

A PLC BASED TEST BENCH FOR EXPERIMENTAL ANALYSIS OF WHOLE-BODY VIBRATION (WBV) EFFECTS ON HUMANS

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Abstract. *In the recent decades, human comfort has become necessary in all the human activities of the modern society. Syndicates and labor unions have vindicated healthy working environments. Healthy life is one of the priorities of people all over the world. In this context, insurance companies have spent great amounts of money paying premiums to workers who have been exposed to dangerous levels of noise, vibration and because of that suffered from permanent injuries. In recent years, vibration effects on human health have become the focus of the attention of the scientific community. Although there are very well established levels for noise in the working environment with good understanding of its effects on health, the effects of vibration exposure on health are not that clear. In 2002, the European Parliament drew some guidelines on the minimum health and safety requirements regarding the exposure of workers to the risks arising from vibration. In-loco-research on the effects of vibration on human health and comfort usually evaluates whether the current levels are above some set of values and performs a cause-effect correlation analysis. However, there still are several unsolved problems. An important task that has to be accomplished in a near future is to clearly establish the hazard levels of vibration in industrial, commercial, domestic and public environments. Although it seems to be a simple assignment, it requires an enormous research investment, in time and resources, due to the large number of parameters involved. In order to isolate the influence of one stimulus the experimentation must be performed in a controlled environment. With this objective in mind, this paper presents the design procedure of a test bench for analysis of Whole-Body Vibration (WBV) effects on human comfort and health. The system is based on a programmable logic controller (PLC) used as a process controller that automatically defines and controls the amplitude and frequency of the vibrations produced by a shaker. Finally, the system block diagrams, project details, simulation and experimental results are presented.*

Keywords: *Whole-Body Vibration (WBV) Effects on Humans, Programmable Logic Controller (PLC)*

1. INTRODUCTION

Since the beginning of the industrial era, the modern society has continuously moved toward the improvement of its quality of life. Labor quality has vindicated by syndicates and labor unions. Human comfort has become necessary in all the human activities of the modern society. Currently, the concepts of comfort and discomfort in human activities are under debate among the international scientific community and societies and there are no widely accepted formal definitions, it is beyond dispute that comfort and discomfort are human feelings that they are subjective in nature.

A great amount of research has been done on the influence of whole-body vibration (WBV) on humans. Most of these studies are related either with comfort, interference on human activities or human health effects (Griffin, 1996; Chen and Robertson, 1972; Reiher and Meister, 1931; Seidel and Heidel, 1986). Depending on the objectives of the study, it may be focused on a specific occupation or group. For example, WBV comfort studies are usually related to vehicles or buildings. Some interesting works are the ones from Murray (1998), Misael (2001), Griffin (1995-1996) and Klaeboe and Turunen-Rise (2002). WBV health effects on human drivers and others have also been object of studies by Balbinot (2001), Silva and Mendes (2005), Scarlett and Stayner (2005), Rehn *et al.* (2005), Ling and Leboueuf (2000) and others. Howard and Griffin (1990), Seidel *et al.* (1988, 1989, 1992, 1997), Manninen and Ekblom (1984) and Manninen (1983, 1985, 1988), for example, have studied the combined effects of noise and vibration in humans.

In 2002, the European Parliament issued the Directive 2002/44/EC drawing some guidelines on the minimum health and safety requirements regarding the exposure of workers to the risks arising from vibration. The assessment of the exposure levels is made in accordance with the ISO Standard 2631-1 (1997). Following the directive, several studies have been accomplished to evaluate the exposure levels and to establish guidelines for future studies and preventive measures based on real levels (Scarlett and Stayner, 2005; Diaz, *et al.*, 2003). Previously, Griffin had compared the methods used to predict the hazards of WBV and repeated shocks and found a list of problems (Griffin, 1996). Neither the Directive nor the Standard mentions the influence that WBV has on specific parts of the human body. Studies related with this topic are, in general, concern with the effects on the spine of drivers (Bovenzi and Hulshof, 1999; Ling and Leboueuf, 2000; Rehn *et al.*, 2005; Scarlett and Stayner, 2005). An especially interesting topic, very little explored so far, is the effects of WBV on human hearing.

The studies of the effects of noise and vibration in human hearing are frequently performed in loco (Silva and Mendes, 2005). However, separating the effects of one stimulus from the other is simpler to carry out in laboratory.

Laboratory studies on the combined effects of noise and vibration on human hearing have been accomplished by Manninen (1983, 1985, 1988), Manninen and Ekblom (1984) and Seidel *et al.* (1988, 1989, 1992, 1997).

