DEVELOPMENT OF AN ACTIVE CONTROL SYSTEM FOR A WHOLE BODY VIBRATION PLATFORM

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Abstract. *This work presents the implementation of a control system for a Whole Body Vibration (WBV) platform used to study the influence of vibration in the human body. The platform was developed to be used in WBV test where it is necessary to maintain a specified amplitude level of vibration which varies according to the test type to be performed and it is evaluated by specific norm and the purpose of the test. The amplitude level depends on the exposure time and the vibration frequency. The WBV platform consists of a chair, where the volunteer sits for the test, located in a plate supported by four compression springs and excited at the base using an electro-dynamic shaker. The control system automatically adjusts the vibration amplitude of the platform according to a reference value, which changes according to the test being performed in both vibration amplitude and in exposure time. As the tests will be performed in humans, the control system must be fast enough to exposure the volunteer to an initial vibration, that is, the transitory vibration before stabilization, without overshooting, guarantying also that possible changes in the amplitude caused by the volunteer's movement are eliminated. Here, the control system is implemented in a data acquisition board using a PID controller. The use of the control systems eliminates the necessity of adjusting the amplitude manually, what normally takes more time to be performed properly. The decrease in the time adjustment using the active control was estimated to be at the order of more than 50% compared with the manual control.*

Keywords*: PID Control, Platform Control, Whole Body Vibration*

1. INTRODUCTION

Whole Body Vibration (WBV) analysis consists in verifying the influence of vibration in the human body when the exposure enters the body by a supporting surface (such as a seat, a floor, or a bed) and achieves the entire body, (Griffin, 1996), (Duarte et al 2009a). The human body is considered as a physical system owns the natural frequencies and vibration modes of each component, in this case, internal organs, and members like legs and arms. Each one submitted to vibration can generate unpleasant sensations in the person.

The problem involving WBV studies is that each person has a different response when exposed to the same vibration level, which is known as the intra-subjective variability, (Griffin, 1996). Therefore, the data must be treated as averages obtained from jury tests, i.e., several volunteers with different height, weight, and gender are submitted to vibration to generate a response pattern, (Griffin, 1996), (Duarte et al. 2006). It means that several tests must be performed to establish a criterion in relation to the acceptable vibration level.

Nowadays, the $GRAVI_{SH/UFMG}$ (Group of Acoustics and Vibration in Human Beings of UFMG) owns a platform to study WBV effects, fig. 1, which consists of a chair where the volunteer is placed, located over a plate supported by 4 compression springs, excited at the base using a electro-dynamic shaker, (Duarte et al. 2009b) and (Galvez et al. 2007).

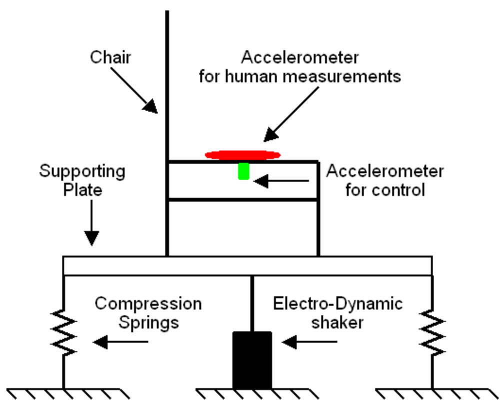


Figure 1: Whole Body Vibration Platform

The test consists in maintaining a specified amplitude level of vibration evaluated by specific norms ISO 2631/1 (1997), ISO 2631/1 (2010), Directive 2002/44/EC (2002) and ISO 13090/1 (1998), which depends on the test type to be performed. The amplitude level depends on the exposure time and the vibration frequency and it is evaluated in either Vibration Dose Value (VDV) or weighted acceleration *aw*, (Griffin, 1996) and (ISO 2631/1, 1997). The experimental procedure starts with placing the volunteer in the platform with the vibration system turned off. Then the shaker is turned on and the vibration amplitude is adjusted until an accelerometer located in the chair measures the desired level, (Duarte et al. 2009b).

