Dispersion analysis of accelerometer shock calibrations by comparison using a new exciter developed at Inmetro

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Abstract. The applicability of a new mechanical shock exciter developed at the Vibration Laboratory of Inmetro for primary calibrations was analysed for calibrations of accelerometers by the comparison method. Using two back-to-back reference transducers and a single-ended general purpose accelerometer as device under test (DUT), calibrations were performed using the exciter developed at Inmetro, and the results were compared with those obtained with a commercial shock exciter. Two shock amplitudes and two pulse durations were applied to evaluate the dispersion of the DUT shock sensitivity. This analysis shows that the new exciter provides appropriate repeatability for shock sensitivity measurements, indicating a powerful system for generation of shock pulses.

1. Introduction
Accelerometer calibrations under impulsive excitations are of interest in several areas where measurements of mechanical shocks are needed, such as automotive industry, mechanical test laboratories, safety industry and engineering design companies. For example, the Brazilian test laboratories accredited for drop-testing of automotive helmets need metrological traceability for their measuring transducers under similar shock conditions that are applied during actual tests.

The objective of a transducer shock calibration is to determine its shock sensitivity under an acceleration pulse with a specific shape. Gaussian, half-sine or half-sine squared are the pulse shapes recommended by international standards [1, 2]. The shock sensitivity is evaluated by measuring simultaneously the reference acceleration pulse and the electric output of the accelerometer under test (DUT). Using a standard accelerometer to obtain the reference acceleration pulse is the principle of the calibration by comparison. On primary shock calibrations of accelerometers, the reference acceleration pulse is measured by a laser interferometric method which includes signal processing techniques as differentiation data processing using digital low-pass filtering [3].

The Vibration Laboratory (Lavib) of the Brazilian National Institute of Metrology, Quality and Technology (Inmetro) is currently improving a developed primary shock calibration system [4, 5] composed by a shock exciter, a heterodyne laser interferometer and acquisition/processing subsystems.

The Calibration and Measurement Capability (CMC) on shock calibration by comparison was obtained and has been maintained by Lavib using a commercial exciter Endevco 2925 Pop Shock Calibrator. This CMC comprises charge and voltage shock sensitivity of an accelerometer submitted to half-sine shock pulse with amplitude from 200 m/s² to 100000 m/s² and durations from 0.1 ms to 3 ms, with a relative expanded uncertainty of 2%. Aiming to improve this uncertainty and considering that
the commercial exciter is twenty years old, it was decided to evaluate the application of the new primary shock exciter also on comparison shock calibrations. The performance analysis of the Lavib-developed exciter for this kind of calibration is presented in this paper.

Calibration results of a shock transducer performed on the Lavib shock exciter and on the commercial exciter were compared. Both of these shock exciters use pneumatic actuators to generate the shock pulse. The same signal conditioning amplifiers and the same data acquisition system were used in the two experimental setups. The objective was to evaluate the repeatability of some parameters of the generated pulses and compare the results. It was expected that the new exciter could allow the reduction of the measurement uncertainties by diminishing the influence of some factors, such as transversal vibration, that increase the dispersion of the results. Another interesting convenience is to have the capability to perform both primary and comparison calibrations using one single system.

2. The Lavib-developed shock exciter

The Lavib-developed shock exciter, presented in figure 1, consists essentially of two 40 mm diameter airborne stainless steel cylinders (hammer and anvil), a pneumatic cylinder used as excitation system and stoppers with dampers to mitigate the energy and to limit the strokes.

A pneumatic cylinder pushes the hammer which shocks against the anvil. A soft elastic interface (pulse shaper) is needed to shape the acceleration pulse properly. A back-to-back reference transducer can be fixed on an adaptor at the other end of the anvil. The single-ended accelerometer under test is
mounted on the top reference surface of the back-to-back transducer. Some milliseconds after the pulse ends, the anvil motion is stopped by a damping system. Two hydraulic shock absorbers with adjustable damping rate are responsible for mitigating the kinetic energy of the anvil. The pulse amplitude can be controlled by the air pressure applied to the pneumatic cylinder and by the stiffness of the pulse shaper.

3. Experimental method
The experimental method used was to perform a calibration of a same transducer on the two exciter systems to compare the obtained results. The commercial shock calibrator (SE1) and the Lavib-developed exciter (SE2) were used to generate acceleration pulses with amplitudes of approximately 3500 m/s² and 500 m/s² and durations of 1 ms and 2 ms, respectively. All the measurement instruments used were the same for both systems, including the reference transducers, signal conditioning amplifiers, cables and data digitizing system.

