Application Note

Calibration at Toyota Motor Corporation using Vibration Transducer Calibration System Type 9610

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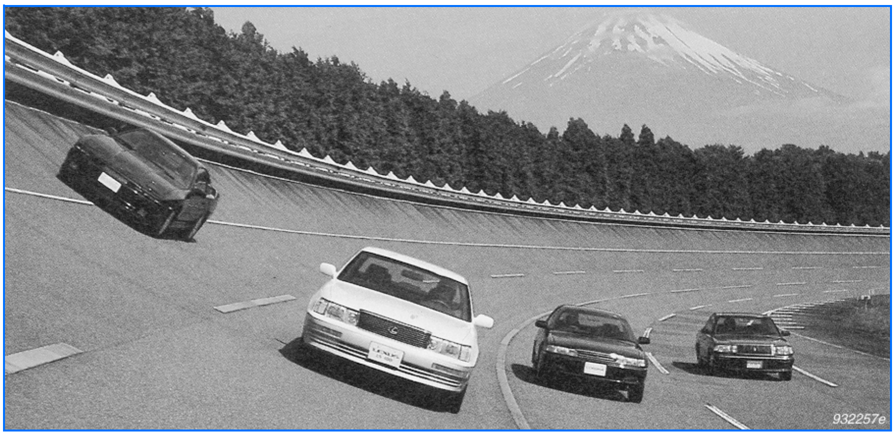
For several years Toyota Motor Corporation have used a traditional manually operated back-to-back vibration transducer calibration system based on older Brüel & Kjær equipment.

However, continuously adding vibration transducers, Toyota Motor Corporation developed a need for a more efficient means of calibrating these transducers. To ensure continued optimum vibration measurement results, reliability, high precision and high accuracy were vital factors when the Calibration Laboratory began looking for a suitable calibration system.

Vibration Transducer Calibration System Type 9610, providing automated FFT-based sensitivity and phase calibration of vibration transducers over a wide frequency range, was chosen for reasons of accuracy, confidence and durability.

This Application Note introduces the concept of FFT-based vibration transducer calibration and discusses the features, advantages and benefits of the Vibration Transducer Calibration System Type 9610 in connection with its use at Toyota Motor Corporation.



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Introduction

Refined Noise and Vibration Harshness (NVH) characteristics of automobiles have become one of the key factors in the quest for higher customer satisfaction. Amongst other things, this implies a large number of vibration measurements, with applications ranging from general one-channel measurements to advanced experimental modal analysis, often requiring multichannel systems with many vibration transducers.

Today, a multitude of sophisticated vibration analysis tools are available, allowing the engineer to validate the analysis. An excellent example of this is the recent development of experimental modal analysis software where the analysis result, the modal model, can be validated using advanced algorithms, giving increased confidence in the analysis results.

However, the validity of the transducers used for the measurements upon which the analysis are founded is totally dependent upon proper calibration and, as should be emphasized, compensating for damaged out-of-tolerance vibration transducers by post-processing is impossible!

The calibration of vibration transducers therefore plays a decisive role in the quality, accuracy and consistency of any vibration measurement.

Aspects of calibration

The reliability and versatility of a vibration transducer is of only limited value if the measurements cannot somehow be traced to an absolute physical standard. Calibration ensures this traceability and hence provides a defined degree of confidence in any vibration measurement. It is therefore an act of establishing the link to the physical quantity of interest, the vibration sensitivity [1].

From a practical measurement point of view, it is advisable to calibrate the sensitivity of a vibration transducer at more than one frequency. Preferably, the vibration transducer should be calibrated over its entire useful frequency range, or at least the frequency response curve should be measured, to ensure that the transducer has not been damaged. Such damage will typically show up as irregularities in the frequency response curve as well as in the curve that can be drawn from the individual, discrete frequency, calibrations.