The isolated effects of noise on human hearing are well known by the scientific community; because of that, labor legislation in several countries has become more rigorous in the last decade. In the specific case of Brazil, relatively recent laws, such as the Regulatory Standards (NR) of the Labor Ministry, NR-7 (specially, Section 19th of 1998) and NR-9 has regulated the area and has made employers to adopt preventive measures.

Such well-defined hazard levels are still to be found for the case of WBV health effects as well. Although the vibration stimulus in real world environments are not in general sinusoidal (Griffin, 1996), using such type of excitation in laboratory gives a better control on which vibration is applied to volunteers, providing good guidelines whether the applied levels will have effects on human health, comfort or tasks performance.

The cases in which a specific level of WBV needs to be applied require a full accurate control of the WBV platform. In order to keep constant the amplitude and frequency of the excitation despite load variation, the WBV system must work in closed loop control mode. This work presents the designing procedure of a PLC-based closed loop control to maintain constant the amplitude of the applied excitation in spite of the volunteer weight and body shape.

This paper is organized as follows: Initially, the WBV test bench, objective of this work, is introduced. Then, a brief review of the ZAP500 PLC characteristics is presented. Next, the closed loop control system design is detailed. Following, experimental results are included. Finally, final comments and conclusions are presented.

2. THE GRAVI_{HUMAN-BEING} WBV TEST BENCH

Figure 1 shows the sketch of the WBV test set up considered in this work. Figure 2 presents an ongoing test being applied to a volunteer.

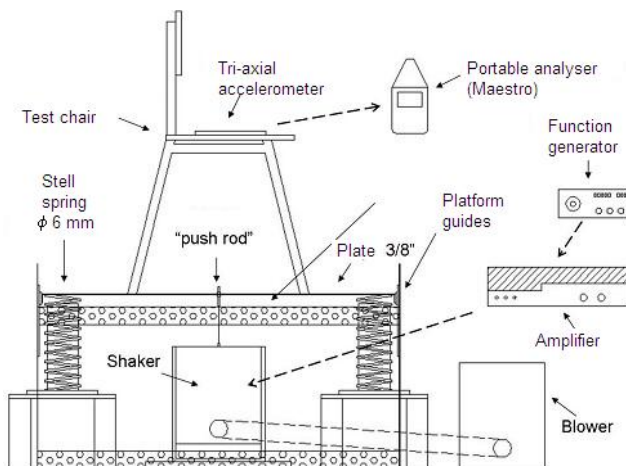


Figure 1. Sketch of the WBV Test Bench.



Figure 2. Picture of a WBV Test.

The research work in the GRAVI_{HUMAN-BEING} laboratory is focused on the study of WBV effects on human beings. In several situations, it is required to ensure that the same specific WBV level is being applied to the whole group of volunteers; in order to statistically verify the WBV effects, for example, on their hearing. With this purpose in mind, an automatic control system for the WBV tests was devised. The proposed system includes the following equipments:

- A 1-axis permanent-magneto-based excitation system (from Dynamics Solution, model VT150) with frequency range from 2 to 8500 Hz, with peak-to-peak displacement of 1 inch and a maximum nominal load of 68.0389 kgf.
- A function generator used to generate input signals in open loop operation mode (excitation set-point).
- A portable analyzer (from 01dB, model Maestro WB) for WBV tests that includes a seat adapter and a 3-axis accelerometer (10 mV/g - 34 grams) with an 8pin cable (from Lemo). The package includes the dBMaestro software to download the measured data for analysis and storage.
- A vibrating platform developed for WBV tests on human beings (z-axis).
- Finally, a ZAP500 PLC based control system from Hi-technology (not shown in the WBV test setup).

3. THE ZAP500 PLC CHARACTERISTICS - A BRIEF REVIEW

Several hardware solutions can be found in the market to solve every part of the shaker control problem. Despite of that, it was found convenient to implement all the required control functions in a single programmable logic controller (PLC). Thus, the ZAP500 a PLC from Hitecnologia, shown in Fig. 3, was chosen in this work.



Figure 3. The ZAP500 PLC from Hitecnologia.

In order to reach the desired excitation level at the shaker output despite the load, it is clear that, the proposed system should include a feedback scheme. So, the two main tasks to be accomplish in the proposed scheme are: a) implementation of a sine function generator with amplitude and frequency defined by the operator and b) a PID controller whose output defines the amplitude of the signal to be applied to the shaker input.

