Latest Design of Sine and Shock Exciters for Calibration Purposes

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Abstract

SPEKTRA is a leading manufacturer of Calibration Systems for vibration and acoustic sensors for use in laboratory applications.

Special hardware, software and system concepts have been jointly developed for the mass production of MEMS. Since in sensor production and some metrological applications extreme requirements for sine and shock levels and frequency ranges have to be met, SPEKTRA has decided to design special exciters of their own.

The paper will present new designs, measurement results and examples of applications to calibration systems. The extended capabilities of the high frequency air bearing vibration exciter SE-09 will be discussed in more detail. Applications to primary and secondary calibration systems will be demonstrated and measurement results will be given.

For the high shock exciters of types HOP-S and HOP-P, theoretical considerations of how to scale up their shock amplitudes without compromising highest quality signal waveforms and excellent stability of mechanical excitation will be discussed and compared with practical measurement results.

Finally an outlook on further developments of vibration and shock exciters for use in calibration and sensor production will be given.

Keywords: calibration, SPEKTRA SE-09, High-Frequency Shaker, HOP-P, HOP-S, Shock calibration

1. Introduction

In any calibration system, the vibration exciter is a key component. The exciter is decisive in ensuring high quality of calibration to obtain the lowest possible measurement uncertainty. Higher and higher demands have been made on the quality of calibration which could not be satisfied any more by means of the existing types of exciters. This is the reason why SPEKTRA has responded to the demands of the market by developing exciters for the calibration of acceleration sensors with sinusoidal and shock-type signals. It has been the aim of this development to further boost the shaker performance beyond the existing state of the art. As a result we were able to introduce two new products: the type SE-09 High-frequency vibration exciter and the type HOP-S or HOP-P High-acceleration shock exciter.

Their modes of operation as well as their technical specification will be outlined in the following.

2. High Frequency Shaker SPEKTRA SE-09 – General Information

The SPEKTRA SE-09 shaker is a high-tech product that is based on extensive theoretical and practical considerations and investigations. It has been designed specifically for use in calibration laboratories and in National Metrology Institutes. In combination with the internal reference standard accelerometer, the usable frequency range of calibration could be extended to 50 kHz.

Figure 1 SPEKTRA SE-09

It is a special feature of this type of shaker that technical ceramic is used for the exciter armature. By using this material and applying FEM techniques we have succeeded in constructing an armature that is light-weight, on the one hand, but extremely rigid, on the other. This type of armature combines excellent vibration characteristics with extremely low wear and tear.

The driver system of the shaker is of the electro dynamic type with permanent magnets. All components of the drive are designed for heavy-duty operation. Consequent application of up-to-date design methods and materials has resulted in clearly improved performance with respect to maximum acceleration amplitude.

Application of specially designed air bearings was a key issue to reduce transverse motions and the mechanical background noise.

Due to the application of top performance materials (armature made from technical ceramic, driver system with high-performance magnets) and its optimized design the shaker has a very high power density. The result is a light-weight shaker with small dimensions.

In conjunction with a standard Laser vibrometer - replacing the internal reference accelerometer - the shaker can be used in class 1 primary vibration calibration systems such as the CS18P HF.

2.1   High Frequency Shaker SE-09 – Data [1]
2.1.1   Fields of application

- **Primary calibration** of vibration sensors according to **ISO 16063-11**

- **Secondary calibration** of vibration sensors, calibrators and meters with very high quality and performance according to **ISO 16063-21** (comparison calibration)
- Calibration of **reference standard transducers**
- **Resonance frequency search**

2.1.2 Potential users

- **Certified calibration laboratories** with outstanding quality demands
- Departments of measuring instrument verification in **research and industry**
- **Quality assurance** in sensor manufacturing
- **National Metrological Institutes** in their capacity as the highest metrological authorities (in combination with CS18P)