An example of this is shown in Fig. 1 where the frequency response of a damaged accelerometer has been drawn. Note the peak/notch phenomenon, a clear indication of damage which did not reveal anything unusual when a back-to-back calibration was carried out at the reference frequency of 160 Hz.

Calibration Methods

Sensitivity calibration of vibration transducers can be divided into three distinct groups: absolute methods (includes laser interferometry, reciprocity and Earth's gravity), comparison or back-to-back methods, and finally calibrator methods, involving the use of an exciter of known vibration level.

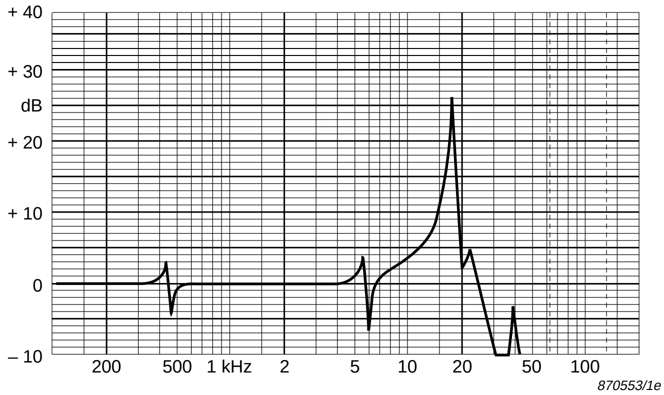

Fig. 1 Frequency response of a damaged accelerometer

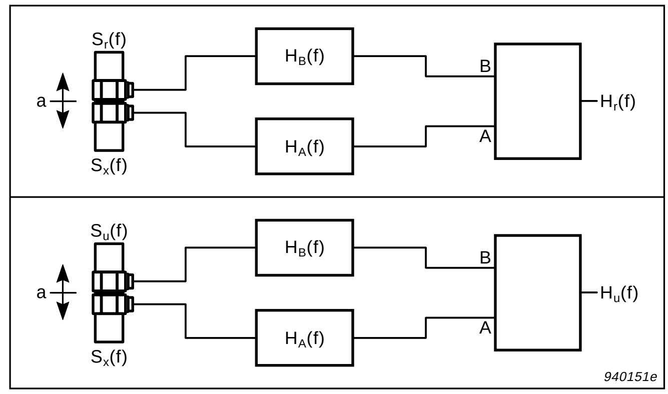

Fig. 3 Principle of improved back-to-back calibration by substitution

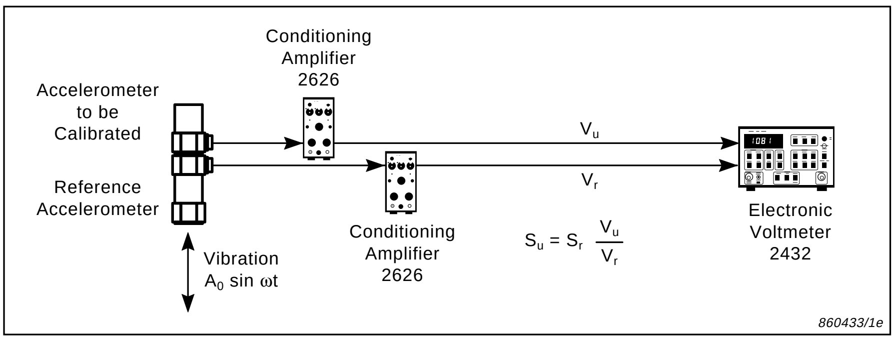

Fig. 2 Principle of traditional back-to-back calibration

The back-to-back comparison method is ideal for every-day calibrations of non-standard reference accelerometers due to its relative simplicity, accuracy and cost effectiveness. Moreover, the method's inherent qualities make it well-suited for large scale vibration transducer calibration.