However, at $GRAVI_{SH/UFMG}$, the vibration level was being adjusted manually without an automatic system what generates small variations between one individual and another. Besides, during the tests, the volunteers must be stuck to a chair throughout a long period of time, sometimes until 20 minutes and so, in practical applications, the volunteer moves sometimes changing the vibration amplitude level, which must readjusted so do not change the exposure using for the studies. These variations between one volunteer and another and the volunteer movements introduce undesirable variations during the tests. Hence, it is necessary to introduce an active control system to automatically adjust the vibration amplitude level of the WBV platform to be more consistent with the desirable exposure levels used.

2. DEVELOPMENT OF THE CONTROL SYSTEM

As a general form, the control system of the WBV platform must follow the requirements listed below, which were formulated to keep the safety and reliability of the test.

- The Platform oscillation must initiate in 0 (zero) to eliminate initial burst in the volunteer;
- The control system must not present overshoot in order to do not expose the volunteer to vibrations level higher than those acceptable by norms, ISO 2631/1 (1997), ISO 2631/1 (2010), Directive 2002/44/EC (2002) and ISO 13090/1 (1998);
- It is expected that the settling time of the controlled system must not exceed 20 seconds. Thus, the volunteer will be exposed only the necessary time of the test, which sometimes takes only 2 minutes. The initial manual adjustment of the system takes around 40 seconds.

2.1. Control Strategy

The proposed control strategy basically consists of generating a sine wave at a certain frequency and correcting its amplitude until reaching the desired vibration level at the platform, (Galvez et al. 2007). The sine wave amplitude correction is performed by PID controller, (Ogata, 1994), (Franklin et al. 1998), (Phillips and Charles, 1995). The input of the controller is the comparison between the desired weighted acceleration a_w and the measured weighted acceleration $a_{w.}$ The desired value (named set point) is filtered by a First Order System as shown in Fig. 2. The measured weighted acceleration a_w used is calculated by taking the absolute value of the measured acceleration after being filtered by a low-pass filter and corrected by a gain (See fig. 2).

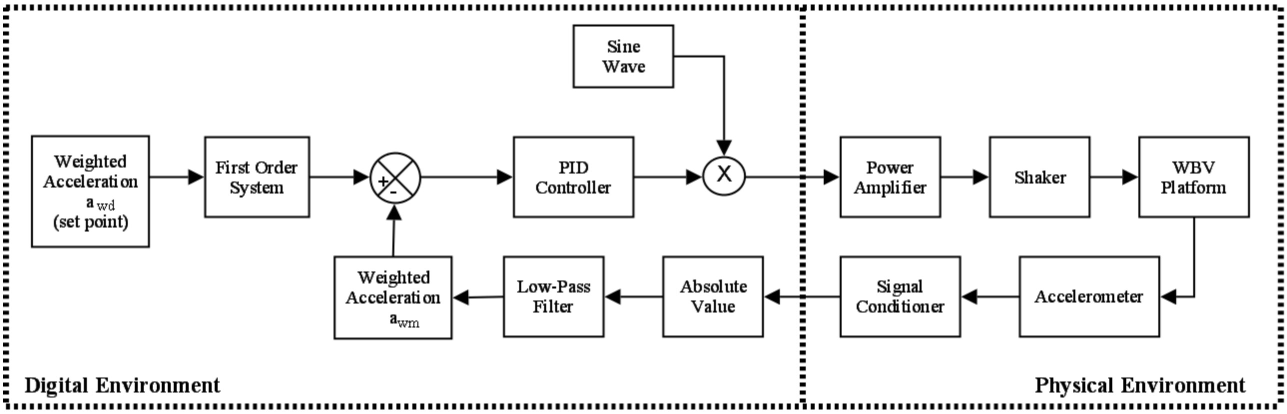


Figure 2: Schematic diagram of the control system

According to fig. 2, the output of the control board is the input of the power amplifier which drives the shaker so to impose the desirable acceleration level in the platform. Therefore, the input of the control board is the output of the signal conditioner introduced to measure the acceleration level.

