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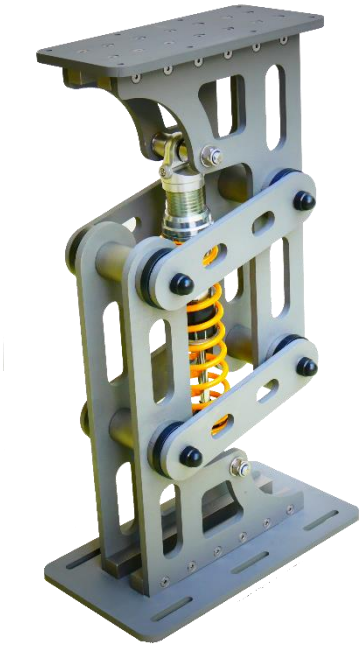
School of Engineering

Electrical and Computer Engineering Department

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Acceleration measurements at high frequency mechanical vibrations (shocks) and evaluation of lumbar spine injuries using ISO® 2631 – Part 5 (2004) Standard on Ermioni HSC Seats: Suspension Ver MIL (Military) and Suspension Ver PL (Pleasure).





Laboratory tests were conducted for:

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Contents

Introduction……3

Chapter 1 – The need of shock absorbers on High Speed Crafts (HSC)……..…..5 – 7

Chapter 2 – The ISO® 2631 – Part 5 (2004) Standard for evaluation of human exposure to vibrations containing multiple shocks…….....9 – 14

Chapter 3 – The test set – up……..15 – 23

3.1 – Mechanical equipment……...15 – 16

3.2 – Pneumatic equipment……17 – 19

3.3 – Electronic equipment……19 – 21

Chapter 4 – Experimental procedure……25 – 32

4.1 – Creation of high frequency mechanical vibrations using pneumatic muscles…..

……..25 – 26

4.2 – Acceleration measurements…….....26 – 27

4.3 – Use of acceleration measurements to evaluate lumbar spine injuries with ISO® 2631 – Part 5 (2004) Standard…….……..….....28

4.4 – Tested systems……...29 – 32

Chapter 5 – Laboratory tests for Ermioni HSC seats……..……..33 – 65

5.1 – Experimental tests…..……...…….....33 – 61

5.2 – Conclusions about shock absorber systems performance…...……...62 – 65

Chapter 6 – Epilogue……67

References – sources…...……..69 – 70

Introduction

Mechanical vibrations is a matter that always concern engineers and vehicles designers, as their effect can cause fatigue and damages to the structure. Besides metal structure effects, mechanical vibrations can also cause health effects. These shocks can be created in all ground, sea and air vehicles that are moving. For example, rough road, or asphalt road with pot holes can cause mechanical vibrations to ground vehicles. Air gaps, or high wind turbulences are part of the reasons which cause vibrations in air vehicles. Rough sea and waves are capable to create mechanical vibrations to sea vehicles. By extension, high speed crafts (HSC) have a higher possibility to deal with mechanical shocks. Several studies have been performed along years in order to eliminate these vibrations, using shock absorbers. Apart from this, these shock absorbers have to be evaluated, according several standards.

The subject of this laboratory experiment is to study the effects of mechanical vibrations on HSC with several shock absorbers mounted in a HSC seat, using a standard for mechanical vibrations effect on human lumbar spine injuries. For this purpose, we examined four different types of HSC seats: Ermioni Suspension Ver MIL (Military) and Suspension Ver PL (Pleasure) seats, with two different types of shock absorbers. The standard which used for evaluating the effects of mechanical vibrations on human lumbar spine injuries, after the use of these HSC seats, is ISO® 2631 – Part 5 (2004).



Figure 1. Natural reasons for mechanical vibrations in ground (left), air (right) and sea (center) vehicles.

Chapter 1 – The need of shock absorbers on high speed crafts (HSC)

High-speed craft is a craft capable of a maximum speed, in meters per second (m/s), equal to or exceeding 3.7 times the one – sixth power of the volume of displacement corresponding to the design waterline (m^3), excluding craft the hull of which is supported completely clear above the water surface in non – displacement mode by aerodynamic forces generated by ground effect. (SOLAS X/1.2, HSC Code 2000 para 1.4.30).



Figure 2. Examples of HSC.

Practically, the levels of mechanical vibration should be, measured and assessed for any craft that can move with speed over 20 knots. An HSC sailing in either rough or not sea, when accelerating at high sea speeds, has always to deal with shocks, due to the crash with sea water. These impacts are having effects not only in vessel's infrastructure, but also in passenger's health. These effects are augmented when a sailor keeps using the HSC for a long time in his life.

The reason that sea waves shocks can have health effects on sailors is the compression of lumbar spine, for both peoples with normal health and for peoples with spine disorders, for example osteoporosis.

Some health effects caused by lumbar spine compression due to multiple shocks created by sea waves impact on HSC are:

1. Damages in lower lumbar spine and connected nervous system
2. Damages in lumbar vertebral endplates
3. Scoliosis
4. Pain
5. Lumbar spines traumas that affect spine structure and can cause spine collapse



Figure 3. Lumbar spine compression caused by sea waves shocks in HSC (left) and human effects on nervous (center) and vertebral (right) system.

Having presented some of the causes of lumbar spine compression, we can easily understand the need for using specially designed HSC seats with shock absorbing mechanisms that can eliminate up to a safety level the vibrations. The difference between a plain seat and a specially designed HSC seat is not the seat by itself, but the standing mechanism. The "heart" of the standing mechanism is a shock absorber which mitigates the mechanical impacts caused by sea waves on high speed sailing. The largest of the amount of potential energy that derives from wave impact is absorbed by the shock absorber, which allows the standing mechanism to oscillate and convert this energy to kinematic (standing mechanism oscillation) and thermal (inside absorber's pressurized liquid, e.g. nitrogen). A very small amount of potential energy is driven to seat pad and vibrates the seated human. Even this small vibration can have health effects, but far less than when a specially designed standing mechanism is absent.

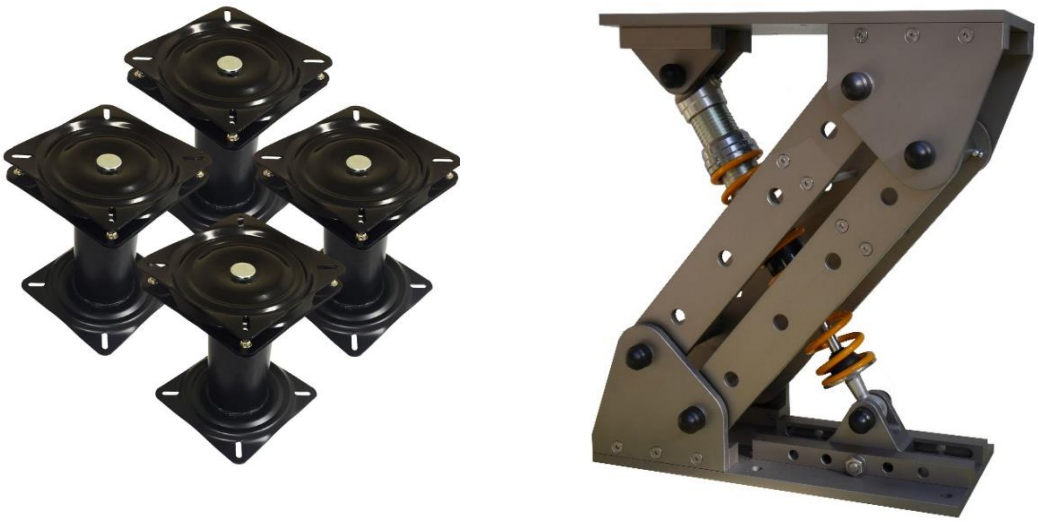


Figure 4. A plain seat standing mechanism (left) and a specially designed seat standing mechanism for HSC.

There are several standards to evaluate the health effects in human's lumbar spine of a person seated and sailing in a HSC. Purpose of this project is to evaluate those effects for Ermioni HSC seats, Suspension Ver MIL (Military) and PL (Pleasure), using ISO® 2631 – Part 5 (2004) standard. In general, multiple mechanical shocks are applied to these seats and seat pad acceleration is measured. These acceleration measurements are then used to evaluate the possibility for lumbar spine injuries.



Figure 5. EMAL® Ermioni HSC Series seats with shock absorber mechanism mounted.

Chapter 2 – The ISO® 2631 – Part 5 (2004) Standard for evaluation of human exposure to vibrations containing multiple shocks.

ISO® 2631 – Part 5 (2004) is a standard which evaluates human's lumbar spine injuries when exposed to vibrations with multiple shocks. This standard is meant to be the most efficient method for such evaluations, that concern not only HSC, in respect to NATO *"Shock Mitigation for the Human on High Speed Craft: Development of an Impact Injury Design Rule"* (RTO – MP – AVT – 110) Report. It is chosen from many design rules, such as Root – Mean – Square (RMS), ISO® 2631 – Part 1 (1985), Dynamic Response Index Statistics (DRI), Onset – Rate Statistics and Power Spectral Density (Bandwidth – Limited) rules. According to two more other references [(1) Paper: Prediction of Injury Risk for Occupants of HSC planning - University of Virginia, (2) IRCOBI Conference - Prague - September 2005: The modeling and measurement of humans in high speed planning boats under repeated vertical impacts] the repeated impact standard ISO® 2631 – Part 5 (2004) for seated occupants has been found to be as good as or better than any of the other injury criteria for application to the assessment of injury criteria in high speed planning craft.

It requires acceleration measurements in all 3 axes (x, y and z) as input and as output, it returns the possibility for lumbar spine injuries, after a specified time space. The requirements to perform lumbar spine injuries evaluation are:

1. The test load (human) must be seated in an upright position and belted to the test platform. It must always be in mechanical contact with seat pad.
2. The sign of acceleration must be taken into account and acceleration measurements must contain measurements in all 3 axes (x, y and z).
3. For the x and y axes, acceleration measurement sampling frequency must be higher than 80 Hz. For z axis this frequency must be higher than 160 Hz. If sampling frequency does not meet the above requirements, a resample is necessary.
4. Measurements must be sufficient (in duration).

Acceleration measurements in seat pad higher than 4 g (39.24 $^{m}/_{s^2}$) cannot be evaluated by ISO® 2631 – Part 5 (2004) Standard.

In general, this standard uses the acceleration measurements of seat pad to compute acceleration response of lumbar spine and calculate peak values. With these peak values it computes the lumbar spine compression in x, y and z axes and estimates the possibility for lumbar spine injuries. This possibility can be normalized for a vast time space, far more than the experiment duration, even for half a century. The model that this standard is using to analyze the lumbar spine compression is Palmgren – Miner material fatigue theory.

It must first calculate the response acceleration of lumbar spine. This contains the response in x, y and z axes of lumbar spine acceleration. The lumbar spine acceleration response in x and y axes follows an almost linear, single degree of freedom model. The lumbar spine acceleration response in z axis cannot be assumed as linear. It is studied that this system is non – linear, so its response is calculated using an artificial neural network. It is a computational algorithm that calculates a response, using a weighted input. These weights are calculated from a learning algorithm, using seat pad acceleration inputs from 2 to 4 g, with frequencies from 0.5 to 40 Hz.

The calculation of response of lumbar spine acceleration in x and y axes, using seat pad acceleration measurements, requires the determination of lumbar spine's natural frequency (f_n), natural angular velocity ($\omega_n = 2\,\pi\,f_n$) and critical damping ration (ζ_n). ISO® 2631 – Part 5 (2004) is using f_n = 2.125 Hz, so ω_n = 13.35 $^{1}/_{s}$ and ζ = 0.22 to compute acceleration response in x and y axes.

So, the linear mathematic model that computes **lumbar spine acceleration response in x and y axes** is given by:

$$a_{lk}(t) = 2\,\zeta\,\omega_n\,(v_{sk} - v_{lk}) + \omega_n{}^2\,(s_{sk} - s_{lk})\;in\;{}^{m}/_{s^2}$$

where:

- k for x or y axis
- v_{sk} cumulative seat velocity
- v_{lk} cumulative lumbar spine velocity
- s_{sk} cumulative seat displacement
- s_{lk} cumulative lumbar spine displacement

The calculation of **lumbar spine acceleration response in z axis**, using seat pad acceleration measurements, is using the following non – linear transformation:

$$a_{lz}(t) = \sum_{j=1}^{7}(W_j\;u_j(t)) + W_8\;in\;{}^{m}/_{s^2}$$

where:

$$u_j(t) = \tanh\left[\sum_{i=1}^{4}(w_{ji}\,a_{lz}(t-i)) + \sum_{i=5}^{12}\left(w_{ji}\,a_{sz}(t-i+4) + w_{j13}\right)\right]$$

where:

W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8
57,96539	52,32773	49,78227	53,16885	56,02619	–27,79550	72,34446	21,51959

Table 1. z – axis model coefficients for $a_{lz}(t)$.

and:

j	1	2	3	4	5	6	7
w_{j1}	0,00130	0,01841	–0,00336	0,01471	0,00174	0,00137	0,00145
w_{j2}	–0,00646	–0,00565	–0,00539	0,01544	–0,00542	0,00381	0,00497
w_{j3}	–0,00091	–0,02073	0,00708	–0,00091	0,00255	–0,00216	0,01001
w_{j4}	0,00898	–0,02626	0,00438	–0,00595	–0,00774	–0,00034	0,01283
w_{j5}	0,00201	0,00579	0,00330	–0,00065	–0,00459	–0,00417	–0,00468
w_{j6}	0,00158	0,00859	0,00166	0,00490	–0,00546	0,00057	–0,00797
w_{j7}	0,00361	0,00490	0,00452	0,00079	–0,00604	–0,00638	–0,00529
w_{j8}	0,00167	–0,00098	0,00743	0,00795	–0,01095	0,00627	–0,00341
w_{j9}	–0,00078	–0,00261	0,00771	0,00600	–0,00908	0,00504	0,00135
w_{j10}	–0,00405	–0,00210	0,00520	0,00176	–0,00465	–0,00198	0,00451
w_{j11}	–0,00563	0,00218	–0,00105	0,00195	0,00296	–0,00190	0,00306
w_{j12}	–0,00372	0,00037	–0,00045	–0,00197	0,00289	–0,00448	0,00216
w_{j13}	–0,31088	–0,95883	–0,67105	0,14423	0,04063	0,07029	1,03300

Table 2. z – axis model coefficients for $u_j(t)$.

Our next step is to calculate cumulative acceleration, using peak values from lumbar spine acceleration response in x, y and z axes. These peak values are derived from the absolute maximum value of acceleration between two successive zero – crossings. For x and y axes both positive and negative peaks are taken into account and for z axis, only positive peaks are counted. For the total duration that the experiment occurred, we compute **cumulative acceleration** by:

$$D_k = \left[\sum_{i=1}^{N} {A_{ik}}^6\right]^{1/6} \quad in \ {}^{m}/_{s^2}$$

where:

- k for x, y or z axis
- A_{ik} for ith peak value of $a_{lk}(t)$

A first indication of the possibility for lumbar spine injuries, that provides information only for the experimental procedure duration is **the equivalent static compressive stress**:

$$S_e = \left[\sum_{k=x,y,z} (m_k \, D_k)^6 \right]^{1/6} \; in \; MPa$$

where:

- m_x = 0.015 $MPa / {m/s^2}$
- m_y = 0.035 $MPa / {m/s^2}$
- m_z = 0.032 $MPa / {m/s^2}$

A normalization of the S_e value, to a daily equivalent requires first the normalization of cumulative acceleration D_k to an **average daily dose**:

$$D_{kd} = D_k \left[\frac{t_d}{t_m} \right]^{1/6} \; in \; {m/s^2}$$

where:

- t_d is the duration of the daily exposure to vibrations
- t_m is the duration over which D_k was measured (duration of experiment)

Note that D_{kd} provides results for once a day exposure to vibrations. When the daily exposure consists of **multiple exposures to vibrations**, **the daily equivalent** derives from:

$$D_{kd} = \left[\sum_{j=1}^{n} ({D_{kj}}^6 \, \frac{t_{dj}}{t_{mj}}) \right]^{1/6} \; in \; {m/s^2}$$

where:

- t_{dj} is the duration of daily exposure to vibrations in j condition
- t_{mj} is the duration over which D_{kj} was measured (duration of j experiment)

To acquire **the daily equivalent static compression dose**, which is an indicator for the daily possibility for lumbar spine injuries, we normalize S_e value to S_{ed}, by normalizing D_k to D_{kd}, so:

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k \, D_{kd}) \right]^{1/6} \; in \; MPa$$

For a more general view of this possibility, S_{ed} value has to be normalized to a life span equivalent. For this purpose, we have to know the start age when a person started being exposed to vibrations, the average number of days per year and the finish age. Also, because of the fact that bone density of the vertebrae changes over the years, we must take it into account. So, the **ultimate strength of the lumbar spine** derives from:

$$S_{ui} = 6.75 - 0.066 \, (b + i) \; in \; MPa$$

where:

- b the start age of being exposed to vibrations
- i the year counter

At this point, we are about to compute **the possibility for lumbar spine injuries** after a long period of the life span of a person, who was being exposed to vibrations, by computing R factor as:

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed} \, N^{1/6}}{S_{ui} - c} \right)^6 \right]^{1/6}$$

where:

- N the number of exposure days per year
- i the year counter
- n the number of years of exposure
- c = 0.25 MPa, a constant for static stress due to gravitational force

By having acquired R value, we are now ready to conclude about the possibility for lumbar spine injuries in respect to ISO® 2631 – Part 5 (2004) Standard:

0.5 < R < 0.8	**0.8 < R < 1.2**	**R > 1.2**
Low risk for lumbar spine injuries	Moderate risk for lumbar spine injuries	High risk for lumbar spine injuries

Finally, we have to notice that all of the above computations can be conducted in a programming language, as acceleration measurements should contain over 5000 samples. ISO® 2631 – Part 5 2004 provides a Matlab® source code to compute every value up to cumulative acceleration D_k.

The next steps are quite easy to be implemented. Also, in all of our laboratory tests, we computed S_e values for an 8 hour per day, once a day usage of the seat. The R value was normalized for a person who started the use of the seat at an age of 20 years old, for an average 240 days usage annually and finished the usage at an age of 65 years old, in order to have a more efficient opinion for the possibility for lumbar spine injuries, when being exposed to vibrations for a whole life working period.

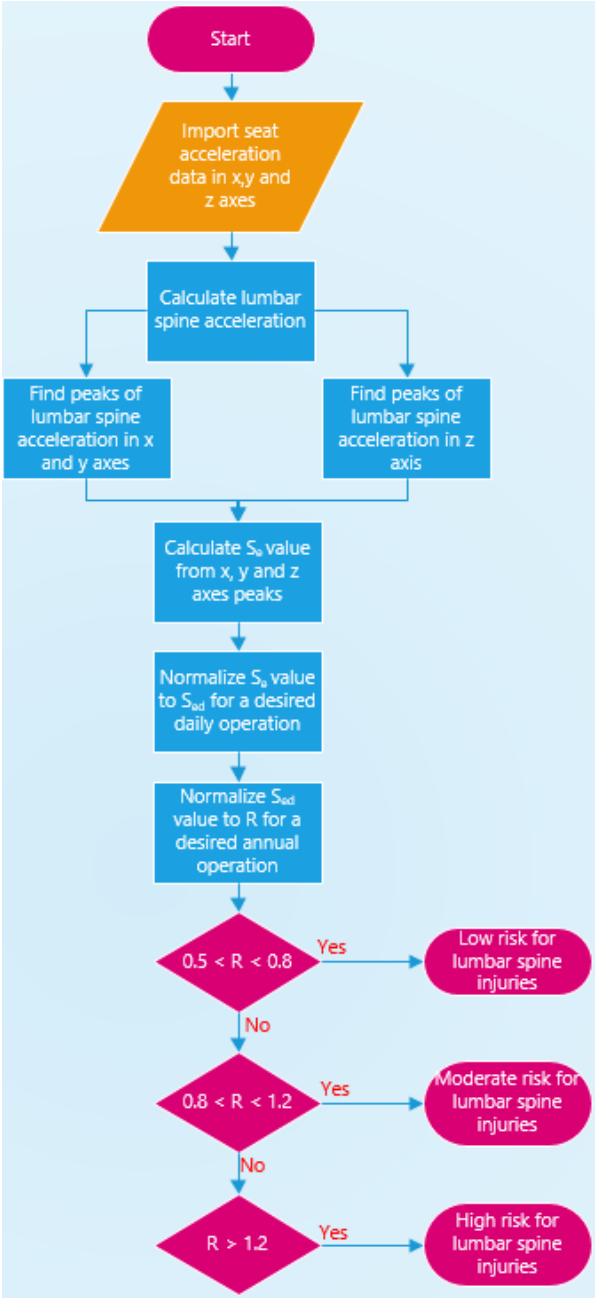


Figure 6. Generalized algorithm of ISO® 2631 – Part 5 (2004) Standard for evaluation of human exposure to vibrations containing multiple shocks.

Chapter 3 – The test set – up

Our laboratory test set – up, which from now on will be also called as "Test Bed", consists of three parts:

1. the mechanical part which is the basic metal structure and the suspension system, with the shock absorber mechanism for evaluation,
2. the pneumatic part which consists of pneumatic muscles and pneumatic valves which drive the muscles and
3. the electronic part, which consists of two sensors and a microcontroller which drives the pneumatic valves. The electronic part also has a Windows® based computer with Matlab® command window and an application for monitoring and recording from the sensors.

The Basic operating principle of this Test Bed is that a movable platform is used to simulate the vibrating boat deck. The platform move/acceleration is driven by the muscles which are controlled by the valves and the electronic part under an "open" loop system architecture. The relative motion between the lower and the upper part of the suspension system defines the absorption level of the mechanism.

3.1 – Mechanical equipment

The metal structure that holds the "Test Bed" set – up was constructed by EMAL® SA. It is about a frame structure with basic members to be 50 x 30 x 3 mm made by steel.

Four members consisting of tubes and welded in angle shape has been used as pillars to support the four (4) pneumatic muscles in a vertical position. The upper ends are fixed (clamped) and retain all movable weight.

The base platform is a reinforced aluminum plate (L x W: 360 x 550 mm, thickness t:10mm), where the lower ends of the pneumatic muscles are attached. This platform can be moved thru the stimulation which is given by the muscles and it is used to simulate the boat vibrating deck.

On this platform, the lower part of the suspension system is attached. Any vibration of the platform, accelerates (push upwards) the lower part of the suspension system reproducing in this way the vibrating deck in the laboratory environment.

In the upper part of suspension system, another aluminum reinforced metal plate is attached. This plate is used to load and a 90 kg weight. For safety reasons, the weight is belted.

Two motion tracking sensors are attached, in the lower and upper part of the suspension system, in order to monitor the input (stimulation) and the output (result).

At the end, the difference between these two signals will define the effectiveness of the absorbed system. The lower sensor helps also to maintain the platform the vibration between the range 2 to 4g.

Finally, for extra safety reason, the whole "Test Bed" set – up was clamped on the ground floor.

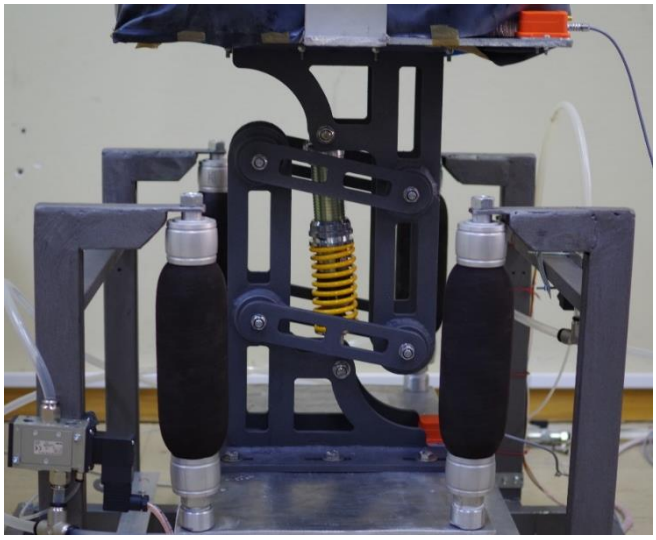


Figure 7. Front view of "Test Bed" with Suspension Ver MIL (Military) mounted. Pneumatic muscles, base and seat platform, motion tracking sensors and air valves can be seen.

