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Advanced Dynamics: Laboratory Tutorials

Master's study programme

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April 3, 2013

1 Vibration testing of products **2**

Literature **9**

This material provides necessary terms for following the laboratory tutorials; it is assumed the student has obtained the knowledge from lectures and tutorials.

Student:		
Tutorial	Date	Assistant's signature
First		
Second		
Third		
Fourth		
Fifth		

We use $\LaTeX\,2_\varepsilon$.

1 Vibration testing of products

1.1 Tutorial purpose

Numerous branches of industry, especially automotive, marine and aviation, vibration testing is a general practice. They are used to check whether the individual components will hold up the entire lifetime without damage, according to the expected loads. The supplier can therefore verify of prove the sustainability of their product with vibration tests.

The purpose of this exercise is to present the essential steps of vibration testing on an industrial product. The basics of handling the shaker will be presented, which will be used to excite the test structures and the limitations of the test system will be examined. The differences between random, sinusoidal and impulse excitation will be presented. At the end you will also assess whether the tested product is vibrationally adequate.

1.2 Task definition

Your task is to perform an accelerated vibration test of a 'product', shown in Fig. 1. It needs to be verified whether the available equipment can be used for testing, and measuring resonance frequencies. Finally, it need to be validated whether the product can withstand the loads which occur in the accelerated vibration test.

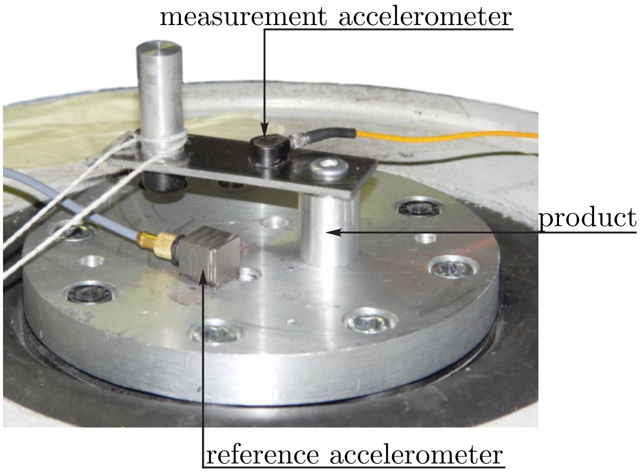

Figure 1: Test product and mounting.

1.3 Shaker LDS V555

During the laboratory tutorial, the LDS V555 shaker will be used, shown in Fig. 2. Its characteristics are listed in Table 1. LDS V555 is an electrodynamic shaker, therefore the vibrations are generated using a magnetic field acting on a ferromagnetic core inside. The shaker is connected into a measurement loop, shown in Fig. 2. The computer allows setting the excitation parameters and the controller uses a feedback loop (measuring amplitudes of acceleration using a reference accelerometer, shown in Fig. 1) during the measurement to ensure the shaker displacements are consistent with the prescribed excitation parameters. The controller signal is amplified, which ensures suitable excitation of the electromagnetic coil of the shaker. The acquisition of the vibration response of the product is performed by the analog to digital converter, connected to the computer.

