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Primary high shock generator with fast and strong linear motor drive for accelerometer calibrations

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ABSTRACT

This paper describes improvements of PTB's high intensity shock acceleration standard, which lead to an enhanced repeatability of a shock generation over an acceleration intensity range from 0.5 km/s^2 up to 100 km/s^2.

The challenge was to implement of a new, fast, and more precise shock generator using a linear motor drive.

1. Introduction

Primary shock acceleration calibrations are carried out according to ISO 16063-13-2001 [1]. High intensity shock calibrations can be carried out with dipole excitation using the "Hopkinson Bar Technique". Most of the existing high intensity shock standards work generally in an acceleration range from 5 km/s^2 to 100 km/s^2 and even higher. In the concerning laboratories are pneumatic, magnetic or gravity-based shock excitation devices in use to calibrate accelerometers [2,3] The main disadvantage of pneumatically operating shock generators is often a poor metering of compressed air by imprecise or worn-out solenoid valves, seats, or other leakages.

The main challenge implementing this kind of shock generator is to accelerate a 0.5 kg (diameter 50 mm) steel ball (as projectile) to a velocity up to 4 m/s or 5 m/s in some 10 milliseconds to reach highest acceleration rates impacting a (mitigator) ball which is in direct contact to a large Hopkinson bar [4].

The slider who pushes the projectile ball is adjustable from a velocity of a few mm/s to a velocity of a few m/s. By impacting the mitigator ball, the shock energy is transmitted with the speed of sound into the Hopkinson bar. At the end of this bar the device under test (DUT) is screwed on. The generated excitation is registered by both, the DUT and a reference.

The reference acceleration in this case is measured by means of two laser-Doppler vibrometers (LDVs) working in parallel, which detect the shock excitation by optical path length alteration. The raw output of the two LDVs is acquired simultaneously with the voltage output of the DUT.

The LDV signals are then demodulated numerically, which gives the displacement over time.

Based on the derived change in displacement, the reference acceleration is calculated by numerical derivation, then the primary measured acceleration peak and the sensor peak are used to determine the shock sensitivity according to:

$$S_{sh} = \frac{q_{\text{peak}}}{a_{\text{peak}}} \tag{1}$$

By definition of (1), the shock sensitivity S_{sh} in the time domain is calculated as the quotient of the output charge peak value of the deployed accelerometer q_{peak} and the peak value of the interferential measured shock acceleration a_{peak}. The evaluation is carried out in the time domain. The result is dependent on the mechanical impact spectrum, the duration of impact as well as the peak acceleration value [5].

2. Initial configuration

PTB's original shock generator, which was designed for medium and higher acceleration intensities, mainly consists of an air pressure drive which accelerates a projectile steel ball through a barrel which hits an in diameter equivalent second steel ball – the so-called mitigator ball – which is mounted at the near end of a Hopkinson bar. The mitigator ball transfers a shock pulse into the Hopkinson bar. On the far end of that bar, the DUT can be attached. The shock wave is runs through the 4 m Titanium rod within about 700 μs.

As can be seen in Fig. 1, the mounted transducer as well as the two laser doppler vibrometer which detect the transducer surface in opposite positions.

To compensate for surface effects the two vibrometers, measuring the path length changes are directed to the diametral surface of the Hopkinson bar.

The design and realization of the pneumatical shock acceleration calibration device was one of the first of this type and already constructed in the early nineties of the last century [2,3]. Other national metrology institutes have set up similar devices in the meantime, at once with different drive methods [4,5].

The original powering mechanism is shown in Figs. 2 and 3. There, to accelerate the projectile, a ball is driven by an air regulating solenoid valve set which has several losses.

These valves open the air fleet proportional to a voltage set point between 0 V and 10 V.

