Vibration Testing to Assess the Transport Behaviour of Reference Standards and Mobile Scientific Devices

Leonard Klaus, Stephan Hannig, Harald Bothe
Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
E-mail: leonard.klaus@ptb.de

Abstract. It is becoming increasingly important to assess the suitability for transportation of reference standards used for intercomparisons and of scientific devices developed to be transportable. For this purpose, normative documents were analysed in order to find a suitable test schedule, and two devices under test – one inductance standard and one optical cavity – were exposed to acceleration spectra simulating the typical transportation of each of the devices under test for different durations.

The different devices under test are described and the motivation for the transport simulation is given. The results of the different tests are presented.

1. Introduction
Scientific devices are often fragile and not designed for transportation. But if transportation is still necessary, an assessment of whether the device is capable of withstanding the vibrations occurring during shipment can be helpful. In interlaboratory comparisons, a reference standard will be shipped from the pilot laboratory to all other participating laboratories. Its dedicated properties will be measured at each laboratory and then it will be sent back for verification measurements. The chosen reference standard should be stable in terms of the achievable measurement uncertainties at least for the time of the comparison. For this purpose, extensive tests are carried out, and the standards are monitored long before the comparison in order to analyse their long-term stability [1]. Data loggers are used to monitor temperature, humidity and the maximum acceleration during transportation of reference sensors [2]. Similar requirements and precautions exist for the transportation of art works, which are very valuable goods which cannot be replaced if damaged and therefore need to be prepared carefully for transportation [3].

If scientific devices are designed to be transportable, their stability under transportation conditions is of great interest to ensure reliable operation after transportation.

2. Normative Documents and Literature Review
Road vibration tests are used extensively in the packaging industry for the optimisation of product packages. Several standards describe test procedures for the assessment of packages [4, 5, 6, 7]. Research has shown that the actual exposure of packages to shocks and vibrations during transportation can vary significantly. It depends strongly not only on the quality of the road surface, but on the vehicles used as well. While some standards [5, 6] are rather vague in terms of the different excitation spectra, [7] gives a huge number of different...
spectra according to the type and location of transportation. In [4], different spectra in different locations were measured, too [5], but a general spectrum for typical purposes is offered as well. Nevertheless, in terms of test duration, this standard remains still vague.

The standardisation documents recommend random noise excitation with Gaussian distribution. This distribution does not ideally represent the vibration occurring during transportation due to the vibration’s non-stationary nature [9]. Different analysed exposure spectra showed a wide range of distributions, which could be described e.g. by a Weibull distribution [9], or could be generated by a vehicle model and previously recorded road surface data [10]. However, analysing the distributions in [9] gave a majority of the acquired spectra with a symmetric distribution with strong similarities to Gaussian distribution. As the Gaussian random noise excitation is easy to implement, we decided to carry out the vibration test schedules according to [4], but taking the limitations into account by extending the vibration magnitude and/or the test duration.

3. Test Stand
The test stand used for the simulations is a three component exciter system, which is capable of generating oscillations in the three transversal degrees of freedom [11]. For this purpose, three electro-dynamic shakers are connected by a hydraulic bearing unit. In each axis of excitation, accelerations of up to 100 m/s² and displacements of 50 mm can be generated in a frequency range of 1 Hz up to 1 kHz. The maximum payload is 100 kg (then with limited excitation levels).

Usually, the system is used at PTB for the calibration of multi-axis accelerometers, for the analysis of the transverse sensitivity of uniaxial accelerometers, and for the calibration of heavy sensors as seismometers.

The generated oscillations are controlled by a multi-input-multi-output control system, which enables the automatic generation of sinusoidal or random noise signals. Additionally, arbitrary signals (e.g. from measured data) can be replicated by the control system. In the case of uniaxial excitation, the control system compensates for crosstalk between the different axes and suppresses parasitic movements of the inactive axes.

4. Example: Inductance Reference Standard
The issue of reference standards, which are not stable enough during transportation, exists in the field of electric quantities [12, 13] as well as in the field of mechanical quantities [14]. For a new comparison of inductance standards, the influences of transportation were assessed by analysing similar inductances as designated for use during the comparison [15]. The General Radio GR1482 inductance standard has been used at PTB and other national metrology institutes since the 1960s for maintaining the measurand inductance and for the dissemination of this unit to accredited laboratories. Therefore, the long-term behaviour of such standards is well known (see figure [1]). However, in the past, these standards have been carefully carried from door to door by experienced laboratory staff, avoiding temperature changes and shocks as far as possible and they have not been exposed to the kind of stresses that widely unattended air transport may cause.

