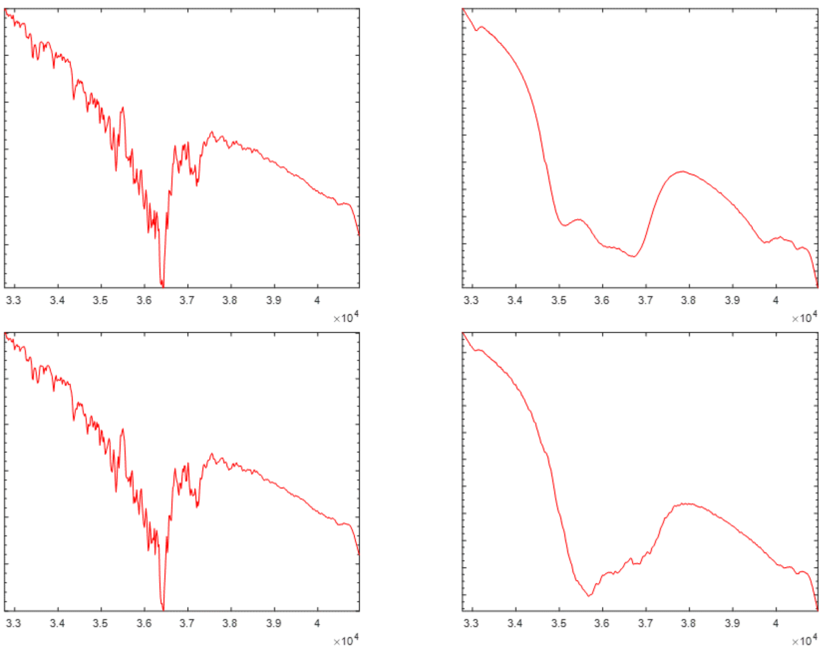


Figure 11: Responses from an accelerometer properly mounted (left) and freely hanging (right).
No external noise added (top). External noise added (bottom).

3.2.2 Procedure and FRF measurements

Accelerometer Mounting Check is implemented via a classification algorithm based on semi-supervised learning, where the difference between the current and a reference mounting state is used as an indicator for changed mounting conditions [6].

The procedure involves the following steps:

1. Mount the accelerometers on the test structure and connect them to the data acquisition hardware.
2. Make sure that all accelerometers are mounted correctly.
3. Press a single button to create the “Reference” mounting state based on measured FRF and Coherence functions. See automated procedure below.
4. Perform measurements according to your test plan. When finished, create a “Current” mounting state using the same procedure as for the “Reference” mounting state.
5. Comparing the “Reference” and “Current” mounting states, a classification algorithm determines whether the accelerometers are properly mounted or not.
6. If the “Current” and the “Reference” mounting states differ significantly, the software informs the user about a potential problem with the accelerometer mounting, providing information about where the affected accelerometers are mounted such as channel and DOF information in the HW Setup Table, and in the Hardware Matrix’s graphical representation of the hardware (see Figure 13). Properly mount the accelerometers that were detected as not properly mounted and go to step 3.
7. If the current state does not differ from the reference state, the software informs the user that all accelerometers are mounted correctly. Go to step 4 to continue the measurements.