2.1.3 Features

- **Air bearing** ceramic armature
- **Very high** first axial **resonant frequency** of **head**
- **Very high acceleration amplitudes** (up to 400 m/s²)
- **Negligible Transverse motions** according to ISO 16063-11
- Usable frequency range up to **50 kHz**
- Maximum displacement 10 mm (peak-peak)
- Maximum payload mass (DUT) **350 gram**
- Extremely wear resistant **ceramic armature** with definite small electrical conductivity **(ESD characteristics)**
- **Internal high frequency reference accelerometer** (ICP$^®$-type, sensitivity approx. 1 mV / m/s²)

2.2 High Frequency Shaker SE-09 – Aptitude for Calibration Purposes

The type SE-09 Vibration exciter has been developed with the aim of meeting the ever growing demands of primary and secondary calibration. Apart from a general increase in performance (increase in maximum acceleration amplitude, reduction in transverse vibration, reduction in mechanical disturbances, etc.) the exciter is particularly well suited for use in primary calibration.

The extremely low-wear ceramic armature makes it nearly impossible to scratch the armature coupling surface when mounting a test object. This helps to maintain very high reflectivity of the vibrometer even after a very long period of time. The vibration-related design of the armature coupling surface is another positive feature.

We have succeeded in optimizing the shape of the armature such that the deformation of the coupling surface is clearly smaller in comparison with those of our competitors. Deformation can be expressed by the difference between the acceleration amplitudes along the coupling surface when exciting an attached payload with a signal of definite vibration amplitude and frequency. At 20 kHz, 100 m/s² and for a payload of 20 gram the difference in acceleration amplitudes between the brim of the armature and its centre is approx. 4 % for the SE-09. Compared to this, the coupling surface of a type 2911 shaker deforms twice as much.

On the one hand, the differences in acceleration amplitudes on the coupling surface inevitably have an effect on the calibration result. Measured sensitivities of the test objects are higher than their real values. On the other, this deformation increases the base strain of the test objects and so causes an additional contribution to the measurement uncertainty budget.

In addition to the excellent general aptitude of type SPEKTRA SE-09 for secondary calibration as mentioned above, this exciter features an integrated internal reference standard sensor with an excellent frequency response. The next figure shows the frequency response curves of two reference standards up to 20 kHz. In this figure the SE-09 is compared with the internal reference standard of type 2911 (2270M18).
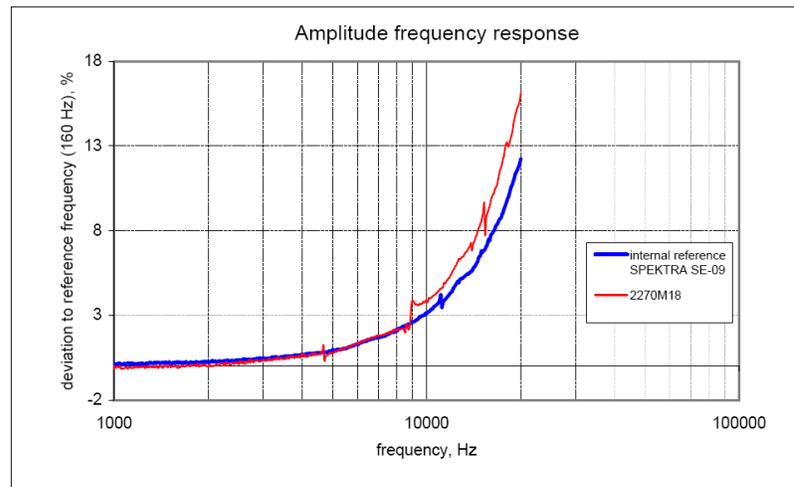

Figure 2 Frequency Response up to 20 kHz

You can clearly see strong discontinuities in the frequency response curves of the reference standard 2270M18 (approx. 2 % at 9 kHz). In SPEKTRA calibration systems the frequency response values are stored and will be taken into account or corrected when doing a calibration run. This is possible on the assumption that the frequency response curve is continuous. It would be pointless to try correcting the discontinuities of type 2270M18, thus it is inevitable that they must be taken into account in the form of contribution to the measurement uncertainty budget.