The ZAP500 programming environment (SPDSW) includes: A Ladder language editor, a compiler, a debugger tool and hypertext based help. The PLC hardware is constituted by: The ZAP500 controller, the MPB510, the ZEM530 expansion board, and a HMI (human-machine interface) panel, a power source, and serial (RS232 and RS485) communication ports. Notice that, in this case, the ZAP500 PLC already includes four PID controllers in its firmware.

The Ladder editor is capable of manipulating binary (R), integer (M) and real (D) variables. Two types of constants: integer (K) and real (Q). The PLC inputs are defined as digital (I) and analog (E). Additionally, the outputs can be defined as digital (O) and analog (S). Three block types can be defined (using a block-identifier parameter T): BLK, PID or MSG. The specifications of the ZAP500 analog input-output (I/O) system are summarized in Tab. 1. The electrical specifications of the ZAP500 digital input-output (I/O) system are summarized in Tab. 2.

Table 1. The ZAP500 Analog I/O System.

8 ANALOG INPUTS (ADC – 12 bits)		2 ANALOG OUTPUTS (DAC - 12 bits)	
Input	Type of Signal	Output	Type of Signal
E0	0-5 V	S0	4-20 mA
E1	0-5 V	S1	4-20 mA
E2	0-5 V	ADC: Analog to Digital Converter DAC: Digital to Analog Converter	
E3	0-5 V		
E4	0-5 V		
E5	0-5 V		
E6	0-5 V		
E7	0-5 V		

Table 2. The ZAP500 Digital I/O System.

8 DIGITAL INPUTS		18 DIGITAL OUTPUTS	
Input	Type of Signal	Output	Type of Signal
I0	24 V	O10	24V
I1	24 V	O11	24V
I2	24 V	O12	24V
I3	24 V	O13	24V
I8	24 V	O16	24V
I9	24 V	O17	24V
I10	Dry Contact	O18	24V
I11	Dry Contact	O19	2-2000Hz, 24V
		O0 – O9	HMI (Leds)

Figure 4 presents the internal structure of the ZAP500 with the expansion module ZEM530.

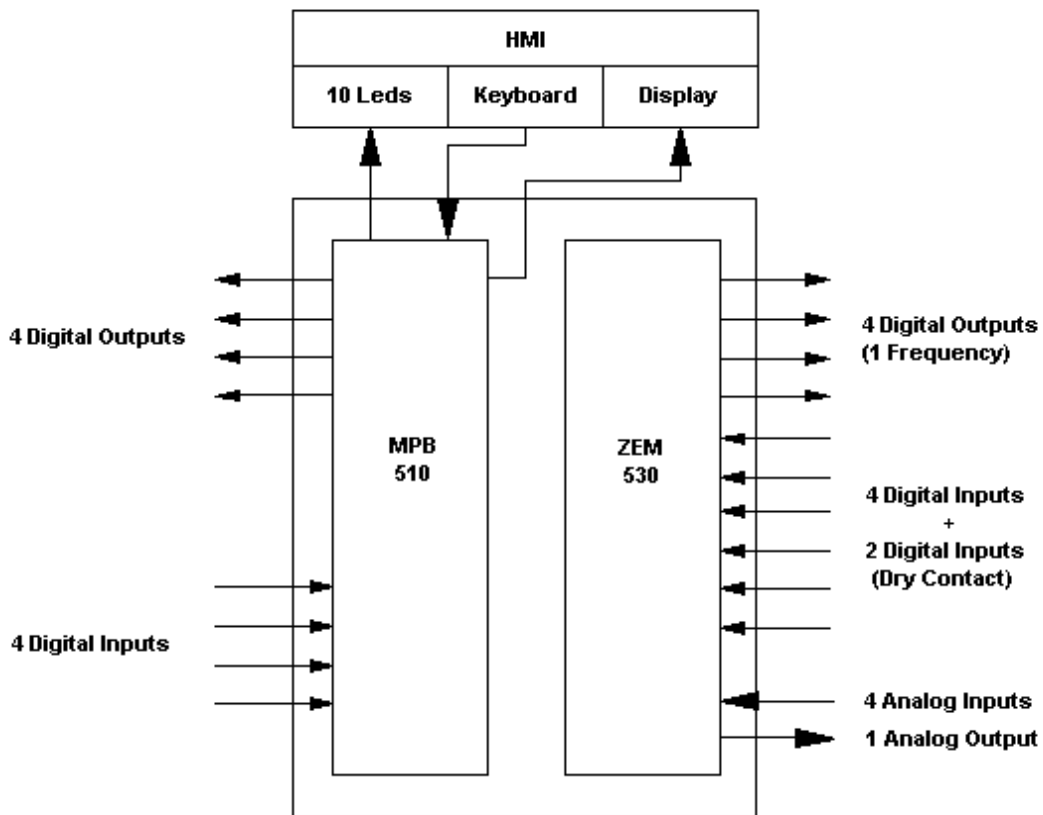


Figure 4. The ZAP500 PLC Internal Structure.