2.2. Experimental Model Identification

In order to simulate the controller, it was performed an experimental identification of the WBV platform, which consists of a chair where the volunteer is placed, located over a plate supported by 4 compression springs, excited at the base using a electro-dynamic shaker, (Duarte et al, 2009b) and (Galvez et al. 2007). Therefore, it is assumed as a simple model of a mass suspended by a spring. The spring constant was estimated putting a mass of approximately 94.5 kg, the spring deflected around 0.0585 m, so the spring constant was estimated as 15.85 kN/m. The worst situation in control applications is found in systems without damping, so the platform damping was considered as null. The input of the platform can be force and the output is measured in acceleration, so the WBV platform transfer function can be expressed as,

$$\frac{A(s)}{F(s)} = \frac{s^2}{ms^2 + k} = \frac{s^2}{(m_v + 12)s^2 + 15850} \tag{1}$$

Where 12 kg represents the platform weight by itself and m_v is the volunteer mass, $A(s)$ is the acceleration and $F(s)$ the force introduced by the shaker.

2.3. Simulation of experimental data

The most important frequency in human beings whole body vibration experiments is when the seated subject is submitted to amplitudes around 5 Hz, due to the maximum transmissibility seat-to-head (Griffin, 1996). Therefore, the simulation here is performed assuming such frequency. However some constraints are imposed by the control board system. Although the desired sine wave is set to 5 Hz, the control board has a fixed sampling frequency of 8 kHz. Moreover, the maximum output of the control board is around 1 V, which means that the power amplifier must be correctly adjusted to prevent problems in the control law. The relationship between the force applied in the platform and the output of the control board was experimentally estimated as a simple gain around 300 N/V by observation.

The low-pass filter is a 4th order Butterworth filter with 1 Hz cut-off frequency used to extract the value to be compared with the desirable weighted acceleration a_w. The 1st order system was chosen to have a time constant τ = 1s. The gains observed in Fig. 3 were estimated experimentally, and the most important is the relation between the peak amplitude and the weighted acceleration a_w, estimated as 0.8250 (see section 3.1 for more details). The relationship between the peak amplitude and the output of the 4th order filter is 1.5709. So, only one gain is necessary, that is, 0.8250 x 1.5709 = 1.296.

In order to simulate a disturbance in the acceleration level (for example, a person moving at the platform), it was introduced a sequence of steps by multiplying the output of the platform at t = 25s and 45s by a 20% change in the acceleration amplitude. The resulting block diagram can be seen in Fig. 3.

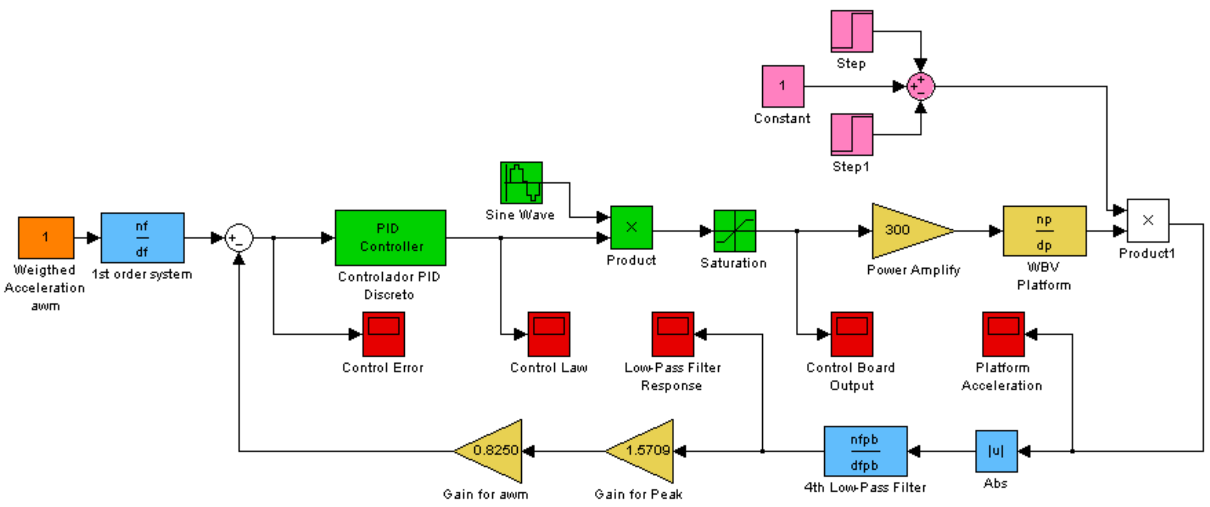
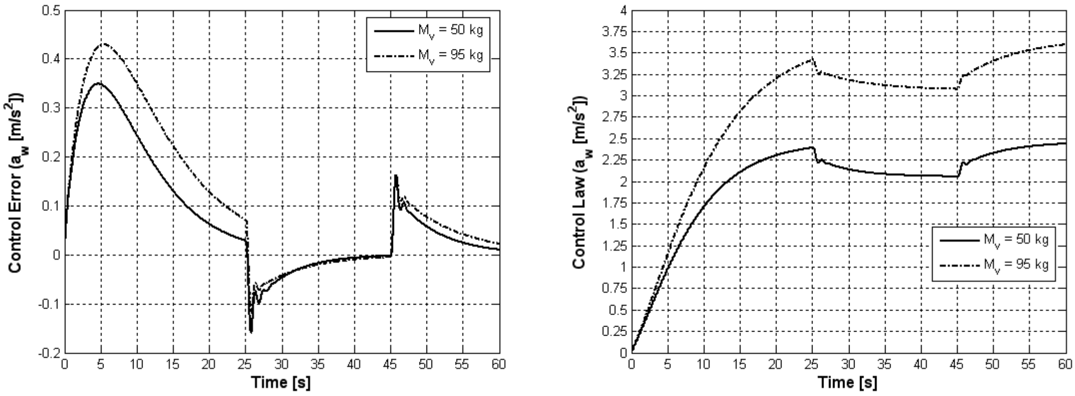


