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THE NEED FOR CONTROLLED SHOCKS - A NEW TYPE OF SHOCK EXCITER ALLOWS TO APPLY WELL DEFINED MECHANICAL SHOCKS

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Abstract – Shock exciters available on the market today suffer from a lack of control of the generated shocks. This paper will present a new type of shock exciter developed by SPEKTRA which is based on the well known Hopkinson-Bar but using a piezoelectric actuator to apply the force pulse input (* patent pending, [1]). It will be shown that a piezoelectric actuator driven Hopkinson-Bar generates well defined shocks allowing the control of pulse width and amplitude independently over a wide range. Furthermore the spectrum of the applied shocks can be controlled accurately by shaping the input force pulse coming from the actuator. Thus this new shock exciter is a valuable tool for shock calibration in metrology as well as for sensor characterisation in development departments.

Keywords: Shock Exciter, Hopkinson-Bar, Piezoelectric Actuator, MEMS Testing

1. INTRODUCTION

Common shock exciters based on the hammer-anvil principle allow only a limited control of shock amplitude and pulse width with a limited repeatability of the applied shocks. Because the impact between hammer and anvil is not completely elastic a certain wear of both parts can be observed. Thus even if parameters like the kinetic energy of the hammer could be controlled well the shock amplitude and width would change from shock to shock. In fact many shock exciters like a shock pendulum can't even control the kinetic energy of the hammer precisely. Depending on how the operator releases the hammer pendulum the shock amplitude can change up to 10% and more.

Furthermore pulse width and amplitude cannot be chosen independently from each other. 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 width. With increasing amplitude the width of the generated shocks decreases.

A similar behaviour can also be observed with a Hopkinson-Bar shock exciter which uses the hammer-anvil principle (e.g. impact of a projectile on the front surface of the bar) to generate the input force pulse. The relationship between force pulse and shock acceleration applied to the device under test (DUT) can be described by means of (1) where c_0 is the velocity of sound in the bar material, E its Young's modulus and A the cross section area of the bar.

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

The main conclusion 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. That is the 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. The bar works like an amplifier on the input force pulse. On the other hand if a hammer-anvil force pulse generator is used the dependency between shock amplitude and pulse width is even stronger than in a 'conventional' shock exciter.

To cope with this dependency mitigators can be used, materials like rubber or different metals placed on the surface of the anvil that changes the mechanical characteristics of the impact zone. So the rigid coupling between amplitude and pulse width can be overcome in certain limits by choosing an appropriate mitigator. But mitigators are also additional wear parts that reduce the repeatability of shocks even more.

2. A NEW TYPE OF SHOCK ECITER

Some time ago SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, a renowned manufacturer of high precision calibration systems for shock as well as sine calibration, decided to develop a medium shock calibration system for amplitudes up to 40.000 m/s^2. Since the experiences with available shock exciters showed that they suffer from a lack of control and often also of proneness to defects, it was decided to develop a new shock exciter. The main goals were

- easy and precise control
- very good repeatability of shocks
- easy and convenient to operate
- usable for primary and for secondary calibration
- no wear parts

It turned out quickly that only a Hopkinson-Bar can provide shocks in 'metrological quality' for secondary and primary calibration in this amplitude range. But as shown above the mechanical hammer-anvil system as force pulse generator causes some trouble regarding repeatability and control of the shocks. So the idea was born to use a piezoelectric actuator as generator. The actuator is attached with one end directly to the front surface of the bar and has a reaction mass attached on its other end [1].

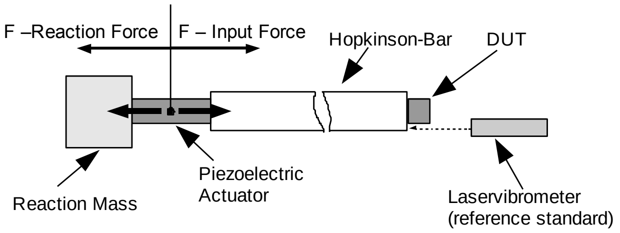


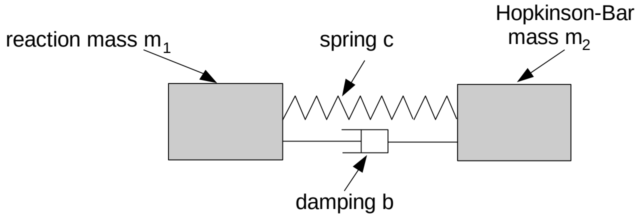
Fig.1 Principle drawing of the new SPEKTRA HOP-MS Shock Exciter with a laser vibrometers as reference (* patent pending, [1])

The advantage of this solution is that it can be controlled completely by electrical signals and does not have any mechanical wear parts.