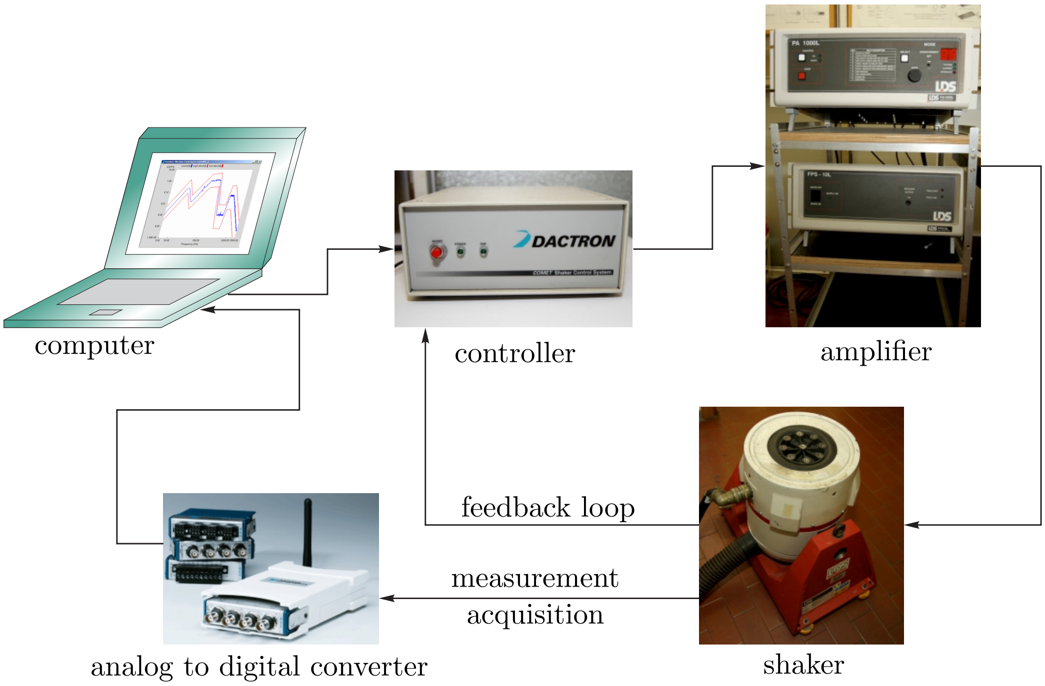

Figure 2: Measurement chart.

The shaker has a useful frequency range from 5 to 6300 Hz while the controller of the shaker enables random, sine or impulse excitation.

Table 1: LDS V555 shaker characteristics.

Features	Value
Maximum vector force for sine excitation	940 N
Maximum vector force for random signal	636 N
Armature mass	0.99 kg
Resonance frequency of empty armature	4850 Hz
Useful frequency range	$5 \rightarrow 6300$ Hz
Maximum acceleration	981 m/s^2
Maximum speed	1.5 m/s
Maximum displacement	25.4 mm
Maximum added mass to armature	25 kg
Diameter of the armature fitting plate	ϕ 110 mm
Measurements: height×width×length	$430 \times 300 \times 530$ mm

1.3.1 Calculating the shaker limitations

Maximum allowed mass. Due to static loads on the bearings, which lead the shaker head in the axial direction (predominantly in the case, when the shaker is put in the horizontal position), the mass of the *load* (product and mounting) has an upper limit. All the equations needed are available in the shaker manual [1]. The maximum allowed mass of the load P is calculated by:

$$P = \frac{A}{B + X} \quad \text{in [kg]}, \tag{1}$$

where A and B represent the constants of the bearing loads, determined by the shaker manufacturer (A = 567 kg mm, B = 44 mm), and X represents the distance between the shaker head and the load center of mass (shown in Fig. 3).

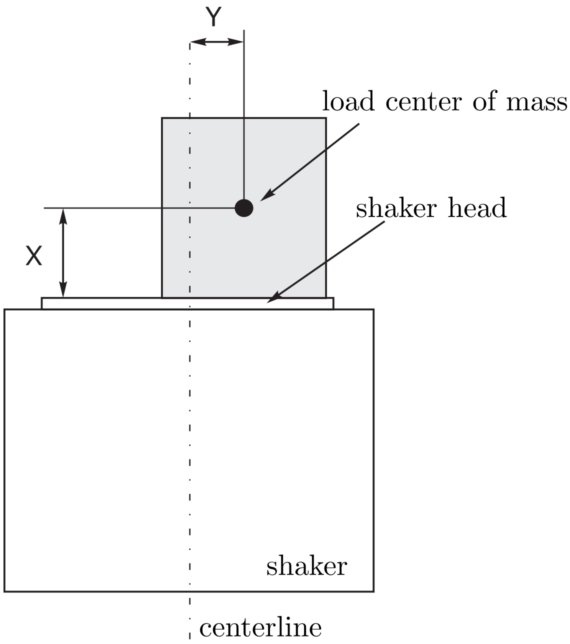

Figure 3: Load center of mass with respect to the armature and the shaker axis.

Maximum acceleration. By adding more mass to the shaker, the amplitudes of the acceleration decrease due to a limited maximum force. This can be simply explained using Newton's second law of motion, stating:

$$a = \frac{F}{M}, \tag{2}$$

where F is the maximum force which can be produced by the shaker (Table 1), M is the mass of the load on the shaker, and a is the theoretical maximum acceleration, which can be reached[1].