Back-to-Back Vibration Transducer Calibration

The traditional back-to-back calibration technique is based on the principle shown in Fig. 2. The device under test (DUT) is mounted back-to-back with a standard reference accelerometer. The combination is mounted on a suitable vibration source. When excited, the input acceleration to each accelerometer is identical and consequently, their sensitivity ratio is simply the ratio of their outputs.

Traditionally, the accelerometers are excited at one frequency and their outputs are measured (after preamplification) using a high-quality electronic voltmeter of known accuracy. This method produces good results, but as it produces a measure of the sensitivity at a single frequency, attaining a comprehensive knowledge of an accelerometer's characteristics can be rather time consuming.

However, the advent of two-channel FFT analyzers, coupled with broad-band random excitation techniques, meant the introduction of innovative calibration techniques since the two-channel FFT analyzer made it possible to calibrate a vibration transducer at a large number of points over a wide frequency range in a single measurement. Combining this with the ability of a PC to control the analyzer formed the basis for an advanced automated vibration transducer calibration system. By supplying the output from the standard reference accelerometer to the channel A input, and the output from the DUT to the channel B input, the ratio of the sensitivities can be measured as the frequency response function.

It has been shown [2] that such a basic FFT-based back-to-back calibration will result in a total uncertainty of approximately 5%. To improve this method and achieve an even better uncertainty, a new technique, calibration by substitution, was developed.

Improved Back-to-Back Calibration by Substitution

This unique technique involves making two measurements in order to obtain the final calibration result of the DUT. Initially, the frequency response function between a so-called working standard accelerometer and the standard reference accelerometer is measured and stored. Then the frequency response function between the DUT and the working standard accelerometer, known as the reference frequency response function, is also measured and stored. The working standard accelerometer remains fixed to the calibration fixture. Now, the charge sensitivity of the DUT can be calculated as:

$$\frac{S_u(f)}{S_x(f)} \times \frac{S_x(f)}{S_r(f)} = \frac{H_u(f)}{H_r(f)}$$

or

$$S_u(f) = S_r(f) \times H_u(f) / H_r(f)$$

where (as a function of frequency):
$S_u(f)$ is the DUT's charge sensitivity
$S_r(f)$ is the standard reference accelerometer's charge sensitivity
$S_x(f)$ is the working standard accelerometer's charge sensitivity
$H_u(f)$ is the frequency response function between the DUT and the working standard accelerometer
$H_r(f)$ is the frequency response function between the standard reference accelerometer and the working standard accelerometer

The principle of improved back-to-back calibration by substitution is shown in Fig. 3. The complete Vibration Transducer Calibration System Type 9610, centring around Multichannel Analysis System Type 3550 as the two-channel FFT analyzer, is shown in Fig. 4. The system calibrates the sensitivity and phase of accelerometers and velocity pick-ups in a frequency range from 5 Hz up to 5 or 10 kHz.

Note that since the contribution from the working standard accelerometer cancels out, the working standard accelerometer does not have to be a primary (absolute) calibrated standard reference accelerometer. Vibration Transducer Calibration System Type 9610 employs a standard Delta Shear® Accelerometer Type 4371 as a working standard accelerometer.

Much more than just providing an extremely low total calibration uncertainty value (approximately 1% [2]), the improved FFT calibration by substitution technique also provides a number of distinct benefits. Most importantly, it provides calibrations which are intrinsically independent of all system inaccuracies except for those occurring due to the standard reference accelerometer and the precision attenuator*.

An important consequence of this is that it makes system self-calibration unnecessary, enhancing calibration efficiency and reliability. In addition, improved FFT calibration by substitution reduces the need for recalibration of system components, because only the above-mentioned instruments need to be recalibrated.

A full description of the improved FFT calibration by substitution technique and its implementation in Vibration Transducer Calibration System Type 9610 can be found in references [3] and [4].

The Vibration Transducer Calibration System Type 9610 in use at the Toyota Head Office Technical Center

Founded in August 1937, the Toyota Motor Corporation has grown to be a world leading car manufacturer with more than 70 000 employees and sales representatives around the world. Armed with a constant striving for automotive perfection, Toyota Motor Corporation has over the years made several significant contributions to automotive technology.