Due to its overall design and its integrated internal reference sensor, the type SE-09 vibration exciter is extremely well suitable for secondary calibration with frequencies up to 20 kHz. In particular it is the continuity of its frequency response that makes this shaker the first choice compared with competitors' products.

Another significant benefit of this shaker becomes obvious when you compare the frequency response curves of the internal reference sensor type SPEKTRA SE-09 with that of type 2911 for frequencies up to 50 kHz. In this extended frequency range the SPEKTRA shaker can be used in testing the frequency response of test objects for the presence of resonances (resonance search) using swept sine signals.
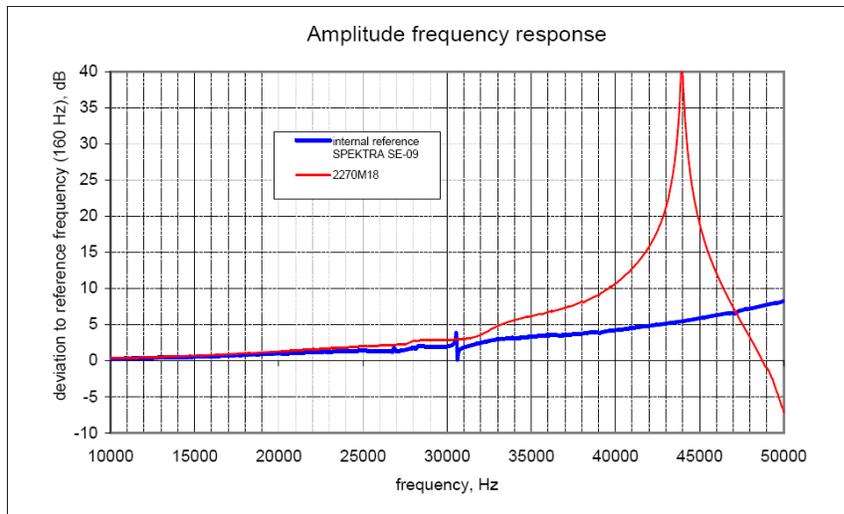
Figure 3   Frequency Response up to 50 kHz

From Fig 3 you can see that the resonant frequency of the internal reference standard of type 2911 is located at approx. 44 kHz. This resonance is an extreme discontinuity and so reduces the usable frequency range to approx. 40 kHz.

Compared with that, the frequency response of the SE-09 reference standard is free from disturbances in the entire frequency range, with the exception of a small discontinuity at 30 kHz. Consequently the shaker can be used for resonance search up to 50 kHz without any problems.

The fluctuation of sensitivity due to warming-up is another vital characteristic of every reference standard sensor. Since the armature of a vibration exciter will inevitably warm up as soon as a driving signal is applied, the amount of heat to which the reference standard is exposed makes itself felt in form of a permanent disturbing quantity. Assuming an ideal test object (i. e. one without any temperature response of its own), the values of sensitivity determined at the beginning of a longer test run would differ from that at the end.

Thus the effect of temperature on the calibration result can be reduced by optimizing the driver system (less warming-up) and selection of a reference standard with a small temperature response.

For this reason a test was worked out by SPEKTRA by means of which this effect could be evaluated. The sensitivity of the reference standard is measured over a period of 30 minutes by means of a primary method, with the exciter vibrating at 80 Hz with 200 m/s². In the example shown in Fig 4 the sensitivity fluctuation of the internal reference standard of a type 2911 shaker is compared with that of the internal   reference   standard   of   a SPEKTRA SE-09 exciter.

We learn from Fig 4 that the sensitivity of type 2270M18 changes by approx. 0.5 %. Consequently this change must be taken into account as a contribution to measurement uncertainty.