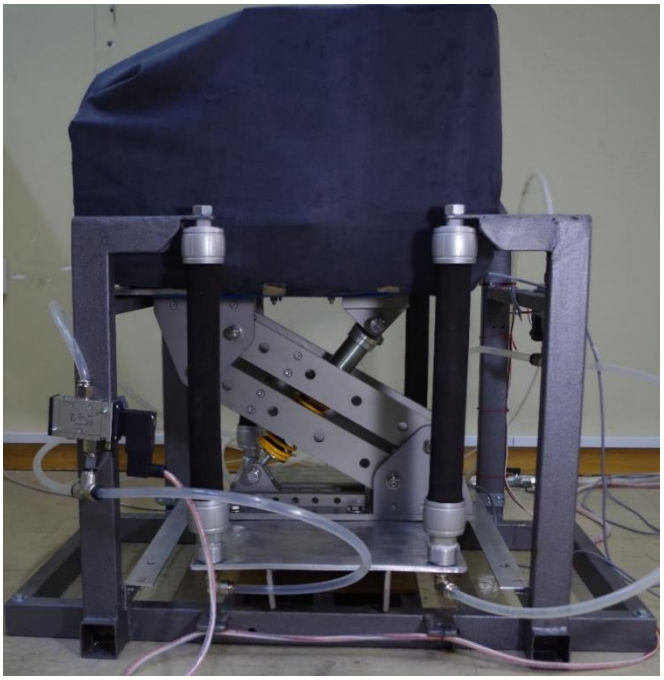


Figure 8. Front view of "Test Bed" with Suspension Ver PL (Pleasure) mounted. Pneumatic muscles, base and seat platform and air valves can be seen.

3.2 – Pneumatic equipment

Our motion actuator are pneumatic muscles. We use four muscles constructed by Festo®, models DMSP-40-305N AM-CM. Pneumatic muscles are tensile actuators which mimic the natural movement of a muscle. They consist of a contractible tubing which is made up of a rubber diaphragm with non – crimped fiber, which is made of aramid yarns on the inside. The diaphragm provides a hermetic seal enclosing.

Their length is 40 cm and they weight about 770 gr. Air pressure range is 0 to 6 bars, with nominal value 8 bars. Their ambient temperature operation is between -5 to +60 ^{o}C. The nominal load they can carry is 305 N, or approximately 31.1 kg for each one, so four of them in a parallel connection to the platform, can carry up to 124.4 kg.

Their operating principle is based on air intake and outtake, that changes their length. While air is pumped in the muscle, the muscle is shrinking and while air is pumped out, the muscle is extended up to its normal length. The shrinking and extension is linear (stroke in centimeters per input air pressure) from 0 bars (0 stroke) to approximately 3 bars (50% of stroke) and then is quite non – linear (a saturation area in muscle characteristic). When not loaded, the nominal stroke can reach up to 22.5 cm. In our tests, with approximately 120 kg of load (30 kg for each muscle) nominal stroke was approximately 14 cm. Also, air intake and outtake frequency is a factor which effects stroke. The lower the frequency, the higher the stroke and reversely. In our laboratory tests, with a load of 120 kg, pneumatic muscles could operate fine up to 20 Hz of air intake and outtake frequency and quite worse at the range of 20 to 30 Hz. For frequencies more than 30 Hz, the muscles with that load could not move at all.



Figure 9. A Festo® DMSP – 40 – 305N AM – CM pneumatic muscle (left) and its inside part (right).

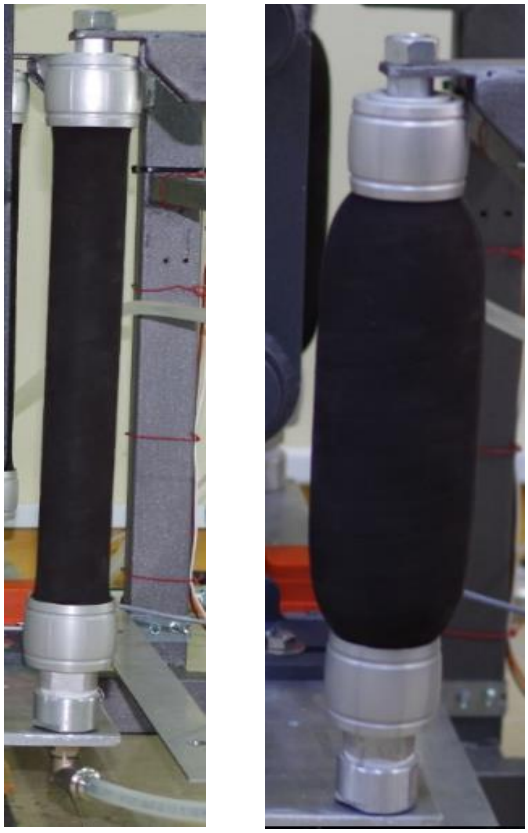


Figure 10. Pneumatic muscle on its natural length (left) and fully pumped with air of 8 bars pressure and shrinking (right).

Our pneumatic muscles actuator are two air valves (one for each pair of muscles). We preferred digital (ON – OFF) valves than analog pressure regulators, due to the fact that analog regulators could not reach high frequencies. Our valves are coming from SMC Pneumatics®, models EVF S312OR – 5YZB – O3F – Q. This series of air valves is characterized by its high operating frequency (up to 300 Hz). High frequency ON – OFF air valve use is mandatory in applications like this.

Their operation principle is simple. While their internal coil is connected to 24 V DC power supply, it attracts a metal strip that allows air flow. When power supply is cut off, metal strip is returned to its normal position from a spring and flow is prevented. Each valve consumes a power of about 3 W. Our air valves are driven by ON – OFF pulses created by a microcontroller and air is supplied by an air compressor with nominal pressure of 8 bars, through a compressed air network in laboratory.



Figure 11. High frequency ON – OFF air valve from SMC Pneumatics®.

3.3 – Electronic equipment

As mentioned before, ON – OFF air valves need a pulse generator to be driven with the desired frequency. For this purpose, a microcontroller is needed. We use an Arduino UNO® microprocessor because of its simplicity in programming and connection. Its operating voltage is 5 V (V_{CC}) and can be supplied by a USB 2.0 cable which is connected to a computer, which is also used for programming the microprocessor. Arduino Uno® has a CPU clock of 16 MHz, that allows us to program timers with a minimum value of 1 μs. The source code is stored in an EEPROM of 1 KB, so program is not lost after power supply cut off.

We program the microprocessor to create pulses in a specific digital output (PWM) with specified frequency and duty cycle. By the term duty cycle we determine the % percentage of a period that PWM pulse will be high. For example, a duty cycle of 60 % in a period of 1 s means that for the first 600 ms the pulse will be in logic "1" and for the rest 400 ms (rest 40%) the pulse will be at logic "0". This allows us to operate the pneumatic muscle with more efficiency and robustness per frequency. For example, at low frequencies (5 to 10 Hz) a duty cycle of 70 to 80 % is good enough. At frequencies from 10 to 20 Hz a duty cycle of 50 to 70 % can operate the pneumatic muscles with enough robustness. At higher frequencies (20 to 30 Hz) starting the operation from a fully empty with air muscle does not provide an effective stroke. For this condition, we first preload the pneumatic muscle with air for 3 to 5 s and then we operate it with a pulse signal. All the above programming techniques lead to the more efficient operation of the pneumatic muscles and can be easily implemented in Arduino® programming environment.

The steps followed to execute an experiment, in general, is the determination of frequency and duty cycle of the driven pulses to the ON – OFF air valve, the selection for preload or not, or even the hold of the set – up (keep the muscles always filled with air) for maintenance use. Then, a switch is used to activate and execute the desired routine, which drives 5 V (logic "1") to the specified digital input of the microprocessor. Finally, because of the fact that Arduino Uno® can drive PWM signals (digital or analog) from 0 to 5 V and our ON – OFF air valves require 24 V DC and 3 W power supply, a solid state optical relay is driven by the digital PWM output of our microcontroller and performs a short circuit between the power supply and the valves. The choice of optical relay in that type of applications is mandatory, because normal electromechanical relays first, cannot reach high frequencies and second, they will be damaged in a short time period from voltaic arcs and from the movement at that frequencies of their moving mechanical parts.

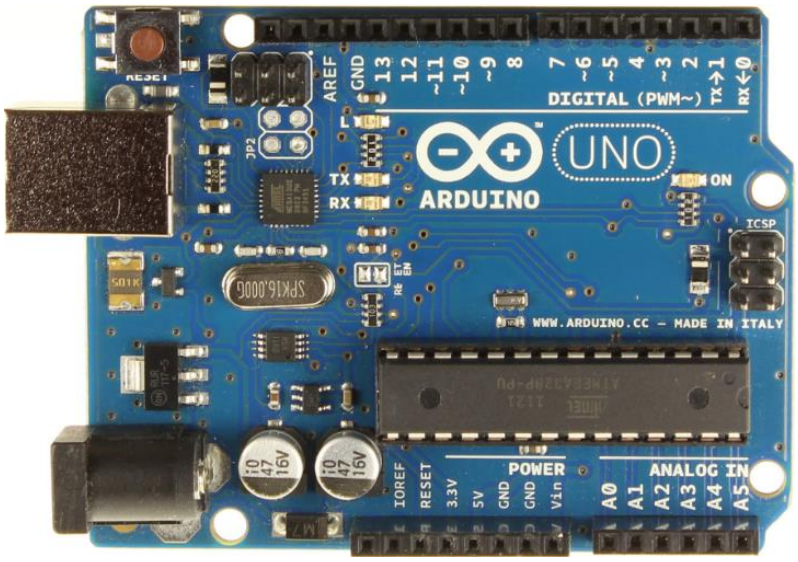


Figure 12. Arduino UNO® microcontroller.

To be sure that input vibrations are kept in a range of 2 to 4 g and to measure seat acceleration, to use these measurements in R value calculation, we use two motion tracking sensors. Two Xsens® MTi – G motion trackers are attached: one to the base platform and one to the seat pad. They consist of four different sensors: a 3 axes accelerometer with a range of -5 to +5 g, a magnitude amplitude meter, an angular velocity meter and a GPS, used in aeronautics (e.g. drones).

The accelerometer part is useful for our application, so we are about to discuss only for acceleration sensor. As it is mentioned, the accelerometer sensor has a range from -5 to +5 g, with a sampling frequency of 120 Hz (which is resampled in ISO® 2631 – Part 5 (2004) Matlab® source code to compute the z axis acceleration response). Its accelerometer operation is based in M.E.M.S. (Micro Electromechanical System) inertial sensor, something that means more accuracy. Note that for this type of applications, a more accurate sensor with high enough sampling frequency is required.

For example, an IMU sensor could not be as accurate as this application requires. Furthermore, this type of sensors is using a USB protocol to communicate and not an analog output, as high sampling frequency is required. Also, Xsens® provides a computer application for monitoring and recording data coming from the sensor. Settings may also be done to the sensor by this application.



Figure 13. Xsens® MTi – G motion tracking sensor (orange) with GPS antenna (black).

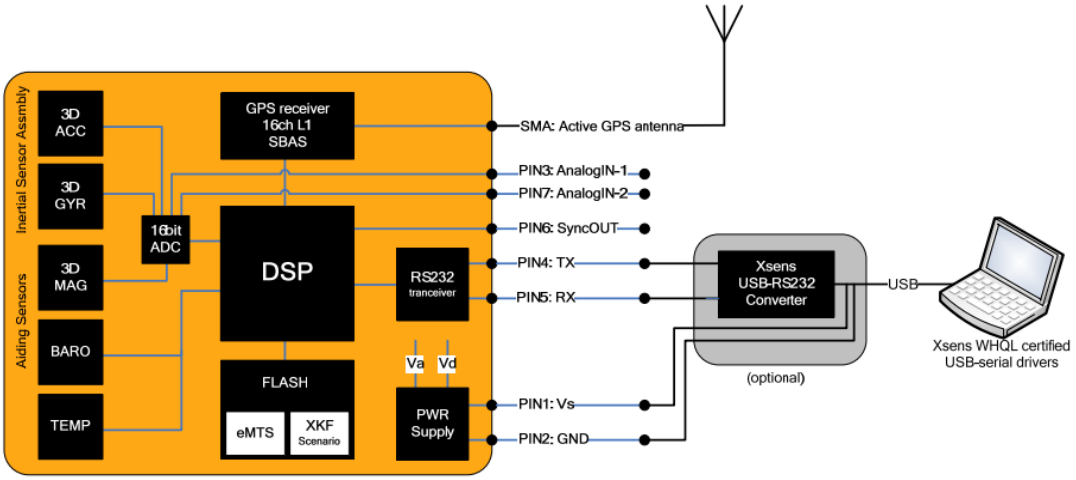


Figure 14. Architecture overview of Xsens® MTi – G system.

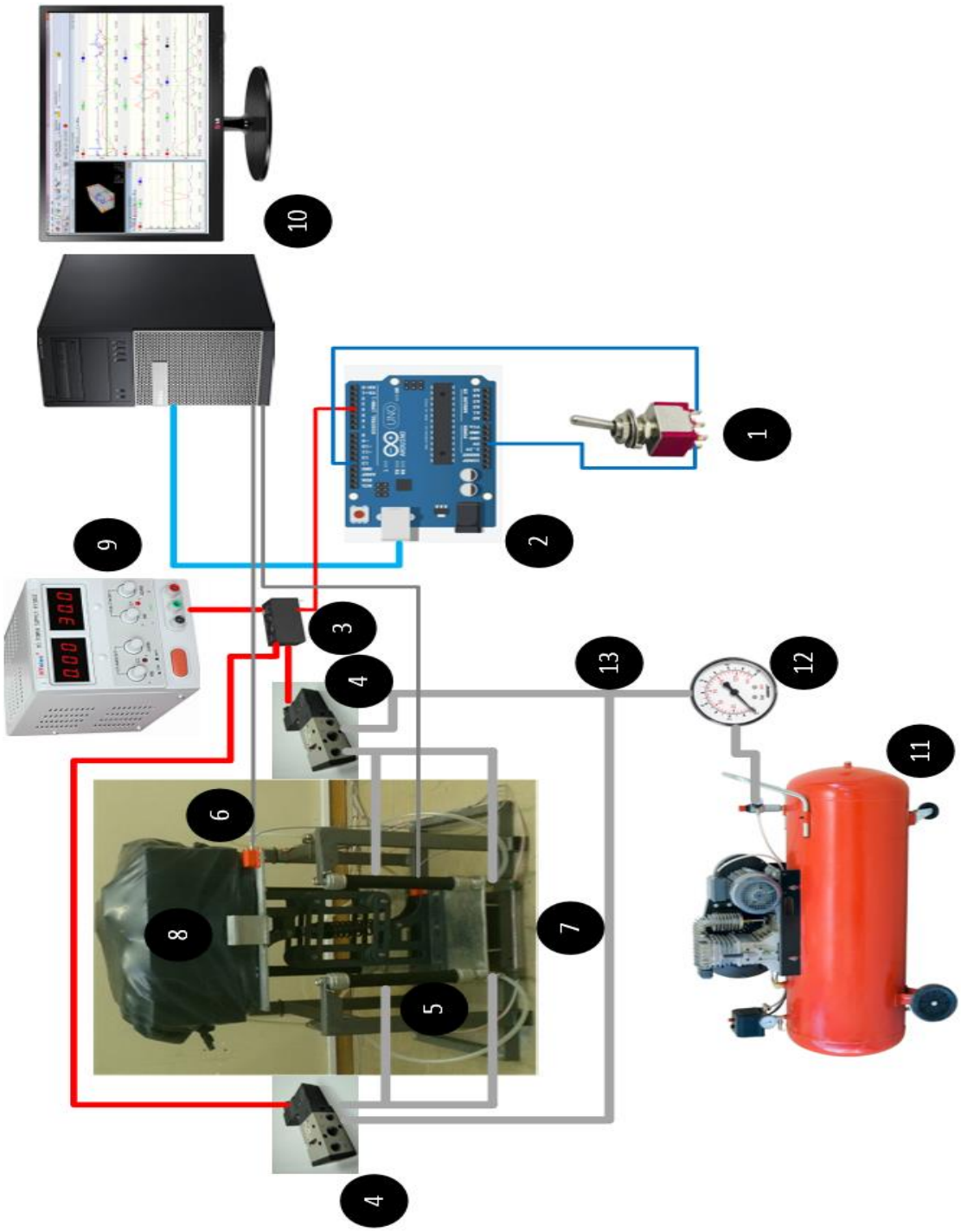


Figure 15. General overview of the test set – up.

In general, our laboratory test set – up consists of:

1	Switch to activate a routine in microprocessor so that mechanical move of "Test Bed" will occur.
2	Arduino UNO® microprocessor – microcontroller which drives ON – OFF air valves via optical relay (3).
3	Optical relay which connects ON – OFF valves (4) with power supply unit (9) and is driven by microcontroller (2).
4	SMC Pneumatics® high frequency ON – OFF air valve (x2) which drives pneumatic muscles (5) and is driven by microprocessor (2) via optical relay (3).
5	Festo® pneumatic muscle (x4) which actuates mechanical vibrations to "Test Bed" (7).
6	Xsens® MTi – G motion tracking sensor (x2) to measure acceleration in base platform and seat pad.
7	The "Test Bed" set – up, to evaluate Ermioni HSC suspension systems.
8	A belted load of 90 kg to seat pad that simulates an average human, seated at the seat pad.
9	A power supply unit of 24 V DC which is needed for ON – OFF Air valves (4).
10	A windows based computer to program Arduino Uno® microcontroller, monitor and record Xsens® MTi – G measurements and run ISO® 2631 – Part 5 (2004) Matlab® command window to evaluate Ermioni HSC suspension system.
11	Air compressor with nominal air pressure at 8 bars.
12	Manometer
13	Compressed air laboratory network.

Chapter 4 – Experimental procedure

There is a series of steps that have to be implemented before an experiment begins. First of all, we mount the suspension system that is going to be tested. We attach the 90 kg load and we check the balance of seat pad. For safety reasons, we tie the load with belts. It is important to be calibrated, in order to test the shock absorber with ISO® 2631 – Part 5 (2004) standard. Then, it is also important to have assured that compressed air is enough to conduct an experiment, also air pressure must be near 8 bars. For this purpose, we refill the air compressor's tank and we check air pressure with a manometer. After that, we decide what kind of test are we going to execute, continuous pulses, or single pulse. For continuous pulses, we decide frequency and duty cycle. These test's parameters are programmed in an Arduino Uno® microcontroller. After that, we are ready to conduct an experiment. We have to execute the motion tracking sensors' application and record the measurements, as long the experiment is being conducting. At the finish of experimental procedure, we import both base and seat acceleration measurements to Matlab® command window that runs ISO® 2631 – Part 5 (2004) source code and results about S_e, S_{ed} and R values are shown for shock absorber's evaluation.

4.1 – Creation of high frequency mechanical vibrations using pneumatic muscles

Pneumatic muscles are known for their capability to be loaded with a lot Newtons of force. Furthermore, they can perform a linear movement between 0 and stroke (in cm), by proportionally adjust their air intake pressure (between 0 bars and 6 bars), using proportional air valves. Note that their stroke differs, whether they are loaded or not.

Applications that require frequencies higher than 1 to 2 Hz, have to be approached with a different philosophy, when pneumatic muscles are going to be the movement actuators. There are many limitations in that kind of movements, such as the highest frequency that can be reached, the maximum stroke, the heat developed in pneumatic muscles and the needs for compressed air. The frequency and stroke parameters differ between pneumatic muscles' types. By choosing a "big" muscle, we gain in nominal load, but we lose in stroke per frequency. This problem can be solved by choosing "smaller" muscles, but more of those muscles are required in order to hold the load (in parallel connection). The reason why "smaller" muscles are "quicker" than "big" is the total amount of air that they can be filled with. A smaller pneumatic muscle can store less air than a big one, so pumping in and out time is less. That provides the possibility to reach higher frequencies and keeping a good enough stroke simultaneously.

Pneumatic muscle's stroke differs also from one frequency to another. In our laboratory experiments, with a total average load of 120 kg, pneumatic muscles could operate optimally at frequencies between 10 and 20 Hz. ***The criterion for their optimal operation is the maximum acceleration that can create in base platform and also keep it for a long time***.

Furthermore, an optimal combination of duty cycle per frequency has to be found, when continuous pulses experiments are about to be conducted. For low frequencies, high duty cycles are suggested. In our laboratory tests, with a 5 Hz increment in frequency, a 5% decrement in duty cycle was being applied at most of experiments. Our tests start at a frequency of 5 Hz, with a duty cycle of 70% or 80% and reached 30 Hz with a duty cycle of 45% or 50%.

At frequencies higher than 20 Hz, base platform was not able to move enough, due to the minimized stroke of pneumatic muscle. For that purpose, we first prefilled muscle with compressed air for about 3 seconds. Then, high frequency pulses were applied. The reason for prefilling pneumatic muscle at high frequencies, is to operate in a more robust state. At frequencies higher than 30 Hz, pneumatic muscle couldn't move at all with 120 kg of approximate total load.

All the above parameters can be easily adjusted in Arduino Uno® microprocessor programming window. When type of mechanical input and/or frequency and duty cycle are decided, we program them and then with a switch we "turn on" the set – up. By the term "turn on", it is meant that a specific routine that creates a signal in Arduino's® digital PWM output is called. This signal drives the optical relay which performs a short circuit between 24 V DC power supply unit and ON – OFF air vales. Then, muscles perform the movement that we programmed before.

4.2 – Acceleration measurements

In order to evaluate the HSC seats for lumbar spine injuries with ISO® 2631 – Part 5 Standard, acceleration measurements are needed. Matlab® source code requires only seat acceleration in all 3 axes to compute lumbar spine acceleration response, but to be sure that input shocks keep in an acceleration range of 2 to 4 g and a frequency range of 5 to 30 Hz, we use two acceleration sensors, one in the base platform and one in the seat pad.

As it is mentioned before, acceleration measurements at that type of mechanical shocks require a higher precision and sampling frequency. For this purpose, a high precision motion tracking sensor from Xsens® is used. This sensor uses a 120 Hz sampling rate. Also, ISO® 2631 – Part 5 (2004) acceleration measurements at z axis require a sampling rate of 160 Hz, because neural network coefficients are calculated for that frequency, so a resampling is then executed in Matlab® programming script. Furthermore, acceleration sensor has to be calibrated in order to take accurate measurements. Xsens® MTi – G motion tracking sensor is already calibrated by Xsens®. The most popular accelerometers' calibration technique, with enough precision is the 2 – point calibration: first, we hold accelerometer with z axis vector indication looking straight up and we assign 1 g of acceleration. Then, we repeat that with z axis indication vector looking straight down and we assign -1 g of acceleration. We repeat that for x and y axes at the same way. Also, when conducting accelerometers' calibration, tempe-

rature has to be compensated. In low budget sensors, temperature is considered as 25 ^{o}C. For higher budget sensors, a temperature sensor is also included inside acceleration sensor.

It is very important to acquire acceleration data on line. Most medium budget accelerometers are coming with a software that visualizes measurements on line. Apart from this, measurements recording is required. Because of the fact that ISO® 2631 – Part 5 (2004) Matlab® source code requires an ASCII input file – format, sensor's software is needed to export that type of files (.txt). So, measurements recording is required as long as experimental procedure is being conducting. A good enough experimental procedure must include a large number of samples. So, measurements have to be taken for time space of more than 30 seconds.

