Calibration or Testing of High-g Shock Accelerometers to 1,000,000 m/s^2 and Higher

Dr. Brucke, Martin
Mende, Michael
SPEKTRA Schwingungstechnik und Akustik GmbH Dresden
Heidelberger Str. 12
01189 Dresden

Introduction

Testing and calibration of shock accelerometers up to 100,000 m/s^2 amplitude is commonly performed and well understood. If higher accelerations up to 1,000,000 m/s^2 are required, new challenges appear and an improved design of the shock exciters as well as a careful operation and interpretation of the measurements is necessary.

Common shock exciters are based on the hammer - anvil principle: The device under test (DUT) is mounted on an anvil that is accelerated by an impact of a hammer. Typically such devices generate a type of half-sine shock acceleration. An example for such a shock exciter is the shock pendulum where a hammer pendulum hits an anvil pendulum that swings away after the impact (Fig. 1). A shock pendulum is typically used up to amplitudes of some thousand m/s^2. To obtain higher accelerations a stiffer and more compact anvil than a pendulum is necessary.

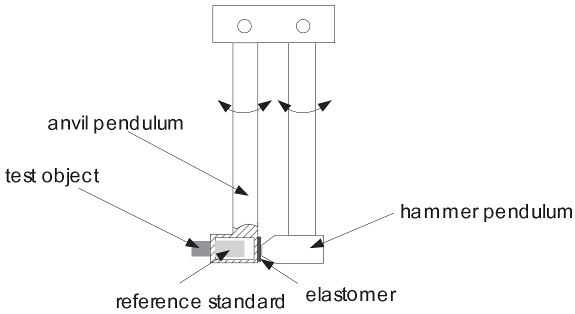

Fig. 1 Working principle of a pendulum as shock exciter

Thus shock exciters for amplitude ranges above 10,000 m/s^2 typically use a kind of projectile that impacts a compact anvil where the DUT is mounted. An example for such an exciter is the SE-210 P-LMS from Spektra that covers the broad amplitude range from 500 m/s^2 to 150,000 m/s^2. It uses a projectile as hammer that is pneumatically accelerated and a compact metal anvil guided by an air bearing that restricts any cross motion of the anvil (Fig. 2).

Fig. 2 Working principle of a SE 210 pneumatic shock exciter

The kinetic energy of the projectile is controlled via a movable mechanical stop that allows changing the distance over which the projectile is accelerated while the air pressure is kept constantly. This allows a more accurate amplitude control and an all automatic operation compared to the manually operated shock pendulum. On the other at shock amplitudes above 100,000 m/s^2 the wear of the materials in the contact zone is increasing significantly and the reproducibility of shocks becomes worse. At even higher amplitudes the metal materials are stressed so hard that the anvil may be deformed and break. Thus for an amplitude range up to 1,000,000 m/s^2 and more, another type of shock exciter has to be used, the so called Hopkinson-Bar.

Hopkinson-Bar Shock Exciters

On the first view a classical Hopkinson-Bar shock exciter seems to work quite similar to a simple hammer-anvil shock exciter since again an impact is needed to generate the shock. But in this case the hammer or projectile does not hit an anvil but a long slender metal bar. Instead of accelerating an anvil a compression wave is generated in the bar that propagates to the other end of the bar where the DUT is mounted (Fig. 3). The compression wave is reflected at the end of the bar and causes a small short back and forth movement that accelerates the DUT (full sine wave acceleration). Theory shows a relationship between force input, mechanical parameters of the metal bar and acceleration output as described in equation (1) (see also ref. [1]):

$$a(t) = \frac{2c_0}{E \cdot A} \frac{dF(t)}{dt} \qquad (1)$$

In this equation c_0 is the velocity of sound in the bar, E its Young's modulus and A the cross section area of the bar. One of the main conclusions of (1) is that due to the time differentiator, the shorter the input force pulse is (force amplitude assumed to be constant) the higher the output shock amplitude will be.

