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A Microprocessor Based Test Bench for Analysis of Vibration Effects on Human Health and Comfort

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Abstract: Since the beginning of the industrial era, the modern society has continuously changed toward the improvement of the quality of life. Human comfort has become necessary in all the human activities of the modern society. Labor quality has vindicated by syndicates and labor unions. Healthy life is one of the priorities of people all over the world. Insurance companies have spent great amounts of money paying premiums to workers that have been exposed to dangerous levels of noise and vibration and suffered from permanent injuries. In this context noise and vibration health effects has become the focus of the attention of the scientific community.

An important task that has to be accomplished in a near future is to clearly establish the hazard levels of noise and 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.

This paper presents the design procedure of a test bench for analysis of noise and vibration levels on human comfort and health. The system is based on a programmable logic controller used as a process controller that automatically defines and controls the amplitude and frequency of the vibrations produced by a shaker. The system block diagrams and project details are presented. Finally, experimental results and comments on its use are also included.

Keywords: Vibration and Human Comfort, Vibration Effects, Hearing Disease.

NOMENCLATURE

r = reference signal
u = control output
y = plant output
d = output disturbance
m = measurement noise
e_A= amplitude error
r_A= amplitude reference
y_A= amplitude output

T = sampling rate
ω = frequency
A = amplitude
K_p = PID controller proportional gain
K_i = PID controller integral gain
K_d = PID controller derivative gain
δ = Dirac's function

F(z) = cosine function z-transform
f(k) = cosine function sequence
K(s) = controller transfer function
G(s) = plant transfer function
T_{sh} = shaker time constant
K_{sh} = shaker nominal gain
K = shaker gain
W = load (weight)

INTRODUCTION

In the last decades, human comfort has been the main issue to assess life-quality in modern societies. The concepts of comfort and discomfort in human activities are under debate among the international scientific community and societies. There is no widely accepted formal definition, although it is beyond dispute that comfort and discomfort are feelings or emotions that human beings experiment and that are subjective in nature. If one wants to describe discomfort enough, he or she has to evaluate it from four standpoints: intensity, quality, body location and in what body part it is felt and its behavior in time (Ravnik, 2005).

A great amount of research has been done investigating the influence of whole-body vibration (WBV) on human beings. Most of these studies are related with either comfort, interference with activities or health effects (Chen and Robertson, 1972; Reinh and Meister, 1931; Seidel et al, 1986). Depending on the objectives of the study, it may be focused on a specific occupation or group. WBV comfort studies are usually related to vehicles or buildings, interesting works have been presented by Murray, 1998; Misael, 2001; Griffin, 1995; Griffin, 1996; and Klaoboe et al., 2002. WBV health effects on human drivers have also been object of studies by Balbinot, 2001; Silva and Mendes, 2005; and Scarlett et al., 2005; and others, Howard and Griffin (1990) have studied the combined effects of noise and vibration in humans.

In 2002, the European Parliament issued the Directive 2002/44/EC (2002) drawing some guidelines on 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 (Starlett and Stayner, 2005; Diaz, et al, 2003). Previously, Griffin had compared the methods used to predict the hazards of WBV and repeated shocks and had found a list of problems (Griffin, 1998).

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 & Hulshof, 1999; Ling and Leboueuf-Yde, 2000; Rehn et al., 2005 and Sacarlett and Stayner, 2005). An especially interesting topic, very little explored so far, is the effects of WBV on human hearing. The studies, directed to investigate the effects of noise and vibration in human hearing, are usually performed in loco (Silva and Mendes, 2005). However, separating the effects of one stimulus from the other is usually easier to be accomplished in laboratory.

The combined effects of noise and WBV on human hearing have been investigated by Manninen and Seidel (Manninen, 1983; Manninen, 1985; Manninen, 1988; Manninen and Ekblom, 1984; Seidel et al, 1992; Seidel et al, 1988; Seidel et al, 1989; Seidel et al, 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 and 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.