Two Endevco 2270 back-to-back transducers, identified here as BTB1 and BTB2, were used as references to calibrate a single-ended accelerometer Endevco 2225 (DUT) for the 3500 m/s² tests. To evaluate the effect of smaller amplitudes, the BTB2 was applied for the 500 m/s² case.

The same data processing was applied to all signals acquired. The shock sensitivity of the accelerometer under test was calculated by taking the ratio of the charge amplitude generated by the accelerometer to the peak acceleration amplitude to which it was submitted. These amplitudes were calculated by the difference between the peak value and mean of the signal offset levels measured before and after the pulse. It was applied a 5th order polynomial fit in the peak region of the pulse to identify a maximum value regardless the digital restriction of amplitude and time resolutions.

The pulse durations were calculated by the time difference in milliseconds at 10% of the peak amplitude of each pulse. Second order polynomials were fitted to the data in the ascending and descending regions of the pulse to evaluate the corresponding time values. Twenty measurements were taken for each case with a sample rate of 250000 Sa/s for 1 ms pulse durations and 100000 Sa/s for 2 ms pulse durations.

4. Measurement results
Typical pulses obtained using BTB2 as reference in the two exciter systems SE1 and SE2 are presented in figure 2. The curves relative to 3500 m/s² amplitude and 1 ms pulse duration are presented in figure 2 (a). The pulses relative to 500 m/s² amplitude and 2 ms duration can be observed in figure 2 (b).

![Figure 2. Shock pulses of (a) 3500 m/s² and (b) 500 m/s² amplitudes.](image)

Mean values of the shock pulse parameters obtained from the data processing of the measurements, are presented in table 1 for the reference transducer BTB1 and in table 2 for BTB2.
Table 1. Calibration results for BTB1 as reference transducer.

| Quantity                  | 3500 m/s² (1 ms) |         |         |         |
|---------------------------|------------------|---------|---------|---------|
|                           | SE1   | SE2     | Difference          |
| Acceleration amplitude [m/s²] | 3578  | 3603    | + 0.7 %        |
| DUT shock sensitivity [pC/(m/s²)] | 0.0884 | 0.0875  | - 1.00 %      |
| Reference pulse duration [ms]  | 0.97   | 0.85    | - 0.12         |
| DUT pulse duration [ms]       | 0.98   | 0.86    | - 0.12         |

Table 2. Calibration results for BTB2 as reference transducer.

| Quantity                  | 3500 m/s² (1 ms) | 500 m/s² (2 ms) |         |         |         |         |
|---------------------------|------------------|-----------------|---------|---------|---------|
|                           | SE1   | SE2     | Difference | SE1   | SE2     | Difference |
| Acceleration amplitude [m/s²] | 3403  | 3338    | - 1.9 %  | 437   | 462     | - 11.7 %  |
| DUT shock sensitivity [pC/(m/s²)] | 0.0884 | 0.0879  | - 0.59 % | 0.0896 | 0.0891  | - 0.55 %  |
| Reference pulse duration [ms]  | 0.99   | 0.87    | - 0.12   | 1.95   | 1.93    | - 0.02    |
| DUT pulse duration [ms]       | 1.01   | 0.88    | - 0.13   | 1.98   | 1.95    | - 0.03    |

It can be observed that considering the same reference transducer, the acceleration levels obtained were close for both exciters indicating a similar condition of excitation. The acceleration amplitude difference was larger for 500 m/s². Considering the parameter pulse duration, the closest results occur at 500 m/s².

In the three measurement cases, the DUT’s shock sensitivity obtained on the new exciter system SE2 was lower than on the commercial machine SE1. The difference was greater with the reference accelerometer BTB1.

To analyze the repeatability performance, the standard deviations of measurements were computed and are presented in table 3 for the reference transducer BTB1 and in table 4 for BTB2. Relative percentage values are used to facilitate direct comparisons.

Table 3. Relative standard deviations (%) for BTB1 as reference transducer.

| Quantity                  | 3500 m/s² (1 ms) |
|---------------------------|------------------|
|                           | SE1   | SE2     |         |
| Acceleration amplitude    | 2.33  | 1.54    |         |
| DUT Shock Sensitivity     | 0.18  | 0.20    |         |
| Reference Pulse duration  | 0.70  | 0.37    |         |
| DUT Pulse duration        | 0.94  | 0.63    |         |

Observing the results presented in tables 3 and 4 it can be noted that almost all the measurement standard deviations of the parameters analyzed here have decreased with the use of the new exciter system. Just the DUT shock sensitivity using the reference accelerometer BTB1 at 3500 m/s² presented a negligible difference.
Table 4. Relative standard deviations (%) for BTB2 as reference transducer.

