A method for high-shock accelerometer calibration comparison using a 2-DOF model

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Abstract. By applying a parameterized 2-DOF model to an Endevco type 2270 B2B sensor for the transfer of the unit shock sensitivity $S_{Sh}$, the drawback of the systematic spectral influence to $S_{Sh}$ of shock exciters with different spectral composition can be compensated in the frequency domain. The method and first results are presented.

1. The challenge to compare different high shock calibration results
The shock sensitivity $S_{Sh}$, as relationship between the peak accelerometer output quantity and the peak acceleration, depends on the spectral sensitivity of the accelerometer and the spectral composition of the exciting shock acceleration [1, 2, 3]. This leads to increased uncertainties in laboratory comparisons even if their capabilities would allow smaller uncertainty margins.

With different exciters, such as piezo or projectile driven Hopkinson bars, pendulum or piston shock, the current characterization of the pulse by peak acceleration value, ranging from 1000 m/s² to more than 100 km/s², and pulse length, typical range from more than 1 ms down to less than 20 µs, is not sufficient to characterize the spectral composition. Additionally, a calibration should reflect the actual use case, which rarely is bound to a single spectrum.

2. The 2-DOF model based approach
A method to circumvent this systematic drawback of the peak sensitivity is given in the recent standard ISO 16063-43 "Calibration of accelerometers by model-based parameter identification" [3]. By characterizing the accelerometer with a parameterized model, it is possible to reconstruct the exciting acceleration by the accelerometer response.

Figure 1: The 2-DOF model extends the common 1-DOF model of $m_1$, $c_1$, $d_1$ by a coupling mass $m_2$, $c_2$, $d_2$.

In [4, 5] it was shown that the common 1-DOF model is not sufficient to describe the commonly used Endevco type 2270 back to back (B2B) accelerometer transfer standard and an extended 2-DOF model was proposed as shown in figure 1. The common 1-DOF model build by the seismic mass $m_1$,
and the piezoelectric, damped spring $c_1$ and $d_1$ is extended with a coupling system build by $m_2$, $c_2$ and $d_2$. The red dotted arrows mark the two laser Doppler vibrometers (LDV) used to measure the acceleration.

The 2-DOF transfer function results to:

$$S_{2D}(\omega) = \frac{S_0 \cdot [\omega_1^2 \cdot (i\omega\delta_2 + \omega_2^2)]}{((\omega_1^2 + \eta\omega_1^2) + i\omega(\delta_2 + \eta\delta_1) - \omega^2) \cdot (\omega_1^2 + i\omega\delta_1 - \omega^2) - \eta(i\omega\delta_1 + \omega_1^2)^2}.$$ (1)

Where $S_0$ is the sensitivity, $\omega_1 = \sqrt{c_1/m_1}$ the resonance frequency and $\delta_1 = d_1/m_1$ the damping of the seismic system, $\omega_2 = \sqrt{c_2/m_2}$ and $\delta_2 = d_2/m_2$ the corresponding quantities of the coupling system and defining $\eta = m_1/m_2$ as the mass relation.

By a series of shock excitation one obtains the complex sensitivity of the accelerometer and apply a nonlinear parameter fit using the Levenberg-Marquardt algorithm. The data flow is shown in figure 2.

The transfer function (1) of the parameterized model is now used instead of a measured sensitivity for a FFT-based secondary calibration according to ISO 16063-22 [2] Version 3: Sensitivity calculation using FFT analysis. The transfer function $S_{\text{ca}}$ of the charge amplifier and the remaining group delays are compensated in the frequency domain. The uncertainties are estimated according to GUM supplement B by applying Monte-Carlo-Methods. For details see [6].

Figure 2: Data flow of the primary calibration for the parameter identification (left) and the secondary calibration with input prediction by using the model based transfer function of the transducer (right).
3. Experimental setup

Two transfer standards Endevco type 2270 B2B with the serial numbers BD47 and BA69 are primary calibrated using the high-shock Hopkinson bar exciter at PTB. Additionally, the BA69 was excited on a small ball drop exciter, where a 6 mm steel ball drops from a height of 22 cm on the back of a mounting mass of ~30 g, resulting in sharp, high bandwidth pulses with a pulse length in the range of about 14 µs and a peak acceleration of about 10 km/s². Typical shapes of both pulses are shown in figure 3.

For the parameter identification of the BA69, the data obtained by the ball drop exciter was used. The parameters of the BD47 transducer are identified using a series of 100 km/s² shocks obtained with the Hopkinson bar exciter. The IDFT bandwidth was set to 130 kHz covering the first resonance at about 56 kHz of the Endevco type 2270 transducers.

With the transfer functions of the parameterized model, the raw data of actual and historical primary calibrations on the Hokinson bar was used for a secondary calibration with input prediction (see right side of fig. 2) and compared to the primary calibration. The historical data spans calibrations with different charge amplifiers and operators, and a rework and modification of the Hopkinson bar in 2015, which resulted in a measurable shift of the peak sensitivity.

4. Results

Figure 3 shows the time domain results of a Hopkinson bar shock on the left and a ball drop shock on the right. The LDV reference is plotted in black, the scaled charge output of the in blue and the acceleration reconstructed from the transducer output in red. The reconstructions show a pleasingly high fidelity to the LDV references.

![Figure 3: Hopkinson bar pulse und ball drop pulse in the time domain with reconstruction.](image)

The secondary calibration results of the shock sensitivity are now compared to those obtained by the primary calibrations. Figure 4 shows the relative errors of the comparison over the peak acceleration. The filled red marks identify the data used for the parameter identification. The bold gray traces show the expanded \(k=2\) uncertainty of the primary calibration.
Figure 4: The relative error of the reconstructed shock sensitivity. The bold gray lines mark the expanded (k=2) primary uncertainty.

A systematic trend in the deviations can be identified. A plausible explanation is the well matching but still simplified 2-DOF model. A detailed analysis of the uncertainties yield to a expanded uncertainty (k=2) of $u_{S_{sh}}<0.5\%$ and is given in [6]

5. Conclusion and outlook

By applying a parameterized 2-DOF model to an Endevco type 2270 B2B sensor for the transfer of the unit shock sensitivity $S_{Sh}$, the drawback of the systematic spectral influence to the shock sensitivity when comparing different shock exciters can be compensated. The method proposed is covered by the actual standards [1, 2, 3] and has the potential to lead to unprecedented uncertainties in the transfer and comparison of high-shock calibrations.

References

[1] ISO 16063-13:2001, Methods for the calibration of vibration and shock transducers — Part 13: Primary shock calibration using laser interferometry
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[6] Volkers, Bruns, Ostermeyer: A 2-DOF model based input prediction for high shock accelerometer calibration (in process of publication)