Limitations of speed and displacement. There are other limitations of the shaker, aside form the maximum allowed mass, which depend on the excitation frequency:

- From 5 to 20 Hz, the maximum displacement is limited to 25.4 mm.
- from 20 to 100 Hz, the maximum speed is limited to 1.5 m/s.
- from 100 Hz upwards, the maximum acceleration is limited to 981 m/s^2.

Eccentricity of the shaker load. When the load is fitted eccentrically, the shaker bearings are loaded with a dynamic torque. The instructions for use [1] dictate the calculation of the maximum allowed

[1] A more detailed calculation is not the subject of this laboratory tutorial.

excitation acceleration a_c, which does not present a risk for damaging the shaker. The acceleration depends on the lowest excitation frequency:

$$a_c = \frac{(A - M\,Y)\pi^2 f^2}{250\,B\,C} \quad \text{in [g]}, \tag{3}$$

where C is a constant ($C = 2280$ N/mm), f is the lowest excitation frequency and M is the mass of the load.

Resonance frequency of the mounting. To ensure suitable vibration profile, the mounting and its own dynamics should not affect the amplitude and shape of the vibration signal. The first resonance frequency of the mounting must be therefore well above the maximum frequency of the excitation. Among other things, it must be verified that the resonance frequency of the mounting bolts is appropriate. First, the total stiffness of the bolts K must be determined:

$$K = \frac{E\,A_v\,n}{L} \quad \text{in [N/m]}, \tag{4}$$

where E is the Young's modulus of the bolt material (typically steel), A_v is the area of the cross-section of a single bolt, n is the number of mounting bolts, and L is the length of each bolt. The first resonance frequency F_l is estimated as:

$$F_l = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \quad \text{in [Hz]}. \tag{5}$$

1.3.2 Excitation types

The shaker enables three types of excitation - sine sweep, broadband random excitation and impulse excitation. The first two types are characterized in the frequency domain, while the last one is characterized in the time domain.

The shape of the excitation signal, e.g. The shape of the impact in the impulse excitation or changing the amplitude of the signal with respect to frequency in the sine sweep is called *excitation signal profile.*

Sine sweep. Historically, the sine sweep was the first excitation profile, which were used with shakers. It is typical that the test structure is excited from the lowest frequency towards the highest and then in the reverse direction. The entire frequency range is therefore "swept", while an arbitrary acceleration amplitude can be set for each frequency (as shown in Fig. 4). Only a narrow frequency range is excited at once, therefore this profile is especially appropriate for studying nonlinear systems.

Broadband random excitation. The spectrum consists of infinitely many different sine waves, which differ in amplitude and frequency, therefore the excitation of the test structure is random. This enables a good description of excitation from the real world, e.g. when riding a car on the road. The profile shape of the spectrum can be therefore arbitrary, while the limitations of the excitation are mainly the physical capabilities of the shaker and controller. An example of broadband random excitation profile is shown in Fig. 5.

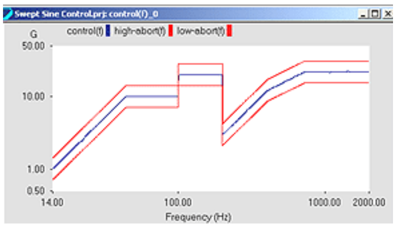

Figure 4: Example of Sine sweep profile. [2]

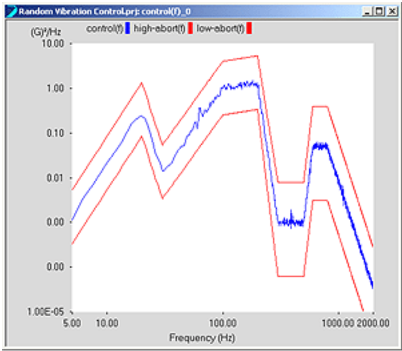

Figure 5: Example of broadband random profile. [2]

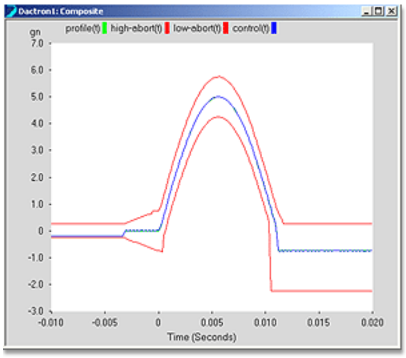

Figure 6: Example of impulse profile (half-sine). [2]

Impulse excitation. Using the shaker, an impulse can be generated. The impulse profile is determined by its shape in the time domain (half-sine, triangular, ramp. . .), the amplitude and the duration in milliseconds. An example is shown in Fig. 6. This profile is typically used for the simulation of impacts on the product, e.g. closing the door, the load of the product in a car crash. . .