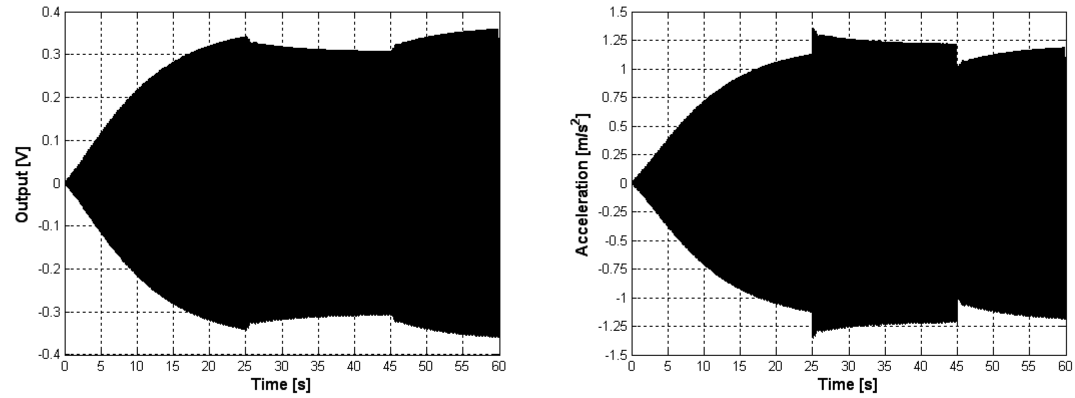
Figure 3: Block diagram of the control system

The platform is constructed to be used with subjects weighing around 50 to 95kg. For weights out of this range, the compression springs do not work properly. Using the Close-loop Ziegler Nichols method for the PI project (Ogata, 1994) with a critical gain around 5 and the wave period of 1s resulted after some iterative simulations in a proportional gain (Kc) = 0.8 and integration time (Ti) = 1.5s, to be conservative and to assume the constrains mentioned at section 2 (such as the overshoot, etc). The results of the simulation can be seen in Figs. 4 and 5, where it is observed that the fatter the volunteer is, the higher is the amplitude and the longer is the settling time, but it is not observed the overshoot in both cases, and the system behavior seems to be stable. Although around 30 seconds for complete stabilizations seems to be a long time for control systems, it should be remembered that the system is developed for humans' applications and a slow stabilization time tends to be more comfortable for the volunteer, avoiding initial burst. Figure 5(a) shows that for a desired a_w = 1 m/s^2 at the seat, the maximum control board output is less than 0.4 V which is an acceptable level (considering the board constraint of 1V output) and Fig. 5(b) shows the WBV platform instantaneous acceleration around 1.1 m/s^2.