THE GRAVI$_{\text{DEMEC/UFMG}}$ WBV TEST BENCH

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

Figure 1. A Picture of the WBV Test Platform.

Figure 2. A Picture of a WBV Test.

The research work in the GRAVI$_{\text{DEMEC/UFMG}}$ 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) 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. (150 lbf).

b) A function generator used to generate input signals in open loop operation mode (excitation set-point).

c) 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.

d) A vibrating platform developed for WBV tests on human beings (z-axis).

e) Finally, a ZAP500 PLC based control system from Hi-technology.

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 analogue (E). Additionally, the outputs can be defined as digital (O) and analogue (S). Three block types can be defined (using a block-identifier parameter T): BLK, PID or MSG. The specifications of the ZAP500 analogue input-output (I/O) system are summarized in Tab. 1.

Table 1 – ZAP500 Analogue I/O System.

8 ANALOGUE INPUTS

(ADC – 12 bits)

INPUT	TYPE OF SIGNAL
E0	0-5 V
E1	0-5 V
E2	0-5 V
E3	0-5 V
E4	0-5 V
E5	0-5 V
E6	0-5 V
E7	0-5 V

2 ANALOGUE OUTPUTS

(DAC - 12 bits)

OUTPUT	TYPE OF SIGNAL
S0	4-20 mA
S1	4-20 mA

ADC: Analogue-Digital Converter

DAC: Digital-Analogue Converter

The electrical specifications of the ZAP500 digital input-output (I./O) system are summarized in Tab. 2.

Table 2 – ZAP500 Digital I/O System.

8 DIGITAL INPUTS		18 DIGITAL OUTPUTS	
INPUT	TYPE OF SIGNAL	OUTPUT	TYPE OF SIGNAL
I0	24 V	O0 – O9	HMI Led
I1	24 V	O10	24V
I2	24 V	O11	24V
I3	24 V	O12	24V
I8	24 V	O13	24V
I9	24 V	O16	24V
I10	Dry contact	O17	24V
I11	Dry contact	O18	24V
		O19	2-2000Hz, 24V

