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MULTISINE SHOCK AND VIBRATION TESTING USING A HIGH-FREQUENCY 6-DOF SHAKER TABLE

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Abstract

Shock and vibration testing of railway applications is regulated by the European Norm EN 61373. Within the norm, acceleration spectra are specified by level, slope and cut-off frequencies. Tolerance on the spectra is +/- 3dB, which require carefully generated random driving signals and a reliable response of the global testrig-specimen system.

Random driving signals with appropriate power spectra can be obtained by filtering white noise signals or by using random multisine signals. The deterministic character of the amplitude spectrum of a multisine is one of the main advantages of this type of excitation over white noise excitation. It can be shaped exactly to any desired specification. Moreover, it provides a better signal to noise ratio at all excited frequency lines. In addition, multi-sine signals are periodic, therefore avoiding leakage errors in the estimated power spectra.

The reliability of the response of the global testrig-specimen system to the driving signal is improved by the use of a CUBE^{TM} High Frequency 6-DOF Shaker. Such a shaker table has recently been installed at the KULeuven-Noise and Vibration Laboratory and the present work is part of an extensive test and benchmarking program. In this paper the difference between displacement and acceleration driving signals is discussed based on both theoretical concerns and experimental results.

INTRODUCTION

This paper describes shock and vibration testing according to the European Norm EN 61373 [1] for railway applications. First the most relevant items of the norm are summarized, followed by a theoretical discussion on the multisine technique used for generating the random driving signals. Next the High-Frequency Hydraulic Shaker table and test setup are shortly discussed, followed by a discussion of the test results.

THE EUROPEAN NORM EN 61373

The EN 61373 Shock & Vibration Certification Test-procedure consists of a sequence of 11 tests:

- Initial full performance check of the device under test
- Three endurance random vibration tests (in X-, Y-, and Z-direction separately) of 5 hours at high excitation level without the device operating
- Three sequences of six (3 positive – 3 negative) 30 ms half-sine acceleration shocks (in X-, Y-, and Z-direction separately) at 3 or 5 g level, while the test device is not operating.
- Three functionality random vibration tests (in X-, Y-, and Z-direction separately) of 10 minutes at moderate excitation level, while the test device is in operation.
- Final full performance check of the test device

At the K.U.Leuven Noise and Vibration Laboratory, 12 different types of kitchen equipment for use in a railway wagon have been tested, according to thisEN 61373 procedure. The railway wagon fixture has been identified as Category 1 (=body mounted); Class A (=directly body fixed). [1]

A MULTISINE TECHNIQUE FOR RANDOM DRIVING SIGNALS

The driving signals for the endurance and functionality test are specified by their Acceleration Spectral Density (ASD in power per Hz). These acceleration spectra are specified by their level, slope and cut-off frequencies. From 5 to 20 Hz a constant spectrum is required, from 20 to 150 Hz a first order (6 dB/octave) roll-off is specified. Below 5 Hz and beyond 150 Hz acceleration levels must be inferior to first order roll-off lines. Spectrum tolerance is set at +/- 3dB, requiring carefully generated random driving signals and a reliable response of the global testrig-specimen system.

As driving signals are specified by their acceleration spectra, a driving time signal can be derived from the multisine formula used in [4,6]:

$$acceleration(t) = \sum_{i=1}^{n} \sqrt{ASD(f_i)} * \sin(2\pi f_i * t + phase(f_i))$$

with f_i the discrete frequencies in the acceleration spectrum (5Hz, 6Hz,…,150Hz). A more accurate frequency resolution can be obtained, but then the ASD must be divided by the number of frequency lines per Hz.

The $phase(f_i)$ can be chosen random, or optimized, for example to reduce peak accelerations. This is not further discussed here. A displacement formula can also be derived from the simple relation between displacement and acceleration in the frequency domain:

$$displacement(t) = \sum_{i=1}^{n} \frac{\sqrt{ASD(f_i)}}{(2\pi f_i)^2} * \sin(2\pi f_i * t + phase(f_i) + \pi)$$

When calculating the ASD of the acceleration based on a displacement signal, two methods can be applied: **(1)** double differentiation in the time domain (which can be numerically ill-conditioned for small amplitudes and high frequencies with respect to the sample rate) or **(2)** frequency domain double differentiation which means multiplication of the Fourier transform of the displacement signal with -ω^2. A doubly differentiated displacement ASD is plotted in Figure 1. At higher frequencies the roll-off is higher than that of the ASD calculated from the acceleration time signal. This small difference is due to the imperfections of frequency characteristic of a numerical double differentiation with respect to -ω^2. Sampling rate is 1000 Hz.