Finally, ISO® 2631 – Part 5 (2004) Matlab® command window requires three different files, one for each axis. Also, each file must contain 2 columns: the first column must be the samples (0 or 1 to N-1 or N) and the second column must be the acceleration measurement for that sample. We have to know the output file format that sensor's application exports. If it does not meet the above requirements, it has to be modified. For this purpose, a program has to be written. In our laboratory tests, we used C compiler to implement a small application that sorts measurements in three different files (for x, y and z axes), with first column refer to a sample counter and second column to be the acceleration measurement. That type of application is not difficult to be implemented, even with low skills in programming. The technique requires a few steps. First, it is important to drive the file pointer at the point in which measurements begin, if sensor's output file starts with strings, such as date, sensor's name etc. Then, from that point and up to end of file (EOF), a counter is used to count the number of rows. With that number of rows, an array is then initialized to hold all the measurements. A file scan is then again performed and all measurements are assigned to the board. At finish, we check which column of the original file is our preferred measurement (acceleration at x, y and z axis) and we write a file that contains a column to the left for samples (from 0 to counter) and another column to the right with the specified column of the array. We repeat that for all required measurements (acceleration in x, y and z axis). Note that this implementation is a fast solution, but not a very "clever" program. We can improve it by using dynamic memory allocation and other data structures (struct) than 2 – dimensional floating – point number arrays.

4.3 – Use of acceleration measurements to evaluate lumbar spine injuries with ISO® 2631 – Part 5 (2004) Standard.

Having acquired the required ASCII files that contain acceleration measurements in x, y and z axis, for seat pad (and for base platform), the next step is to execute Matlab® command window that evaluates lumbar spine injuries possibility. The following procedure for evaluation of human's lumbar spine injuries possibility is the same as described at Chapter 2 but implemented programmatically. It is also mentioned that ISO® 2631 – Part 5 (2004) Matlab® source code can provide results up to D_k values. The next steps ($S_e, D_{kd}, S_{ed}, S_{ui}$ and R) values calculations, are easy to be implemented. Then, program is executed and results about S_e, S_{ed} and R values are calculated. Also, acceleration in base platform, seat pad and lumbar spine response for all 3 axes, are plotted (9 plots). This helps us to have a better view of seat pad and lumbar spine acceleration response at that type of input.

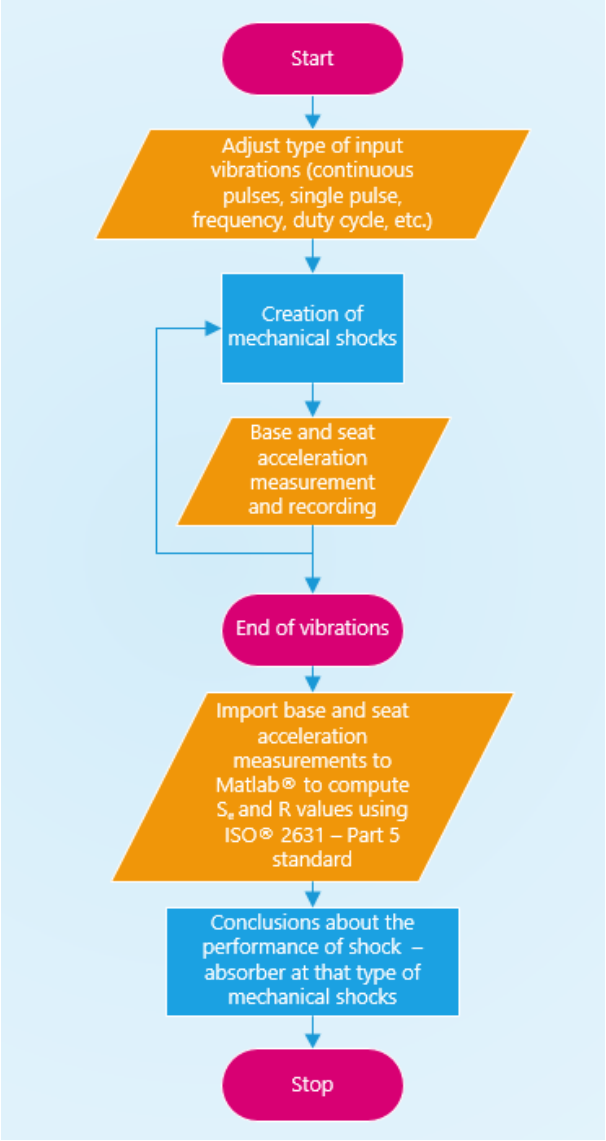


Figure 16. Laboratory tests experimental procedure

4.4 – Tested systems

Four systems were tested in this test set – up. All those systems are HSC seats designed and manufactured by EMAL® SA. These seats are the "Ermioni HSC Seats" series and are coming at two different versions: Suspension Ver MIL (Military) and Suspension Ver PL (Pleasure), with two different types of shock absorbers (type 1 – black and type 2 – yellow). The need for shock absorbers in HSC is previously discussed.

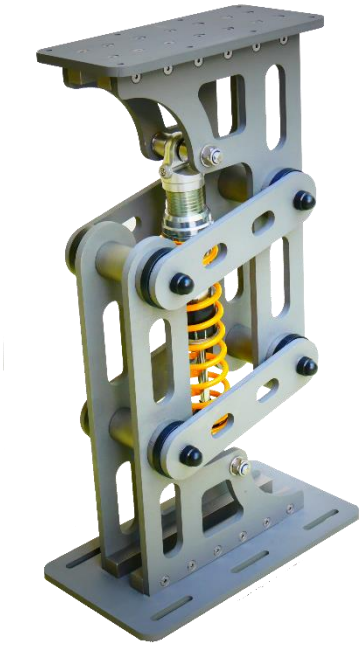


Figure 17. Suspension Ver MIL (Military) system.



Figure 18. Suspension Ver PL (Pleasure) system.



Figure 19. Suspension Ver MIL with type 1 shock absorber mounted

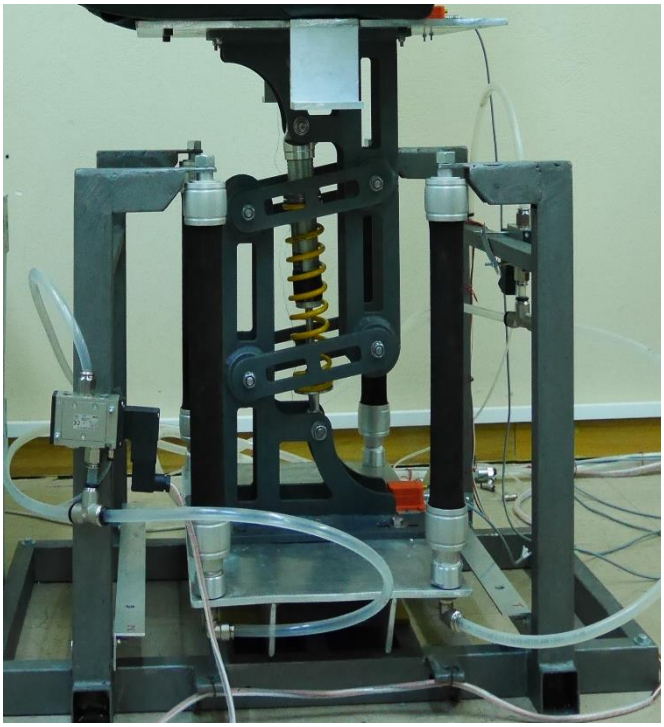


Figure 20. Suspension Ver MIL with type 2 shock absorber mounted

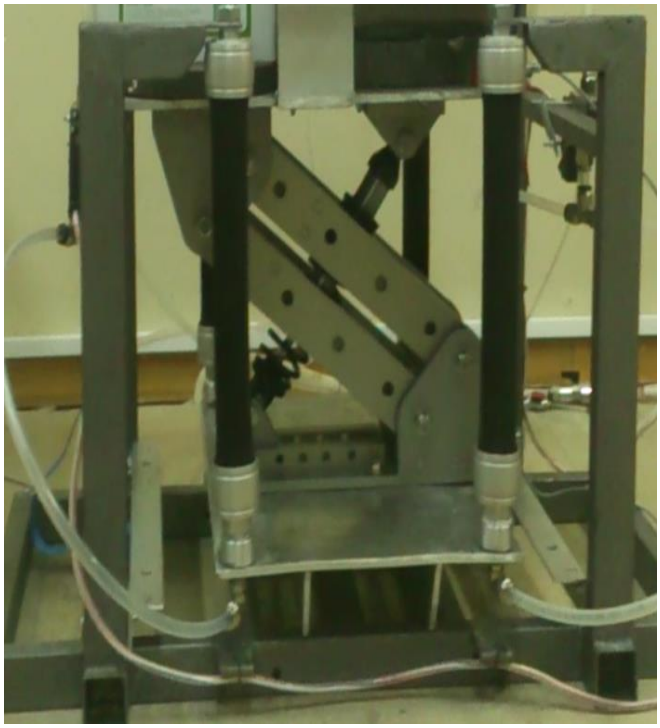


Figure 21. Suspension Ver PL with type 1 shock absorber mounted

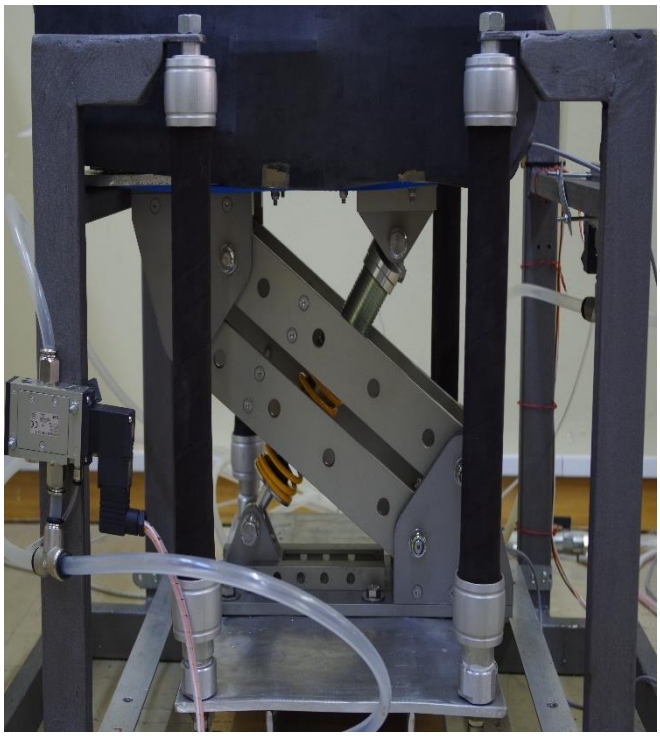


Figure 22. Suspension Ver PL with type 2 shock absorber mounted

Chapter 5 – Laboratory tests for Ermioni HSC seats

Laboratory tests include continuous pulse mechanical vibrations inputs, starting from a frequency of 5 Hz and finishing at 30 Hz. In following pages, tests for all four systems are presented, with a board that concentrates average peak values of acceleration in base platform, seat pad and lumbar spine, S_e, S_{ed} and R values for each frequency. Also, acceleration measurements and response at z axis are plotted. Finally, conclusions about each system are discussed.

5.1 – Experimental tests



Safety comes first. To perform safe experiments and fulfill ISO® 2631 – Part 5 (2004) Standard rules for high frequency mechanical vibrations experiments, follow these rules:

1. Attach the load to seat pad and be sure that it is calibrated.
2. Tie the load with strong belts.
3. Be sure that the set – up will not vibrate and move: house base on the ground floor.
4. Be sure that seat pad will not lean in x and y axes.
5. Prepare an emergency stop button and use it to stop mechanical vibrations when a problem appears.
6. Be sure that compressed air is enough to conduct an experiment (quantity and pressure).
7. Program the microcontroller to perform a specific routine.
8. Always keep a distance more than 1.5 meter from the set – up while mechanical vibrations are taking place.
9. When set – up is held up with pneumatic muscles for maintenance, be very careful when accessing the part below base platform.

5.1.1 – Suspension Ver MIL with type 1 shock absorber

The following tests include mechanical vibrations (shocks) of the base platform starting from a frequency of 5 Hz and ending at a frequency of 30 Hz, with an increment of 5 Hz, for the Suspension Ver MIL (Military) with type 1 shock absorber mounted. Our target was to keep a continuous 2 to 4 g acceleration at base platform in order to test the Suspension Ver MIL system. Mechanical shocks duration was about 30 seconds, S_{ed} value was normalized to an **8 – hour per day** operation, once a day usage of the seat and R value was normalized for **240 days per year** usage, starting from an age of **20 years old** and finishing at an age of **65 years old**.

Frequency in Hz	Average base peak acceleration in g*	Average seat peak acceleration in g*	Average lumbar spine peak acceleration in g*	S_e in MPa	S_{ed} in MPa	R	Risk for lumbar spine injuries
5	3.2	1.3	1.15	0.019619	0.059621	0.093267	LOW
10	3.1	1.3	1.15	0.018323	0.055856	0.087377	LOW
15	4	1.4	1.2	0.019243	0.05857	0.091623	LOW
20	3.5	1.4	1.15	0.015081	0.046222	0.072307	LOW
25	2.8	1.6	1.15	0.023578	0.072536	0.11347	LOW
30	3	1.5	1.1	0.028148	0.093799	0.14673	LOW

*Acceleration measurements refer to z axis.

Table 3. Laboratory tests for Suspension Ver MIL with type 1 shock absorber, at continuous pulse type mechanical vibrations.

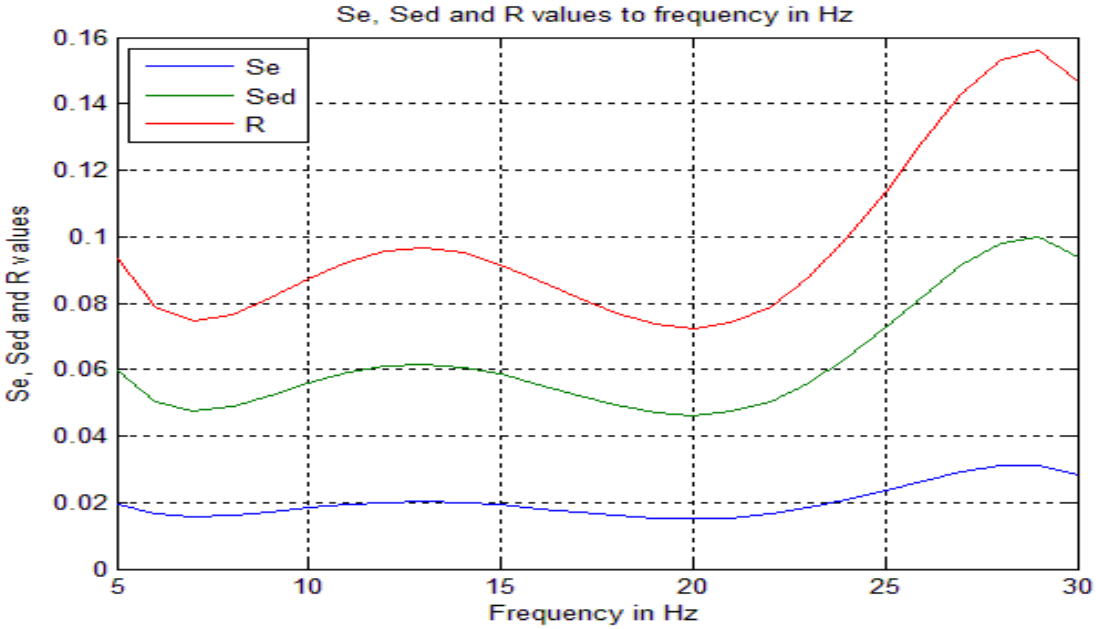


Figure 23. S_e, S_{ed} and R values plot with low regression error ($R^2 \approx 1$) for Suspension Ver MIL with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 5 Hz with 80% duty cycle.

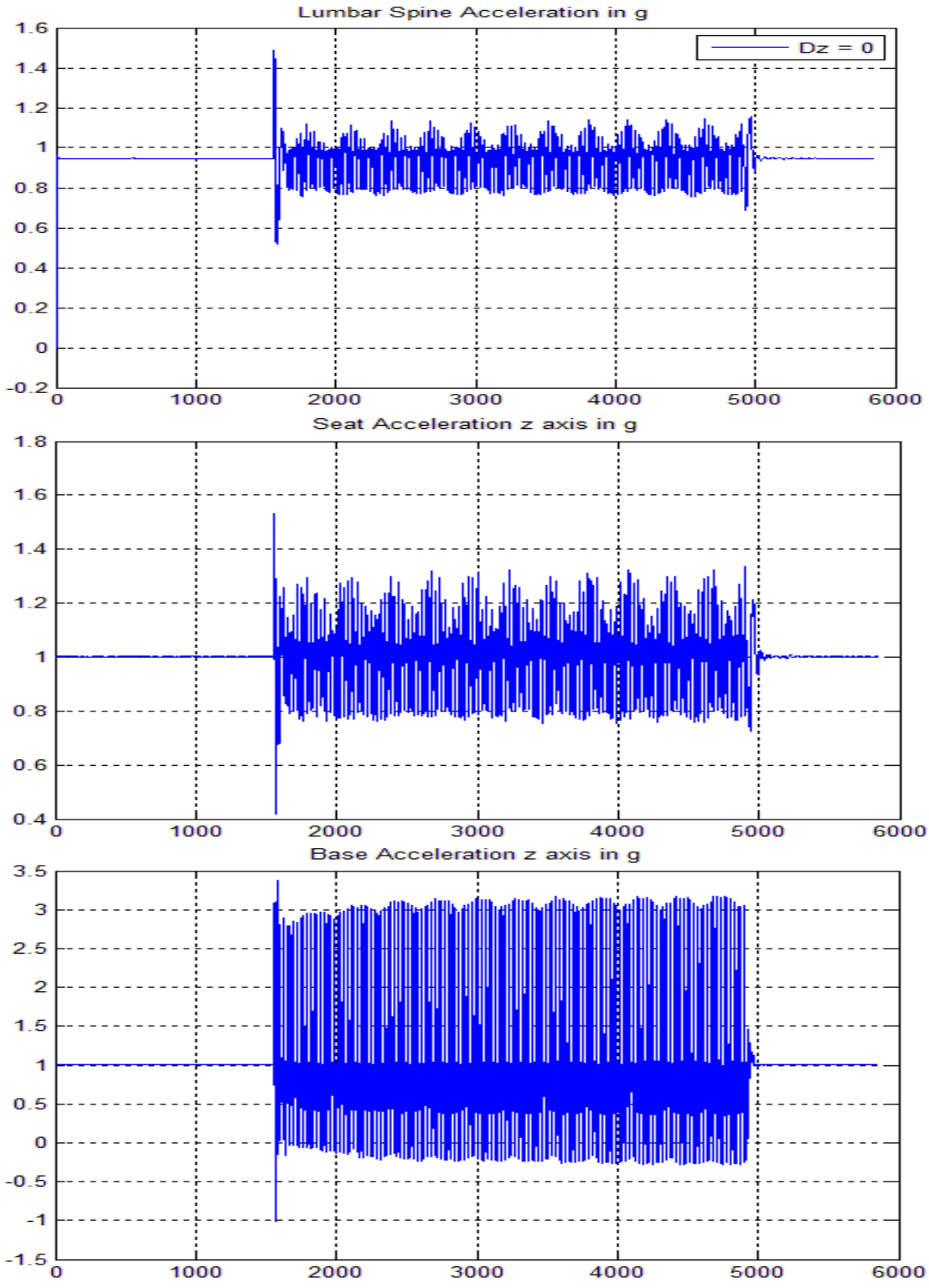


Figure 24. Base, seat and lumbar spine acceleration at mechanical vibrations of 5 Hz frequency with 80% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 10 Hz with 70% duty cycle.

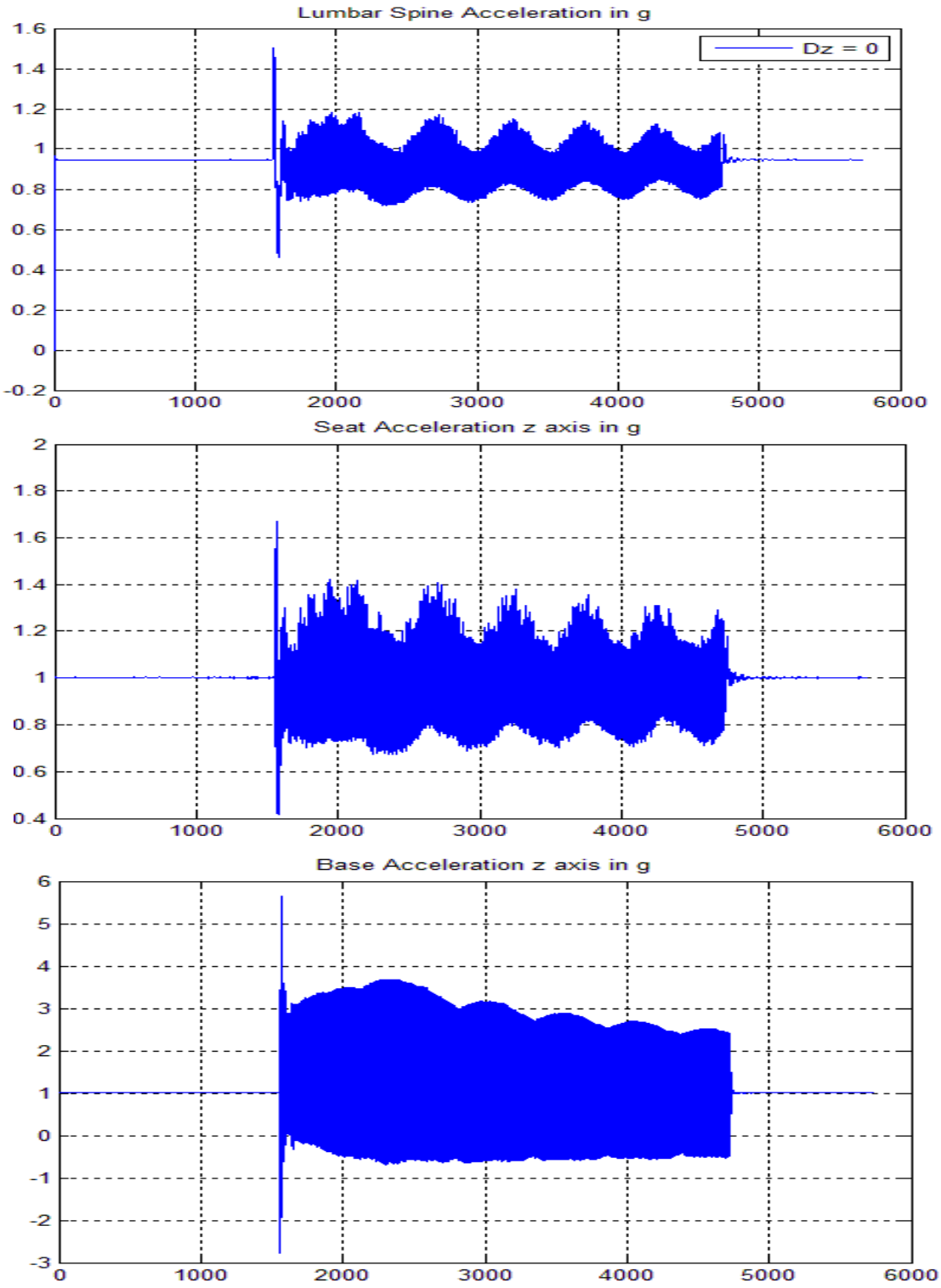


Figure 25. Base, seat and lumbar spine acceleration at mechanical vibrations of 10 Hz frequency with 70% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 15 Hz with 70% duty cycle.