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

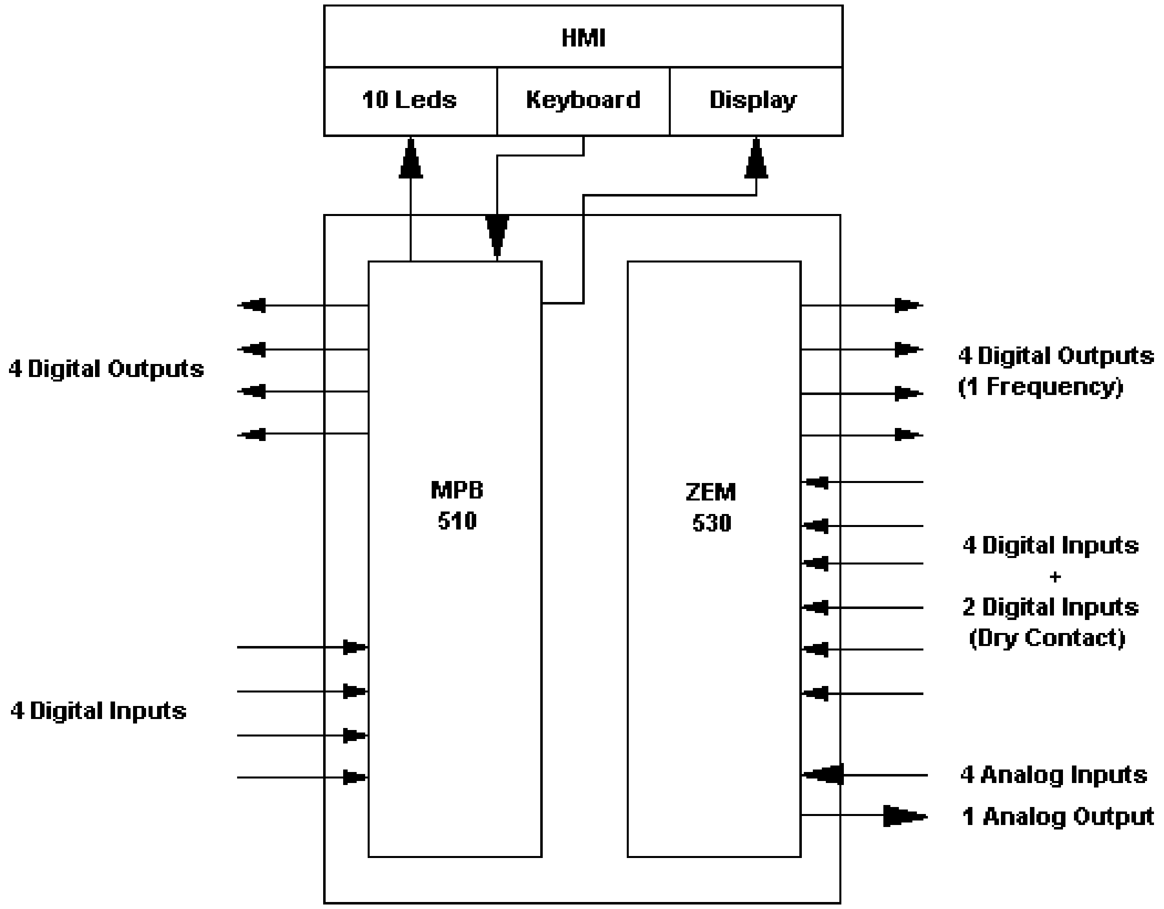

Figure 4 - The ZAP500 PLC Internal Structure.

THE CLOSED LOOP CONTROL SYSTEM

In general, commercial shakers are usually operated in 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.

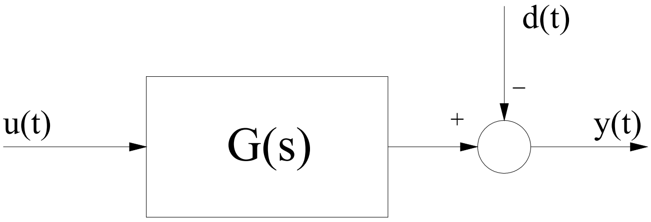

Figure 5 – Open Loop System Block Diagram.

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 the typical system closed loop 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 a filter required 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).

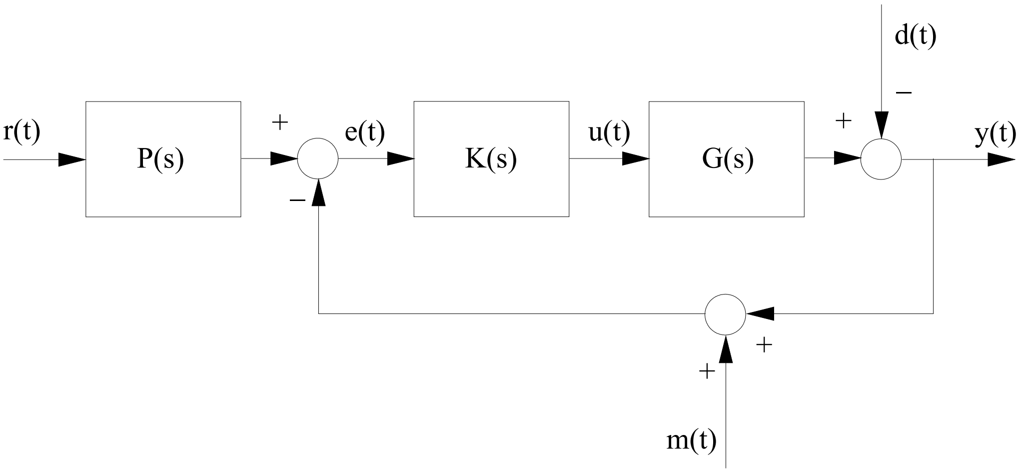

Figure 6 – A Typical Closed Loop System Block Diagram.