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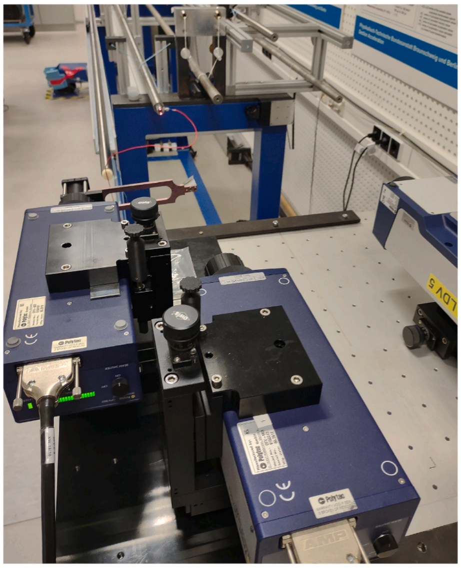

Fig. 1. LDV beams on the Hopkinson bar with a DUT.

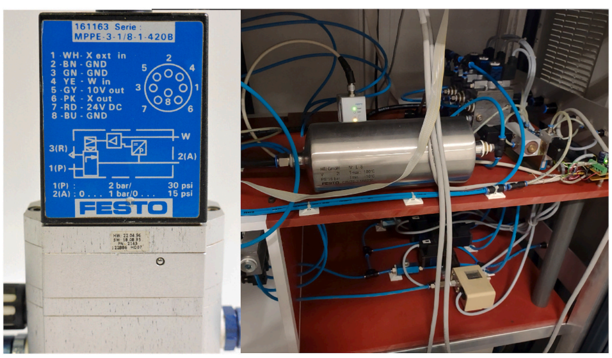

Fig. 2. A proportional solenoid valve (left) and compressed-air reservoir for the pneumatic shock generator (right).

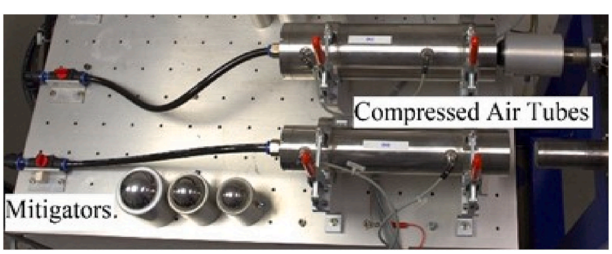

Fig. 3. Pneumatic shock generating devices: Compressed air tubes with pressure hoses next to three different mitigators balls.

All these pneumatic units suffered from some substantial drawbacks, such as:

- The metering and control of the air flowing into the tube is somewhat imprecise from central compressed air generators even when using air reservoir.
- Therefore, the repeatability of adjusted shock intensities is of only moderate quality. Hysteresis effects of 4 % up to 8 % are usual.
- Risk of transducer damage by high overshoots cannot be ruled out.
- The calibration process involves a lot of manual interaction and adjustments.

The hysteresis influences the magnetic switching of the proportional magnet. The reversal range and the response sensitivity describe the resolution of the entire valve unit (magnets, pistons, springs and, if necessary, the control electronics). The response sensitivity is approximately 50 % of the reversal range. As discussed, the pneumatic shock generating unit proved to be a weak point in this old design. Electromechanical valves seats have also become very inaccurate over time supplying the tubes with exact air pressure. Furthermore, the pneumatic generator is for all time dependent of an expensive compressed air supply.

To address the issues listed above, a project had been started to update the shock generator as well as the driving unit specifically.

3. The new drive unit

The addressed issues could not be overcome with a modernization approach still using pneumatics. Instead, after positive experience with linear motor drives at another shock acceleration calibration device [6], a similar route was chosen for the high intensity shock acceleration calibration. Industrial linear motor drives are very strong, fast, and precise to control. Their repeatability depends only on the accuracy of the control at the desired setpoints and the sliders friction. Weight, friction, and nonlinear hysteresis effects can be compensated widely by means of the controlling unit.