(a) (b)

Figure 4: a) Control Error and b) Control Law for volunteer mass of 50 kg and 95 kg



(a) (b)

Figure 5: a) Control board output and b) WBV platform response for volunteer mass of 95 kg

3. EXPERIMENTAL IMPLEMENTATION

The WBV platform control system was divided in two parts, the first one consists of verifying the measurements, while the second is the control implementation. The equipments used are listed in table 1.

Table 1. List of equipments used in the experiment

Equipment	Model	Manufacturer
Control board	NI Speedy 33	National Instruments
Acquisition System	Photon II	LDS
Acquisition System	Maestro	01dB
Monoaxial Accelerometer	352A	PCB
Triaxial Accelerometer	AP2082	APTechnology
Signal conditioner	482A28	PCB
Shaker	VTS 150	Dynamic Solution
Power Amplifier	2718	B&K
	CE 2000	Crown

3.1. Measurements Verifications

The most important part of the experiment is guarantying that the measurement performed, in this case, the input signal, corresponds to the weighted *aw* desired for the Whole Body Vibration test. Such value for the experiments performed here was obtained using the Acquisition System Maestro from 01dB (see Tab. 1). So, the objective here is to compare the measurement performed with the Acquisition system Photon II (which has no weighting function for WBV) with the Acquisition system Maestro (which has such function) in order to extract a correlation which should be representative of the weighting function used for WBV measurements. That was necessary since the shaker is not capable of generating a pure sine wave at low frequency. As the weighted acceleration depends on the frequency, the experiment is performed in the frequency used for the WBV studies performed at $GRAVI_{SH/UFMG}$ that is 5 Hz.The initial frequency was generated in the Photon II – power amplifier CE 2000 – shaker. The monoaxial accelerometer (used for the control system) was positioned on top of the triaxial accelerometer (used for human measurements) and both were mounted at the top of the shaker, in order to guarantying that both measured the same acceleration level. The gain relating the peak and the *aw* was obtained applying curve fitting as $G_{Pk\text{-}aw} = 0.8250$.

Table 2. Comparison in between the Photon II and the Maestro

Maestro Weighted acceleration	Photon II Unweighted acceleration	
aw (m/s^2)	Peak (m/s^2)	RMS (m/s^2)
0.50	0.61	0.43
0.75	0.92	0.65
1.00	1.22	0.86
1.25	1.51	1.07
1.50	1.82	1.29
1.75	2.12	1.50
2.00	2.42	1.71
2.25	2.72	1.92
2.50	3.03	2.14

The second experiment was related to the control board NI Speedy 33 input and output gains. A simple experiment was performed, generating a sine wave of amplitude 0.5 m/s^2 and frequency of 5 Hz in the control board NI speedy 33 and connecting it to the input of the acquisition system Photon II. The same procedure was used to generate a sine wave in the Photon II with the same characteristic and send to the input of the control board NI Speedy 33. Comparing the results it was possible to establish the gains as $G_o = 20400$ and $G_i = 1/57700$, for the NI Speedy 33 output and input respectively.

3.2. Control Implementation

The control system implementation at the NI speedy 33 control board using Labview can be seen in Figs. 6 and 7, where it is not observed the 1st order system in the set point due to limitations in the control board software. As the output of the control board is limited to 1 V, it is necessary to place two power amplifiers in line to achieve enough amplification for the WBV control. Besides, it is important yet to maintain the Maestro with the triaxial accelerometer to observe if the control system is able to control the WBV platform.