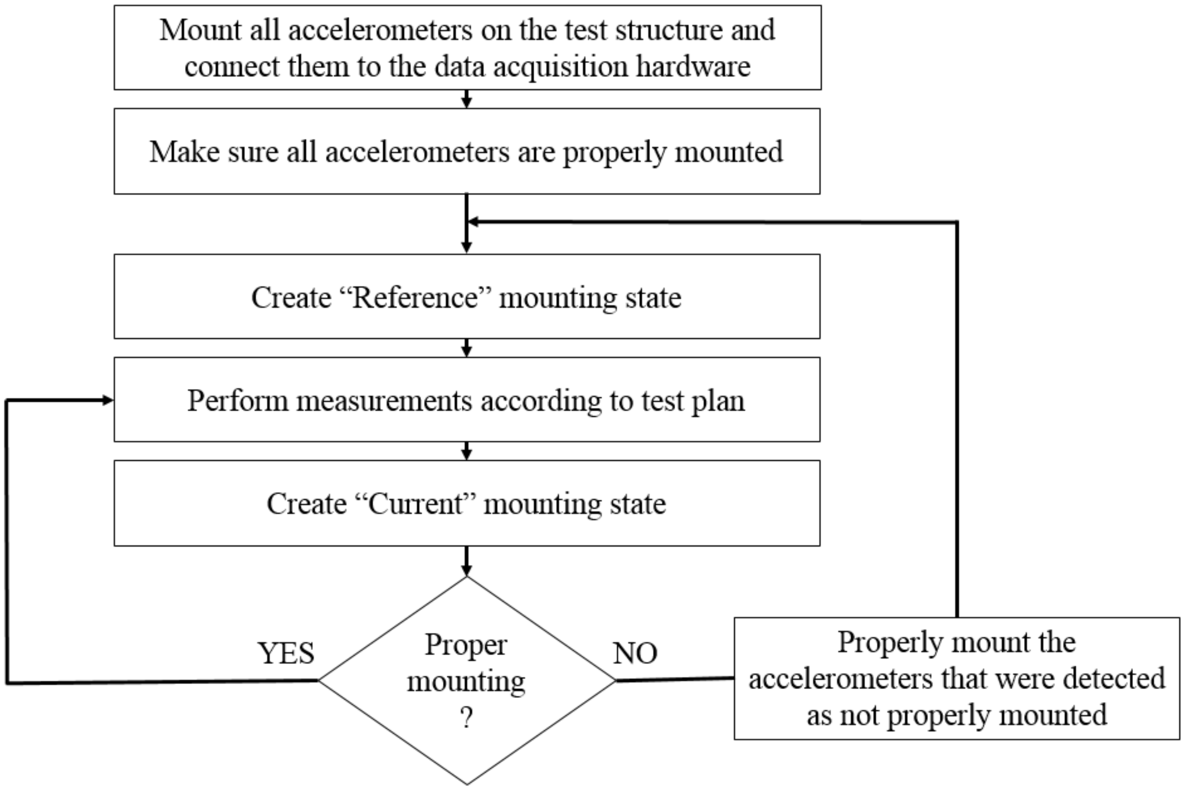


Figure 12: Accelerometer Mounting Check procedure.

Figure 13 shows the user interface implemented in PULSE Reflex™ with the Hardware Matrix, the HW Setup Table and the Accelerometer Mounting Check form. Examples of the user interface are shown after having measured the Reference mounting state for the setup’s 12 accelerometers being supported, after a successful check of the Current mounting state and after a check revealing improper mounting conditions.

The FRF and Coherence functions used in step 3) and 4) above are automatically calculated in PULSE Reflex™ using a single mouse-click:

1. PULSE Reflex™ sends the connected LAN-XI data acquisition hardware a command to start the Accelerometer Mounting Check test.
2. One or more LAN-XI hardware modules, using their built-in signal generator, generate a number of sine sweeps and send them to the accelerometers. The sine sweeps are generated around the resonance frequency in free hanging position.
3. Simultaneously, the modules measure the accelerometer’s responses and send the digitized data accompanied with the “sweep start” trigger events to PULSE Reflex™.
4. Knowing the chirp characteristics (the start and stop frequencies and the sweep rate), the software reconstructs the sine sweep signals that were used for exciting the accelerometers. Using the reconstructed signals and the measured responses, it calculates the FRF and coherence functions. The noise is attenuated by means of averaging.
5. PULSE Reflex™ sends the LAN-XI hardware a command to end the Mounting Check test.