The goal of this project was to overcome all disturbing issues using a modern linear drive technology. But it is important that the new type of drive does not have any negative influences on the calibration results. Similar to the former pneumatic shock generator, the intention was not to hit the heavy projectile ball directly but to push and accelerate the ball inside a barrel or on a rail by the slider of the linear motor. As a result, the projectile hits within some milliseconds free run onto the mitigator, which is in direct contact with the Hopkinson bar. The slider's velocity is adjustable continuously from a few centimetres to a few meters per seconds.

The contacting of the mitigator to the titan bar must be made without any rigid fixation since the ball has to move backwards from the Hopkinson bar after an impact. This action prevents any bouncing during the impact initiation. To keep the mitigator in contact to the bar, there must be no gap between both. Therefore, the mitigator ball has to be aspirated to the Hopkinson bar before the hit, this is carried out by means of vacuum/underpressure suction. This action ensures equal initial conditions for each impact. The underpressure is produced now by a small electric vacuum pump, which replaces the former "Venturi nozzle", driven by a compressed air supply. The controlled switch-on time of the vacuum pump is only 3 s and ends instantaneously before the slider's movement.

Based on the experiences derived from the previous modernization also using a linear motor drive, we chose a motor from the same manufacturer LinMot.[1] Fig. 4 shows the front of the linear motor with the slider entering the barrel as well as the end of the same tube with steel- and mitigator ball.

After the acceleration phase of the projectile, it hits the mitigator at the other end of the barrel. The contact situation, imitating the moment of impact, can be seen in Fig. 5. Fig. 6 shows an overview over the whole shock device.

The slider's head is magnetic and can easily return balls to the starting position if necessary.

The advantage of the presented linear motor drive set-up is the option of preselecting an accurate target value using a software interface. The chosen linear motor controller can be parametrized and controlled

[1] Commercial devices are identified in this paper only to adequately specify the experimental set-up. Such identification does not imply recommendation by PTB, nor does it imply that the equipment identified is necessarily the best available for the purpose.

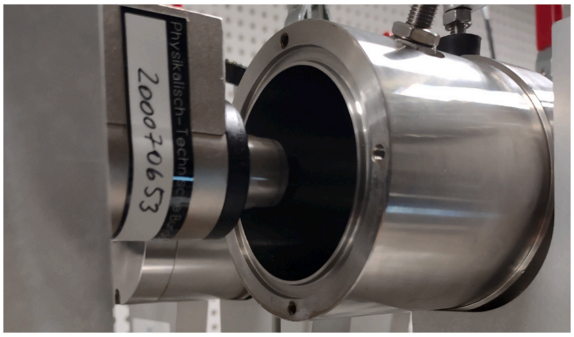

Fig. 4. Front of the slider (left) inside the open tube (steel ball inside, on the right).

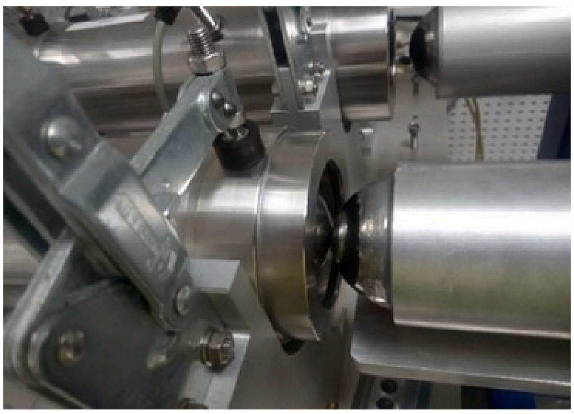

Fig. 5. Linear drive shock generating device (steel balls in contact – the same arrangement for both systems).