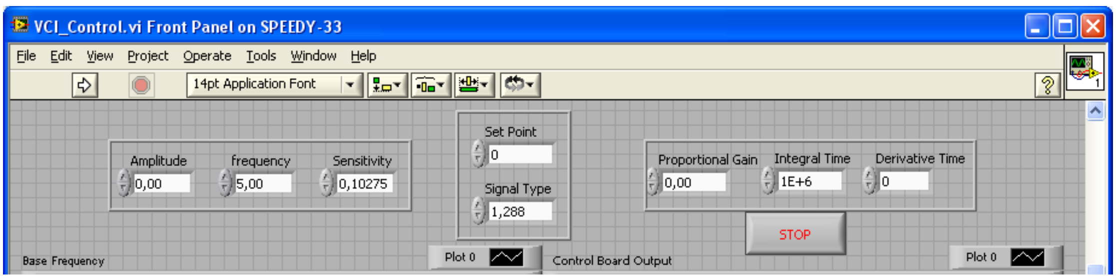


Figure 6: Control system front panel implemented in Labview

The experimental setup is performed setting both power amplifiers to 70% of the full amplification. Fig. 6 shows the front panel initial setup of the experiment. As the experiment starts, the control parameters need to be adjusted, as follows, the amplitude is set to 0.1 m/s^2, the frequency to 5 Hz and the accelerometer sensitivity to 0.10275 $V/(m/s^2)$ according to the calibration sheet. The set point is the weighted acceleration *aw* set to 1 m/s^2, and the signal type gain is 1.288. Such gain is used to transform the output of the 4th order filter to the weighted acceleration. Initially, the simulated value of 0.8250*1.5709 = 1.2960 was used (see item 2.3), however experimental observation shown that 1.288 worked better.

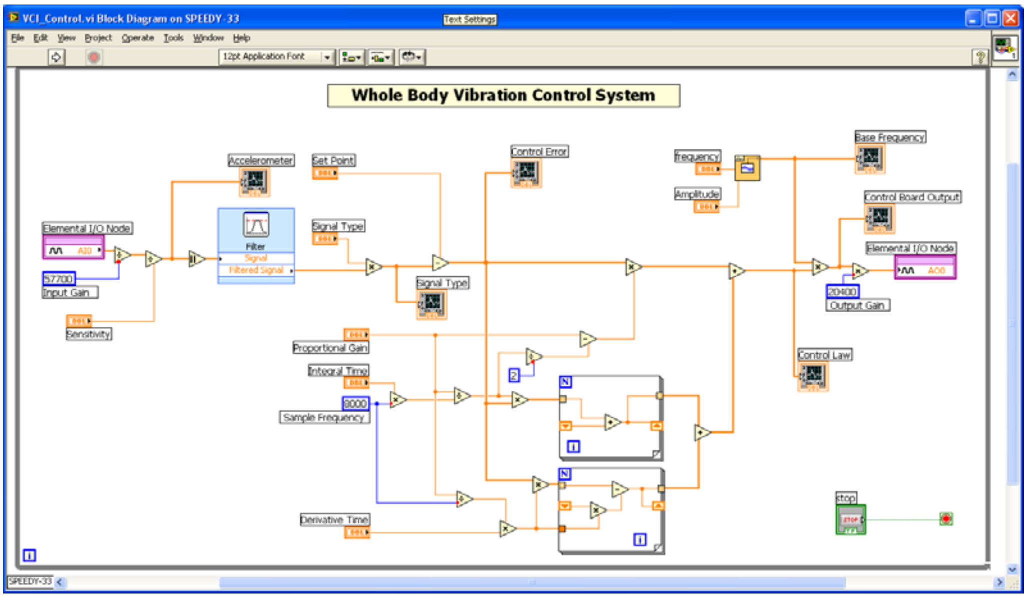
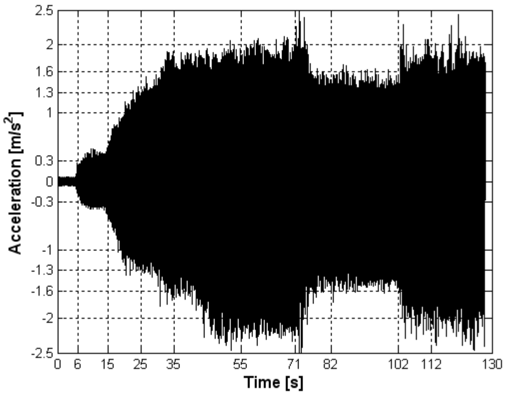