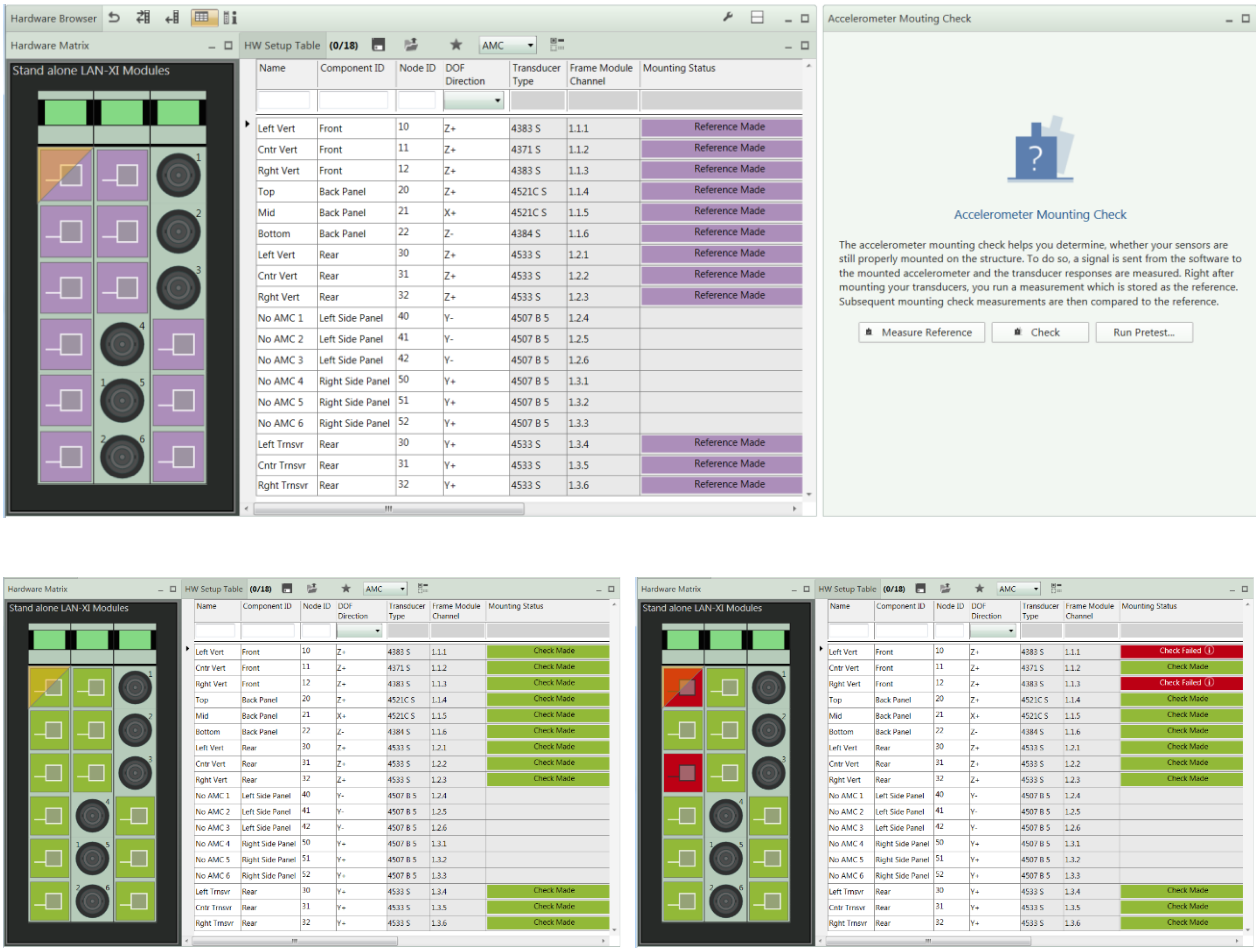


Figure 13: PULSE Reflex™ user interface.
Measured Reference mounting state (upper). Successful check of the Current mounting state (lower left) and check revealing improper mounting conditions for two accelerometers (lower right).

3.2.3 Classification algorithm

A classifier with two features divides the mounting states into two classes: “Proper” and “Improper” [6]. The first feature characterizes the difference between the reference FRF and the current FRF based on a normalized scalar product of the two FRFs’ magnitude weighted by the corresponding coherence values:

$$f_1 = \frac{\sum_{\omega_1}^{\omega_2} \gamma_R^2(\omega)\gamma_C^2(\omega)\,|H_R(\omega)||H_C(\omega)|}{\sum_{\omega_1}^{\omega_2} |H_R(\omega)|\sum_{\omega_1}^{\omega_2} |H_C(\omega)|} \tag{1}$$

where the subscripts R and C denote the reference and current states, respectively. $\gamma^2(\omega)$ is the coherence function and $[\omega_1;\ \omega_2]$ is the frequency range of interest.

The second feature is the coherence index:

$$f_2 = \frac{1}{N}\sum_{\omega=\omega_1}^{\omega_2} \gamma_C^2(\omega) \tag{2}$$

where N is the number of frequency lines in the $[\omega_1;\ \omega_2]$ range. $f_1, f_2 \in [0; 1]$.

Each state of the system can be presented as a point in the features space. For the two features’ classification problem, the state is a point with coordinates f_1 and f_2 on the (f_1, f_2) coordinate plane, see Figure 14. Collecting several points representing the proper and improper mounting states, two clusters will be formed. They are coloured green and red, respectively.