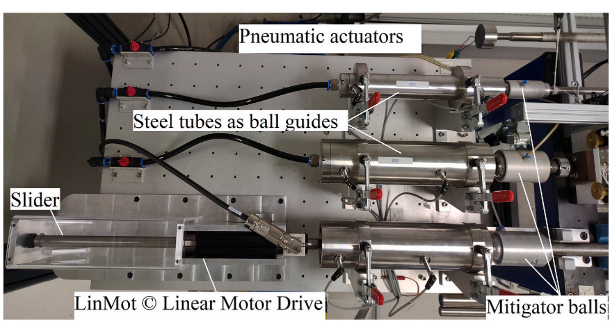

Fig. 6. Top view of the placement of the new LinMot shock generator.

via digital interfaces by the supplied vendor software or a freely available National Instruments LabVIEW driver which can be adapted to individual needs.

For any given settings, the spread of the repeatedly realized acceleration peak values is drastically reduced compared to the original pneumatic drive set of the PTB's laboratory. For both drives, the absolute range around the nominal value increased linearly with the shock intensity. However, for the new linear drive, the spread is one order of magnitude lower than before.

For both calibration devices, whether pneumatically or electrically driven, the well proven measuring procedures remain the same. Only the shock generator had been improved for a better repeatability as well as to reach also small shock impacts lower than 5 km/s^2.

Fig. 7 illustrates the whole dimension of the Hopkinson bar with the high shock device to adumbrate its dimension. On the near side concrete basement (Fig. 7, bottom left) there is the linear motor drive next to the older pneumatic shock generator.

Fig. 7. Hopkinson bar shock generating device with linear motor and pneumatic actuators on the bottom left side.

4. Requirements and design

To ensure the full operation and availability of the customer calibration services during the upgrade, it was necessary to preserve a "fall-back solution" during the development, testing period and beyond. This resulted in some dimensional design constraints as the components should be swappable with the old pneumatic drives.

By applying laws of basic mechanics, the required mechanical specifications were easily derived from the involved moving masses, impact speeds and ball dimensions. Subsequent market research covering mechanic, pneumatic, hydraulic, and electro-magnetic actuators have been done and led to the decision to use a "ready-made" electric linear motor drive system from the same manufacturer as already used within the laboratory [6].

This kind of drives are originally designed for so-called "fast pick and place" operations in industrial production lines. Strong and speedy enough to move up to 1 kg in a few 10 ms. The use of industrial equipment results in only moderate hardware costs.

For the developed solution, the linear motor model LinMot PS01 - 37 x 120F- HP- C with a magnetic slider PL01-20x500/440-HP as well as a type C1100 standard closed loop controller and a LinMot NTI AG two-phase power supply have been chosen and set up [7].

The package also includes a software solution for the controller programming. Furthermore, a stable drive mounting had to be designed and constructed, as well as the adaptation of the slider's movement by software. The slider pushes the ball into the centre of the barrel and then it retreats immediately to its starting position. This prevents the impulse of the returning ball from hitting the slider hard. An additional advantage of this linear motor drive set-up is the option of preselecting of very accurate target values by using an analogue voltage input (offering the use of e.g. potentiometers) or using the software interface for digital adjustment. The controller of the linear motor can be parametrized and controlled via digital interfaces. National Instruments LabVIEW drivers are available which can be adapted to individual needs, as can be seen in Fig. 8.

By means of this software interface the motor can be controlled and the shocks can be carried out. A typical behaviour of a slider movement is shown in Fig. 9. It takes about 10 ms to accelerate a 0.5 kg ball to maximum. The mitigator reaches a velocity of about 4 m/s whereas the acceleration displayed is a setpoint for the controller and only related to the impact acceleration, which is much higher.

Fig. 10 illustrates the whole rack mount control box and a view inside the plug-in module at the controller's placement as well as an overview of all components needed. This includes the linear motor's stator and slider, cable with connector and finally the used vacuum pump.