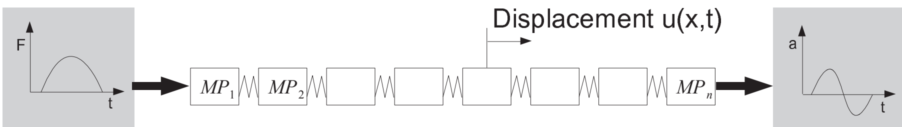

Fig. 3 Working Principle of a Hopkinson-Bar; a force impact generates a compression wave in the bar that causes an acceleration at the other end of the bar

Looking on the input side of the Hopkinson-Bar, we see a classical hammer-anvil interaction when the projectile hits the bar. Although there is no analytical model available, since the interaction between hammer and anvil is nonlinear and quite complex, experiences as well as numerical models show that there is an inverse relationship between acceleration amplitude and shock duration. With increasing amplitude the duration of the generated shocks decreases. Thus the bar works like an amplifier on the input force pulse. That is a reason why a Hopkinson-Bar can be used to generate shocks with very high amplitudes up to 1,000,000 m/s^2 and more, although the input force amplitude is comparable to a pneumatic hammer-anvil shock exciter. Also the choice of the material of the bar (related to parameters c_0 and E) and the diameter of the bar (related to A) can be used to tune the maximum available acceleration amplitudes.

A Hopkinson-Bar like the SE-221 HOP-VHS (Fig. 4) is able to generate accelerations up to 2,000,000 m/s^2 with a shock duration of 15µs and due to the working principle (propagating compression wave) it generates only negligible cross motion. The control of the kinetic energy of the projectile and thus the shock amplitude works in the same way as in the case of the pneumatic shock exciter. Also the Hopkinson-Bar allows an all automatic operation.

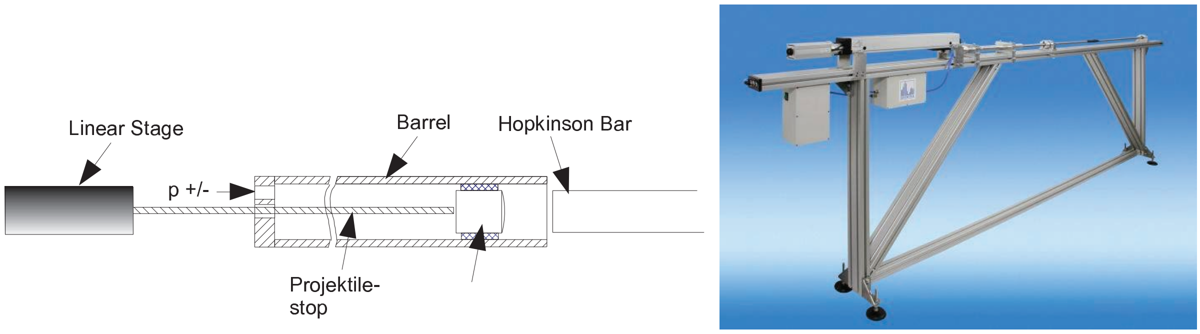

Fig. 4 Working principle SE-221 HOP-HS Hopkinson-Bar Shock Exciter

A property of the classical Hopkinson-Bar that can be regarded as a disadvantage for some applications is the fact that it also has an inverse relationship between shock amplitude and shock duration like simple hammer - anvil exciters and that this relationship is even stronger due to the time differentiator in equation (1). A newly developed Hopkinson-Bar tries to overcome this obstacle and to allow controlling shock duration and amplitude independently in a certain range. The difference between this new Hopkinson-Bar and the classical bar is the mechanism that generates the force input. The new bar uses a piezo-actuator to generate the force (Fig. 5) (see also ref. [1]).

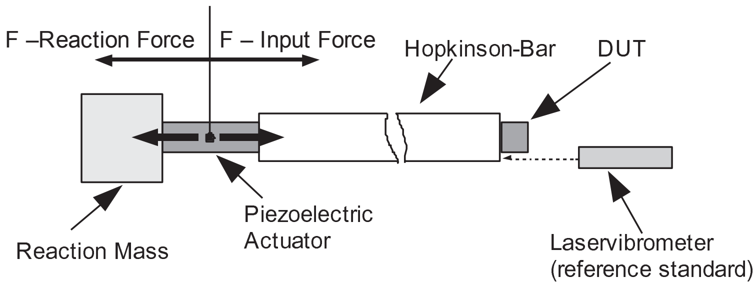

Fig. 5 Working principle of a SE-220 HOP-MS Hopkinson-Bar

Since the dynamic behavior of the piezo can be exactly controlled by electrical signals and the transfer function of the bar can be determined, it is possible to shape the wave that propagates in the bar and thus the output acceleration by means of an appropriate electrical input to the actuator. Shaping means that is not only possible to control the amplitude of the shock but also the shock duration independently (Fig. 6). Furthermore it is possible to apply shocks with a defined spectrum. Due to limitations of the currently available piezo-actuators the amplitude range of this SE-220 HOP-MS Hopkinson-Bar is limited to about 50,000 m/s^2. But it can be used to get information about the *real* frequency response and amplitude linearity of shock accelerometers as will be shown below. *Real* means that amplitude linearity and frequency response can be examined separately since only one parameter, shock duration or amplitude, can be varied while the other is fixed.