In the above test the armature of the 2911 exciter warms up by approx. 7 K, the one of the type SPEKTRA SE-09 by approx. 5 K. This increase in temperature is a measure of how efficiently the driver system of the shaker works.
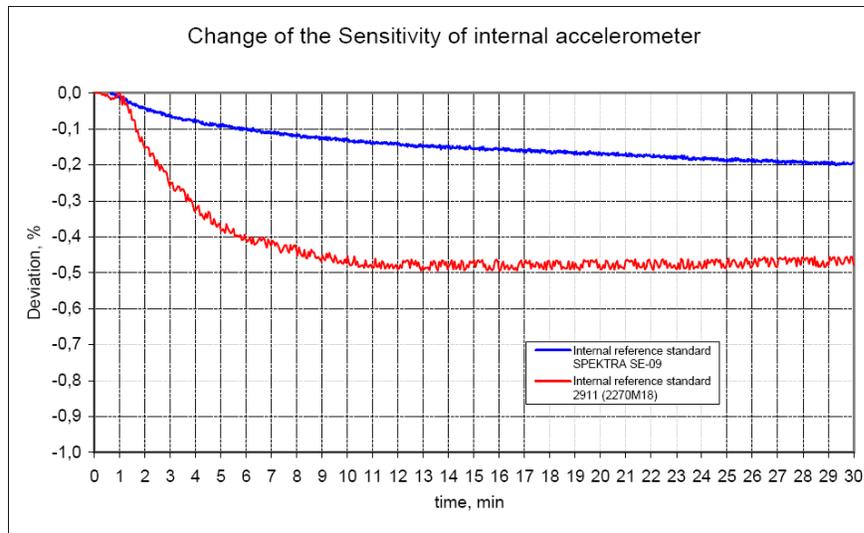
Figure 4 Temporal Fluctuation of Sensitivity of internal accelerometers

2.3   High Frequency Shaker SE-09 – Conclusions

Presenting the SE-09, SPEKTRA has developed a high-frequency vibration exciter that is capable of meeting the increasing demands of the market. The characteristics of this shaker are well above the technical specifications that are typical of the present state of the art. Due to this and in conjunction with the selected internal reference standard, the characteristics of test objects can be determined in extended ranges of the excitation quantity. The extended frequency range of the shaker and the high thermal stability of the entire system are particularly relevant to reaching this goal.

3.   High Shock Exciter HOP – theoretical considerations

The so-called Hopkinson bar principle has been used for a number of purposes since the beginning of the 20th century. It is a common feature of all these applications that a mechanical wave propagating in a long slender bar is exploited.

In the calibration of acceleration sensors, the effect of wave reflection at the free ends is utilized, with the ends of the bar being set in motion. As these movements occur in a very short period of time, they may result in extremely high acceleration.

Existing Hopkinson-bar systems are capable of generating acceleration amplitudes of up to 2,000,000 m/s².

It is a common feature of all Hopkinson bar systems that the mechanical wave is generated by the impact caused by a projectile or the like hitting one end of the bar.

To obtain higher and higher acceleration amplitudes, the shock force must be increased more and more, so the material of the projectile and the bar is exposed to very high mechanical tension. This extreme stress causes high wear and tear of the collision partners which, therefore, must be replaced quite frequently. In the Hopkinson Bar System type 2973A a so-called mitigator is used that must be replaced after each calibration. Due to this high wear and tear, both the reproducibility and the possibilities to scale the acceleration pulse shape are reduced.

To control these problems, thorough theoretical and practical investigations were carried out by SPEKTRA. In the beginning no theoretical model was available for describing the fundamental structure of a Hopkinson bar used in the calibration of acceleration sensors. So the first task to be solved was to work out such a model.