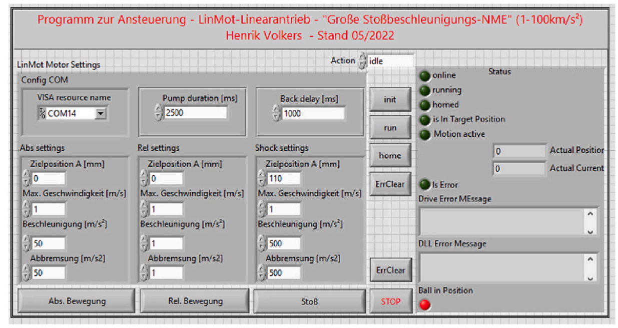

Fig. 8. LabView software control system front end.

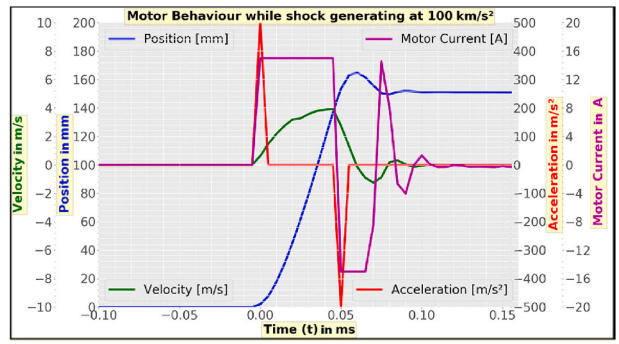

Fig. 9. Dynamic behaviour of the linear drive performing a push action to a 0.5 kg steel ball.

Fig. 10. Fig. 10: Control box (top), inside of the control box (middle), and overview of different system components (bottom).

5. Comparisons of conditions and results

For a comparison of both shock generators, some criteria have been listed in contrast. In principle, the two devices must deliver similarly performances in travel, speed, acceleration, shock peak level and shock duration. The goal was to carry out identical calibrations with both systems. The specifications of both impact generators are listed in Table 1.

The measured parameters are for a 4000 mm Titan-7- Hopkinson-bar with a diameter of 25 mm. The characteristic values would decrease with larger diameters but increase with smaller diameters.

The most important specifications for generating a similar shock behaviour are the ball travel distance in touch with an equal speed range. If the Hopkinson bar remains the same in length and diameter, a very similar amplitude spectrum will be the result.

The benefit of the electrification of the shock acceleration calibration device are the diminution of the peak value standard deviation and a reliable and wider useable shock acceleration range expanding down from 5 km/s^2 to 1 km/s^2. Both generators obtain the desired upper shock acceleration level of 100 km/s^2, but in contrast to the pneumatic drive, the linear motor already reaches its maximum here.

6. Repeatability and signal quality

A comparison between the pneumatic and the electric linear drive was carried out to compare the properties. Different excitation levels were excited and the resulting acceleration magnitudes, as well as their frequency content and the shock duration were analysed.

For any given setting, the spread of the repeated acceleration peak values was drastically reduced compared to the original pneumatic drive set. A comparison is depicted in Fig. 11. For both drives, the absolute scatter around the nominal value increases linearly with the shock intensity. However, for the new linear shock device, the spread is more than a half order of magnitude lower than before. The main improvements are found in the higher repeatability of the velocity, and, at the same time, the reduction of drive force to approximately the half. The magnetic drive can be regulated much more precisely and thus reaches magnitudes down to 1 km/s^2.

To compare the results of the peak value ratios of both drives, intensities from 5 km/s^2 up to 100 km/s^2 have been measured and compared. Under equal conditions, with the similar acceleration dipole, all curves have been recorded. Fig. 12 displays all curves in on chart in the time domain. The upper diagram shows the graded and overlaid measurements of the linear motor driven shock generator at the different excitation levels. The lower diagram of the same figure shows the same magnitudes performed by the pneumatic shock device. At first view, there is almost no significant difference between the curve forms and shock durations. The first half sine represents the actual interesting measurement signal for calibrations. However, the motor driven shock generator behaves more precise to reach the peak values as well as a better repeatability. Furthermore, the better dosed impact energy of the electrical drive leads to a mildly less ringing in the further course. Figure shows the corresponding amplitude spectra for the results shown in Fig. 13, again first with the linear drive and then with pneumatic drive. The sampling rate is in the range of 10 MHz. Whereas only multiples of 650 Hz spectral lines have been recorded and displayed. The

Table 1
Comparison of the pneumatic and linear motor drive shock generator specifications.