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.

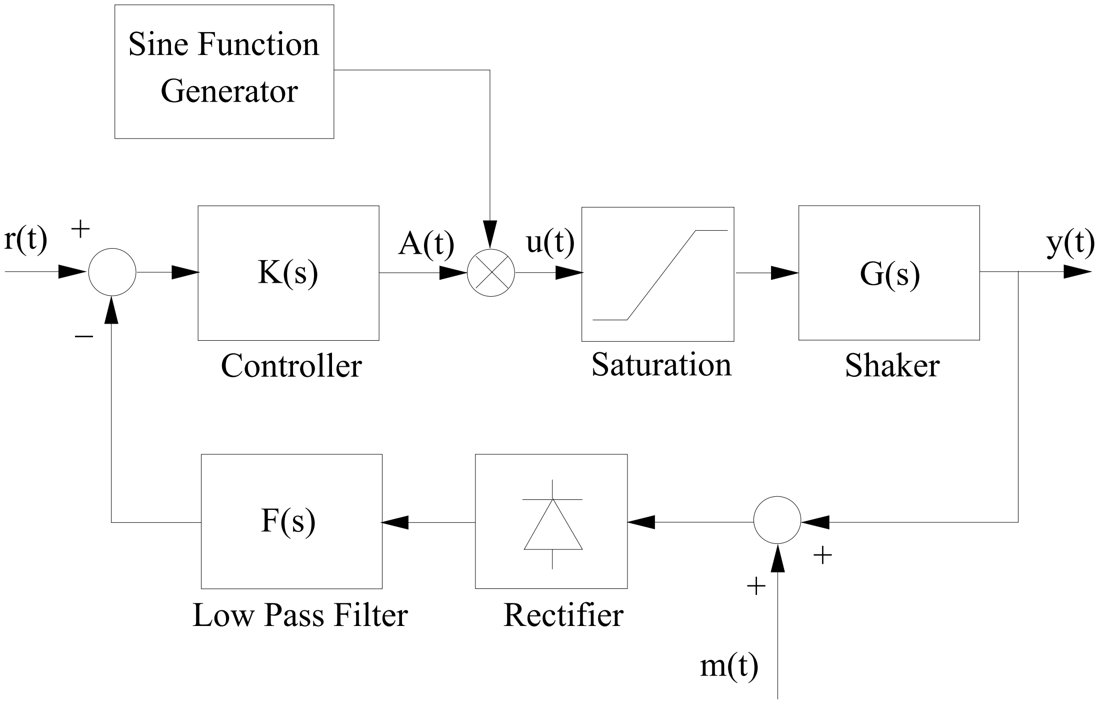

Figure 7 – The Shaker Closed Loop System.

For simplicity, the disturbance signal, *d(t)*, due to the volunteer weight, was embedded in the shaker transfer function such that

$$G(s) = \frac{K}{T_{sh}\, s + 1} \qquad ; \qquad K = \frac{K_{sh}}{1 + W} \tag{1}$$

The basic idea is to generate a sine function using a recursive algorithm that is implemented in the PLC, such that frequency and amplitude of the signal can be independently set. The output amplitude from the accelerometer is rectified, filtered and compared with the desired amplitude; the resulting error signal is processed by a PID controller (also implemented in the PLC). The PID algorithm delivers the amplitude of the sine signal that feeds the shaker.

In this case, a sine function with frequency ω can be generated using the z-transform pair given by

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

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

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

for simplicity, one can omit the sample rate ($kT \rightarrow k$),

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

or,

$$f(k+1) = 2\cos(\omega T) f(k) - f(k-1) + \sin(\omega T)\delta(k) \tag{5}$$

where $\{\delta(.)\}$ is the Dirac's sequence and T is the sampling rate.