4. THE CLOSED LOOP CONTROL SYSTEM

Usually, commercial shakers are operated manually (open loop mode) as shown in Fig. 5. In this case, $G(s)$ is the transfer function representing a dynamics that includes the shaker power source and the shaker itself; $y(t)$ is the actual value of the vibration amplitude applied to the volunteer; $d(t)$ is a disturbance representing the load (weight of the volunteer); and finally, $u(t)$ is a frequency signal usually obtained from a signal generator. The open loop operation performance is good enough when the vibration frequency is the only parameter of interest since the output frequency does not depend on the load conditions.

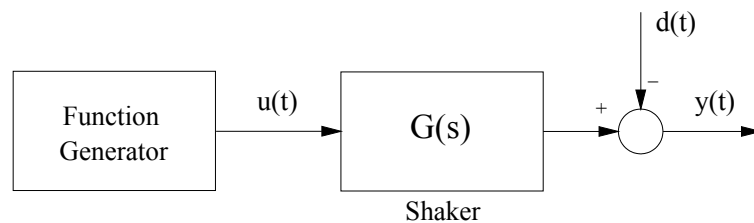


Figure 5. Open Loop System Block Diagram.

However, this is not the general case in which the amplitude of the effort applied to the person is also relevant and requires being precisely defined. Since the amplitude strongly depends on the person weight, the shaker operation in open loop mode will not succeed in those cases.

Another issue that must be taken into account during the test is that the results depend on a subjective evaluation of the comfort or discomfort felt by the volunteers. In those cases, the pre-test tuning time must be as short as possible in order to avoid emotionally or physiologically perturbing the person's assessment.

Finally, a necessary feature in the WBV experimental area is the need to apply the same test parameters (frequency and amplitude) to the whole population despite the weight and body shape of each individual.

Because of that, and in order to ensure repetitivity and a short pre-test tuning time, the WBV experimental setup must be operated in closed loop mode with respect to the vibration amplitude delivered by the shaker.

Figure 6 presents a typical closed-loop system block diagram used for control analysis and design. In this case, $G(s)$ is the transfer function of the shaker and its power source; $K(s)$ is the controller algorithm implemented in a PLC and $P(s)$ is some filter (hardware or software implemented) used to smooth the shaker startup. In the WBV experiment case, the variables have precise physical meaning, as follows: $r(t)$ is the desired excitation amplitude to be applied to the volunteer; $u(t)$ represents the required power to drive the shaker; $y(t)$ is the actual excitation amplitude delivered to the person; $d(t)$ is a disturbance signal due to the individual weight and $m(t)$ is measurement noise in the sensors (strain-gages or accelerometers).

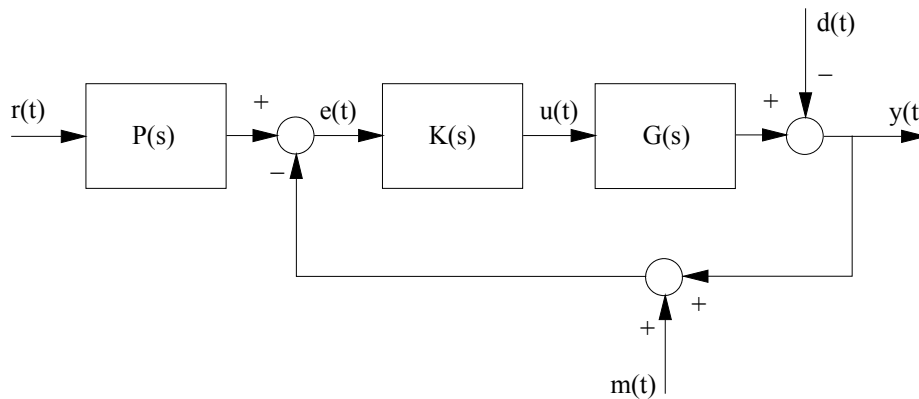


Figure 6. A Typical Closed Loop System Block Diagram.