Criteria	Old state	New state
Sort of drive	Pneumatic	Linear motor
Max. ball travel	250 mm	250 mm
Useable shock acceleration range	5 km/s^2 – 100 km/s^2	1 km/s^2 – 100 km/s^2
Max. shock acceleration	150 km/s^2	100 km/s^2
Maximum speed	4 m/s	4 m/s
Max. drive force	400 N	250 N
Shock duration range	0.067 ms – 0.12 ms	0.067 ms – 0.16 ms
Std. dev. shock magnitude	2.2 %	0.52 %
Amplitude spectrum peak	3.2 kHz – 4.5 kHz	3.2 kHz – 4.5 kHz

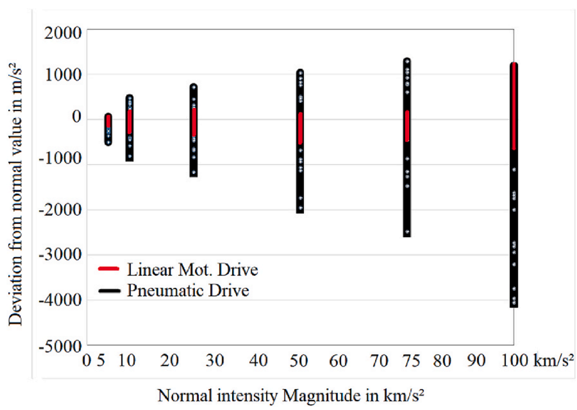

Fig. 11. Comparison of the statistical repeatability of acceleration intensity of pneumatic canon vs. linear motor drive (20 repetitions).

main part of the shock energy is released in a frequency interval from zero to 10 kHz. For shock calibrations the first spectral lines from 650 Hz up to 5.85 kHz are only of interest due to DIN EN ISO 266:1997–08 [8].

The spectral composition of the shock also depends on the material properties and structure of the used Hopkinson bar. Both amplitude spectra have a very similar appearance.

As expected, there is therefore no significant dependency of the shock generator's type on the spectra of the actuate shock. This seems plausible since the boundary conditions of the ball's travel path and ball speed were the same according to Table 1. The system is therefore validated and ready for use [9].

7. Conclusions

The primary high intensity shock acceleration calibration device at PTB has been successfully upgraded by the implementation of a strong industrial electromagnetic linear motor in conjunction with a powerful control unit.

This upgrade was implemented as a replacement of the existing less accurate pneumatic drive. The drive unit accelerates a steel ball to impact a mitigator ball that is hold onto a Hopkinson bar by means of a controlled underpressure. In any case, the impact of the two balls generates a shock wave travelling through the bar which generates a shock excitation at the end of the bar.

The changes in the drive, mechanics and geometry involved constructive adaptations for the motor's fixture.

After a successful implementation of all necessary components the following improvements were noticeable:

- The spread of the set setpoints/actual values compared to pneumatics is about four times lower.