The control signal at the shaker input is then given by

$$u(k) = A(k)\ f(k)\ =\ A(k)\sin(\omega\ k) \tag{6}$$

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. In this case, the error is defined as

$$e_A(t) = r_A(t) - y_A(t) \quad ; \qquad r_A(t) = constant \tag{7}$$

notice that $y_A(t)$ is a DC signal obtained from amplifying, rectifying and filtering the accelerometer output and in this case is related to the desired excitation amplitude by a factor of $\frac{2}{\pi}$.

The PID controller included in the ZAP500 firmware has the form:

$$u(t) = K_p\, e(t) + K_i \int e(t)\,dt\ + K_d\, \frac{de(t)}{dt} \qquad ; \qquad e(t) = r(t) - y(t) \tag{8}$$

in this case,

$$u(t) = K_p\, e_A(t) + K_i \int e_A(t)\,dt\ + K_d\, \frac{de_A(t)}{dt} \qquad ; \qquad e_A(t) = r_A(t) - y_A(t) \tag{9}$$

with

$$u(t) = A(t) \qquad \leftrightarrow \qquad u(k) = A(k) \tag{10}$$

The controller parameters were determined using standard PID control tuning techniques. The objective was to reach a smooth transient response (over damped) with a settling time of about 40 seconds. 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 stress caused by sudden shaker start ups.

EXPERIMENTAL RESULTS

This section presents the system closed loop performance. The PID controller was tuned to achieve damping factor of 1 and a settling time of 40 seconds. This time was defined considering the need of a smooth transition from rest to nominal test conditions.

Figure 8 displays the sinusoidal function generated using Equation 5. Figure 9 shows the error and control signals, it should be observed that the displayed signals are DC type ones. Figure 10 presents the shaker transient response. Finally, Figure 11 shows the tracking shaker response.

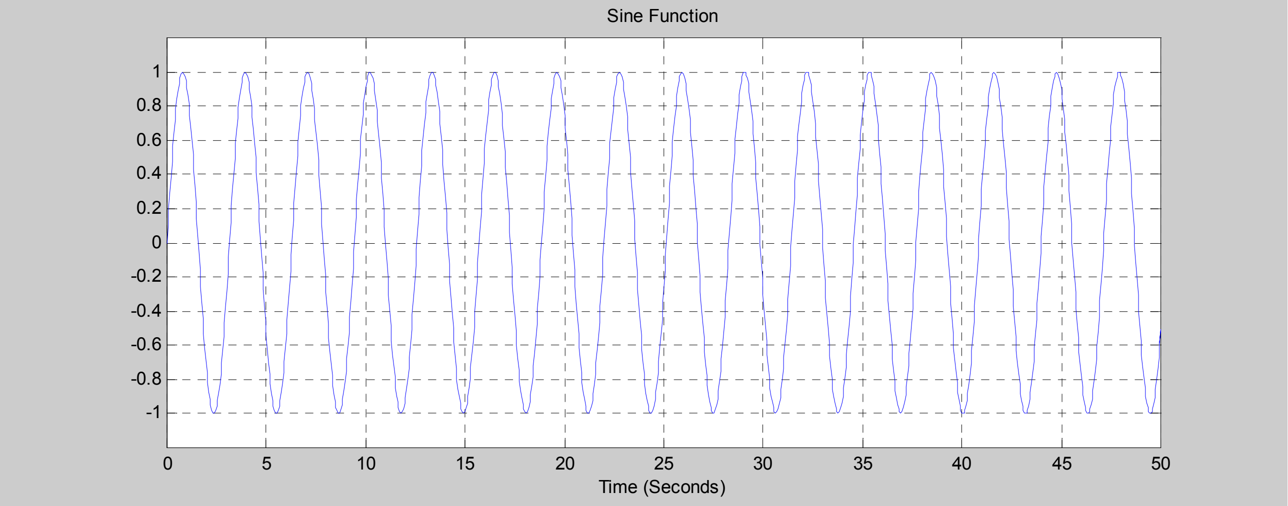

Figure 8 – The Sine Function Generated using Eq. 5.