As a natural consequence of striving for perfection, Toyota Motor Corporation has constantly focused on cost-efficient solutions for its various needs. The best known example of this is probably the "Lean Production" philosophy, attempting to minimize production waste and maximize productivity.

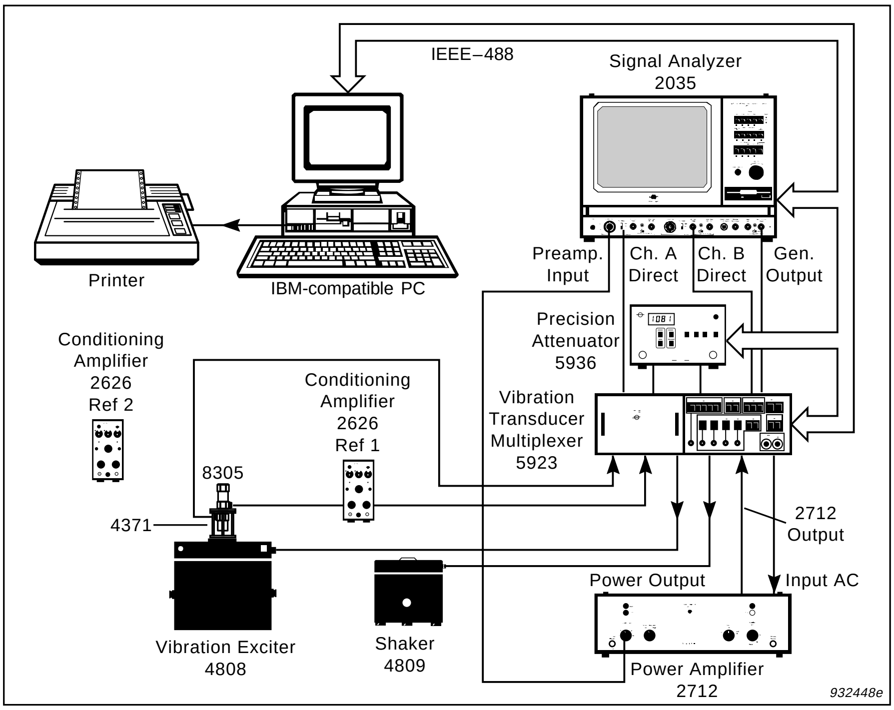

Fig.4 Vibration Transducer Calibration System Type 9610

In the Toyota Motor Corporation, one section of the Technical Administration Division - the "Calibration Center" – controls calibration of piezoelectric accelerometers.

For the calibration laboratory, there are a number of obvious benefits in automating the calibration process. Since installation, and after months of intensive use, the Calibration Center emphasizes the following benefits of Vibration Transducer Calibration System Type 9610:

- High, consistent accuracy
- Reduced operator dependency
- Faster calibration
- Consistent philosophy
- Database management capability
- Reduction of calibration costs
- Company calibration strategy optimization

These benefits have been accomplished in Vibration Transducer Calibration System Type 9610 by taking a number of measures. The most important are outlined in the following.

Firstly, by removing tedious, yet critical, work and allowing the operator to concentrate on the few crucial manual tasks, operator dependency has been drastically reduced. This, in connection with intelligent computer-based interactive decision making†, ensures high and consistent accuracy.

Comparison (Round Robin) calibrations of a Brüel & Kjær Standard Reference Accelerometer, with participation from Brüel & Kjær, The National Institute of Standards and Technology (NIST), USA, and Physikalisch-Technische Bundesanstalt (PTB), Germany, were carried out during 1990 and 1991. The results explicitly confirmed the consistency and the accuracy of Vibration Transducer Calibration System Type 9610 [5].