The block diagram shown in Fig. 6 can be slightly modified to obtain a more realistic representation for the shaker control system as given in Fig. 7. The basic idea is to generate a sine function using a recursive algorithm (that has been implemented in the PLC) such that frequency and amplitude of the signal can be independently set. The output signal, $y(t)$ (delivered by the accelerometer) is amplified, rectified and filtered to produce $y_A(t)$. Then, $y_A(t)$ is compared with the desired amplitude, $r_A(t)$, to produce the error signal, $e_A(t)$. The error signal, $e_A(t)$, is then processed by a PID controller algorithm. The PID algorithm delivers the amplitude of the sine signal that feeds the shaker. The signal $d(t)$ is a disturbance and represents the volunteer weight. Finally, $m(t)$ represents measurement noise.

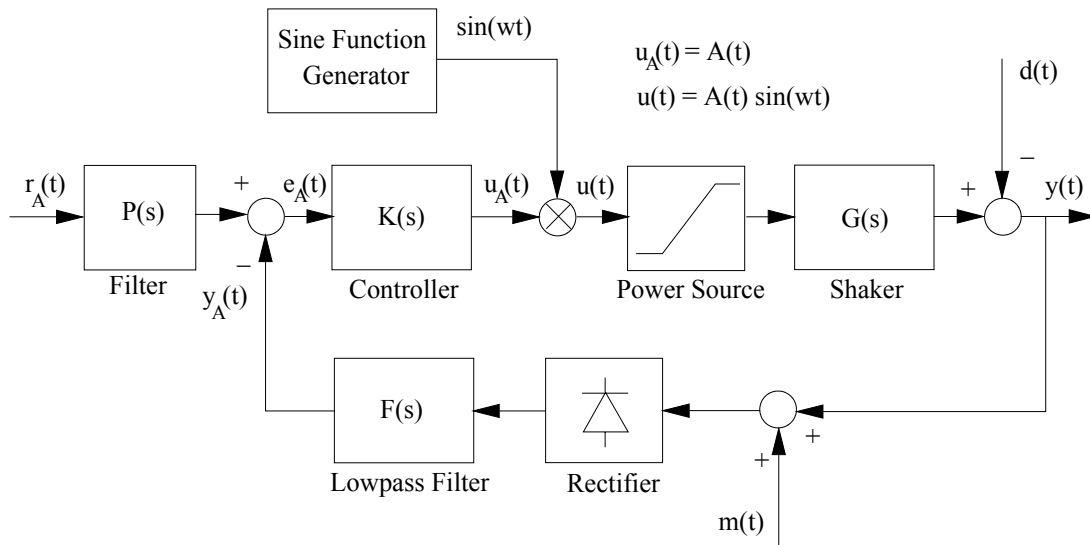


Figure 7. The Shaker Closed Loop System.

Finally, the implementation of the shaker system is summarized in Fig. 8. It should be observed that $y(t)$ is an analog signal produced by a 3-axis accelerometer (10 mV/g - 34 grams).

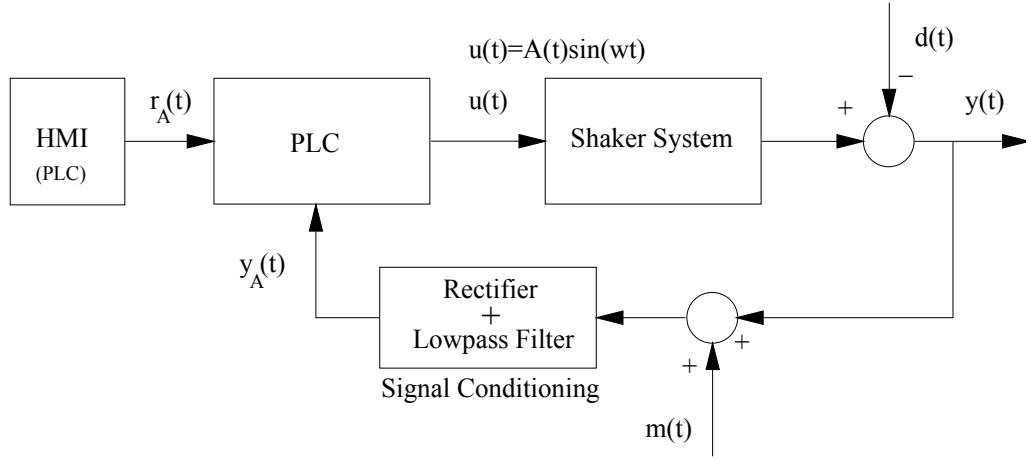


Figure 8. The System Implementation.