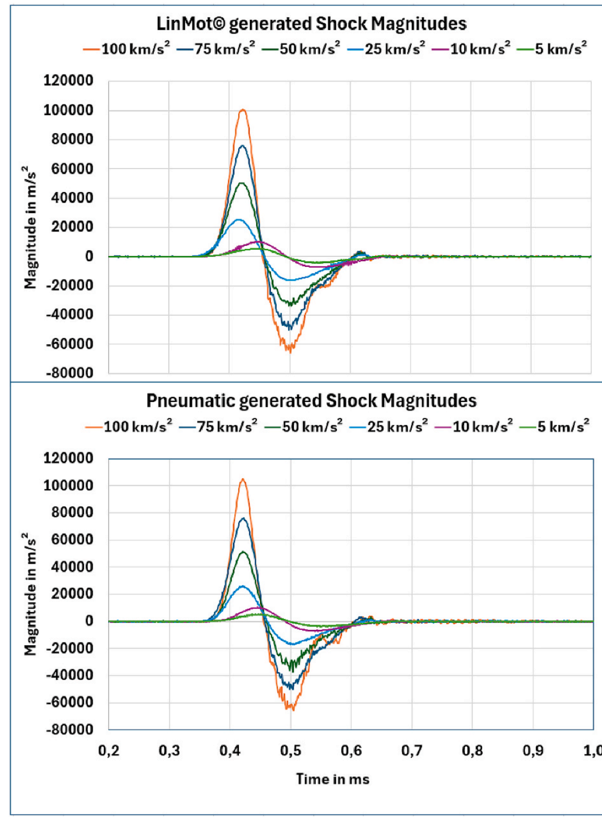

Fig. 12. Raw signal of a shock measurement with an Endevco 2270 accelerometer. The results with the linear motor drive are at the top, the pneumatic drive is at the bottom.

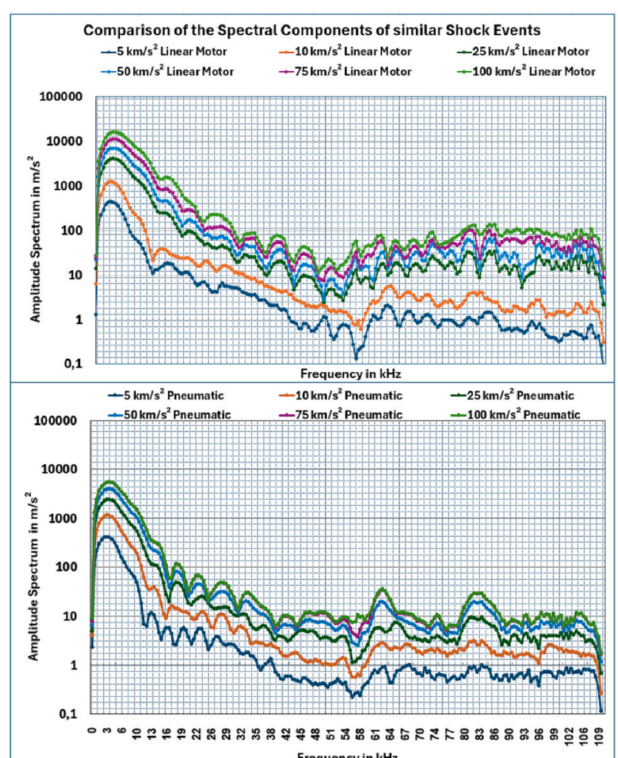

Fig. 13. Amplitude spectrum comparison of shock acceleration measurements with an Endevco 2270 accelerometer. Electric drive at the top, pneumatic drive at the bottom.

- A great improvement of the repeatability of the shock intensity is done.
- The risk of accidental overstressing or damages of delicate customer transducers is significantly reduced.
- Selectively electrical or digital control set-point control for the generated shock acceleration is possible.
- Greatly reduced need for maintenance and operation is practically non-wear and has very little friction.
- A significant reduction in the transfer of mechanical ringing from the ball shot to the Hopkinson bar due to the air pressure.
- Control-setpoints can be adjusted more precisely.
- It is now possible to establish an automated measurement process.
- Excitations as low as 1 km/s^2 can be set and reached, instead of 5 km/s^2. Therefore, a wider acceleration range is possible.
- There is no need any more to provide compressed air for this motor driven device.
- The costs of the new generator are comparatively manageable.

The replaced pneumatic system is at the moment the stronger system although with higher losses. However, the linear drive used reaches the excitation levels required for all calibration services carried on this calibration device.

If higher excitation levels will be needed in the future, a stronger linear motor drive could probably eliminate this inequality. From a technical point of view, replacing the linear motor is not a problem.

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