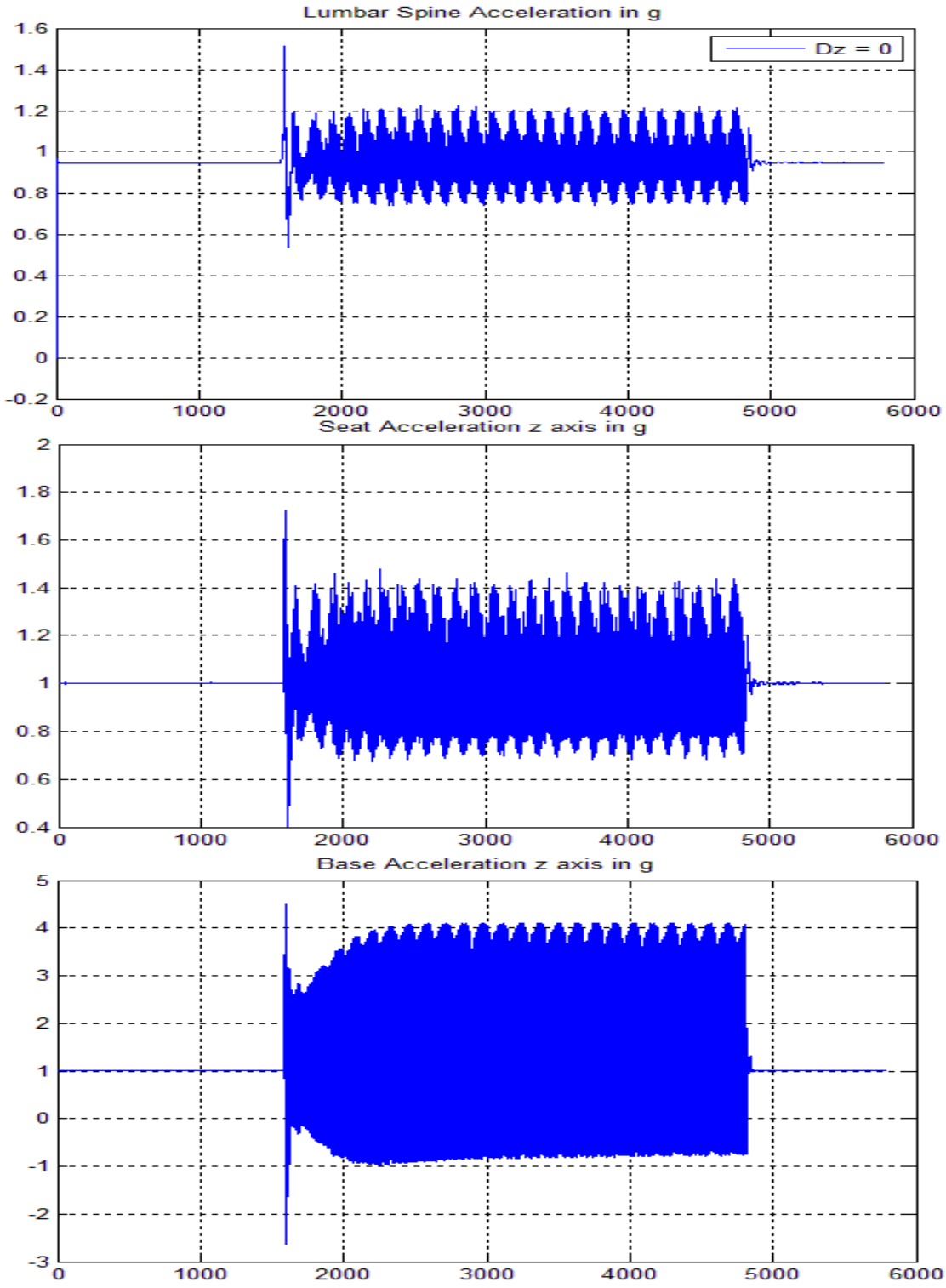


Figure 26. Base, seat and lumbar spine acceleration at mechanical vibrations of 15 Hz frequency with 70% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 20 Hz with 60% duty cycle.

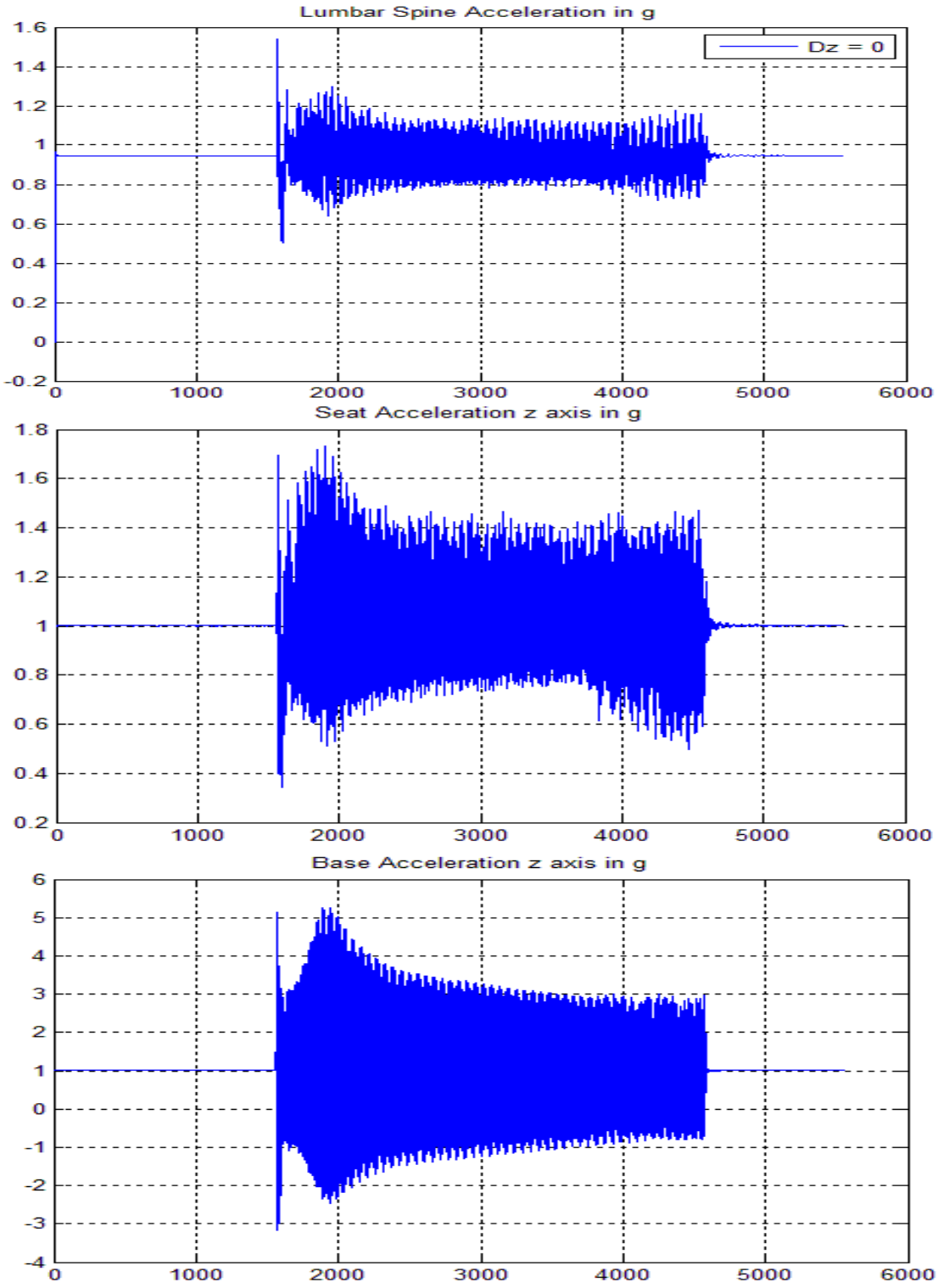


Figure 27. Base, seat and lumbar spine acceleration at mechanical vibrations of 20 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 25 Hz with 60% duty cycle.

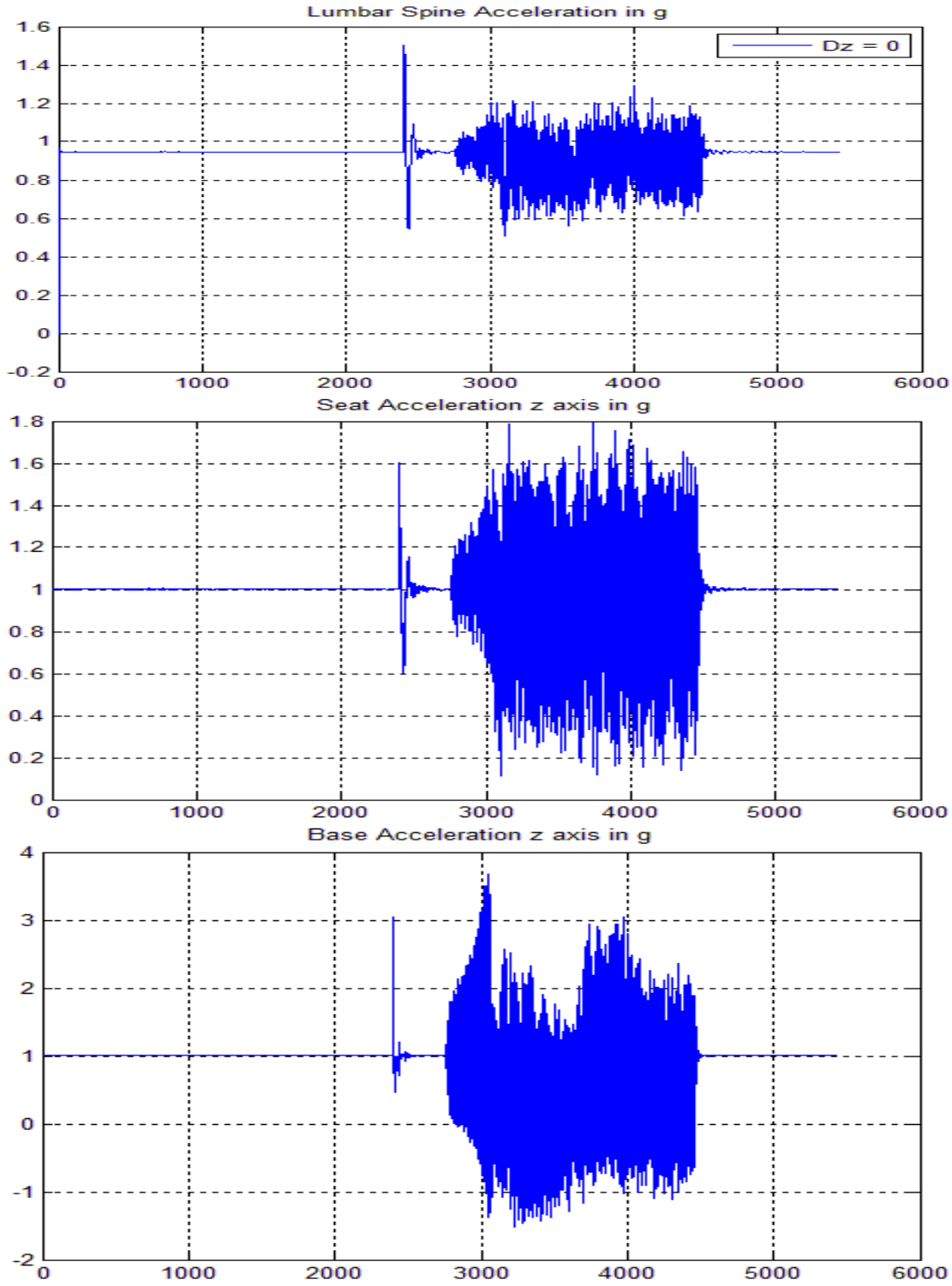


Figure 28. Base, seat and lumbar spine acceleration at mechanical vibrations of 25 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

Suspension Ver MIL with type 1 shock absorber at 30 Hz with 60% duty cycle.

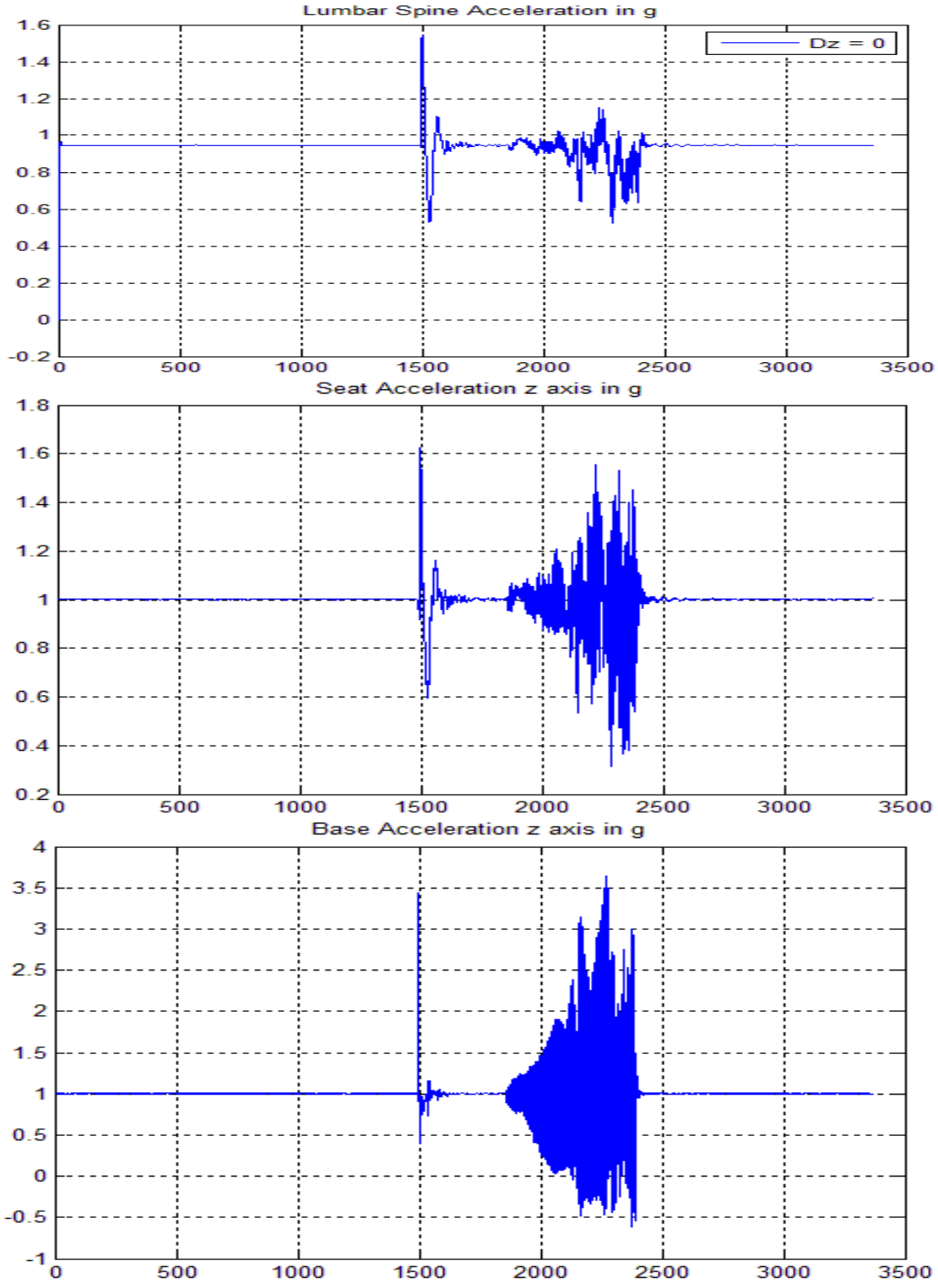


Figure 29. Base, seat and lumbar spine acceleration at mechanical vibrations of 30 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 1 shock absorber.

5.1.2 - Suspension Ver MIL with type 2 shock absorber

The following tests include mechanical vibrations (shocks) of the base platform starting from a frequency of 5 Hz and ending at a frequency of 30 Hz, with an increment of 5 Hz, for the Suspension Ver MIL (Military) with type 2 shock absorber mounted. Our target was to keep a continuous 2 to 4 g acceleration at base platform in order to test the Suspension Ver MIL system. Mechanical shocks duration was about 30 seconds, S_{ed} value was normalized to an **8 – hour per day** operation, once a day usage of the seat and R value was normalized for **240 days per year** usage, starting from an age of **20 years old** and finishing at an age of **65 years old**.

Frequency in Hz	**Average base peak acceleration in g***	**Average seat peak acceleration in g***	**Average lumbar spine peak acceleration in g***	**S_e in MPa**	**S_{ed} in MPa**	**R**	**Risk for lumbar spine injuries**
5	2.8	1.2	1.1	0.017244	0.055794	0.087281	LOW
10	2.8	1.3	1.1	0.017347	0.056329	0.088117	LOW
15	3.4	1.4	1.2	0.024679	0.080145	0.12537	LOW
20	3	1.4	1.15	0.022671	0.073434	0.11488	LOW
25	2.5	1.3	1.1	0.02095	0.083825	0.13113	LOW
30	2.2	1.3	1.1	0.023029	0.094667	0.14809	LOW

*Acceleration measurements refer to z axis.

Table 4. Laboratory tests for Suspension Ver MIL with type 2 shock absorber, at continuous pulse type mechanical vibrations.

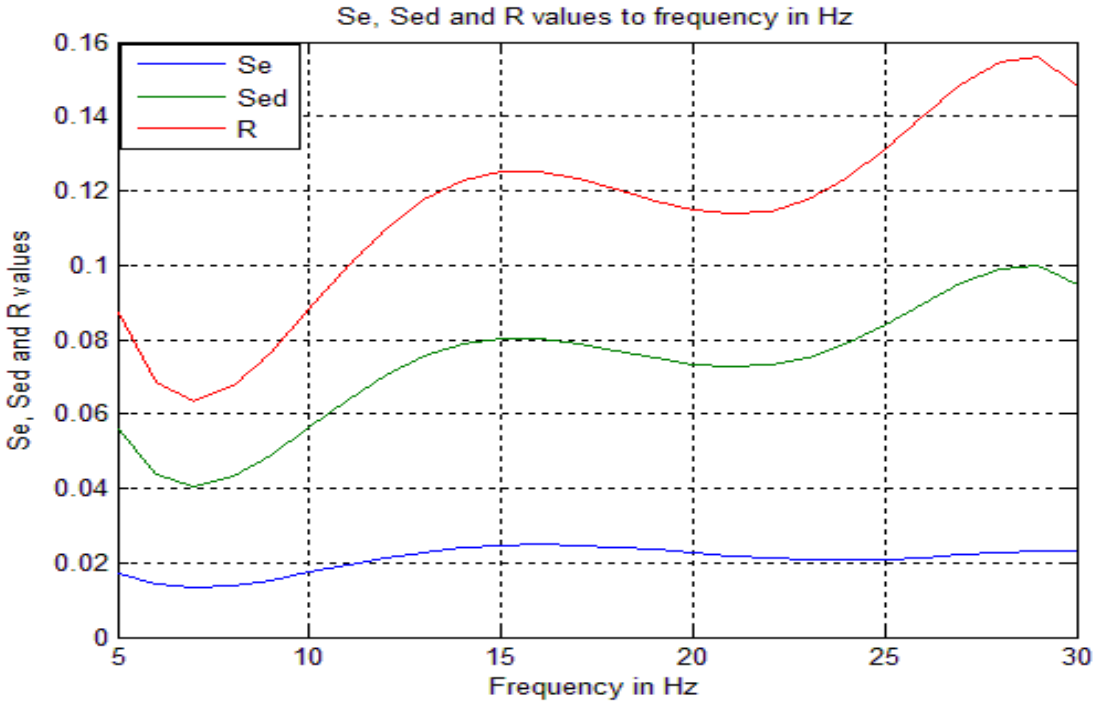


Figure 30. S_e, S_{ed} and R values plot with low regression error ($R^2 \approx 1$) for Suspension Ver MIL with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 5 Hz with 60% duty cycle.

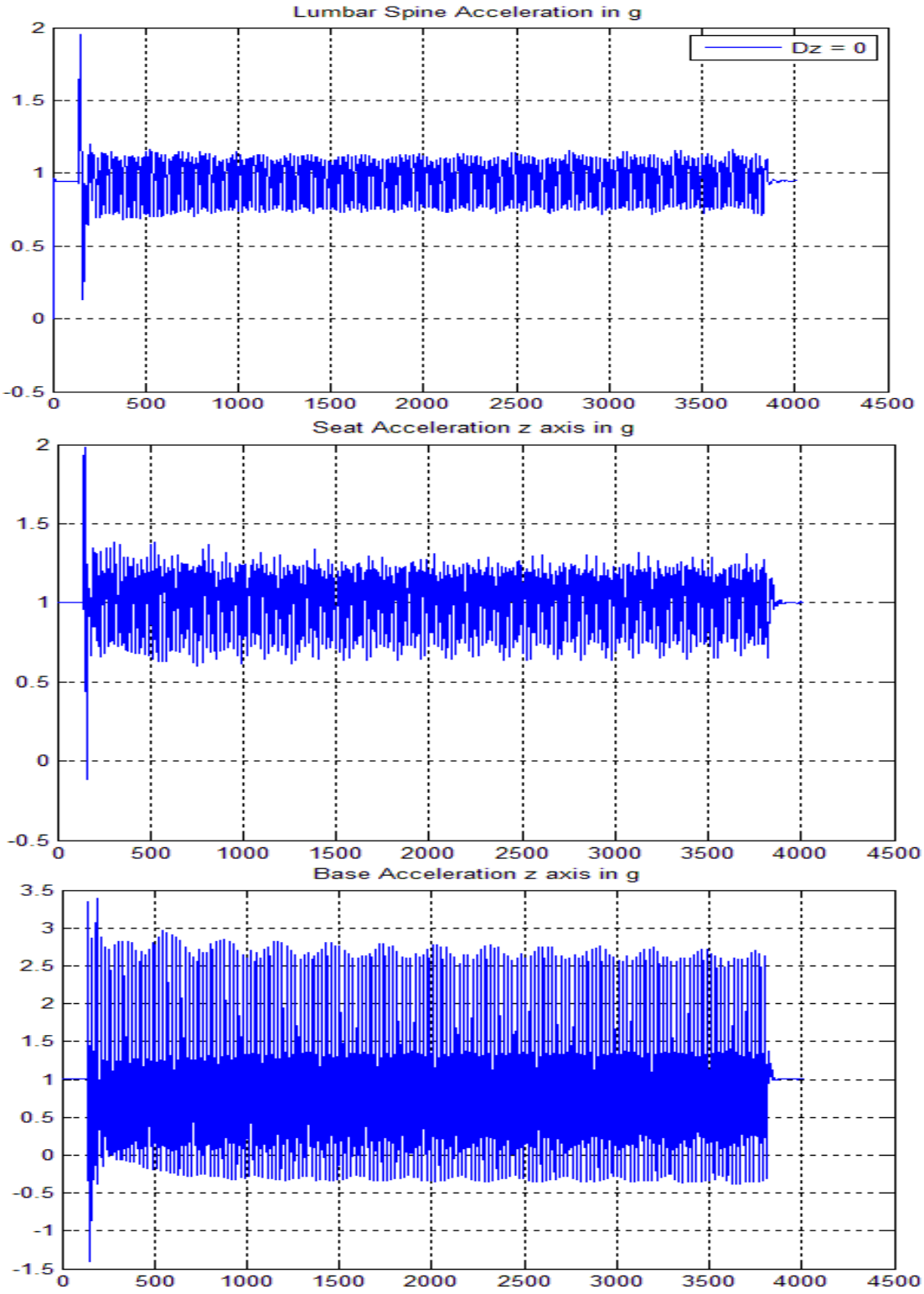


Figure 31. Base, seat and lumbar spine acceleration at mechanical vibrations of 5 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 10 Hz with 60% duty cycle.