| Quantity                  | 3500 m/s² | 500 m/s² |
|---------------------------|-----------|----------|
|                           | SE1       | SE2      | SE1       | SE2      |
| Acceleration amplitude    | 1.60      | 0.94     | 1.65      | 1.54     |
| DUT Shock Sensitivity     | 0.12      | 0.08     | 0.16      | 0.08     |
| Reference pulse duration  | 0.60      | 0.31     | 0.53      | 0.30     |
| DUT pulse duration        | 0.50      | 0.31     | 0.68      | 0.33     |

5. Discussion

In general, the new Lavib shock exciter result presented an appropriate repeatability to provide calibrations of accelerometers by comparison with expanded uncertainties lower than 2%. This occurs probably due the use of small clearance air bearings and a precise control of the hammer propelling system. Air bearings maintain minimal friction along the movement of both hammer and anvil enabling higher repeatability of hammer excitation used to generate acceleration pulses on the anvil.

The pulse durations are basically a characteristic of the exciter, depending mainly on the pulse shaper components used. In this work it was taken the precaution to design pulse shapers to obtain similar pulse durations on the two exciters. This was important for a more reliable comparison between them.

The obtained differences between the two exciters on shock sensitivity, pulse amplitude and duration were considered satisfactory for the purpose of this repeatability analysis.

The ringing effect observed in figure 2 (a) for the SE2 curve at 3500 m/s² is due to excitation of an anvil longitudinal vibration mode by the shock. Initially, a low-pass filter had been applied to these signals to eliminate this effect. However, as the data processing already includes the polynomial fitting in the time domain, the results did not change significantly. Thus it was preferred to avoid the use of the low-pass filter.

The standard accelerometer BTB2 is more stable than the BTB1 and this could be observed on the results. The differences between the two exciters were less prominent when the reference BTB2 was used. This happened with the differences on shock sensitivity and on relative standard deviations of the acceleration pulse amplitude, shock sensitivity and pulse durations. The reason for this can be attributed to a flatter sensitivity response of the reference transducer BTB2 within the frequency ranges excited by the different pulse component frequencies, which were generated by the two shock exciters.

The flatness of the frequency-response sensitivity curve can also explain the difference on DUT shock sensitivity values between the two systems using the same reference transducer. Figure 3 presents the DUT sensitivity results obtained by sinusoidal excitation. The values are normalized by the sensitivity at 500 Hz. A half-sine acceleration pulse excites a broad range of frequencies in the accelerometer which depends on the actual pulse duration. Since the pulse durations obtained in each exciter was not exactly the same, the range of frequencies excited in each case was slightly different. Therefore, if the frequency-response sensitivity is not flat, the shock sensitivity may have been affected, explaining the differences between the sensitivity results of the two exciters.

Another feasible reason for the differences found on shock sensitivity values could be the unknown influence of axial vibration of the developed exciter anvil on the response of the transducers. The reliability of this phenomenon influence was diminished with the results obtained for 500 m/s² peak amplitudes. It was not observed ringing on the 500 m/s² amplitude pulse but it presented the same difference in shock sensitivity from the commercial exciter results.
6. Conclusion

This work has presented the performance of a new mechanical shock exciter developed at the Vibration Laboratory of Inmetro for accelerometer calibrations by comparison. The study was developed making calibrations of a single-ended transducer in the new system and in a commercial machine that has been used by Lavib for customer’s transducer shock calibration. The performance of these two exciters was compared by evaluating the repeatability of acceleration amplitude and duration of the pulses and also of the shock sensitivity values obtained them. The same auxiliary instrumentation as for instance signal conditioning amplifiers, cables and digitizing devices were employed to acquire the generated pulses in both systems.

Calibrations were carried out using two different back-to-back reference accelerometers. The results obtained with the new shock exciter have indicated that the developed apparatus presents an improvement in repeatability to generate shock pulses. Using the reference transducer BTB1, the relative standard deviations of the acceleration pulse amplitude, shock sensitivity, reference and DUT pulse durations were, respectively, 1.5 %, 0.2 %, 0.4 % and 0.6 %. For the reference transducer BTB2, two sets of calibrations were carried out. At 3500 m/s², the pulse amplitude presented a relative standard deviation less than 1% and for 500 m/s² the value was 1.5 %. The relative standard deviations of shock sensitivity and of reference and DUT pulse durations were the same values for the two amplitudes: 0.08 %, 0.3% and 0.3 %, respectively.

This study demonstrates that the new system despite of being developed mainly for primary shock calibrations can also be used for comparison calibrations. Further measurements will be carried out using a flatter sensitivity DUT to investigate the shock sensitivity differences between the systems, excluding this component of influence.

References
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