Fig.2 The new SPEKTRA HOP-MS Shock Exciter with laser vibrometer as reference standard

2.1. Amplitude, Pulse Width and Repeatability

The main challenge in the development of the shock exciter was the choice of an appropriate actuator. To determine the necessary parameters of the actuator the desired amplitude range, shock width and input pulse form were defined first. Then a model transfer function of the Hopkinson-Bar was used to calculate the necessary force input pulse and thus to derive the actuator requirements. The transfer function was derived from a two-mass oscillating system model which was validated with measurements.



$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} b & -b \\ -b & b \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} c & -c \\ -c & c \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = 0$$

Fig.3 Two-mass oscillator model for calculation of the transfer function

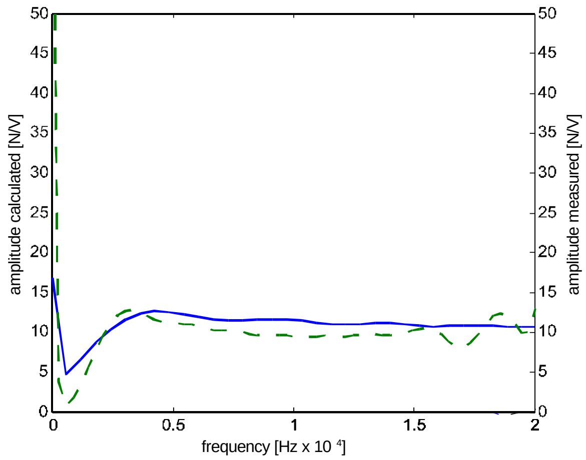


Fig.4 Comparison of calculated and measured transfer function of the HOP-MS

Since a common application for such a calibration system should be the calibration of shock sensors as used for example in automotive crash tests, the goal amplitude range was 20 m/s^2 to 40,000 m/s^2. While it was obvious that the maximum amplitude requires an appropriate maximum force of the actuator, it turned out that for small amplitudes a low hysteresis and the prevention of any slip-stick effects in the actuator is important. But it could be shown that unlike a mechanical hammer-anvil force pulse generator, that produces a poor signal quality at low amplitudes, the piezo-electric actuator allows good signal qualities at lowest amplitudes too.

Regarding the pulse width limits, the fact, that many shock sensors have frequency response (sensitivity over frequency) that is not constant at higher frequencies, had to be considered. So if shocks with different pulse width and thus spectrum are applied to such a sensor, the calibration results may show deviating sensitivity values. In order to minimize such effects the minimum shock width was defined to be at least 100 µs at maximum amplitude which corresponds to an upper frequency of about 5 kHz. The maximum pulse width is mainly limited by the length of the bar. Because the compression wave, which propagates in the bar, is reflected at each end, the applied shock must be over before the first reflection arrives at the DUT. Thus the longer the bar the broader the pulse width can be. On the other hand very long slender bars are mechanical unstable and are not convenient to handle. So for practical reasons a length of 2 m was chosen. Another idea to achieve broader shocks could be to use a material with a lower velocity of sound. But according to (1) this would also reduce the ‘amplification’ of the Hopkinson-Bar and thus the possible maximum amplitudes. In practice a 2 m Titanium bar turned out to be a good solution and allows a maximum pulse width of about 400 µs.

The shape of the acceleration input signal for a calibration according to ISO 16063-13 [2] was chosen to be a full sine period which can be described by (2) where $\hat{a}$ is the acceleration amplitude and T the periodic time. Because T and $\hat{a}$ can be independently controlled by the electrical input signal to the actuator also the shock amplitude and pulse width applied to the DUT can be changed independently.

$$a(t) = \hat{a} * \sin(\frac{2\pi}{T} t) \quad \{0 < \frac{2\pi}{T} t < 2\pi\} \qquad (2)$$

Of course this independency only exists within the physical limits defined by the Hopkinson-Bar and the maximum force and dynamic limits of the actuator as discussed above.