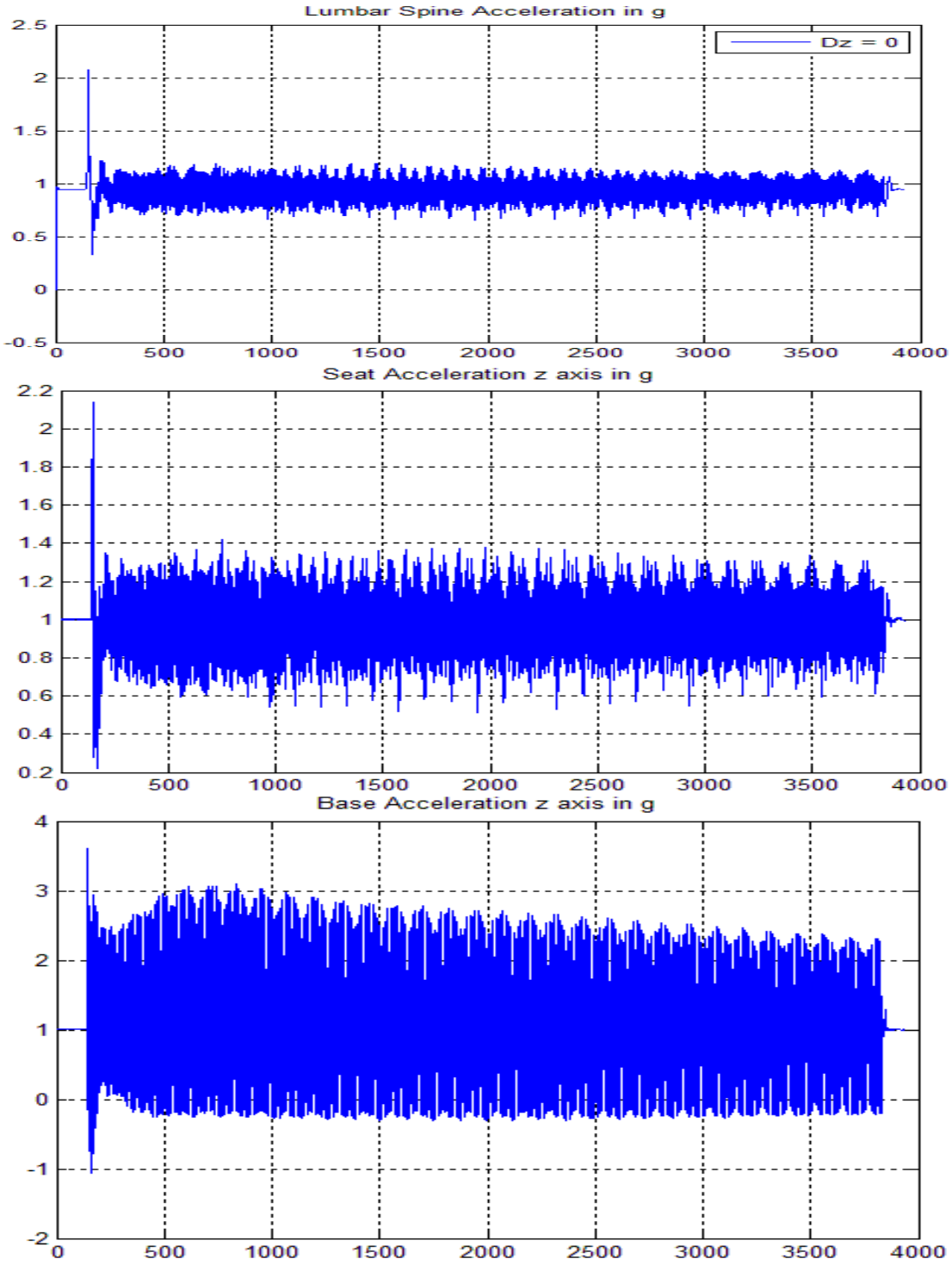


Figure 32. Base, seat and lumbar spine acceleration at mechanical vibrations of 10 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 15 Hz with 60% duty cycle.

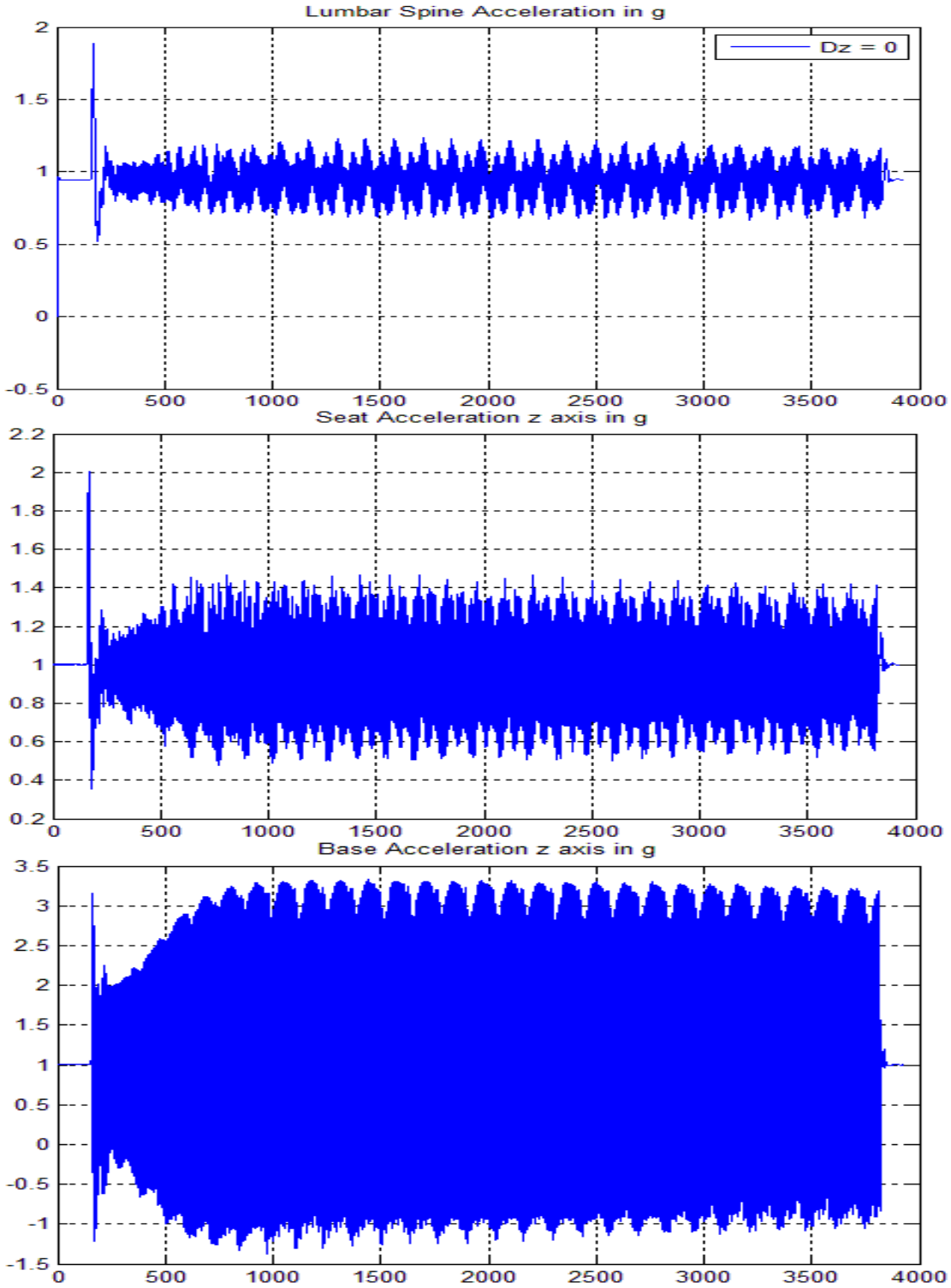


Figure 33. Base, seat and lumbar spine acceleration at mechanical vibrations of 15 Hz frequency with 60% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 20 Hz with 55% duty cycle.

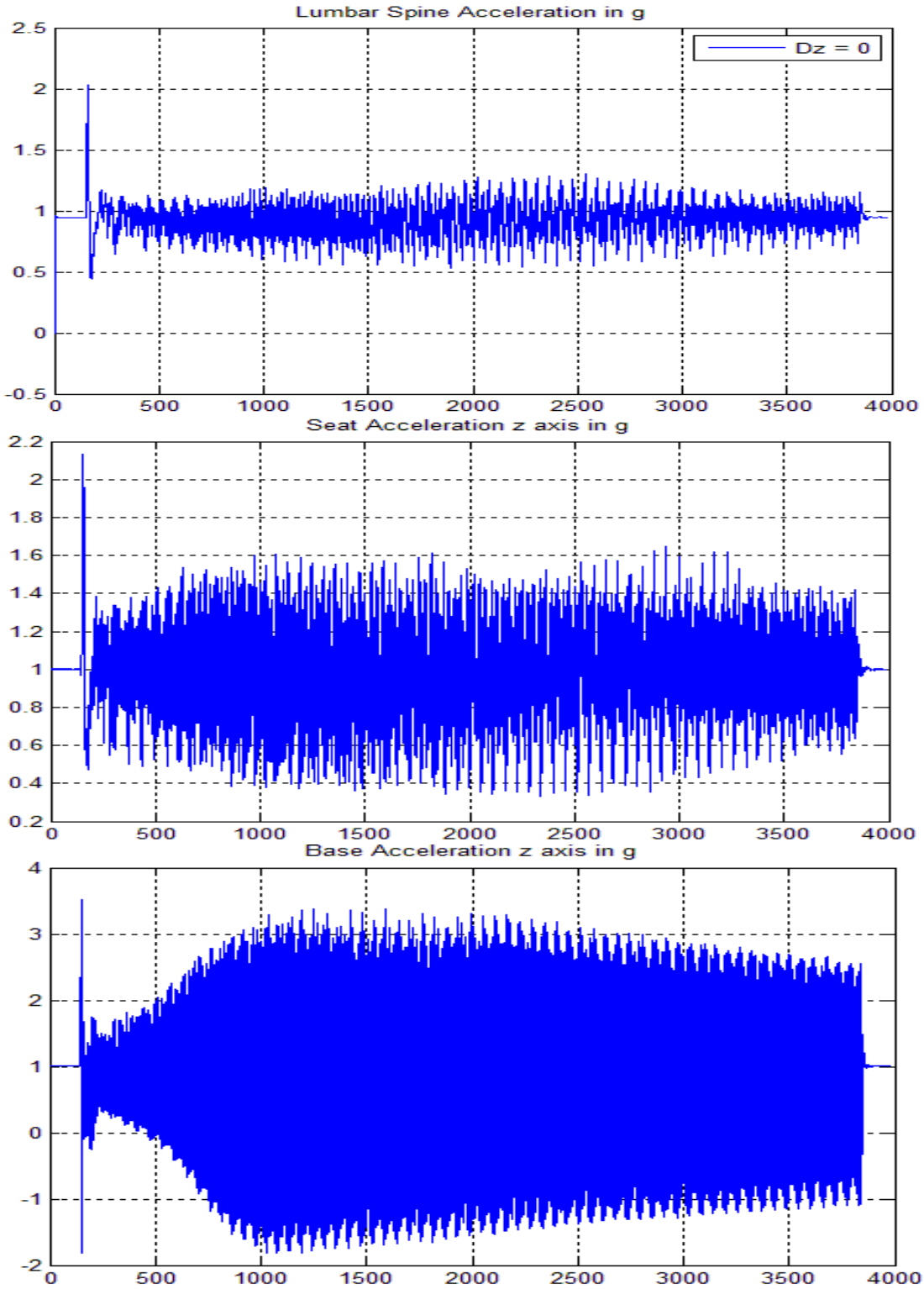


Figure 34. Base, seat and lumbar spine acceleration at mechanical vibrations of 20 Hz frequency with 55% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 25 Hz with 45% duty cycle.

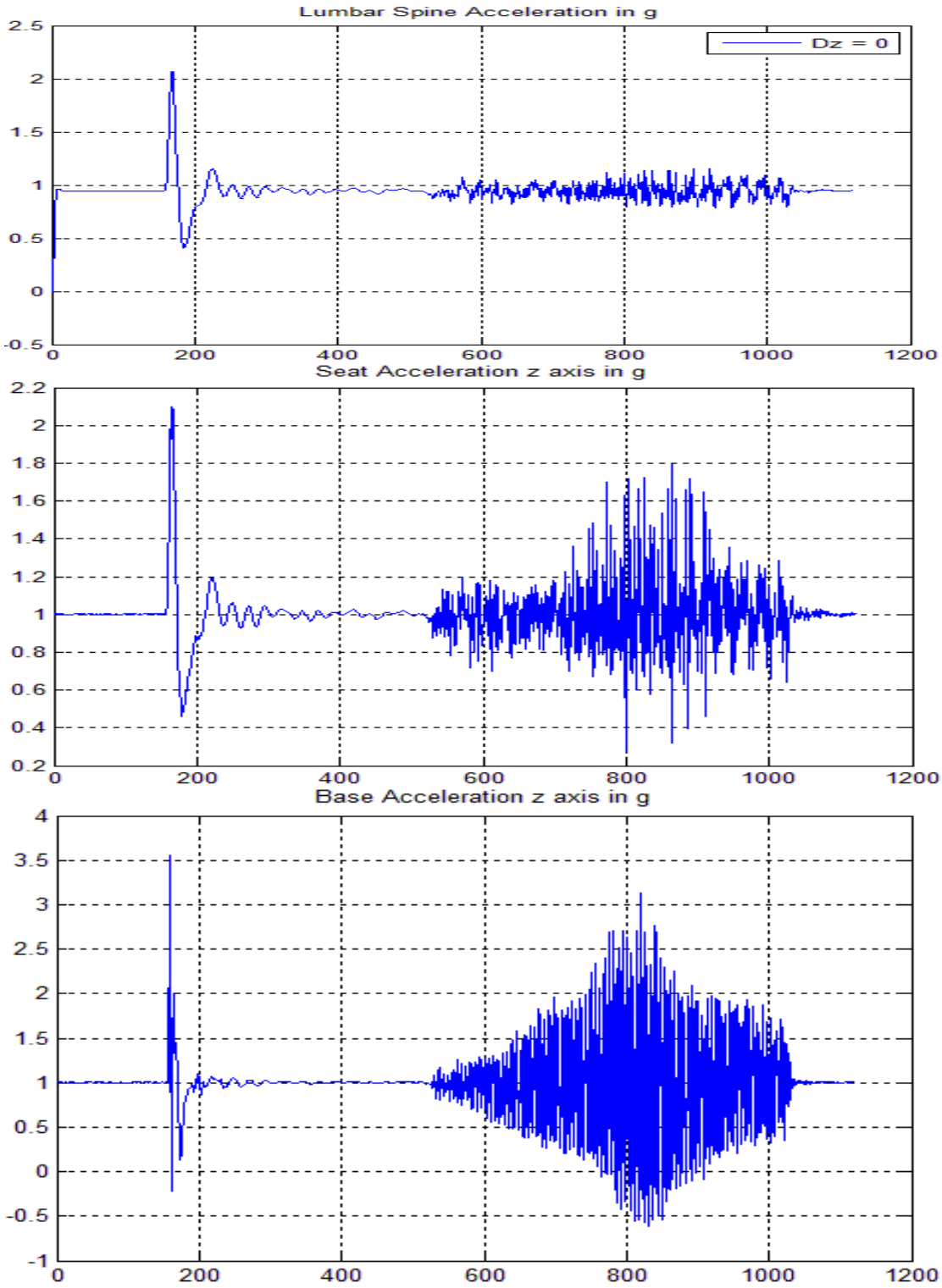


Figure 35. Base, seat and lumbar spine acceleration at mechanical vibrations of 25 Hz frequency with 45% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

Suspension Ver MIL with type 2 shock absorber at 30 Hz with 40% duty cycle.

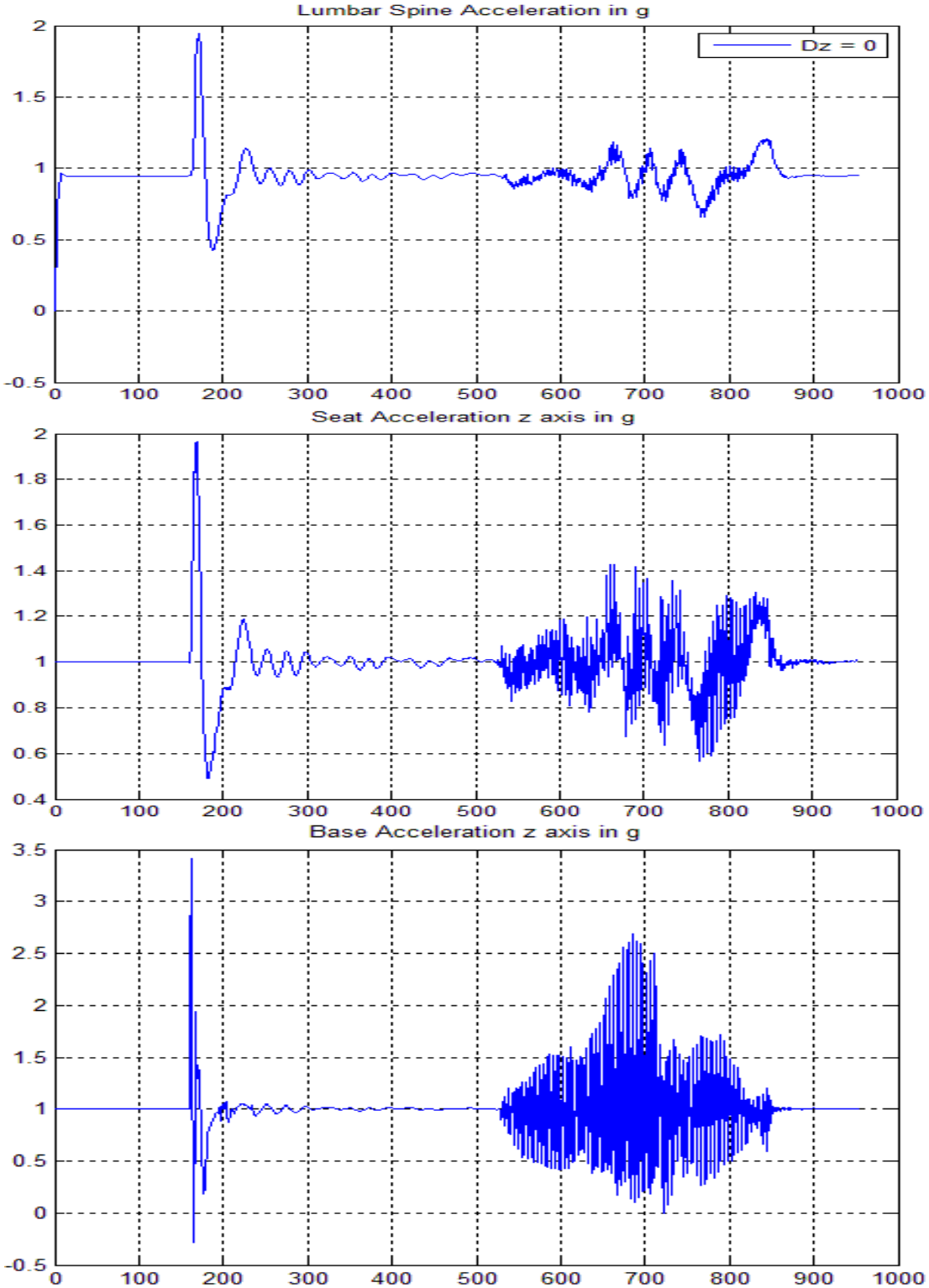


Figure 36. Base, seat and lumbar spine acceleration at mechanical vibrations of 30 Hz frequency with 40% duty cycle for Suspension Ver MIL, with type 2 shock absorber.

5.1.3 – Suspension Ver PL with type 1 shock absorber

The following tests include mechanical vibrations (shocks) of the base platform starting from a frequency of 5 Hz and ending at a frequency of 30 Hz, with an increment of 5 Hz, for the Suspension Ver PL (Pleasure) with type 1 shock absorber mounted. Our target was to keep a continuous 2 to 4 g acceleration at base platform in order to test the Suspension Ver PL system. Mechanical shocks duration was about 30 seconds, S_{ed} value was normalized to an **8 – hour per day** operation, once a day usage of the seat and R value was normalized for **240 days per year** usage, starting from an age of **20 years old** and finishing at an age of **65 years old**.

Frequency in Hz	**Average base peak acceleration in g***	**Average seat peak acceleration in g***	**Average lumbar spine peak acceleration in g***	**S_e in MPa**	**S_{ed} in MPa**	**R**	**Risk for lumbar spine injuries**
5	2.8	1.3	1.2	0.022061	0.072941	0.1141	LOW
10	3.3	1.3	1.15	0.022435	0.073275	0.11463	LOW
15	3.8	1.4	1.15	0.019082	0.064471	0.10085	LOW
20	4.2	1.5	1.2	0.025195	0.08315	0.13008	LOW
25	2.8	1.5	1.15	0.032176	0.10876	0.17013	LOW
30	2.6	1.3	1.1	0.033677	0.11039	0.17268	LOW

*Acceleration measurements refer to z axis.

Table 5. Laboratory tests for Suspension Ver PL with type 1 shock absorber, at continuous pulse type mechanical vibrations.

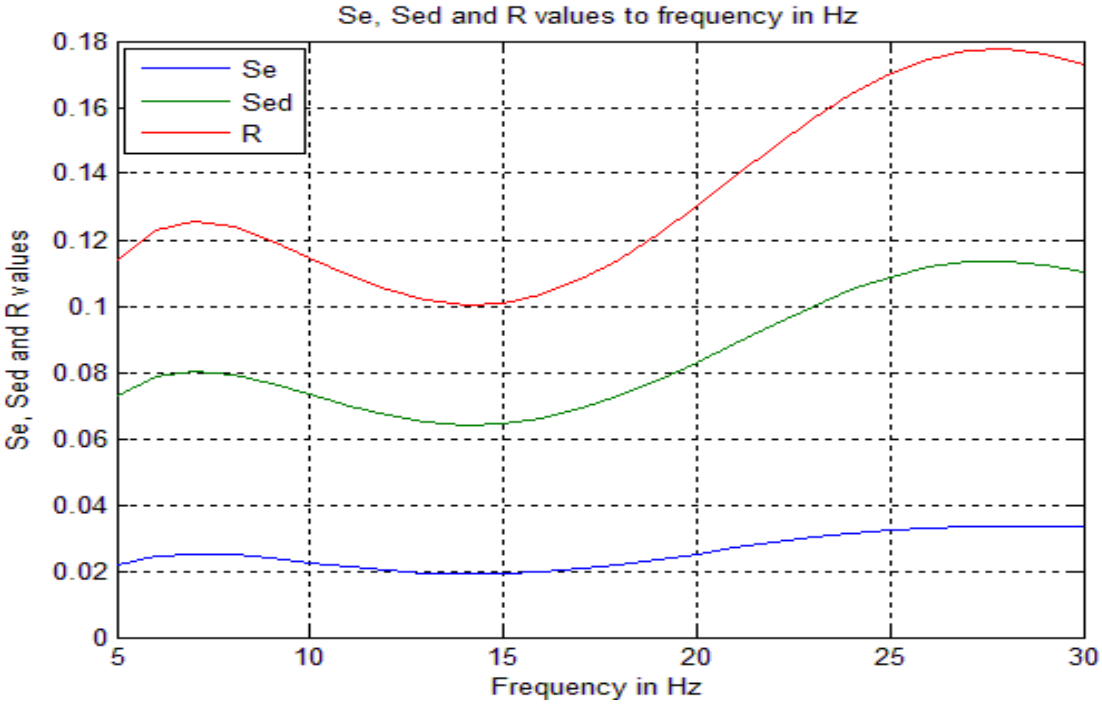


Figure 37. S_e, S_{ed} and R values plot with low regression error ($R^2 \approx 1$) for Suspension Ver PL with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 5 Hz with 70% duty cycle.