5. THE CONTROLLER DESIGN AND EXPERIMENTAL RESULTS

This section presents the proposed control design procedure for the WBV platform described in Section 2. The shaker and its power source can be represented by a first order model of the form:

$$G(s) = \frac{K_{sh}}{T_{sh}s + 1} \quad (1)$$

where T_{sh} is the shaker time constant and K_{sh} is the shaker nominal gain.

The algorithm for generating the sinusoidal function with frequency ω can be easily obtained from the z-transform pair given by:

$$f(t) = \sin(\omega t) \quad \Leftrightarrow \quad F(z) = \frac{z \sin(\omega T)}{z^2 - 2z \cos(\omega T) + 1} = \frac{\sin(\omega T) z^{-1}}{1 - 2 \cos(\omega T) z^{-1} + z^{-2}} \quad (2)$$

Equation (2) can be written in recursive form such that

$$f(kT) = 2 \cos(\omega T) f(kT - T) - f(kT - 2T) + \sin(\omega T) \delta(kT - T) \quad (3)$$

where $\{\delta(\cdot)\}$ is the Dirac's sequence and T is the sampling rate; usually for simplicity, the sample rate is omitted ($kT \rightarrow k$), thus

$$f(k) = \sin(\omega k) = 2 \cos(\omega T) f(k-1) - f(k-2) + \sin(\omega T) \delta(k-1) \quad (4)$$

finally, the recursive algorithm to generate the sinusoidal function is given by:

$$f(k+1) = \sin(\omega(k+1)) = (2 \cos(\omega T) f(k) - f(k-1) + \sin(\omega T) \delta(k)) \quad ; \quad k = 0, 1, 2, 3, \dots \quad (5)$$

To determine the amplitude of the sinusoidal function, the amplitude error can be defined as:

$$e_A(t) = r_A(t) - y_A(t) \quad ; \quad r_A(t) = \text{constant} \quad (6)$$

where, $r_A(t)$ is the amplitude reference, $y_A(t)$ is a measurement of the output amplitude and $e_A(t)$ is the amplitude error.

It should be observed that, $y_A(t)$ is a DC signal obtained from amplifying, rectifying and filtering the accelerometer output, $y(t)$, and it is related (without filtering) to the desired excitation amplitude by a scaling factor. However, it can be shown that the value of the scaling factor can be made close to one by decreasing the crossover frequency of the lowpass filter.

The PID control algorithm included in the ZAP500 firmware has the form:

$$u_c(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} ; \quad e(t) = r(t) - y(t) \quad (7)$$

where, K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain and, finally, $u_c(t)$ is the controller output. Thus, in the case of the shaker system:

$$u_A(t) = A(t) = K_p e_A(t) + K_i \int e_A(t) dt + K_d \frac{de_A(t)}{dt} ; \quad e_A(t) = r_A(t) - y_A(t) \quad (8a)$$

with

$$u_A(t) = A(t) \Leftrightarrow u_A(kT) = A(kT) \Leftrightarrow u_A(k) = A(k) \quad (8b)$$

The controller parameters were determined using standard PID control tuning techniques. The objective was to reach a smooth transient response. It should be noticed that the settling time must be specified as long as needed to keep the volunteer relaxed during the test; avoiding in this way any unnecessary stress caused by sudden shaker startups from rest to nominal test conditions. The PID controller was fine tuned in simulation to achieve damping factor of 1.0 and a settling time of 40 seconds. The PID parameters were determine such that:

$$u_A(t) = A(t) = 0.3 e_A(t) + 0.15 \int e_A(t) dt + 0 \frac{de_A(t)}{dt} \quad (9)$$

Thus, the signal at the shaker input can be built as:

$$u(k) = A(k) f(k) = A(k) \sin(\omega k) \quad (10)$$

it should be noted that $A(k)$ is a function of the amplitude error and corresponds to the output signal of the PID control algorithm.

Finally, the signal-conditioning block of Fig. 8 (rectifier + lowpass filter) was designed to deliver a ripple-free signal that is the converted to digital format and used to implement the error equation given by Eq. (6). In this case, the low pass filter crossover frequency was determined as:

$$\omega_c = 0.1429 \quad rd / sec \quad or \quad f_c = 0.0227 \quad Hz \quad (11)$$

Tables 3 and 4 show the technical specifications of the accelerometer and shaker, respectively, used in this work.