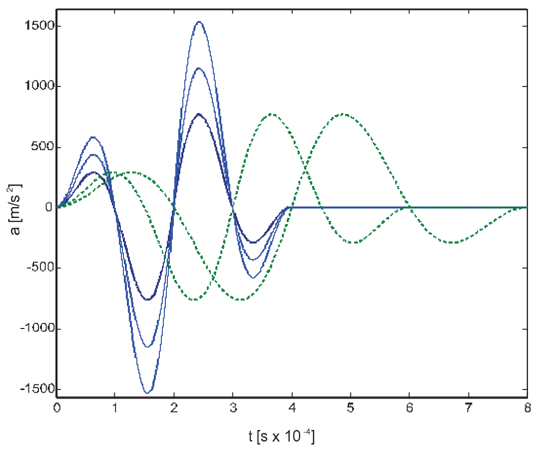

Fig. 6 SE-220 application examples:
Acceleration kept constant while shock duration varies (green graphs)
Shock duration kept constant while amplitude varies (blue graphs)

Precise measurement of 1,000,000 m/s² shocks and more

A shock pendulum or a pneumatic hammer-anvil shock exciter uses commonly a back-to-back reference accelerometer for calibration and test purposes. The reference standard is mounted with its end on the anvil while on its other end the DUT is mounted. This allows an easy and convenient operation up to about 100,000 m/s². At higher amplitudes a back-to-back accelerometer turn out to be too heavy and a sufficiently good coupling between reference standard and anvil becomes more and more a problem. So in the very high shock range other reference sensors have to be used.

A very good solution is the use of a laser vibrometer that allows a non-contact measurement of movement of the DUT side surface of the Hopkinson-Bar without adding any mass and additional coupling surfaces between DUT and shock exciter (Fig. 7). An important parameter for the choice of a reference laser vibrometer is the required velocity range. Many laser vibrometers allow a maximum measurement range of only 10 m/s. This is sufficient for an amplitude range up to about 700,000 m/s². For the range up to 2,000,000 m/s² a measurement range up to 20 m/s is required.

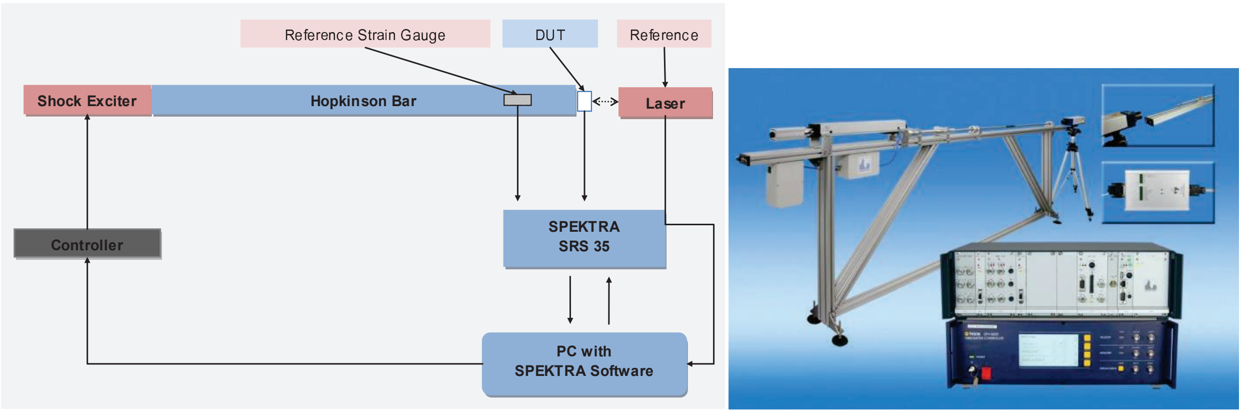

Fig. 7 Hopkinson-Bar exciter with laser vibrometer as reference standard

For calibration purposes a laser vibrometer has another important advantage: It is possible to calibrate a laser vibrometer traceable to the German National Metrology Institute PTB. Although this is done by means of a vibration exciter that provides a sinusoidal signal instead of a transitional signal and the velocity amplitude of such calibrations is quite low compared to a high shock, such a calibrated laser vibrometer currently turns out to be a very reliable reference standard. New methods for a calibration with transitional signals at higher velocity ranges are under development in cooperation of Spektra and PTB.