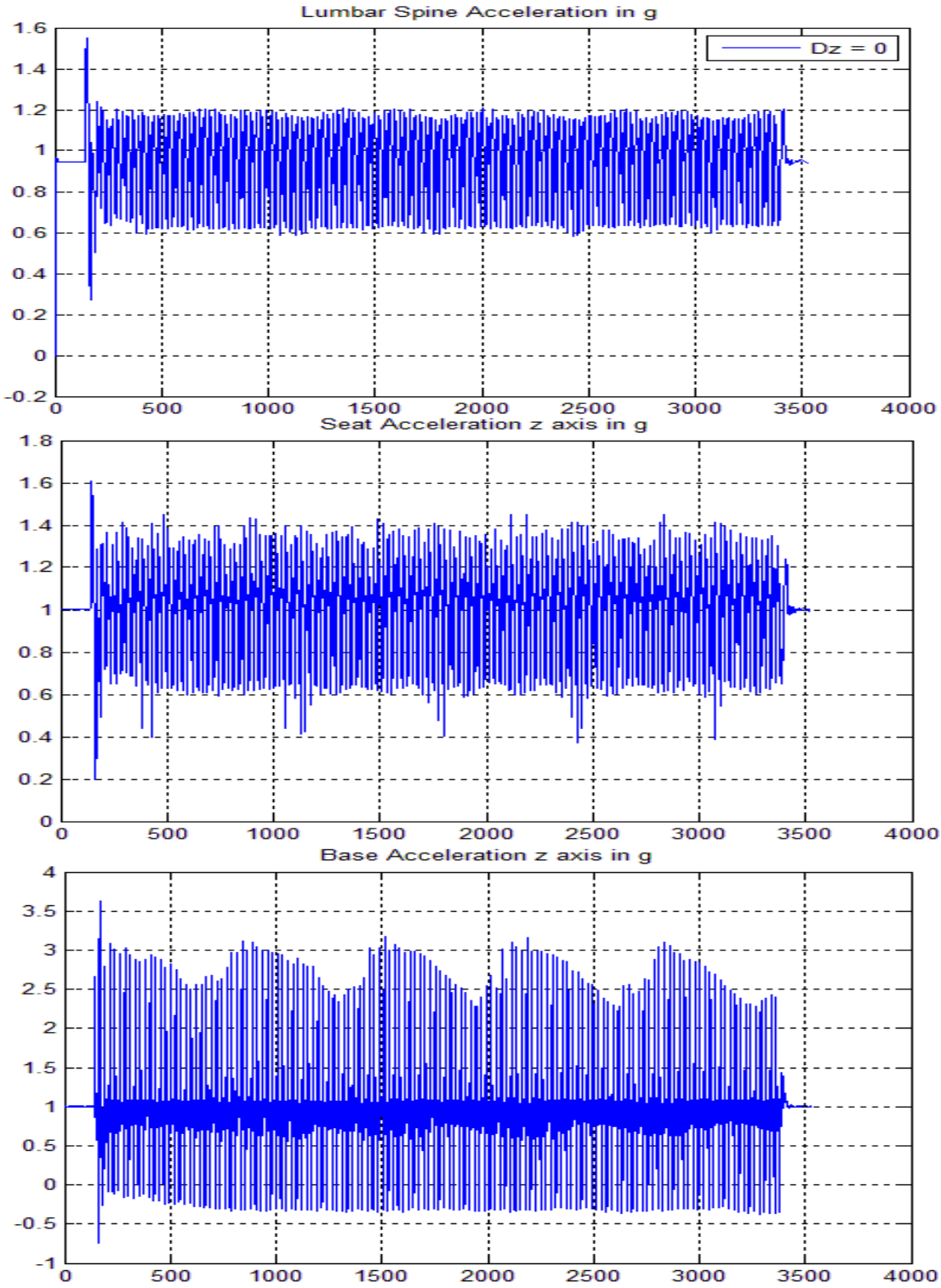


Figure 38. Base, seat and lumbar spine acceleration at mechanical vibrations of 5 Hz frequency with 70% duty cycle for Suspension Ver PL, with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 10 Hz with 70% duty cycle.

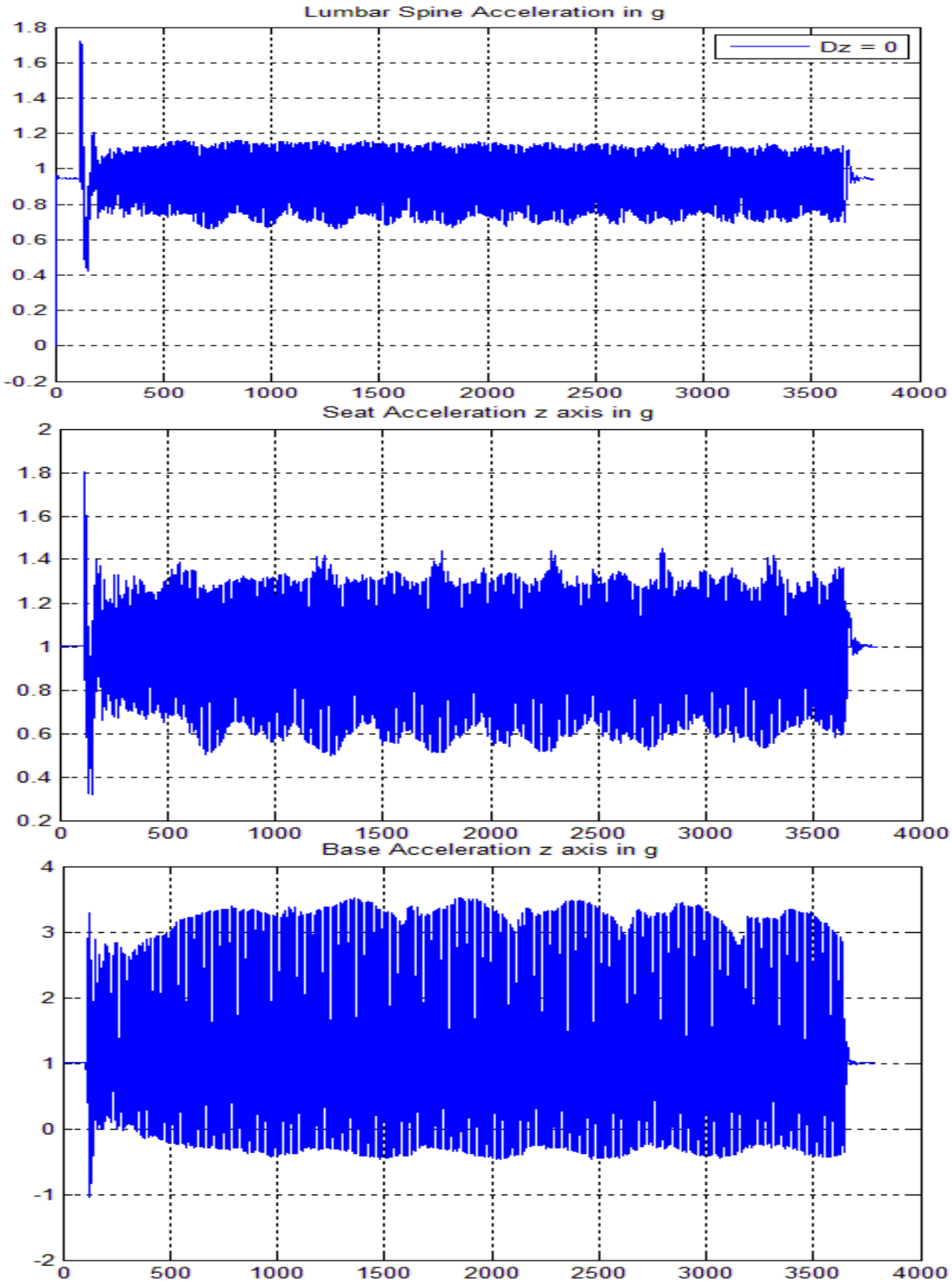


Figure 39. Base, seat and lumbar spine acceleration at mechanical vibrations of 10 Hz frequency with 70% duty cycle for Suspension Ver PL, with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 15 Hz with 65% duty cycle.

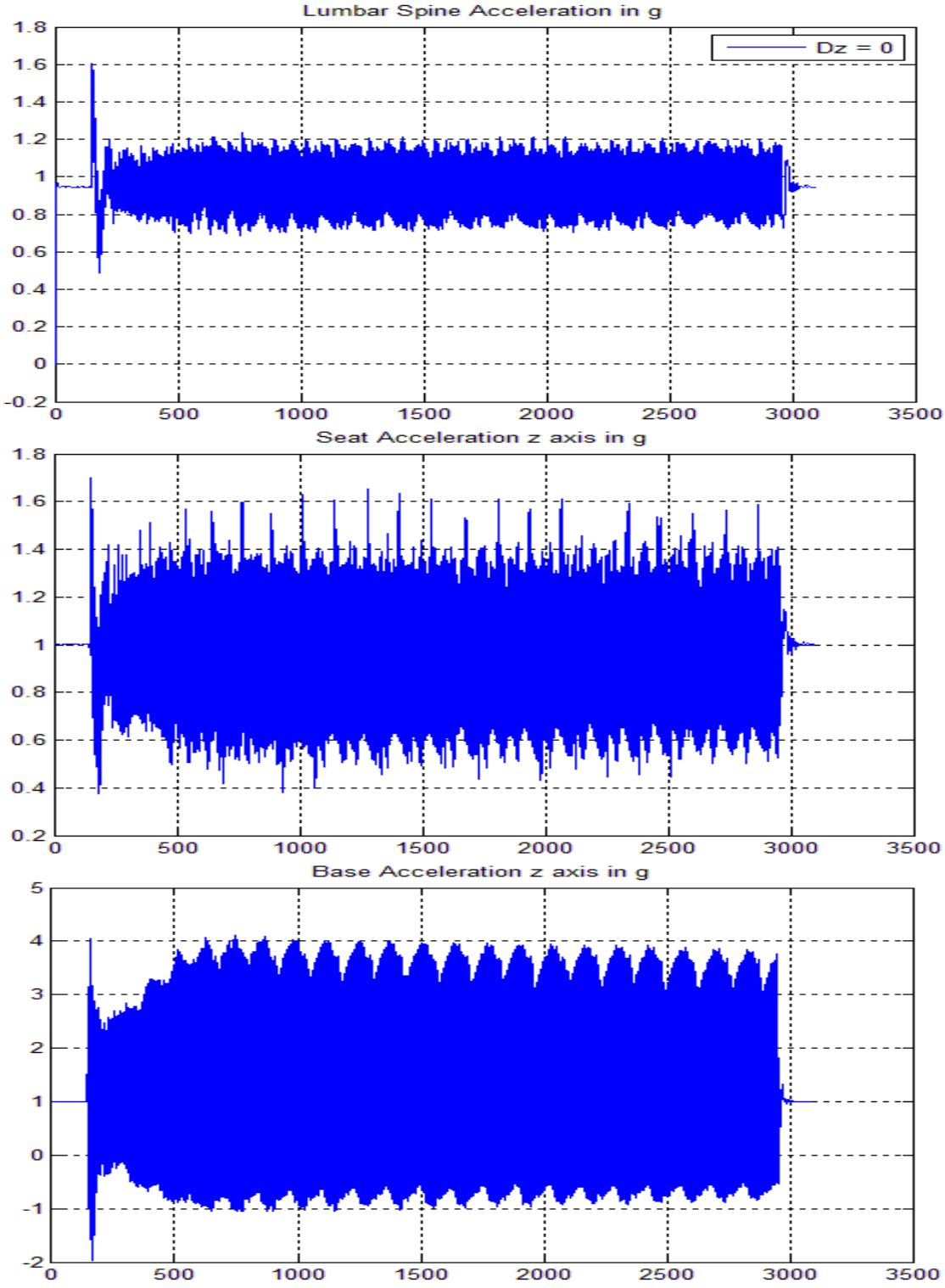


Figure 40. Base, seat and lumbar spine acceleration at mechanical vibrations of 15 Hz frequency with 65% duty cycle for Suspension Ver PL, with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 20 Hz with 65% duty cycle.

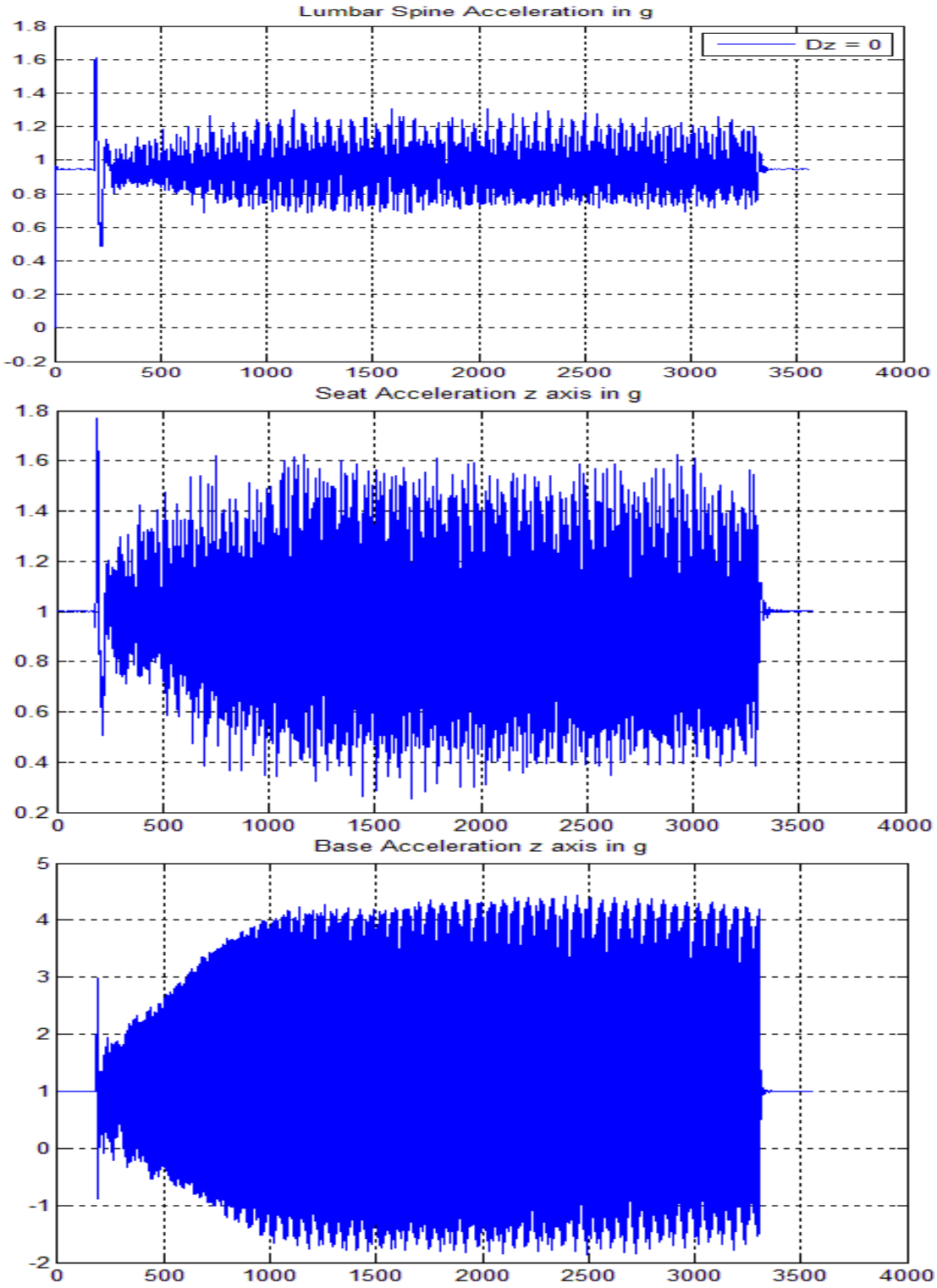


Figure 41. Base, seat and lumbar spine acceleration at mechanical vibrations of 20 Hz frequency with 65% duty cycle for Suspension Ver PL, with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 25 Hz with 55% duty cycle.

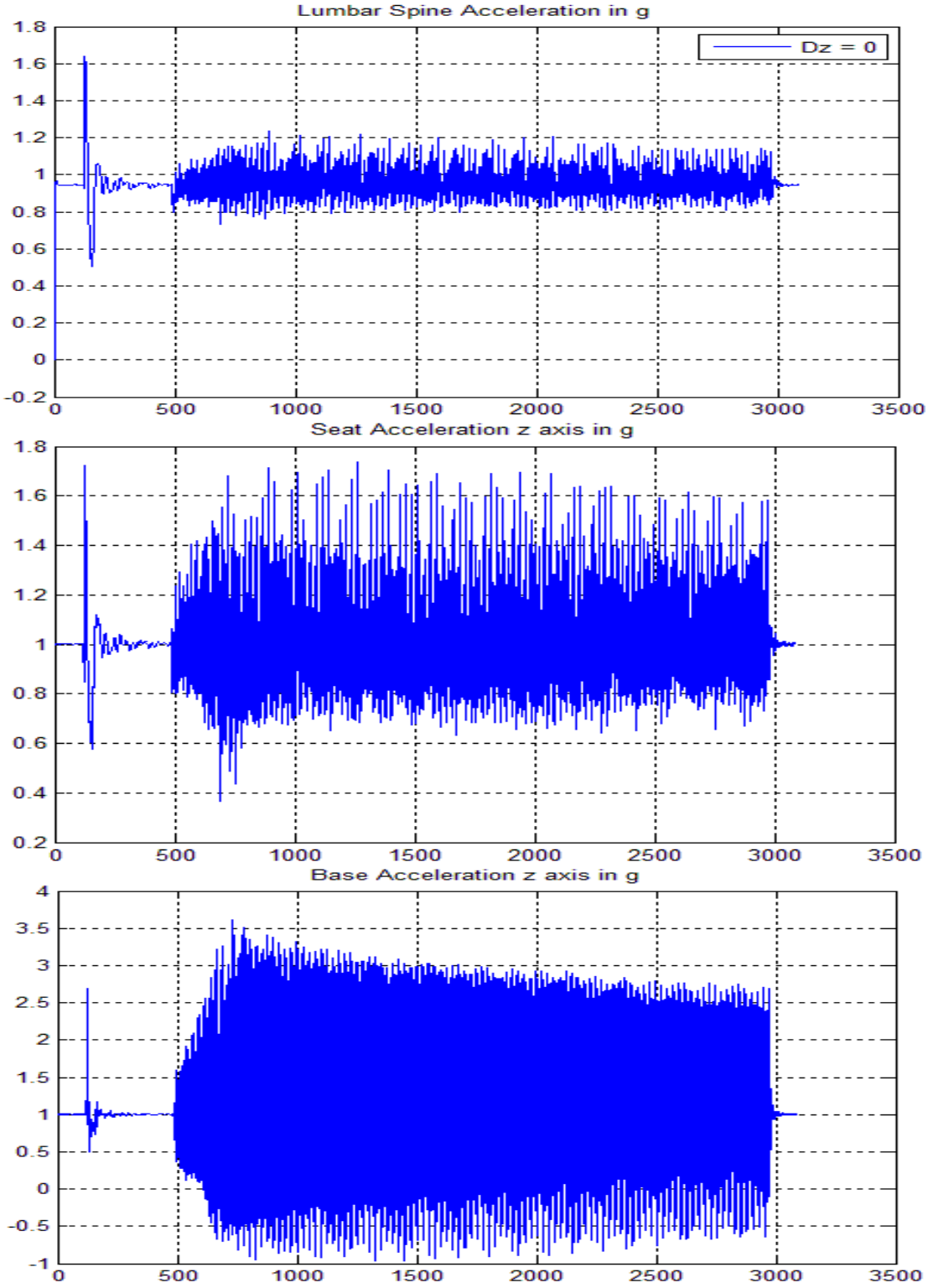


Figure 42. Base, seat and lumbar spine acceleration at mechanical vibrations of 25 Hz frequency with 55% duty cycle for Suspension Ver PL, with type 1 shock absorber.

Suspension Ver PL with type 1 shock absorber at 30 Hz with 60% duty cycle.

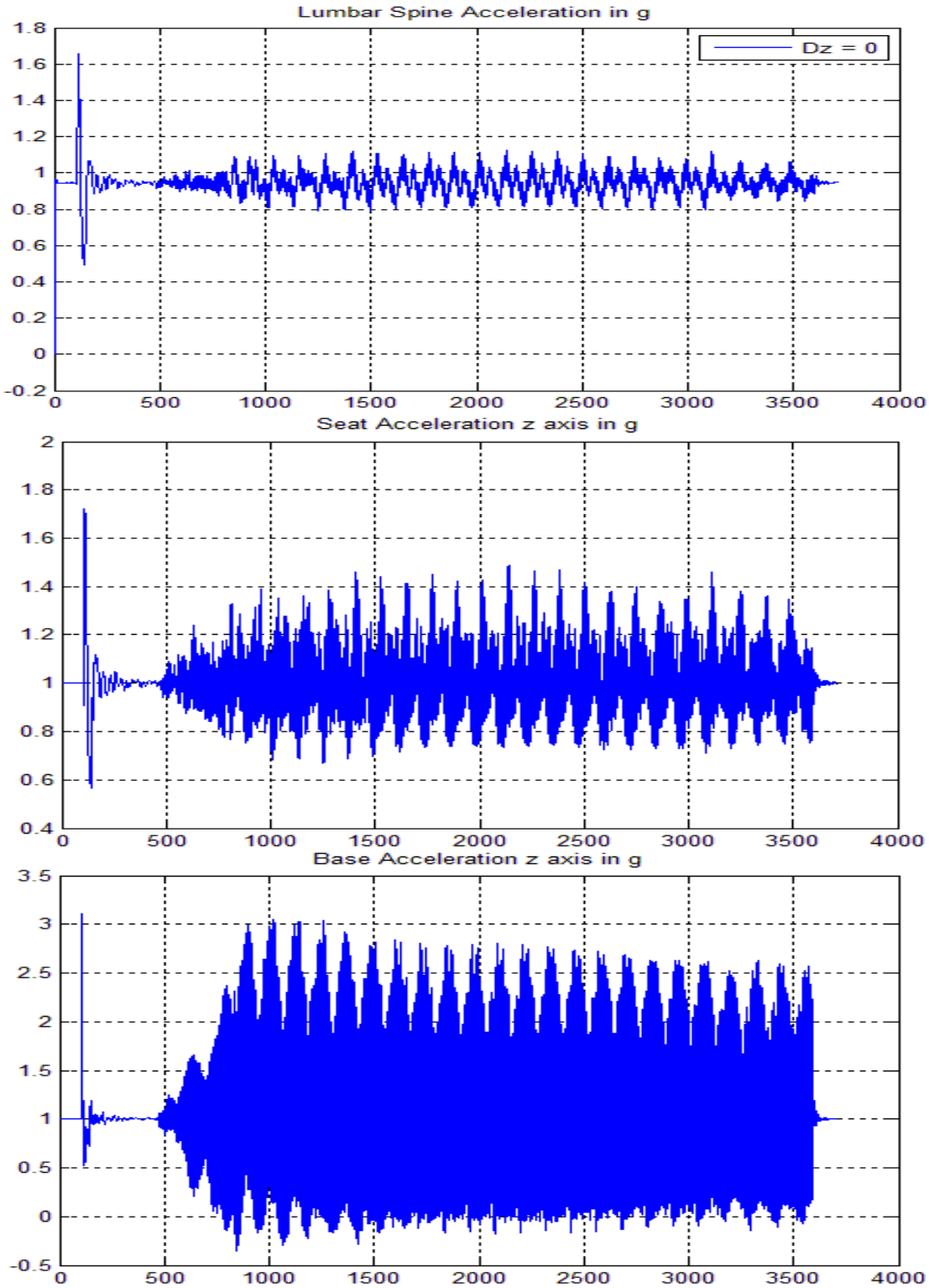


Figure 43. Base, seat and lumbar spine acceleration at mechanical vibrations of 30 Hz frequency with 60% duty cycle for Suspension Ver PL, with type 1 shock absorber.