A linear classifier can be shown as a line separating the clusters. The equation of the line on the (f_1, f_2) coordinate plane is:

$$w_1 f_1 + w_2 f_2 + w_3 = 0 \tag{3}$$

The coefficients $w_1\ w_2\ w_3$ can be found experimentally, and they are invariant to the type of accelerometer, the mounting method and the test structure used.

The distance d between a point with coordinates (f_1, f_2) and the line is calculated as $d = w_1 f_1 + w_2 f_2 + w_3$. If $d > 0$, the point is below the separation line and belongs to the “Proper” mounting class. In contrast, the points with $d < 0$ are classified as belonging to the “Improper” mounting class. If the point is too close to the separation line, $|d| < \epsilon$, it can be classified as uncertain.

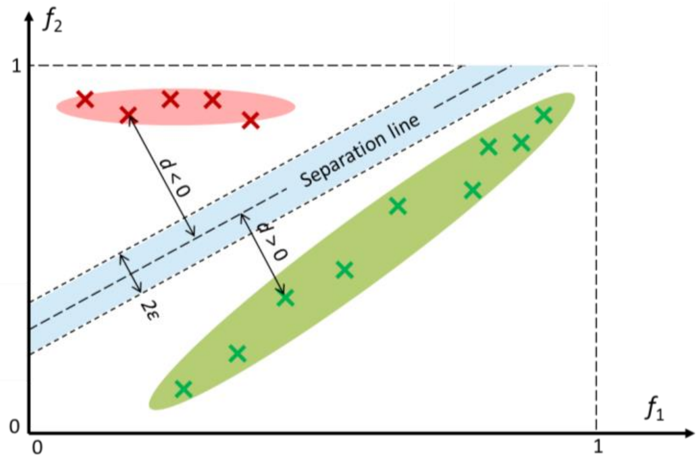


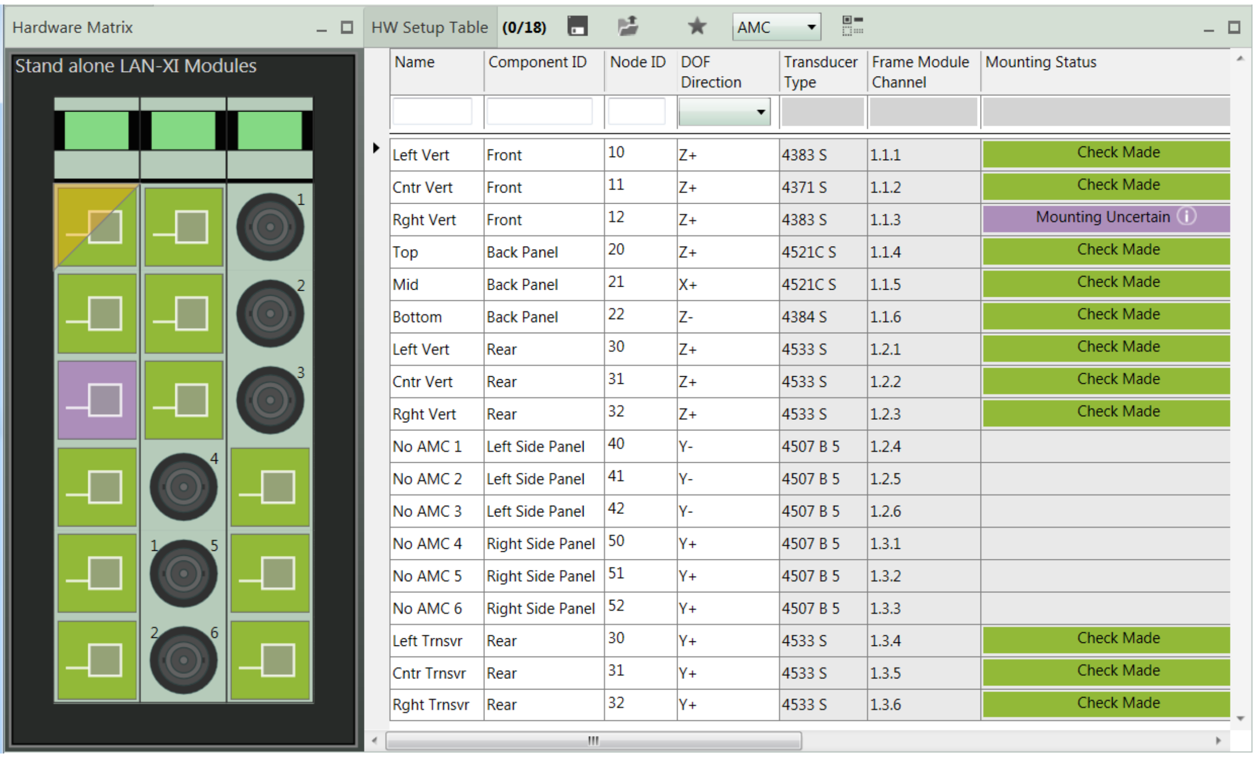
Figure 14: Schematic view of the two features space. Green crosses: states representing proper mounting. Red crosses: states with improper mounting. Linear classification is represented by the separation line.