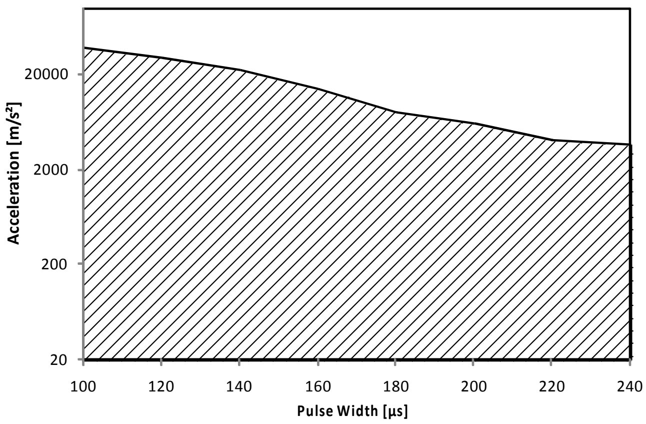


Fig.5 Working Range of the Shock Exciter prototype - Pulse width and Amplitude can be chosen independently in the hatched area

However within these limits this new shock exciter really allows to control amplitude and pulse independently and very precisely. Fig. 6 shows a series of shocks where the amplitude was varied while the pulse width was fixed (blue solid curves) as well as a series where the amplitude was fixed while the pulse width was varied (green dotted curves)

Because there are no mechanical wear parts and the complicated interaction at the hammer-anvil surface doesn’t exist anymore, shock amplitudes can be reproduced with an accuracy of less than 0.1%. Also the repeatability of the shock shape is very accurate.

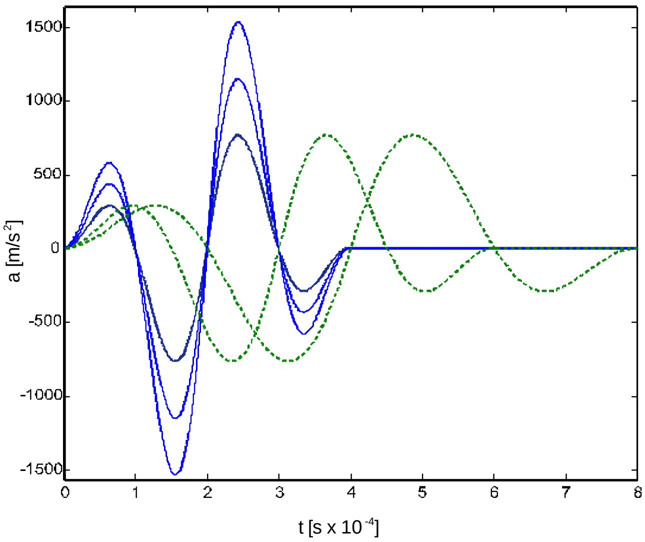


Fig. 6 Independent variation of amplitude and pulse width

2.2. Shaping the Spectrum

In a research project of the Physikalisch Technische Bundesanstalt (PTB) in cooperation with SPEKTRA a new calibration method is under development (see also *XIX IMEKO World Congress* abstract ‘Calibration of Accelerometers using Parameter Identification’ from Th. Bruns, PTB et. al.) that shall overcome incomparable calibration results of shock sensors measured with different shock exciters. Due to the non-constant frequency response of typical shock sensors, the measured sensor sensitivity can depend on the specific spectrum of the applied shock. The new shock exciter was used to validate the new calibration method because it allows repeatable shocks with well defined parameters. Since the frequency response of the sensor causes these problems in addition to the PTB-SPEKTRA project the idea came up if the input acceleration signal of the actuator could be shaped in such a way that the spectrum of the applied shock will be cut off at high frequencies.

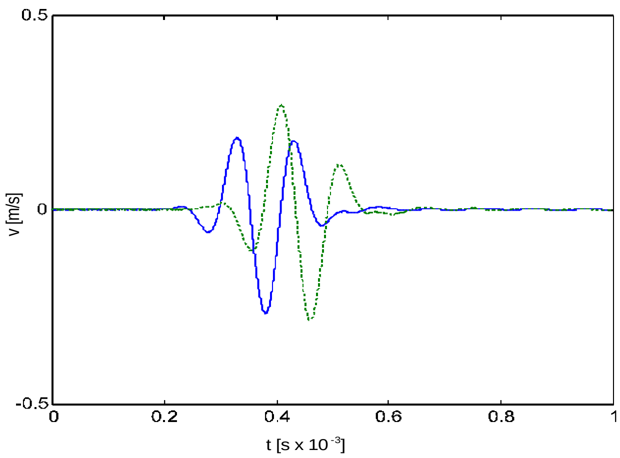
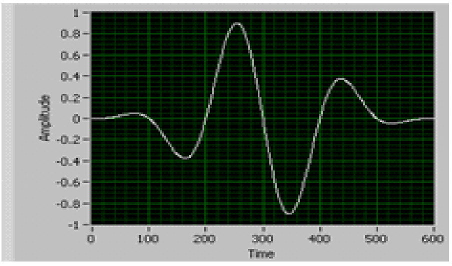