5.1.4 – Suspension Ver PL with type 2 shock absorber

The following tests include mechanical vibrations (shocks) of the base platform starting from a frequency of 5 Hz and ending at a frequency of 30 Hz, with an increment of 5 Hz, for the Suspension Ver PL (Pleasure) with type 2 shock absorber mounted. Our target was to keep a continuous 2 to 4 g acceleration at base platform in order to test the Suspension Ver PL system. Mechanical shocks duration was about 30 seconds, S_{ed} value was normalized to an **8 – hour per day** operation, once a day usage of the seat and R value was normalized for **240 days per year** usage, starting from an age of **20 years old** and finishing at an age of **65 years old**.

Frequency in Hz	Average base peak acceleration in g*	Average seat peak acceleration in g*	Average lumbar spine peak acceleration in g*	S_e in MPa	S_{ed} in MPa	R	Risk for lumbar spine injuries
5	2.8	1.35	1.2	0.018519	0.060363	0.094429	LOW
10	2.9	1.3	1.15	0.018739	0.060486	0.09462	LOW
15	2.6	1.3	1.1	0.022345	0.070211	0.10983	LOW
20	2.6	1.25	1.15	0.02326	0.075059	0.11742	LOW
25	2.5	1.35	1.1	0.032763	0.12168	0.19035	LOW
30	2.5	1.3	1.1	0.034091	0.12913	0.20201	LOW

*Acceleration measurements refer to z axis.

Table 6. Laboratory tests for Suspension Ver PL with type 2 shock absorber, at continuous pulse type mechanical vibrations.

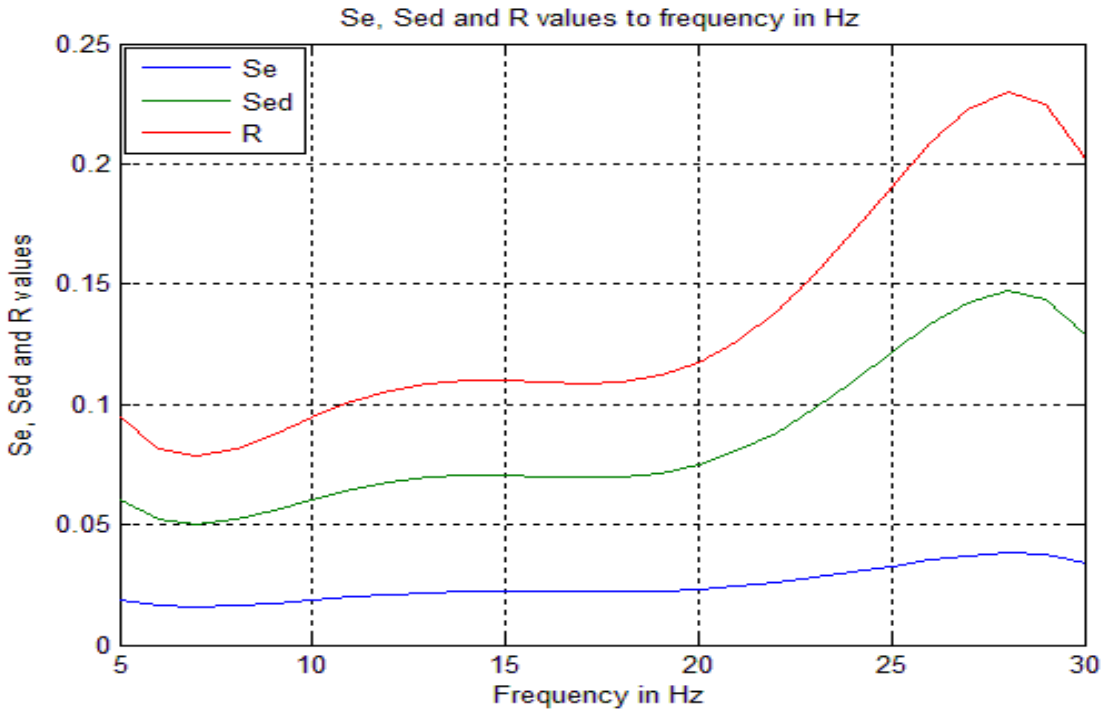


Figure 44. S_e, S_{ed} and R values plot with low regression error ($R^2 \approx 1$) for Suspension Ver PL with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 5 Hz with 65% duty cycle.

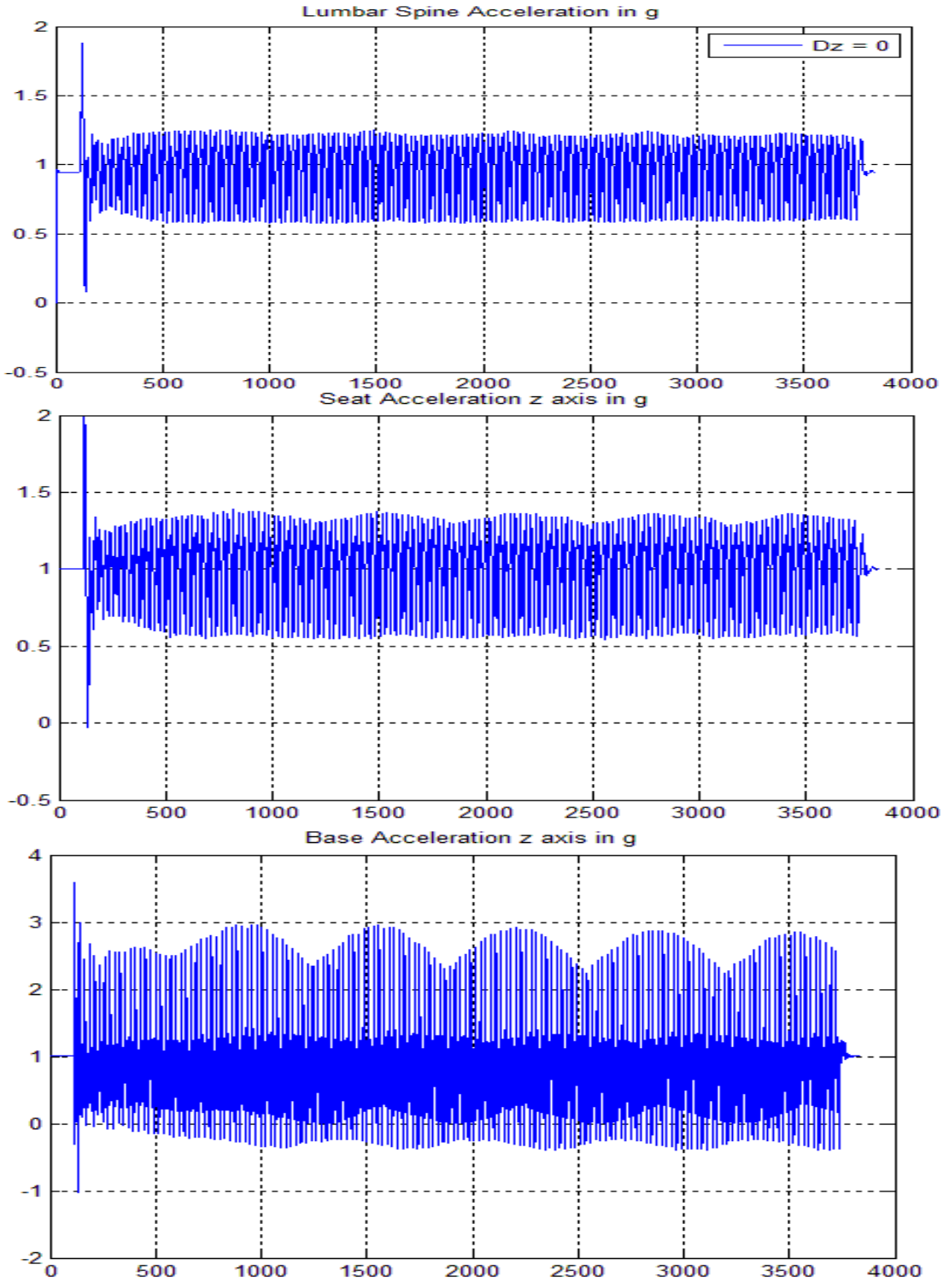


Figure 45. Base, seat and lumbar spine acceleration at mechanical vibrations of 5 Hz frequency with 65% duty cycle for Suspension Ver PL, with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 10 Hz with 60% duty cycle.

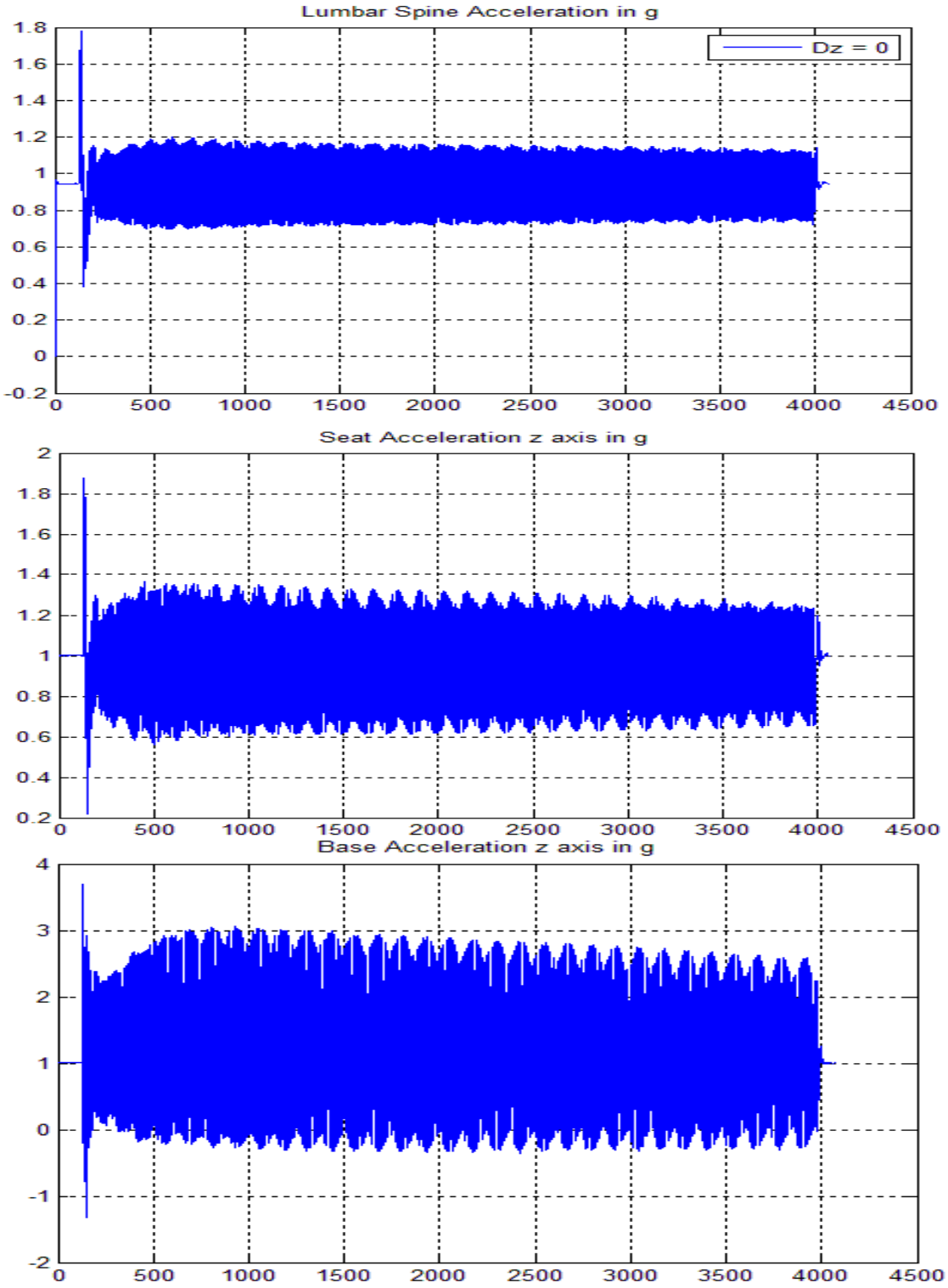


Figure 46. Base, seat and lumbar spine acceleration at mechanical vibrations of 10 Hz frequency with 60% duty cycle for Suspension Ver PL, with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 15 Hz with 60% duty cycle.

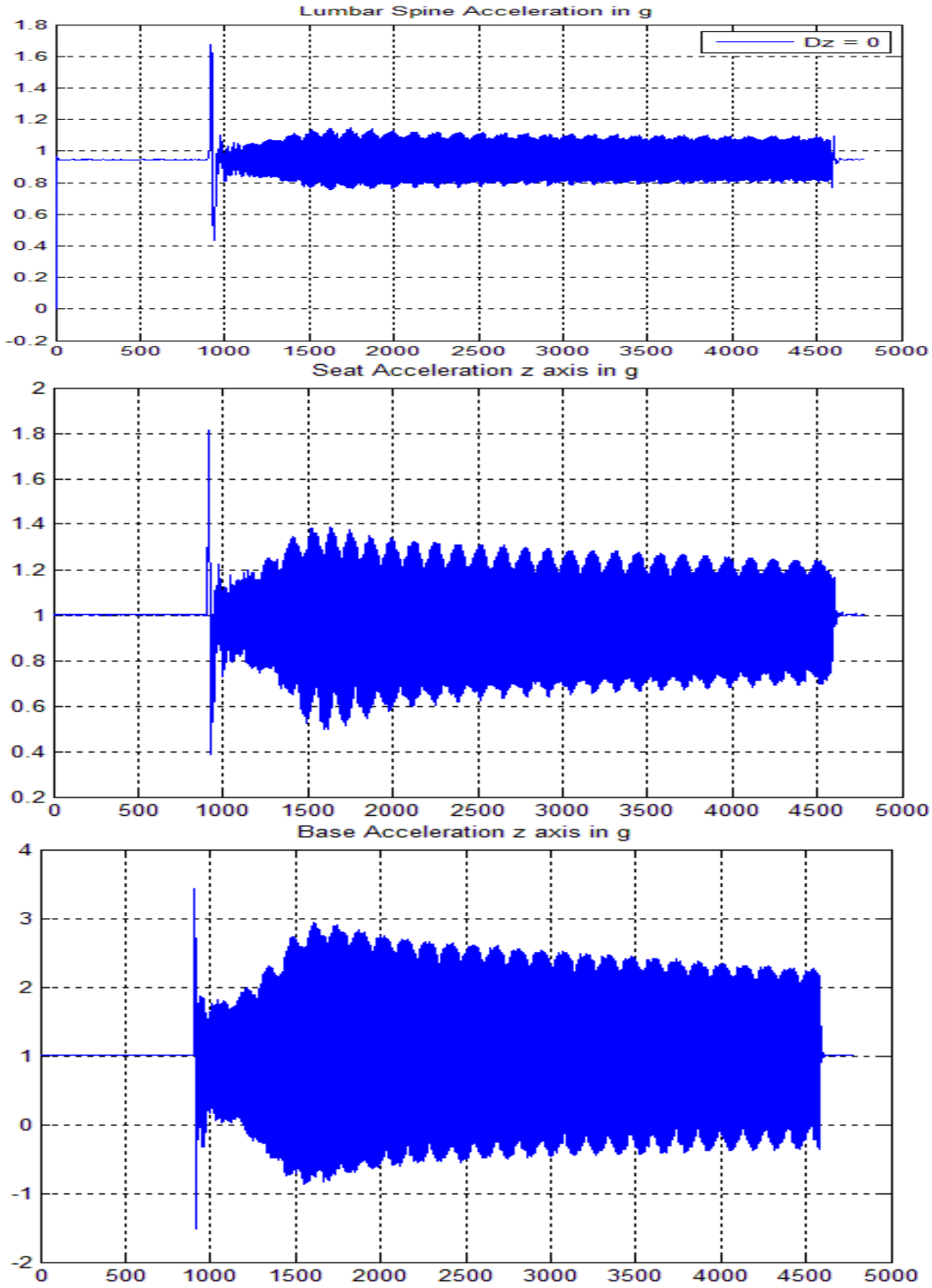


Figure 47. Base, seat and lumbar spine acceleration at mechanical vibrations of 15 Hz frequency with 60% duty cycle for Suspension Ver PL, with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 20 Hz with 55% duty cycle.

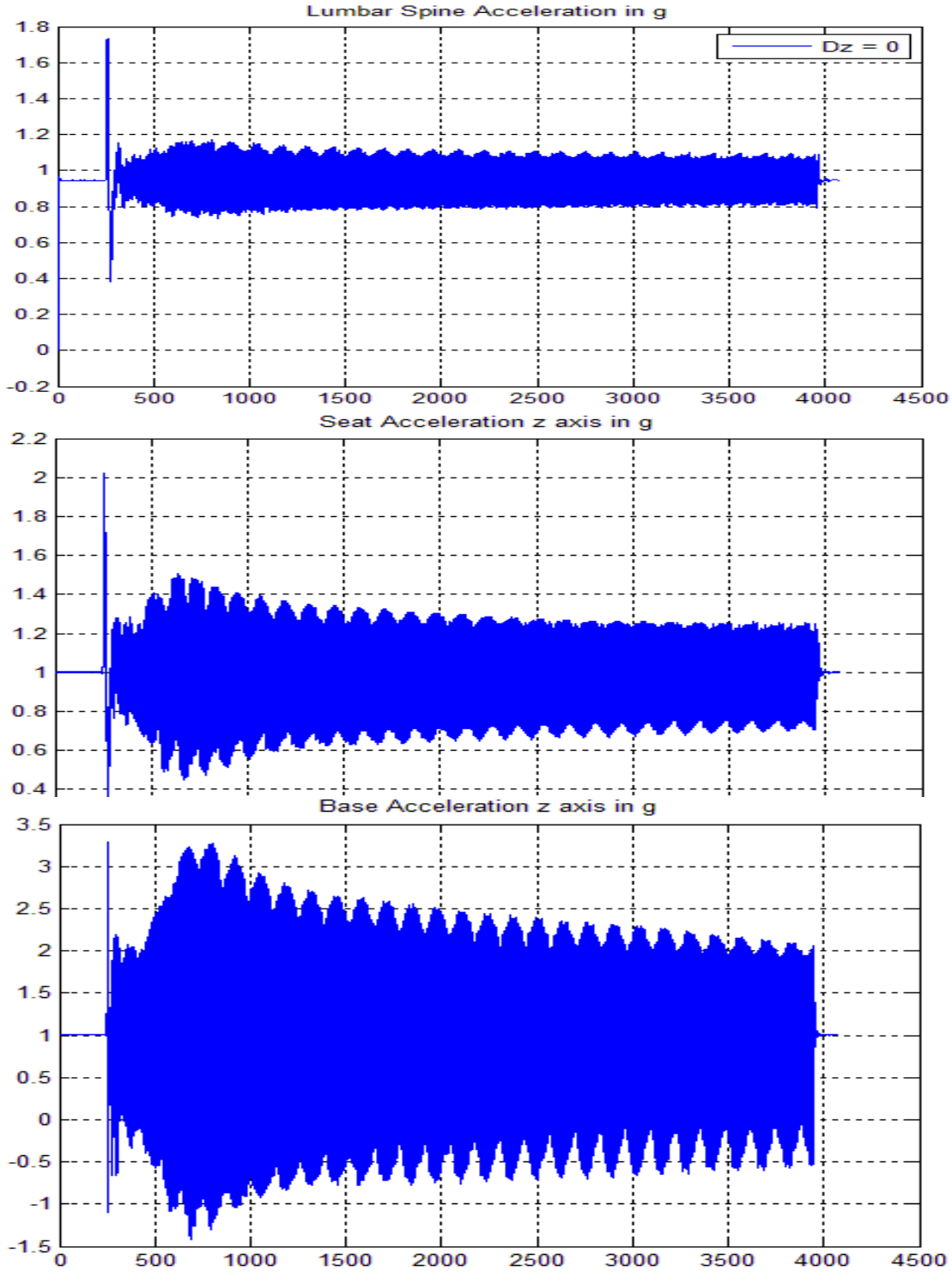


Figure 48. Base, seat and lumbar spine acceleration at mechanical vibrations of 20 Hz frequency with 55% duty cycle for Suspension Ver PL, with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 25 Hz with 45% duty cycle.

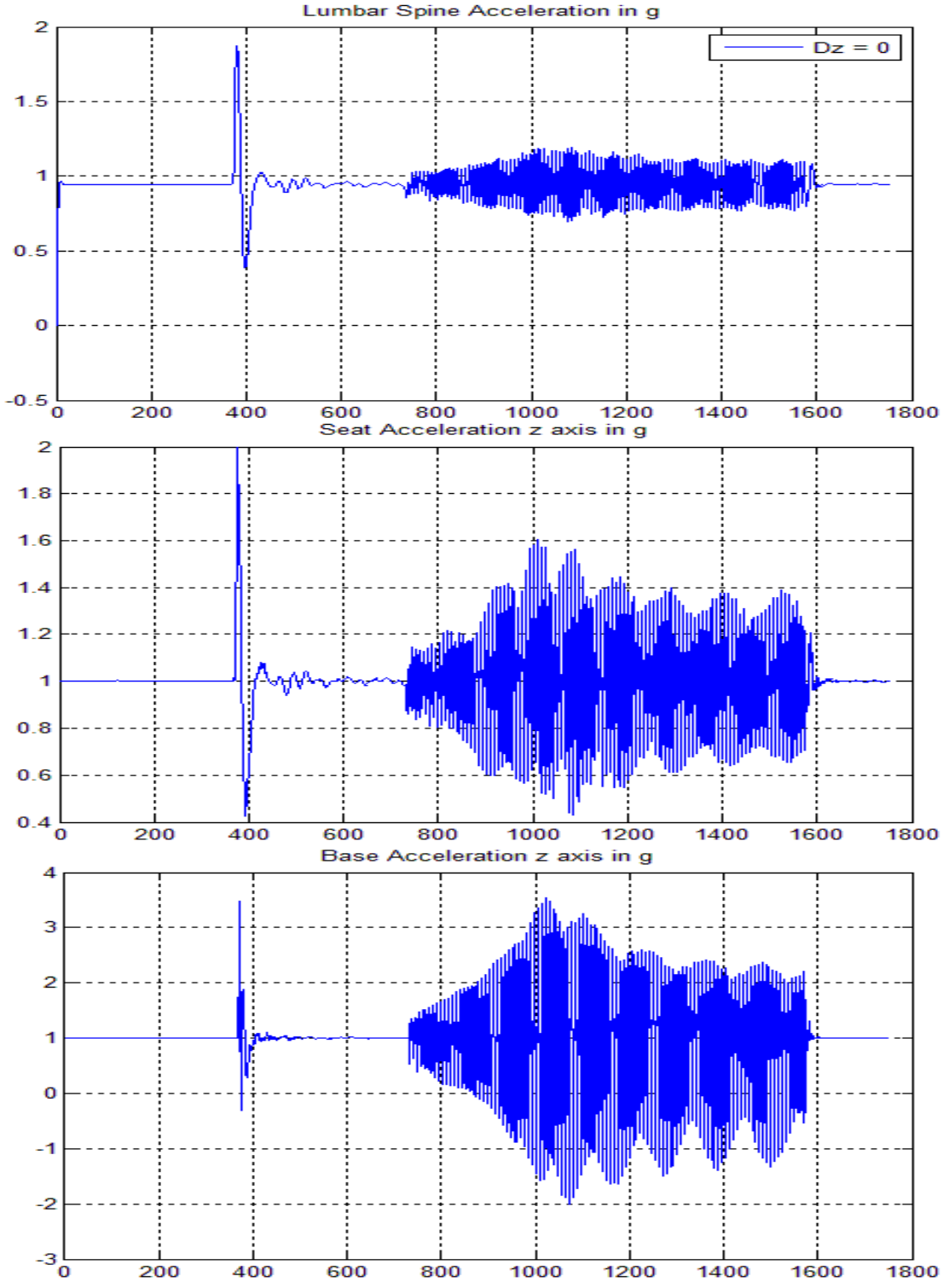


Figure 49. Base, seat and lumbar spine acceleration at mechanical vibrations of 25 Hz frequency with 45% duty cycle for Suspension Ver PL, with type 2 shock absorber.