The elaborated model is made up of two main components:

- mechanical force pulse
- transfer characteristic of the bar (relation between acceleration-time function and force-time function)

Assuming one-dimensional wave propagation, the transfer characteristic of the bar can be derived from the one-dimensional wave equation (Equ 1):

$$\frac{\partial^2 u}{\partial t^2} = c_0^2 \frac{\partial^2 u}{\partial x^2} \qquad \text{Equ. 1}$$

Having introduced the appropriate constraints, the transfer characteristic of the bar can be described by the relation between driving force and resulting acceleration:

$$a(t) \quad \frac{dF(t)}{dt} \qquad \text{Equ. 2}$$

From Equ 2 we learn that the acceleration-time function is proportional to the derivative of the force-time function with respect to time. The proportionality factor depends on the material and geometry of the bar and other constraints.

The mentioned relation is reflected by real measurement results such as those shown in Fig 5.
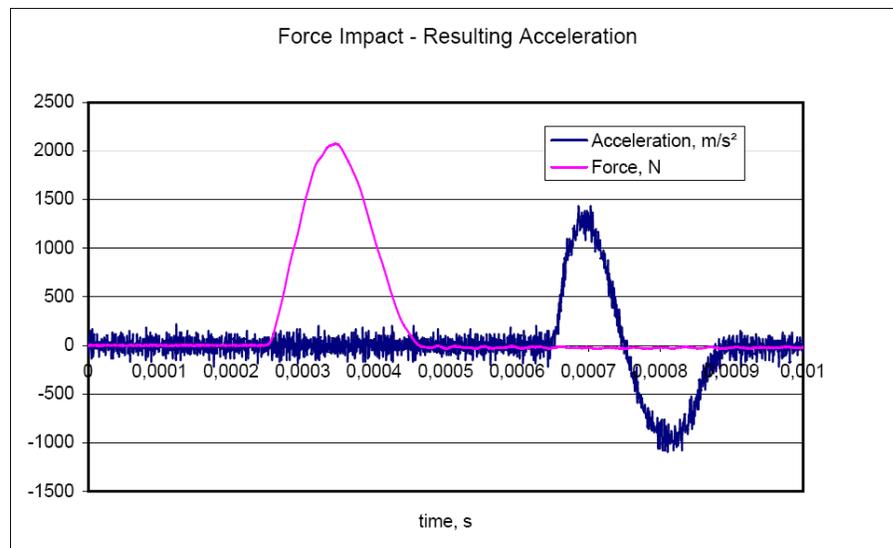

Figure 5 Transfer Characteristic of a Bar

The red trace shows the force-time function resulting from a projectile crashing into the front end of a bar. After a certain run time through the bar, determined by the wave propagation speed, the blue acceleration-time function can be measured at the end of the bar. This result and the results from a great number of further tests proved the correctness of the calculated theoretical transfer characteristic.

The second component of the model describes the effect of projectile that hits the bar on the force-time function. Here some theoretical considerations worked out by H. Hertz as far back as 1881 [2] could be utilized. These are the main effects that determine the force-time structure:

- kinetic energy of the collision partners before colliding,
- material of collision partners (E module, density) and
- geometrical shape of the collision partners.

The two main model components were joined to form a complete model that describes the behaviour of the entire Hopkinson Bar structure used for the calibration of acceleration sensors.

3.1 High Shock Exciter HOP – practical realization

After the complete model had been confirmed by measurements, the material and geometrical design of the structure could be selected such that the special requirements for the acceleration pulse shape (amplitude, pulse duration) are met.

The selection of material and geometrical design was focussed on mechanical durability in the first place.

Another important requirement for the SPEKTRA Hopkinson Bar was the demand that the calibration run should be performed all-automatically. To this end a facility was developed to adjust the movement of the projectile and its kinetic energy.

Figure 6 shows the type SPEKTRA HOP-P. Here a vibrometer is used as a reference standard for the calibration of acceleration sensors.