Table 3. The 3-Axis Accelerometer Model AP2083

Axial Sensitivity (mV/g)	X: 10.2; Y: 9.9; Z: 10.0
Transverse Sensitivity (%)	X:<3.0; Y:<2.9; Z:<2.7
Supply Voltage (V)	+15 to 30
Supply Current (mA)	2 to 20
Noise Level (g)	< 0.0003
Output Voltage (V)	8 to 10
Output Impedance (Ohms)	< 500
Resonant Frequency (kHz)	> 25
Frequency Range (Hz) ± 1 dB	0.5 to 8000

Table 4. The Shaker Model VTS 150

Maximum Force (kgf)	68.0389
Maximum Velocity (m/s)	1.778
Maximum Acceleration (m/s ²)	1078.73
Armour Weight (kg)	0.322051
Suspension Stiffness (kg/cm)	7.1432
Resonance Frequency (Hz)	5400
Frequency Range (Hz)	2 – 8500
Nominal Impedance (Ohms)	6
Nominal Power (A) (V)	28A – 120V

In the following, all variables are represented by their adimensional relative values (per unit values), normalized at the operation point. Figures 9 and 10 illustrate the effects of the lowpass filter in the feedback loop (Fig. 8). Notice that that amplitude error, $e_A(t)$, and the control signal, $u_A(t)$, are both DC type signals and they are calculated using Equations (6) and (8) respectively.

Figure 9 displays the controller performance without the lowpass filter. Notice that in this case the error and control signals are corrupted by measurement noise, despite of that, the tracking performance is well achieved.

Figure 10 presents the controller tracking performance with the inclusion of the lowpass filter. In this case, the error and control signals are clean from noise. In addition, it can be observed that the shaker tracking performance was improved reaching steady state faster than before.

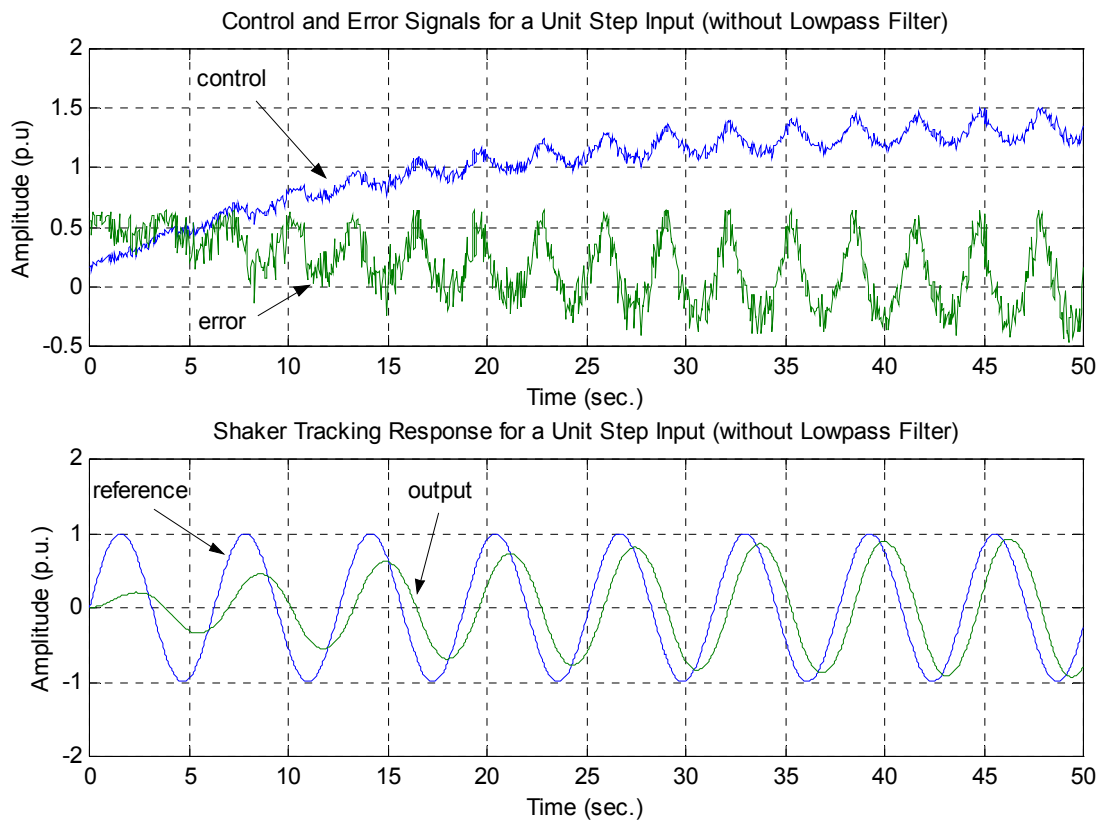


Figure 9 – The Shaker Tracking Response for a Unit Step Amplitude Input without Filtering.