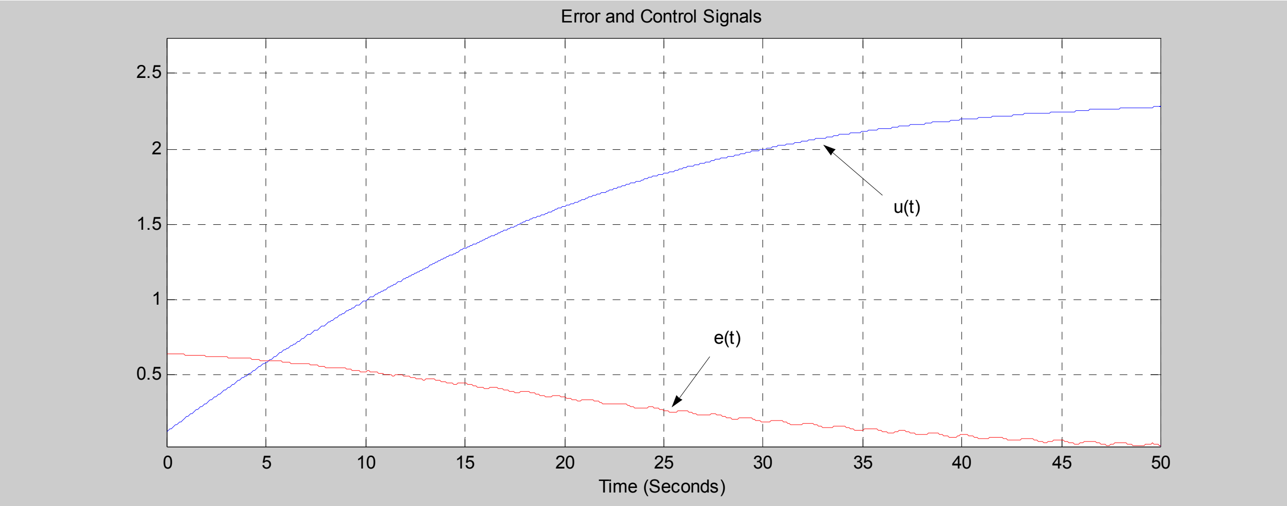

Figure 9 – The Sine Amplitude Error and the Control Signal.