Figure 6   SPEKTRA HOP-P

3.1.1   Fields of application
- **Primary calibration** of shock sensor transducers according to **ISO 16063-13**
- Type of excitation: **Shock** sinusoidal, 1 period
- Primary Calibration of Shock accelerometer reference standards

3.1.2   Potential users

- National Metrology Laboratories in their capacity as the highest measurement authorities
- Certified Calibration laboratories
- Departments of **Measurement Instrument Verification** in research and development, in particular in Aviation and Space travel
- Quality Assurance in Sensor manufacturing

3.1.3   Features

- Traceable to Physikalisch Technische Bundesanstalt (PTB) Braunschweig via SPEKTRA Calibration laboratory DKD-K-27801
- Implementation of **all-automatic calibration operations** according to SPEKTRA's test regime
- **Calibration** of **Sensors** with / without measuring amplifier and **Measuring systems** (sensor plus signal conditioner)
- **Direct connection of piezo-resistive sensors** through integrated **PR Signal Conditioner**
- Determination of **Aptitude for Calibration** (bridge resistance, offset, drift) of PR sensors in conjunction with Software **PR measurement**
- Shock amplitudes up to **750.000 m/s²** (75.000 g_n). Higher levels can be supplied on request as an optional extra
- Position of DUT: **horizontal**
- Sensor (payload) mass (DUT): up to **30 gram**

The maximum amplitude can be generated a few hundred times without the need to replace any component of the system. Fig 7 shows the example of an acceleration-time function generated by a SPEKTRA HOP system.
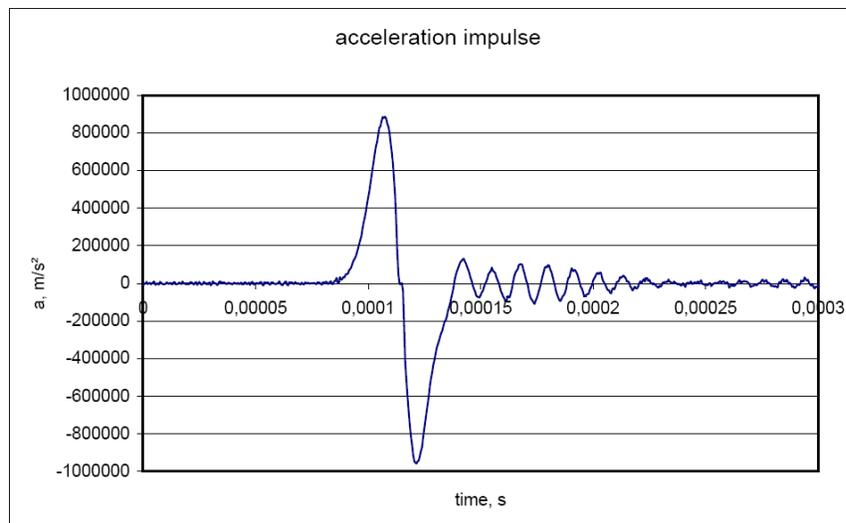

Figure 7   Acceleration impulse

3.2   High Shock Exciter HOP – conclusions

Based on thorough theoretical as well as practical investigations, a high-shock calibration system has been developed that truly meets the demands of the market. The SPEKTRA HOP system stands out from the competitors' products by its high and well-defined mechanical durability. Another singular feature is its capability of performing calibration runs all-automatically.

4.   Conclusions and Outlook

Dealing with the development of acceleration exciters for calibration purposes, this paper clearly demonstrates that well-founded theoretical considerations and investigations are a sound basis for obtaining increased performance. This approach has always been a solid foundation of the SPEKTRA corporate strategy ever and will remain so also in future developments.

Based on the knowledge gained, future operations will focus, among other things, on increasing the range of products in the field of SPEKTRA calibration exciters. One of the goals will be the generation of sinusoidal vibration with higher acceleration amplitudes by exploiting alternative excitation mechanisms.

5.   References

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