Secondly, Vibration Transducer Calibration System Type 9610 uses continuous control to ensure the quality and reliability of the calibration process and the linearity of the DUT. This is achieved by measuring the coherence# between the two channels. Furthermore, Vibration Transducer Calibration System Type 9610 performs a number of verifications** to ensure that the system, the standard reference accelerometer and the standard voltage reference are in a stable working condition. The reference frequency response function is also checked in order to check the mounting and the integrity of the

* Bus-controlled Precision Attenuator Type 5936 is used in Vibration Transducer Calibration System Type 9610 to minimize the contribution to systematic error by eliminating range switching in Multichannel Analysis System Type 3550

† Vibration Transducer Calibration Software WT9301, controlling the calibration process, retrieves pertinent data from the data base, sets up the analyzer, transfers the measured data from the analyzer and processes them to give the calibration result. In this process, the operator is carefully guided by the software. Manual action is needed at transducer mounting/removal and if a situation is detected that requires manual correction (loose cables, wrong preamplifier settings, lack of connections, etc.)

The coherence function is a measure of the linearity between the two input channels to the Multichannel Analysis System Type 3550

Fig.5 Vibration Transducer Calibration System Type 9610 in use at the Calibration Center

standard reference accelerometer and working standard accelerometer.

This ensures a consistent calibration philosophy with a constant and thorough focus on error reduction.

Thirdly, the combination of random excitation and the improved FFT calibration by substitution provides very fast calibrations. Obtaining a typical calibration (sensitivity as well as phase at 1550 frequencies) takes approximately three minutes, including all manual work.

A natural consequence of this is higher calibration productivity and the Calibration Center has, not surprisingly, reported a reduction in calibration costs.

Finally, by combining the FFT calibration technique with a PC to manage data, data retrieval, trend analysis, calibration comparisons, etc. are easy and straightforward.

According to the Calibration Center, the above factors were all carefully examined prior to purchase in order to evaluate their usefulness and their impact on the calibration strategy. The center explains: "Today's automobile customers are extremely demanding and critical, they do not accept half solutions – and neither do we. The Vibration Transducer Calibration System Type 9610 provides us with fast, reliable and accurate calibrations and fits perfectly well into our quality optimization strategy due to its innovative improved FFT calibration by substitution technique".

Fig. 5 shows Vibration Transducer Calibration System Type 9610 in use at the Calibration Center.

** The verification procedures are divided into three: System Verification, Standard Voltage Verification and Standard Charge Verification. System Verification involves a series of measurements to validate the stability of the system. Standard Voltage Verification and Standard Charge Verification are performed to ensure the validity of the Standard Reference Accelerometer and the Calibration Set Type 3506 which are used as charge and voltage standards, respectively

Conclusions

The evolution of the traditional back-to-back calibration method into the FFT-based improved back-to-back calibration by substitution method has been discussed along with the features and benefits of implementing the technique in Vibration Transducer Calibration System Type 9610.

Also, by examining the use of Vibration Transducer Calibration System Type 9610 at Toyota Motor Corporation, it was shown how the system has enabled the Calibration Center to further optimize their calibration strategy, increase productivity and calibrate with more accuracy and more confidence.

References

[1] M. Serridge and T. R. Licht: *"Piezoelectric Accelerometers and Vibration Preamplifiers"*, Brüel & Kjær Handbook BB 0694

[2] Tech. Review, no.2, 1987: T. R. Licht and H. Andersen, Brüel & Kjær: *"Trends in Accelerometer Calibration"*

[3] Brüel & Kjær Product Data sheet BP 1426: *"Vibration Transducer Calibration System Type 9610"*

[4] User Manual: *"Vibration Transducer Calibration System Type 9610"*

[5] E. Schonthal & T. R. Licht: *"Comparison of Accelerometer Calibrations Performed on a Software based System to Calibrations Obtained from two National Laboratories"*, Proc. Nat. Conf. of Standards Laboratories, Albuquerque, New Mexico, USA, August 1991

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