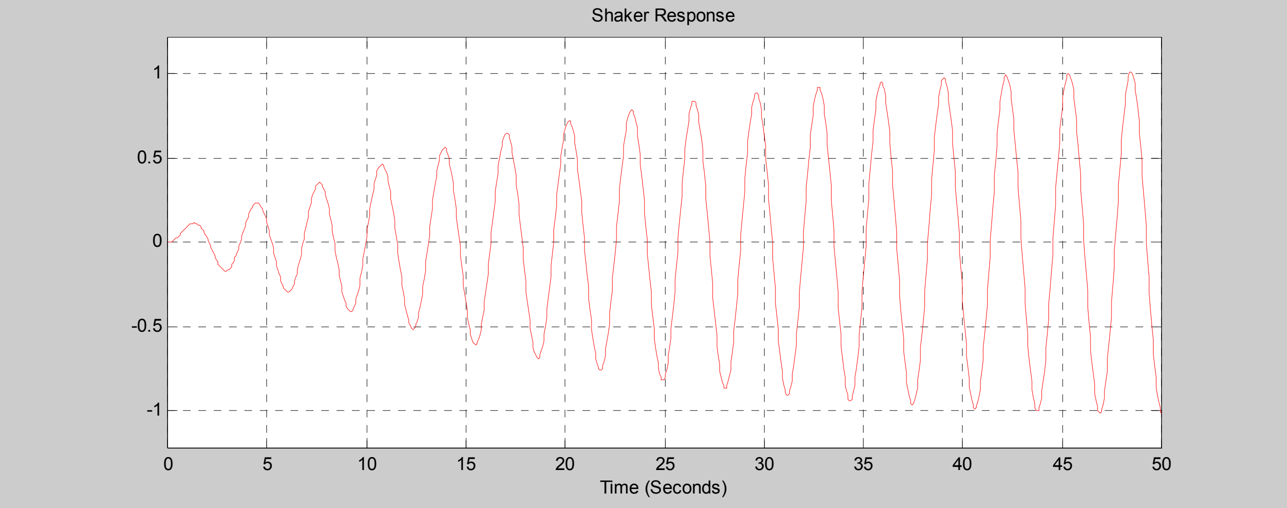

Figure 10 – The Shaker Transient Response.

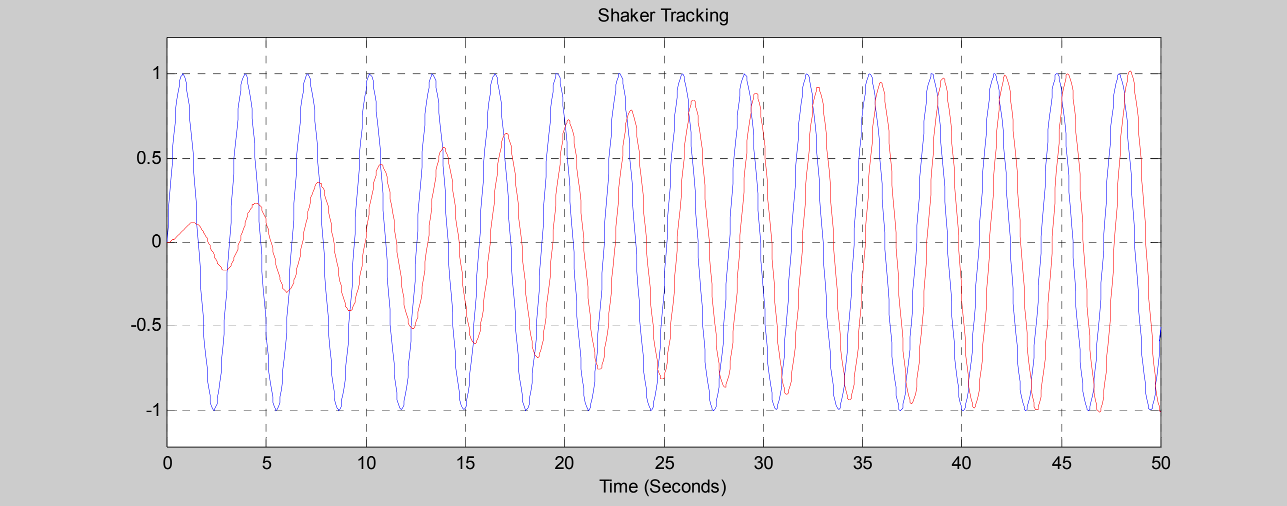

Figure 11 - The Shaker Tracking Response.

FINAL COMMENTS AND CONCLUSIONS

This paper presented a design procedure for the automation of a WBV test bench. The proposed scheme permits the independent control of the amplitude and frequency of the excitation signal in WBV tests.

It has shown that the closed loop scheme allows:

a) Accurate control of the amplitude and frequency of the excitation signal in WBV tests.

b) Fine control of the pre-test waiting time avoiding pre-test volunteer exhaustion.

c) Keep specific test conditions (amplitude and frequency) despite the volunteer weight and body shape.

d) Accommodate system start up to volunteers stress levels shaping the transient response.

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