Fig.7 Measured velocity responses at the DUT side of the Hopkinson-Bar show how the shock can be shaped by applying different input signals to the piezo-actuator

Experiments have shown that the spectrum of the shock can be shaped significantly by shaping the input signal to the Hopkinson-Bar. In fact it is possible to let the software, which generates the input signal, determine the transfer function of the Hopkinson-Bar by applying an appropriate signal and measuring the response of the bar with a reference accelerometer (e.g. laser vibrometer). By means of this transfer function it is possible to calculate the input signal applied to the piezo-actuator that is necessary to achieve a certain mechanical output at the DUT side of the Hopkinson-Bar. Fig. 7 shows an example where the goal was to achieve a velocity output with symmetrical positive and negative maxima. The blue solid line shows the measured velocity as a response to a symmetrical input signal. Due to the transfer function of the system the velocity output wasn't symmetrical any more. After calculation and application of a new the input signal using the inverse transfer function, the desired curve (green dotted line) could be measured.

Thus it is also possible to achieve a good control of the spectrum of the shock as can be seen in the examples Fig. 8 and Fig. 9.



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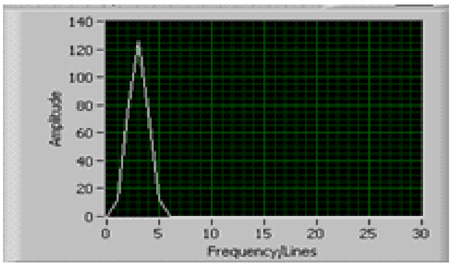
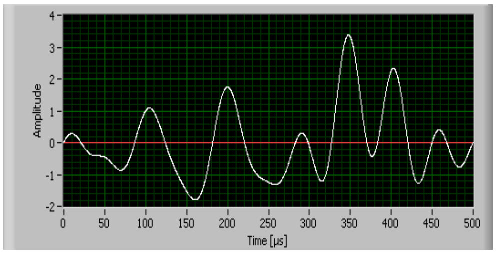


frequency domain

Fig.8 shaped sine wave, three periods long



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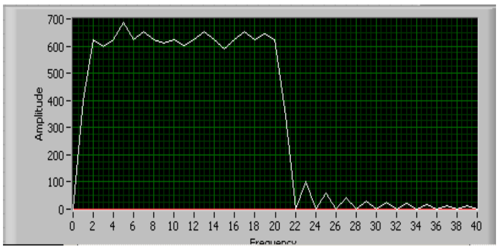

frequency domain

Fig.9 multi sine wave (burst), 10 lines

3. CONCLUSIONS

SPEKTRA developed a really new shock exciter based on the well known Hopkinson-Bar. It allows applying shocks with high repeatability and well controlled amplitude and pulse width. So this shock exciter will be a valuable tool in shock calibration laboratories. Due to the complete electrical control the shock exciter can be well automated. Thus quick and convenient calibration and amplitude linearity measurements are possible saving time and money. Since there are no wear parts the life cycle costs will be also low.

But besides these economical impacts it brings also a new quality into any kind of shock measurements. In metrology a new calibration method may profit from the independent control of amplitude and pulse width or a well controlled spectrum of the applied shock. In sensor development it allows a thorough characterisation of sensors by applying shocks with limited spectral band width. E.g. it may be possible to get a better insight under which conditions some MEMS sensors get damaged during transport on the assembly line or to the customer. Which kinds of shocks disturb the fine structures of the sensor? Spectral shaped shocks may give an answer to this question.

The new SPEKTRA shock exciter HOP-MS (* patent pending, [1]) is capable to open a door to a new kind of shock measurements with applications that may be still behind the horizon.

REFERENCES

[1] Patent pending DE 10 2008 025 866, international PCT application planned

[2] ISO 16063 – Methods for the calibration of vibration and shock transducers – Part 13: Primary shock calibration using laser interferometry