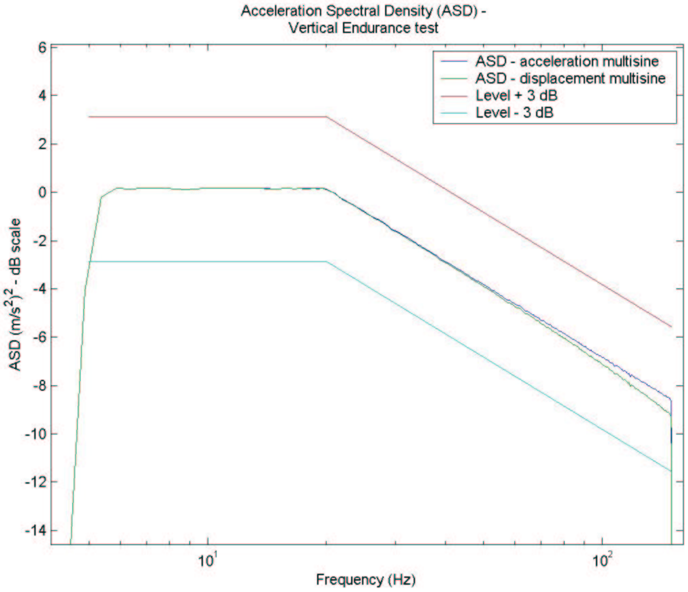

Figure 1: Acceleration Spectral Density - Vertical Endurance Test

For the considered vibration tests, random driving signals with appropriate power spectra can also be obtained by filtering white noise signals. An appropriate filter is obtained by means of a series combination of two first-order low-pass filters with cut-off frequencies at 20 Hz and 150 Hz, and a high-pass filter with a cut-off frequency at 5 Hz. The ASD of the resulting driving signals using this approach approximates the specifications with sufficient accuracy.

White noise signals have stochastic amplitude and phase spectra, while the amplitude and phase spectra of a random multisine are deterministic and random, respectively. This means that a time signal generated with white noise, over short time periods, yields ASD plots that are scattered around the target ASD. If we consider the +/- 3dB spectrum tolerance, the ASD of a long time signal (from a few minutes onwards) will be within tolerance, but the ASD of a shorter section (for example 10 seconds) will for many sections not be within tolerance.

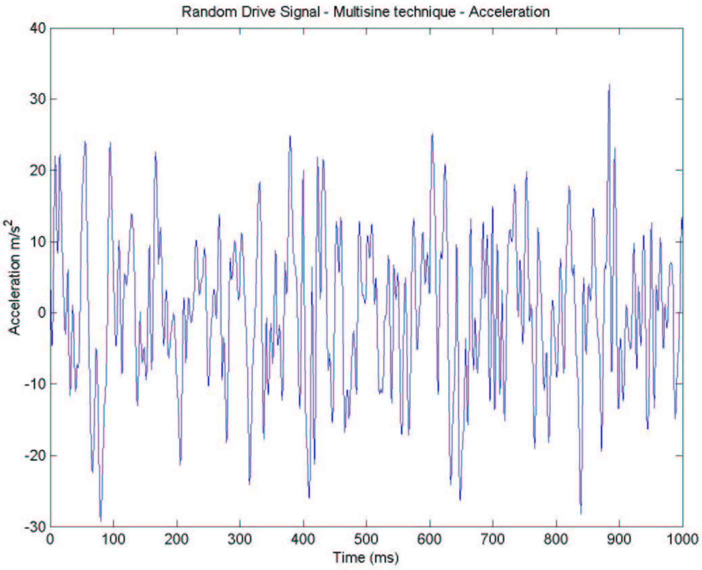

Figure 2: Multisine Acceleration Time Signal (1 second) - Vertical Endurance Test

This is not the case for multisine signals due to the deterministic character of the amplitude spectrum. The amplitude spectrum can be shaped exactly to any desired specification and is independent of the chosen length of the signal. Moreover, it provides a better signal to noise ratio at all excited frequency lines because each realization of this signal has the same deterministic power spectrum. With white noise excitation, the power spectrum differs for each realisation, yielding that occasionally some frequency lines are hardly excited resulting in a bad S/N ratio. In addition, multisine signals are periodic, noise signals are not, therefore avoiding leakage errors in the estimated power spectra.