Also a good and more cost-effective reference standard is a strain gauge. Such strain gauges can be attached to the surface of the Hopkinson-Bar and measure the strain that is caused by the propagating wave. The output of the strain gauges can be related to the acceleration at the surface at the end of the bar by calibration by means of a laser vibrometer. A disadvantage of strain gauges is that they have to be mounted in a certain distance from the end of the bar. Due to dispersion of the wave, the strain gauges ‘see’ a little bit different wave than the laser vibrometer at the end of the bar and thus the measurement uncertainty is increased compared to a measurement with laser vibrometer.

Examples of measurements up to 2,000,000 m/s^2

In this section some results of measurements with high shock accelerometers are shown. Both accelerometers are specified for the measurement of 1,000,000 m/s^2 and more. But the working principle and mechanical parameters of the sensors are quite different (Fig. 8).

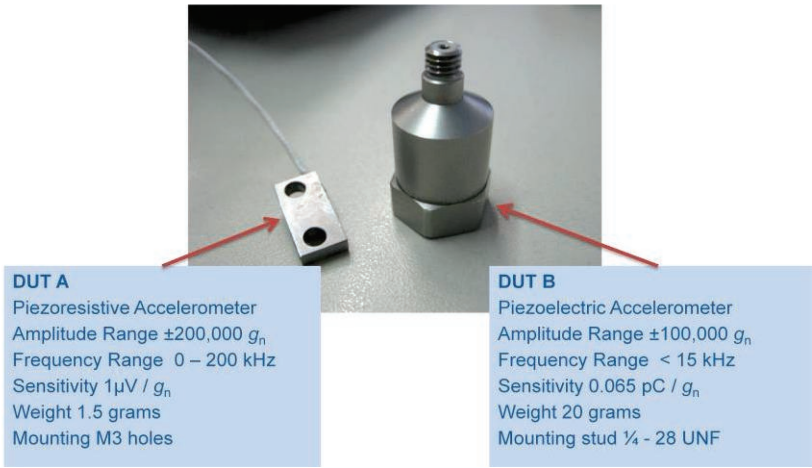

Fig. 8 DUT used for example measurements

In order to characterize the accelerometers the first step was to learn something about the frequency response of the accelerometers. Measurements on a SE-09 high frequency vibration exciter in the frequency range from 5 Hz to 50 kHz showed no usable results. Although this exciter has maximum acceleration of 400 m/s^2, the very low sensitivity of these sensors allowed only a very noisy output signal at this acceleration amplitude. Thus a SE-220 MS Hopkinson-Bar was used to excite the accelerometers with a sufficient shock amplitude while the shock duration and thus the spectral content of the shocks was varied. Since the amplitude was constant all variations of the measured sensitivity of the accelerometer must be related to its frequency response. The results are shown in Fig. 9and clearly show the limited frequency response of DUT 2 in accordance with the specification in the data sheet.

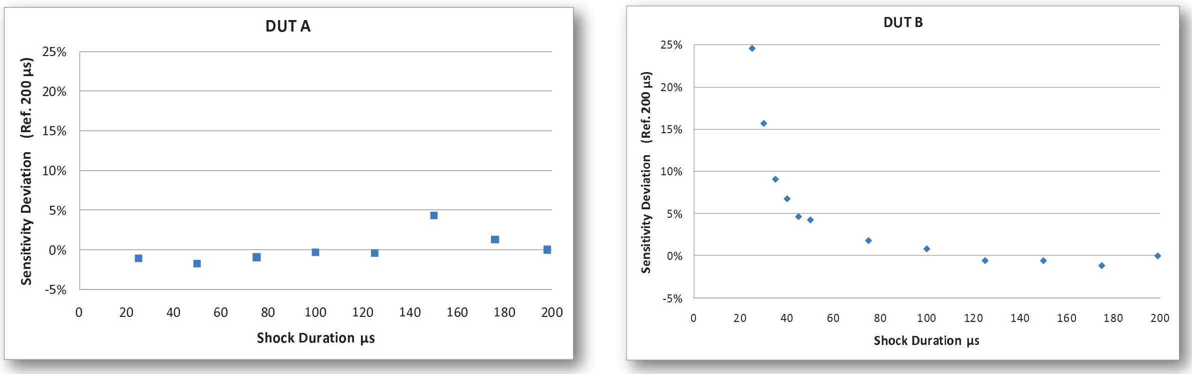

Fig. 9 Measurement results with fixed amplitude but varied duration of the shocks

In a second step the amplitude linearity of the accelerometers was checked up to the specified limits. While DUT 1 turned out to behave very linear up to 2,000,000 m/s^2 , DUT 2 began to behave strange already at 350,000 m/s^2, a third of the specified measurement range (Fig. 10).