3.2.4 Challenges with light structures

When a heavy accelerometer is mounted on a light structure, the distance *d* can be small and the classification uncertain. Giving a simple robust YES or NO answer to the question “Is the accelerometer properly mounted?” might not be possible and the procedure might result in a “false positive” indicating that the accelerometer is properly mounted, when in fact it is not. When the classification is uncertain, the software indicates this in the Hardware Matrix and the HW Setup Table (see Figure 15). To avoid this uncertainty situation, a pretest can be made before mounting the accelerometer.

The pretest consists of a few simple steps:

1. Let the accelerometers in question hang freely from the structure (or from your hand).
2. Create a “Free hanging” mounting state based on measured FRFs and Coherence functions as previously explained.
3. Mount the accelerometers.
4. Create a “Reference” mounting state using the same procedure as for the “Free hanging” mounting state.
5. The software then compares the “Free hanging” and “Reference” mounting states and informs the user. If the mounting states differ significantly, the Accelerometer Mounting Check procedure described in section 3.2.2 can be used to determine whether the accelerometers in question are properly mounted or not.



Name	Component ID	Node ID	DOF Direction	Transducer Type	Frame Module Channel	Mounting Status
Left Vert	Front	10	Z+	4383 S	1.1.1	Check Made
Cntr Vert	Front	11	Z+	4371 S	1.1.2	Check Made
Rght Vert	Front	12	Z+	4383 S	1.1.3	Mounting Uncertain
Top	Back Panel	20	Z+	4521C S	1.1.4	Check Made
Mid	Back Panel	21	X+	4521C S	1.1.5	Check Made
Bottom	Back Panel	22	Z-	4384 S	1.1.6	Check Made
Left Vert	Rear	30	Z+	4533 S	1.2.1	Check Made
Cntr Vert	Rear	31	Z+	4533 S	1.2.2	Check Made
Rght Vert	Rear	32	Z+	4533 S	1.2.3	Check Made
No AMC 1	Left Side Panel	40	Y-	4507 B 5	1.2.4	
No AMC 2	Left Side Panel	41	Y-	4507 B 5	1.2.5	
No AMC 3	Left Side Panel	42	Y-	4507 B 5	1.2.6	
No AMC 4	Right Side Panel	50	Y+	4507 B 5	1.3.1	
No AMC 5	Right Side Panel	51	Y+	4507 B 5	1.3.2	
No AMC 6	Right Side Panel	52	Y+	4507 B 5	1.3.3	
Left Trnsvr	Rear	30	Y+	4533 S	1.3.4	Check Made
Cntr Trnsvr	Rear	31	Y+	4533 S	1.3.5	Check Made
Rght Trnsvr	Rear	32	Y+	4533 S	1.3.6	Check Made

Figure 15: PULSE Reflex™ Hardware Matrix and HW Setup Table showing uncertain mounting condition for an accelerometer.

4 Conclusion

The importance of simplifying the test setup preparation, reducing the measurement time and getting data right first time has been given increased focus in recent years to improve productivity and shorten time-to-market. First, a brief overview of the popular techniques: TEDS support, PTP, PoE, Dyn-X and REq-X was given followed by a more detailed description of two new innovative patented techniques: Transducer Smart Setup, which can dramatically reduce the test setup time and Accelerometer Mounting Check for checking the mounting state of transducers.

Each individual technique adds considerable benefits to most test campaigns and by combining several of these, significant productivity enhancements can be obtained, while ensuring the highest possible measurement data quality.

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