THE CUBE^{TM} SHAKER – TEST SETUP

The reliability of the response of the global testrig-specimen system to the driving signal is improved by the use of a CUBE^{TM} High Frequency 6-DOF Shaker. This device, revolutionary by its concept, shows stunning NVH testing performance, with dynamic excitations up to 10 g between 0 and 250 Hz, for payloads up to 450 kg and beyond [2,3]. Such a shaker table has recently been installed at the KULeuven-Noise and Vibration Laboratory and the present work is part of an extensive test and benchmarking program.

The shock and vibration tests are performed according to the standardized NF EN 61373 procedure. The order of tests have been altered, for practical reasons, with the functionality test preceding the endurance and shock test. The order of excitation directions (vertical-transversal-longitudinal) is as specified by the norm. Since the Cube is a 6-DOF shaker, excitation directions are switched at the push of a button, no intermediate setup time is required, which drastically speeds up the test procedure. Original fixing points and supports without resonances in the frequency range of interest have been used. Some supports are designed based on FE calculations, where required resonance frequencies were experimentally verified.

Figure 3 Cube shaker table with some different device setups

Tests are performed on a CUBE^{TM} High Frequency 6-DOF Shaker. All orientations are correct with respect to the world and the railway wagon reference. The original fixing points are used for attaching the devices. The devices are mounted to the shaker table by means of custom made support frames (see figure 3). Every setup ensures a rigid connection between the shaker table and the device. No temperature or humidity measurements are required.

For verification of the applied shock and vibration signals, a reference signal needs to be defined. The reference signal, one for every DOF, is virtual and obtained by processing two displacement (LVDT) and/or acceleration (Accelerometers) measurements on the CUBE^{TM} body. This reference point is as close as possible to the connection points and rigidly linked to the device, both being directly mounted on the shaker table body. The reference is therefore representative, as specified in the norm, for the connection point's motion and acceleration. No additional measurements at the connection points are necessary, so only the reference signal is measured during the tests.

The time signal for the test is generated using the previously defined multisine technique with a 2^55 (=3.6e16) random number generator for the phase and is non-repetitive in nature, when considering exact signal levels, with respect to the maximum test length of 5 hours (1.8e7 samples at 1000 Hz). For this a little 'trick' was used. The frequency resolution is set to 0.050000001, so theoretically a multisine of 5 Hz and 5.050000001 Hz is only periodical after 1e10 periods (5 Hz) or 2e9 seconds or 2e12 samples. With 2900 separate sines summed, this is sufficient to comply with the norm.

The multisine signals are further processed with the Time Wave Replication [5] method. In an iterative pre-test identification the drive signal is adapted to generate, under the specimen load, the required response spectrum. Excitation levels in this phase are inferior or equal to the required levels. The reference point was used for this procedure. The difference between displacement and acceleration driving signals is clearly observed on the results. In the frequency range below 10 Hz displacement targets are needed, because the accelerometer responses are not reliable in this range. At higher frequencies displacement signal levels are quite low relative to the LVDT resolution yielding a low S/N ratio. Moreover, the method for calculating the ASD has a numerical effect on the displayed results. Therefore acceleration targets are needed in the higher frequencies above 50 Hz.

TEST RESULTS

Results are plotted as an ASD and Cumulative Probability Density Function of the acceleration signal.