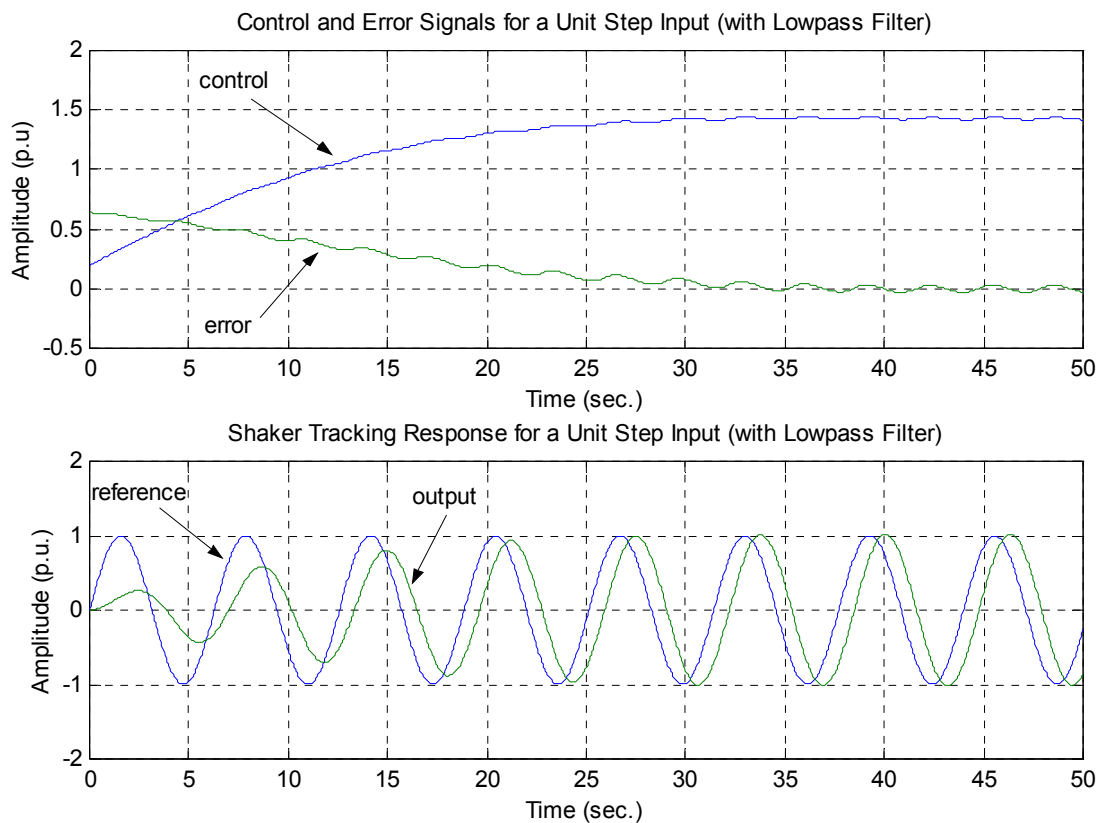


Figure 10. The Shaker Tracking for a Unit Step Amplitude Input with Filtering.

6. FINAL COMMENTS AND CONCLUSIONS

This paper presented the design procedure of a test bench for experimental evaluation of whole body vibration effects on human health and comfort. The proposed scheme permits the independent control of the amplitude and frequency of the excitation signal in WBV tests. Contrary to the shaker manual operation in which the startup tuning time takes several minutes, the proposed scheme substantially reduces the shaker settling time to less than a minute. Among others, the system main features are:

- a) Accurate control (due to the PID loop) of the excitation signal amplitude in WBV tests.
- b) Ease selection of the excitation signal frequency through the PLC human-machine interface (HMI).
- c) Short pre-test waiting time avoiding pre-test volunteer exhaustion.
- d) Keep pre-defined test conditions (amplitude and frequency) despite the volunteer weight and body shape.
- e) Allows system start up fitting to volunteer stress level by shaping the transient response.
- f) Finally, systematic testing is made simpler. The analysis of the effects of WBV in humans is performed in a more controlled way since all the volunteers will be submitted to the same excitation.

7. ACKNOWLEDGMENTS

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