The General Radio GR1482 inductance standards [16] consist of multiple wire layers mounted on an unmagnetic toroidal ceramic core. The coil rests inside a cardboard cylinder on a cork granulate bed. The cardboard cylinder is placed on three wooden stands. It is completely surrounded by a sealing compound and placed inside a sealed aluminium housing. This outer housing poses as an electrostatic guard as well. The shape of the coil determines the course of the magnetic and electric field, and therefore, the inductance. Changes of the wire positions in the coil and of the coil in relation to the housing lead to changes of the magnetic coupling and may change parasitic capacities. Therefore, shocks and vibrations may be of potential harm for the reproducibility and stability of these inductance standards.
The geometry of the windings determines the magnetic and electric field and the resulting inductance. Changes in the position of the turns against each other and of the entire coil against the environment lead to changes in inductance both directly by changed magnetic coupling and indirectly by changes in parasitic capacitances. Therefore, shocks and vibrations potentially endanger the result of a comparison.

To prepare for an international intercomparison, several tests were carried out to assess the stability of the aforementioned inductance standard during transportation. Figure 2 shows the behaviour of our device under test to exposure to hard shocks, as they may occur through improper handling during transportation. Since we would expect the response to the applied shocks immediately after the impact, the delayed response is rather caused by a temperature change due to the handling. However, the acceleration readings are also lower than expected, which indicates a limited bandwidth of the used accelerometer.

To analyse the influence of road vibration during transportation, an extensive vibration test was carried out. The device under test was mounted directly on the shaker table and was exposed to a vibration spectrum according to [4] in a vertical direction. To take into account the typically very long distances during an intercomparison, the duration of the test was extended to 8 hours, which should be equivalent to a (road) journey length of about 6000 km to 7000 km.

After the tests and a subsequent temperature stabilisation, the inductance of the standard was measured again. The final reading compares to the initial measurements within parts of $1 \times 10^{-6}$. Despite the rough handling, the long-term deviation is still considerably below the manufacturer’s specifications. We can conclude that this type of standard is well suited as a travelling standard due to the demonstrated transport stability. The typical temperature dependency of $30 \times 10^{-6} \text{K}^{-1}$ remains the most significant source of influence.

5. Example: Transportable Optical Cavity for Second Harmonic Generation

Traditionally, the large majority of optical experiments has been carried out in highly specialized laboratories. Nowadays, an increasing number of such experiments require (trans-) portability, including laser sources, some of those in the ultraviolet (UV). Examples of this are transportable optical clocks [17, 18, 19], which allow for a height measurement technique named chronometric levelling [20], i.e. exploiting the gravitational red shift by comparing two clocks at different
locations to determine their relative height difference. For many UV wavelengths, there are no direct laser diodes available. Instead, the desired light is obtained by second harmonic generation (SHG)\textsuperscript{[21]} of the suitable wavelength in the visible part of the spectrum. Since SHG processes in nonlinear crystals are rather inefficient in single pass, the latter are placed in optical resonators for the fundamental light. The conversion efficiency of such an enhancement cavity\textsuperscript{[22]} is prone to misalignment of the mirrors, the crystal, and also to changes of the optical roundtrip length. Therefore, a highly stable SHG cavity has been developed at PTB\textsuperscript{[23]}, consisting of a monolithic frame with integrated mirror holders and an aligner for the nonlinear crystal, as schematically shown in figure 3.

In order to demonstrate the suitability for transportable set-ups, the cavity has been exposed to vibrations according to\textsuperscript{[4]} in vertical direction for 30 minutes, as shown in figure 4. The acceleration levels were increased to 9 dB for this test in order to simulate transportation even under very rough conditions. The UV output was not significantly affected by the exposure to the acceleration excitation, i.e. the cavity is qualified for transportable applications.

6. Summary and Outlook
The suitability of PTB’s multicomponent acceleration device for transport simulation was shown based on two examples. The inductance reference has proved its suitability for international transportation during intercomparisons following a long-term test of 8 hours, which simulates a transportation distance of about 6000 km to 7000 km on the road. The specifications of the device under test still remained within the limits given by the manufacturer.

The suitability of an SHG cavity for transportable optical set-ups was demonstrated by exposing it to high vibration levels of 9 dB compared to the standard test procedure for 30 minutes without relevant changes in output power.

For this publication, all devices under test were mounted directly onto the shaker armature. However, it was shown in\textsuperscript{[3]} that a transport package can even increase the acceleration levels of the transported goods due to resonances. In future, these effects may be taken into account by adding the package for the transport simulation.
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