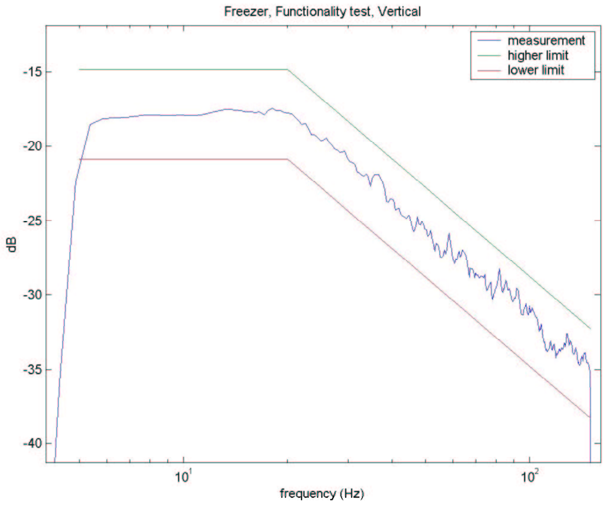

Figure 4: Acceleration Spectral Density - Example Result

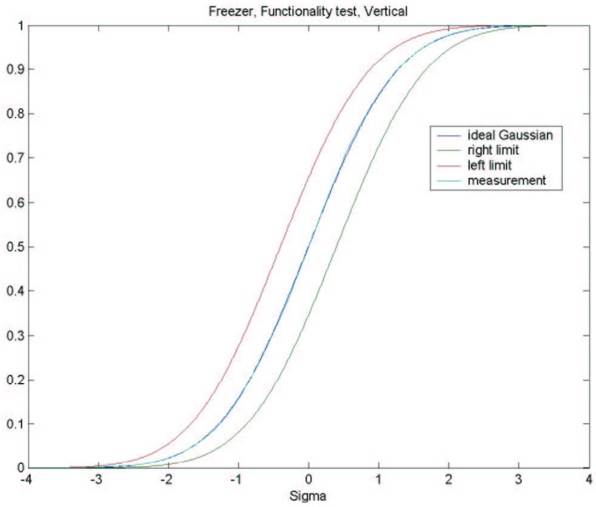

Figure 5: Cumulative Probability Density Function - Example Result

It can be clearly seen from the ASD-plot that results are very well within tolerances. Even better results are possible, but would require much longer TWR training time. The CPDF-plot shows almost ideal Gaussian distribution fulfilling another requirement of the norm. Effective values of the acceleration are also far better than the +/-10% tolerance allowed.

Shock tests were also performed according to the norm. Each time a positive and a negative shock were sequenced.

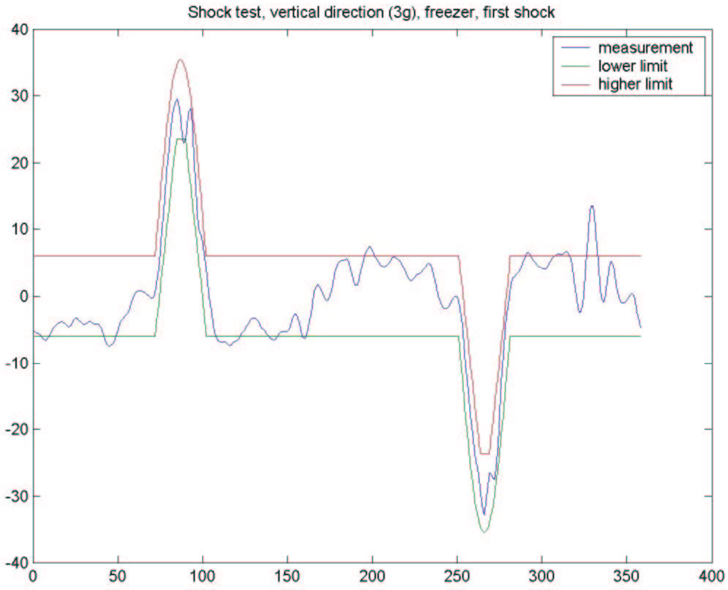

Figure 6: Shock Test - Example Result (acceleration (m/s^2) versus time (ms))

Figure 6 shows short and oscillatory accelerations exceeding the tolerance bands in the settling period between positive and negative shocks. The delta V (velocity change over the integration period specified in the norm) percentages of all shocks need to be within the tolerance band of 85-115%. On the longitudinal axis this tolerance is exceeded with 4-6 %. The deviation in the longitudinal axis is due to a new technique of drive file creation, only used for the 5g shocks, designed to limit the oscillatory accelerations in the settling time. The resulting shocks are somewhat narrower, yielding lower delta V values. Until now shock drive signals were only updated based on the displacement error. This method is limited for very accurate acceleration shock specifications. For the executed tests this was no problem. A new implementation using both displacement and acceleration errors is expected to deliver even better results.

No specific device results can be discussed for confidentiality reasons. A full test procedure on the shaker (9 individual tests, different levels and excitation directions) with a total testing time of 16.5 hours is accomplished within 24 hours, all setup, identification (TWR) and online post-test verification included.

CONCLUDING REMARKS

This paper shows the power of the multisine technique for generating driving signals according to any spectrum specification. Results on the shock and vibration tests, performed on some railway wagon kitchen devices, illustrate the performance, accuracy, speed and versatility of the recently installed CUBE^{TM} High Frequency 6-DOF Shaker. Better results for both shock and vibration tests are within reach. Suggestions have been made on the required methods to achieve this. Next to implementation and testing of the improvements, a new application of the multisine technique is planned with the generation of multi-axial displacement, acceleration and force spectra for structure-borne road noise testing on the CUBE^{TM} High Frequency 6-DOF Shaker.

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