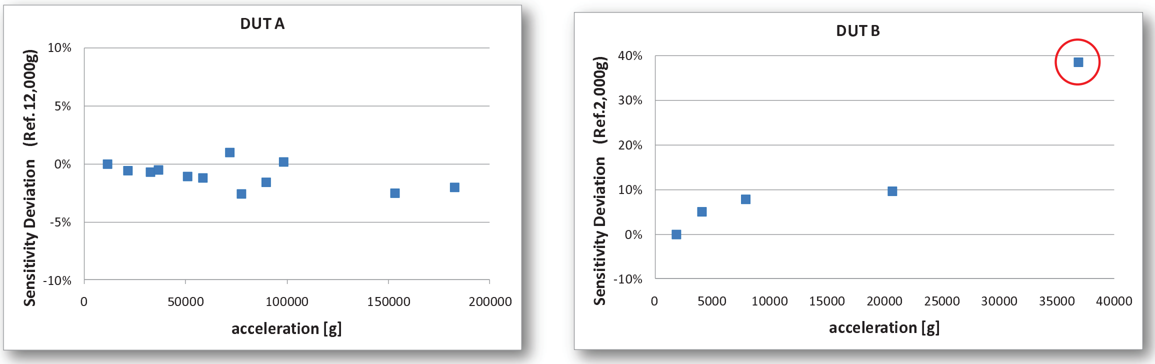

Fig. 10 Amplitude linearity checks up to 2,000,000 m/s^2

A look on the recorded time signals of reference standard (a laser vibrometer) and DUT 2 showed that the signal of the DUT looks quite regular up to 200,000 m/s^2 but get odd at higher amplitudes (Fig. 11). While the first half wave, where the DUT is pushed by the bar still looks good, the signal is erratic in the second phase of the movement when the bar pulls back the accelerometer. The signal indicates that the mounting bold is too weak; the accelerometer lifts off from the surface of the bar and crashes back on the bar causing the subsequent acceleration signals.

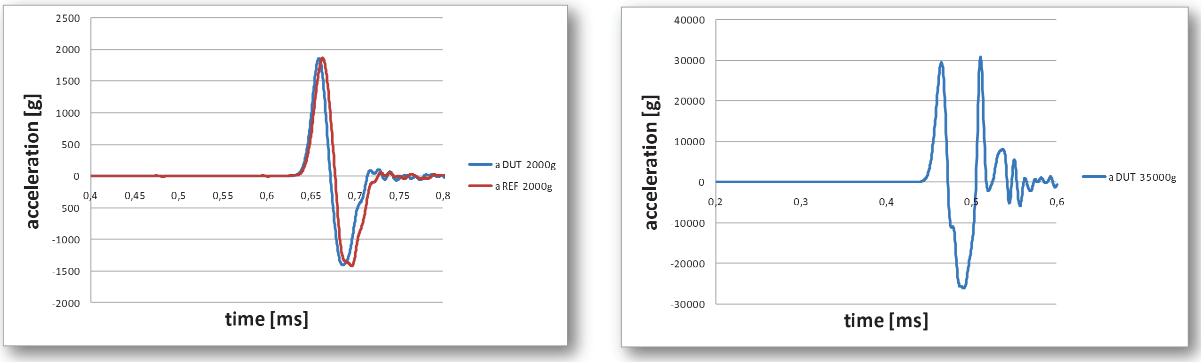

Fig. 11 Regular movement of the DUT B at low amplitudes compared to erratic acceleration signal at high amplitudes

Conclusions

For calibration and testing of high shock accelerometer at amplitude ranges of 1,000,000 m/s^2 and more, Hopkinson-Bars are currently the only practically available shock exciters that can provide a shock excitation in a good quality with negligible cross motion. Although some questions regarding traceable reference standards for this amplitude range are still open, laser vibrometers as well as strain gauges can be regarded as good solutions. Measurement uncertainty is often more influenced by an appropriate mounting of the DUT at the shock exciter than by the accuracy of the reference standard.

The determination of the frequency response of a high shock accelerometer with a very low sensitivity can be a problem since commonly available vibration exciters neither cover the frequency range nor can provide sufficient acceleration amplitudes. A new type of Hopkinson-Bar with a piezo-actuator as force generator that provides shocks with a variable spectrum while the amplitude remains fixed, can deliver some answers regarding the frequency response of such accelerometers.

REFERENCES

[1] „Alternative Methoden zur Anregung von Wellen in Stäben zur Kalibrierung von Beschleunigungsaufnehmern“, Dr. Martin Brucke, Dissertation TU Braunschweig; 2009
[2] Patent DE 10 2008 025 866, international PCT application pending