1.4 Measurements

An imaginary product, shown in Fig. 1, will be mounted to the head of the LDS V555 shaker, which will be used to excite the product. Additionally, the controller, amplifier and a PC will be required. This laboratory tutorial consists of the following tasks:

1. Verify if the selected shaker can be used to test the product.
2. determine the product's resonance frequencies.
3. Verify that the product can withstand the prescribed impact tests.
4. Verify that the product can withstand the prescribed loads of the accelerated vibration test.

1.4.1 Checking the shaker capabilities

The data needed for calculations are listed in Table 2

Table 2: Load data.

Data	Value
Mass of the mounting and product	0.43 kg
Displacement from the armature (X)	25 mm
Imbalance with respect to the shaker axis (Y)	20 mm
Lowest excitation frequency	150 Hz
Bolt type	M6×45 mm
Number of bolts	8

1.4.2 Determining the resonance frequencies

Resonance frequencies of the product can be determined from the frequency response function (ratio between the amplitudes of response end excitation):

$$FRF = \frac{a_{resp}}{a_{exc}}. \tag{6}$$

In the ongoing example, the amplitude of the response is the amplitude of accelerations, measured on the product, while the amplitude of the input signal is the amplitude of the acceleration of the reference accelerometer. The reference accelerometer must be mounted to the base of the mounting, while the measurement accelerometer must be mounted at an appropriate location on the product. Determining the resonance frequencies can be achieved using a sine-sweep excitation between 150 Hz and 1000 Hz with the amplitude of 10 m/s^2 with the sweep rate of two octaves per minute.

1.4.3 Impact tests

In the next phase, the resistance of the product to impacts must be tested. The product is therefore excited with six impulses. The impulse shape is a half-sine with the amplitude of 50 m/s^2 and the duration of 10 ms. The product must not be damaged after the impact testing.

1.4.4 Accelerated vibration test of the expected lifetime

One of the objectives in vibration testing is to validate if the product can withstand the loads in the entire lifespan. The excitation profiles are chosen such that the amplitudes are higher than the expected amplitudes during normal usage. Accelerated vibration test therefore typically loads the product for approximately 50 to 100 testing hours, resembling several years of real-world application loads. During this laboratory tutorial, the product will be subject to a 5 minute excitation with an amplified broadband random profile, defined in Table 3. The product must not be visibly damaged after the test.

Table 3: Random profile parameters.

Frequency [Hz]	Power spectrum $[(m/s^2)^2/Hz]$
150	40
250	40
300	30
600	30
650	15
1000	15

1.5 Review of measurements and results

Symbol	Value	Unit
Calculating shaker limitations		
P		kg
a_c		g
F_l		Hz
Resonance frequencies of the product		
f_1		Hz
f_2		Hz
f_3		Hz
f_4		Hz
f_5		Hz
f_6		Hz

1.6 Theoretical questions

1. Why are products subject to vibration testing?
2. Should the excitation be performed below the first resonance frequency of the mounting?
3. Does the location of mounting the reference accelerometer affect the excitation?
4. Is the location of the measurement accelerometer important when measuring the FRF?
5. Are the FRFs obtained by sine sweep and random excitation equal if the studied system is linear? How about if the system is nonlinear?
6. What is the difference between sine, impulse and random excitation?
7. How does the mass of the load affect the amplitude of the acceleration which can be reached by the shaker?
8. What are the limitations of the shaker?
9. Why is an eccentric load unsafe for the shaker?

References

[1] Ling Dynamic Systems, *Installation and Operating Manual, V550 Series Vibrators*, Instructions for use, Royston, England, 1995.

[2] LADISK, Vibration testing, Presentation of measurement equipment, Ljubljana, 2007.