Suspension Ver PL with type 2 shock absorber at 30 Hz with 40% duty cycle.

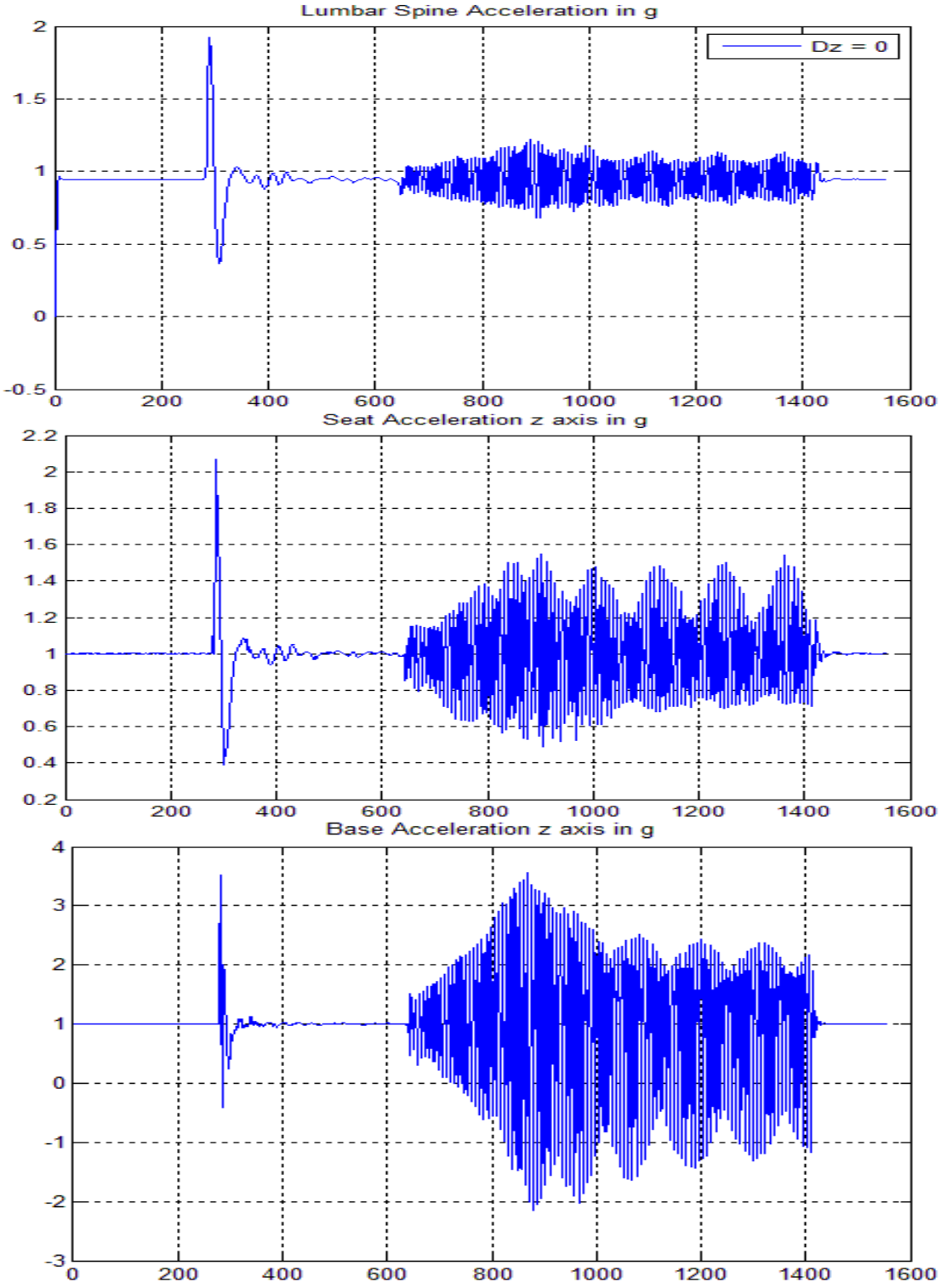


Figure 50. Base, seat and lumbar spine acceleration at mechanical vibrations of 30 Hz frequency with 40% duty cycle for Suspension Ver PL, with type 2 shock absorber.

5.2 - Conclusions about shock absorber systems performance

Using the above experimental tests, we are about to conclude about the tested systems performance. At first, an examination of acceleration measurements will be presented, in base platform, seat pad and lumbar spine response per frequency (total four plots). Then, a comparison between Ver MIL system with type 1 and type 2 shock absorber, between Ver PL system with type 1 and type 2 shock absorber will be presented. An average behaviour for Ver MIL and PL will be calculated and then these behaviours will be compared (total three plots). Our comparison criterion for the last three plots will be R value, because it is a factor that indicates the long – term possibility for lumbar spine injuries. R will be normalized for an 8 hour usage per day, once a day, for a person who started the usage of the seat at 20 years old and finished at 65 years old (**total usage for 45 years**).

So, peak acceleration in base platform, seat pad and lumbar spine response (in g) in z axis per frequency, for Suspension Ver MIL (with type 1 and type 2 shock absorbers) and Suspension Ver PL (with type 1 and type 2 shock absorbers) can be described by the following plots:

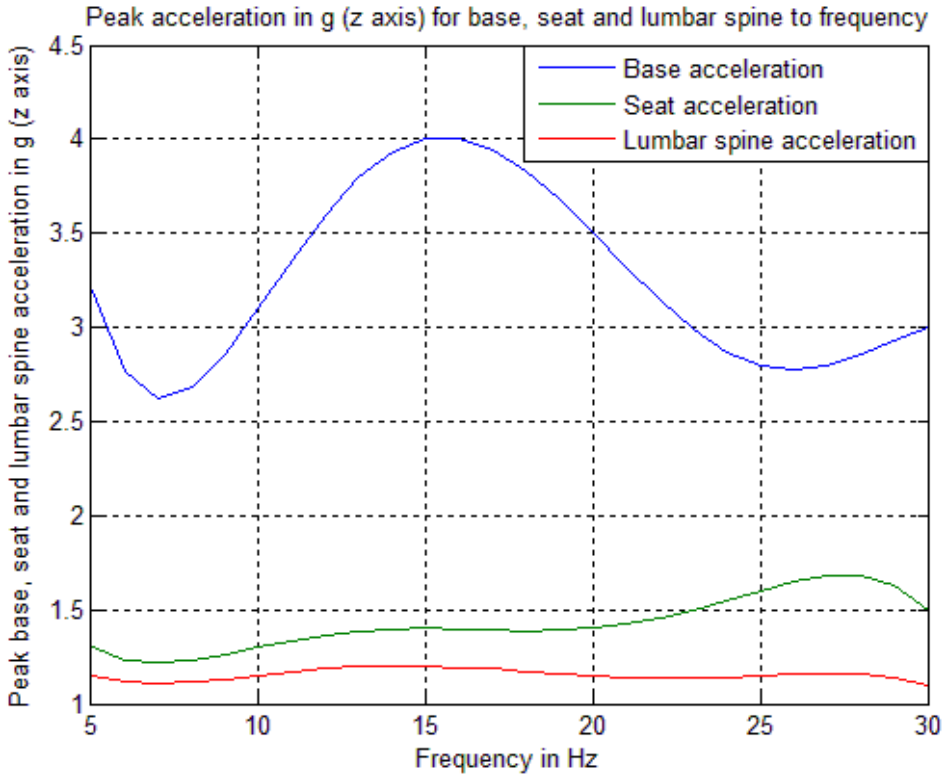


Figure 51. Peak values of acceleration in base platform, seat pad and lumbar spine response in z axis to frequency, with low regression error ($R^2 \approx 1$) for Suspension Ver MIL with type 1 shock absorber.

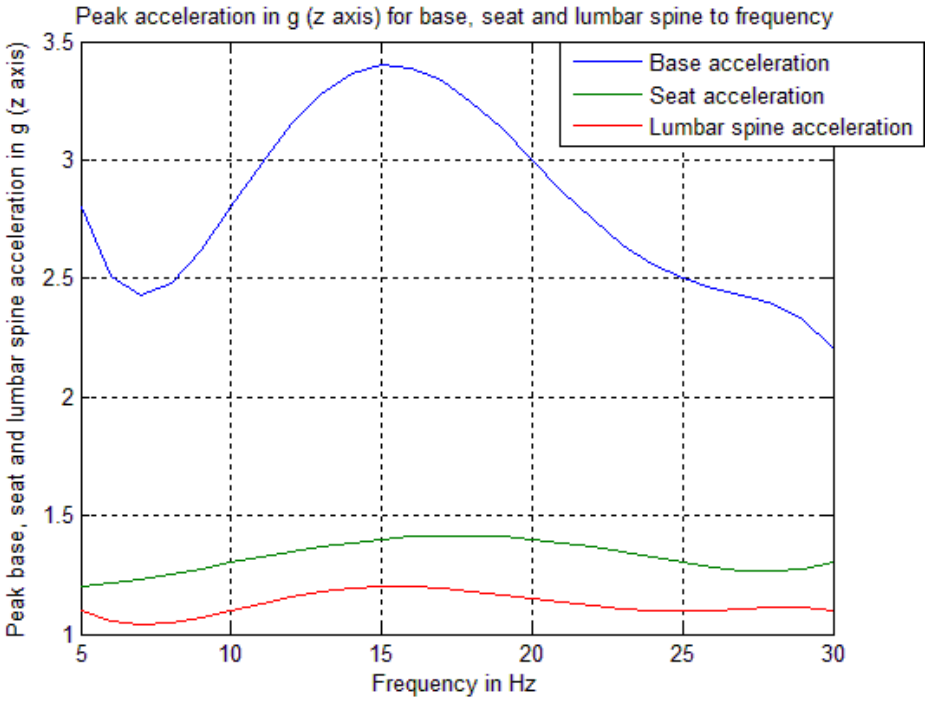


Figure 52. Peak values of acceleration in base platform, seat pad and lumbar spine response in z axis to frequency, with low regression error ($R^2 \approx 1$) for Suspension Ver MIL with type 2 shock absorber.

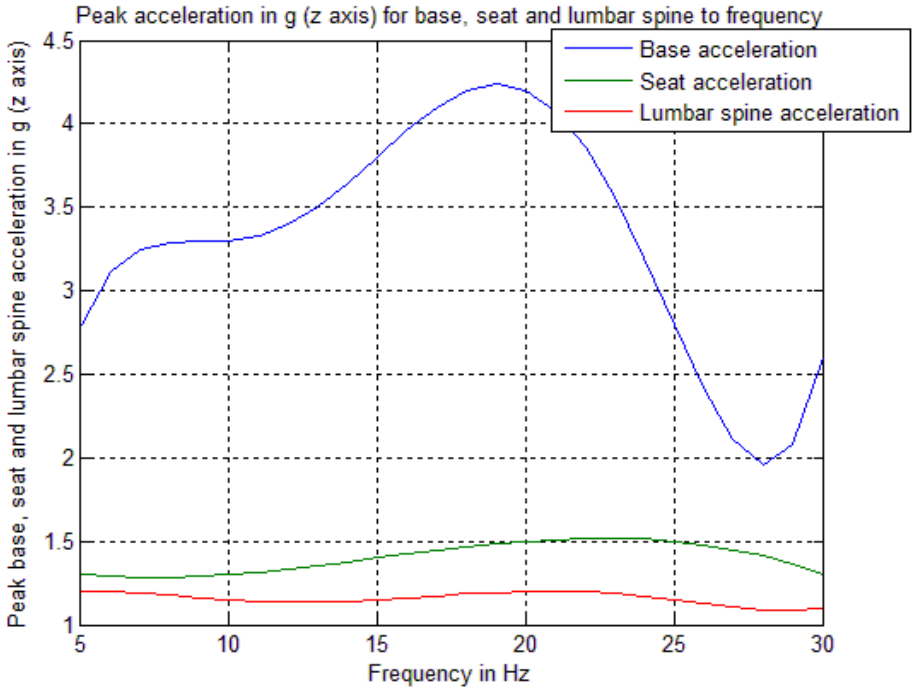


Figure 53. Peak values of acceleration in base platform, seat pad and lumbar spine response in z axis to frequency, with low regression error ($R^2 \approx 1$) for Suspension Ver PL with type 1 shock absorber.

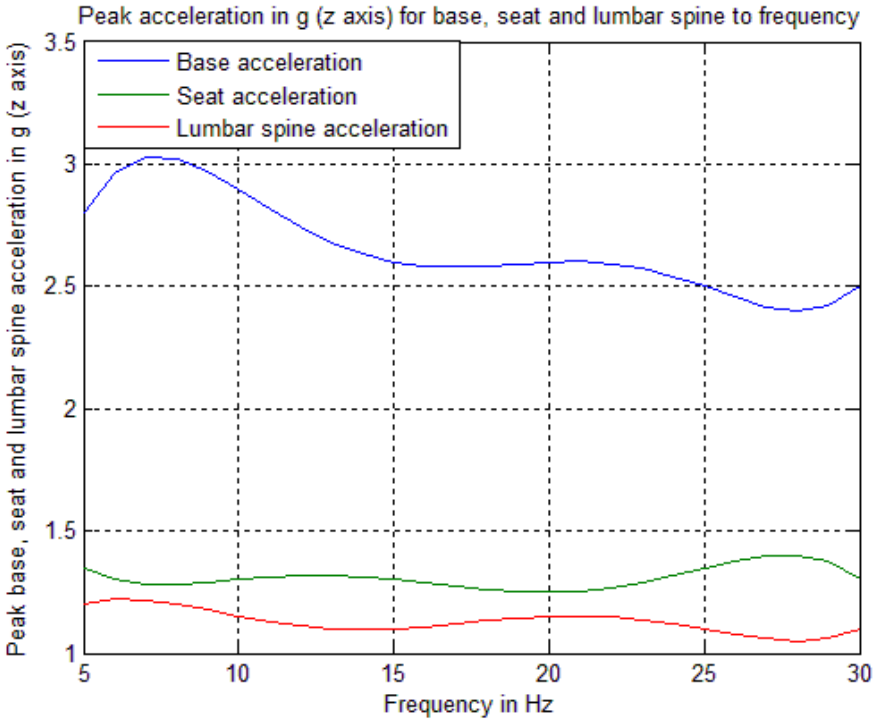


Figure 54. Peak values of acceleration in base platform, seat pad and lumbar spine response in z axis to frequency, with low regression error ($R^2 \approx 1$) for Suspension Ver PL with type 2 shock absorber.

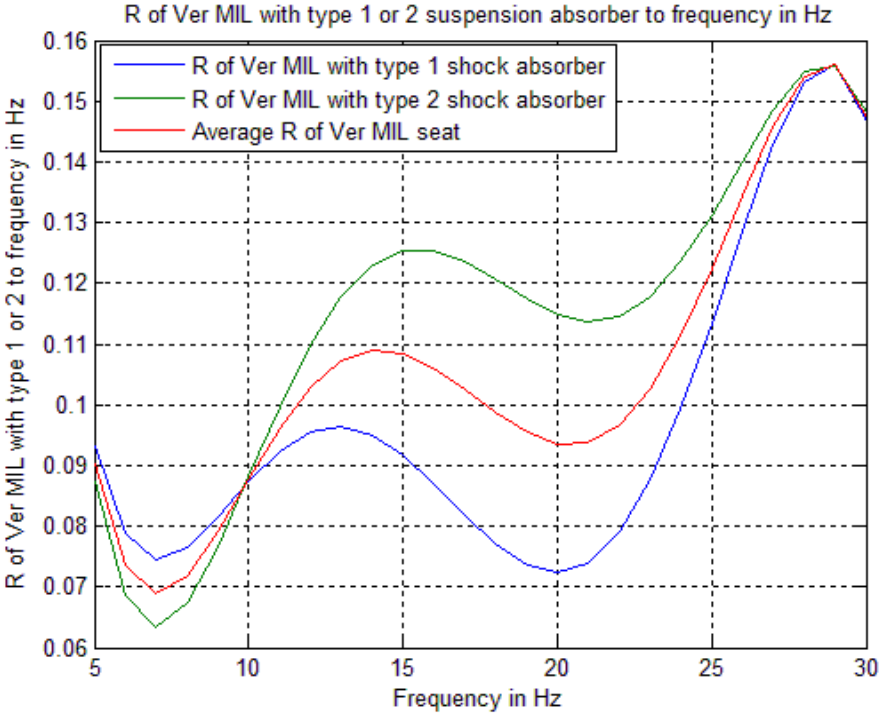


Figure 55. Comparison between R values in a frequency range from 5 Hz to 30 Hz with type 1 and type 2 shock absorbers and average R value for Suspension Ver MIL seat.

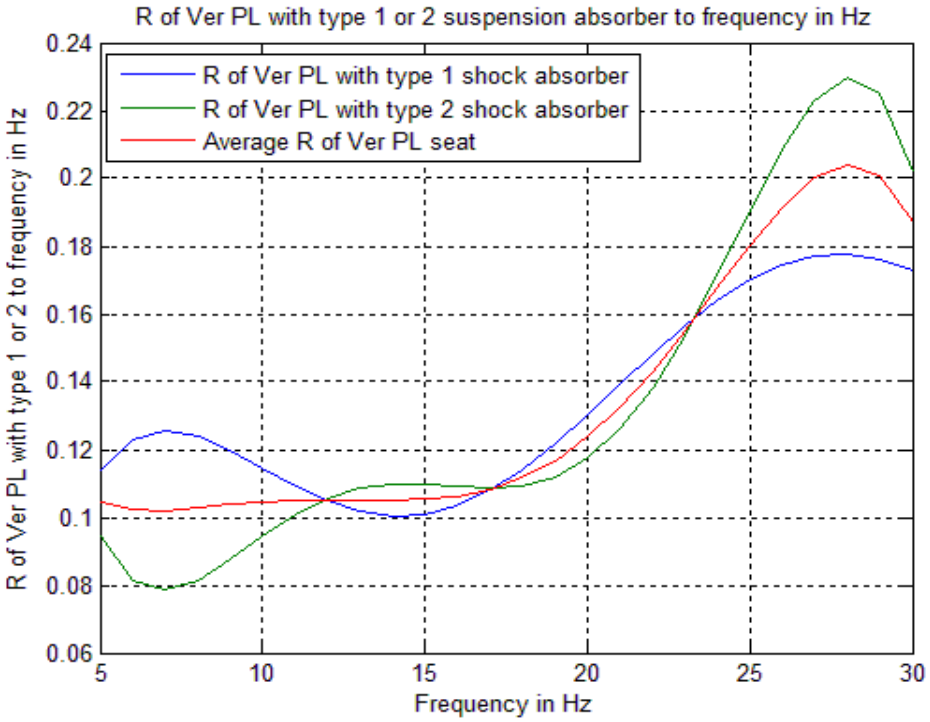


Figure 56. Comparison between R values in a frequency range from 5 Hz to 30 Hz with type 1 and type 2 shock absorbers and average R value for Suspension Ver PL seat.

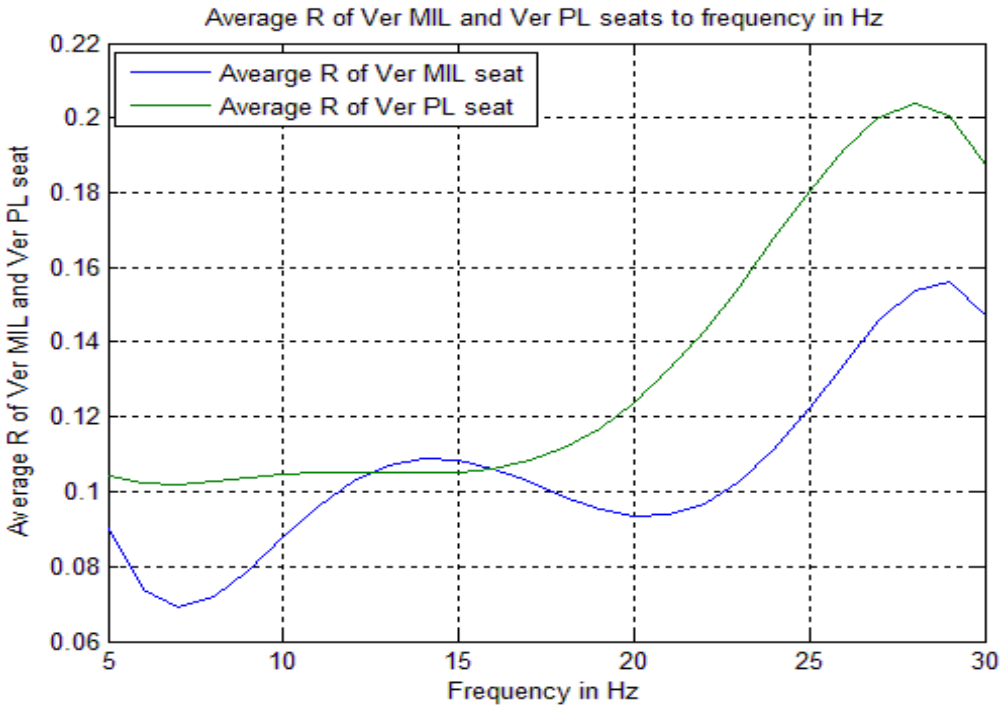


Figure 57. Comparison between average R values in a frequency range from 5 Hz to 30 Hz for Suspension Ver MIL and Suspension Ver PL seats.

Chapter 6 – Epilogue

The above laboratory tests were conducted to certify that EMAL® SA – Ermioni HSC seats comply with ISO® 2631 – Part 5 (2004) Standard's rules for lumbar spine injuries in HSC. **All of the above laboratory experimental tests**, for Suspension Ver MIL with type 1 and type 2 shock absorbers and for Suspension Ver PL with type 1 and type 2 shock absorbers **were successful**. **The possibilities for lumbar spine injuries after a long – term usage** (45 years) of those HSC seats **were far bellow the lower limit that ISO® 2631 – Part 5 (2004) Standard defines**, with the highest shown value being at R = 0.22 (the lower limit is 0.5).

The need for specifically designed HSC seats has been discussed in Chapter 1. Without specified HSC seats severe lumbar spine injuries may occur after years of exposure to vibrations and dizziness will appear after a few seconds of vibrations.

All experiments were conducted in Systems and Measurements Laboratory of the Electrical and Computer Engineering Department at University of Patras, in June 2017.

This report contains experimental tests for certification purpose for:

EMAL® SA – N.BOULELAKIS

contact: http://www.okyalosmil.gr/contact.html

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Laboratory tests were conducted under the guidance and supervision of:

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by:

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References – sources

The Electrical and Computer Engineering Department of University of Patras

http://www.upatras.gr/en

http://www.ece.upatras.gr/en/

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http://www.okyalosmil.gr/index.html

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The ISO® 2631 – Part 5 (2004) Standard of the International Organization for Standardization®

https://www.iso.org/search/x/query/2631-5

Equipment

Pneumatic actuators



https://www.smc.eu/



https://www.festo.com/

Motion tracking sensors



https://www.xsens.com/

Microcontroller



https://store.arduino.cc/