Figure 7: Block diagram of the control system front panel implemented in Labview

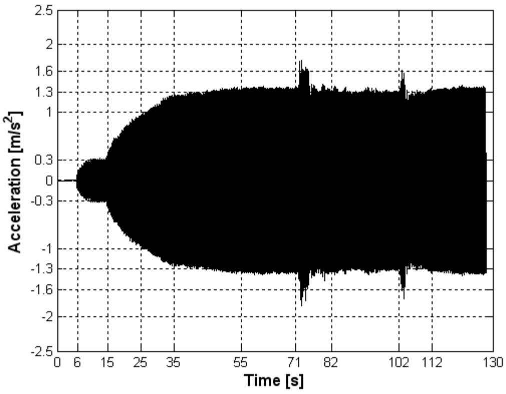
The experimental validation of the control system was performed using a volunteer of 65 kg. To avoid overshooting, the proportional gain *Kc* is changed from 0.1 and to 0.8, and then the integral time *Ti* is set to 1.5 seconds. The results from the experimental WBV platform acceleration were acquired using the Photon II system with Nyquist frequency of 160 Hz as presented in fig. 8. There, fig. 8(a) is the acceleration measured directly, and fig. 8(b) is the acceleration filtered by a Butterworth, 8 poles, and cut-off frequency of 14 Hz. The real WBV platform response is a non-linear response, caused by the shaker and by the volunteer movement. Because of that, it was necessary to filter the results to observe the real control system performance. The power spectrum of the WBV platform can be seen in fig. 9, where it is clear the presence of multiples of the excitation frequency.

So, the time period between 6 and 15 seconds in fig 8(b) represents only the *Kc* actuation, and the time period between the 15 and 35 seconds represents the introduction of the integrator control. Therefore, 20 seconds is the settling time or considering the whole time, 29 seconds. After the initial stabilization, the volunteer was asked to put the feet crossed back, approximately at 71 seconds, and to put the feet back to the original position approximately at 102 seconds. In both cases, the stabilization occurred in approximately 10 seconds. The feet crossed back represents the most typical volunteer movement observed in experiments of that kind.

Comparing fig. 8(b) and fig. 5, it is observed a difference in the acceleration amplitude level. It may be related to the accelerometer sensitivity mismatch. In the model, it was not considered the mass center movement, and most probably the presence of others frequencies in the experiment may have caused such effect.



(a) Real response



(b) filtered response

Figure 8: Experimental WBV platform response

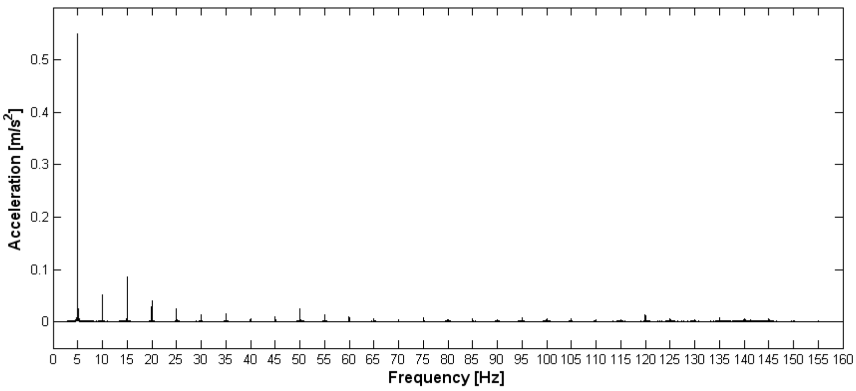


Figure 9: Power spectrum obtained using Fast Fourier Transform of the WBV platform acceleration

4. FINAL REMARKS

It was demonstrate that it is possible to implement a control system in a WBV platform to decrease the settling time, avoiding overshoot, and rejecting disturbances. The overall stabilization time was less than 30 seconds for the initial time, and about 10 seconds to the disturbances rejections. So, as a general trend, the control system seems to work properly for human vibration measurements. However, the experimental measurement presented multiple frequencies in the signal. It means that the WBV platform and maybe the dynamic shaker must be reviewed to decrease the non-linear behavior.

Now, the next step to improve the WBV platform is to develop a fast way to connect the dynamic shaker with the platform plate, because it takes a couple of minutes to be done.

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