# A BIODYNAMIC MODEL FIT FOR VIBRATION SERVICEABILITY IN FOOTBRIDGES USING EXPERIMENTAL MEASUREMENTS IN A DESIGNED FORCE PLATFORM FOR VERTICAL LOAD GAIT ANALYSIS

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## *ABSTRACT*

*The human body may interact with the structures and these interactions are developed through the application of forces due to movement. A structure may undergo changes in their dynamic behavior when subjected to loads. In this paper, the design of a force platform is presented to measure the Ground Reaction Forces (GRF) and acceleration for human gait analysis. The platform consists of two plates placed side by side in relation to the direction of walking. Each plate has three ring-type load cells instrumented with strain gauges. The platform was validated by calibration and uncertainty evaluation in measured parameters. A finite element model was used to evaluate the dynamic features of the platform. The results were frequencies values very close to those measured in the experimental analysis and confirm its adequacy to the use, because the frequencies were higher than the frequencies involved in the human gait. Using the acceleration and force spectrum of walking vertical of several individuals, a biodynamic model for a walking pedestrian was fitted, to represent the whole effect of individuals walking in structures.*

## *RESUMO*

*O corpo humano pode interagir com as estruturas e estas interações são desenvolvidas através da aplicação de forças devido ao movimento. Uma estrutura pode sofrer modificações no seu comportamento dinâmico, quando submetida a esforços. Neste artigo, o projeto de uma plataforma de forças é apresentado para medir a Força de Reação do Solo (FRS) e a aceleração, para análise da marcha humana. A plataforma consiste de duas placas colocadas lado a lado em relação à direção de caminhada. Cada placa tem três células de carga do tipo anel instrumentadas com strain gauges. A plataforma foi validada pela calibração e avaliação das incertezas nos parâmetros medidos. Um modelo de elementos finitos foi utilizado para avaliar as características dinâmicas da plataforma. Os resultados foram valores de frequências bem próximos aos medidos na análise experimental e confirmaram a sua adequação ao uso, porque as frequências foram maiores que as frequências envolvidas na marcha humana. Usando o espectro de aceleração e força da caminhada vertical de vários indivíduos, um modelo biodinâmico para um pedestre caminhando foi ajustado, para representar o efeito completo de indivíduos caminhando em estruturas.*

## 1. INTRODUCTION

Several cases of excessive vibration of footbridges in vertical direction due to human-induced loads have been reported, being usually related to crowd condition. Until recently, the load due to a pedestrian acting on the structure has been obtained from investigations in platforms, gait machines or even prototype footbridges, in which the applied force is that produced by a walking pedestrian. For groups of pedestrians or crowds, a combination of these individual applied forces is considered. The design load is, thus, a force model. However, attention is drawn in some recent publications (Barker and Mackenzie, 2008; Kim et al., 2008; Zivanovic et al., 2010) regarding the potential effect of the dynamic interaction between pedestrians and structure while crossing footbridges in crowd situations. Barker and Mackenzie (2008) called attention to studies that suggested that in crowded situations pedestrians might increase the damping of the system and thus reduce the structural response. Kim et al. (2008) investigated the effect of the dynamics of pedestrians walking along a footbridge. Each pedestrian was represented as a biodynamic system, presenting equivalent mass, stiffness and damping. They observed differences on the response of the structure between force and biodynamic models for the pedestrian action. However, the biodynamic parameters to model the pedestrian body adopted in their paper were applicable to a standing person and may not represent the dynamics of a walking person, due to bending of the knees during walking, which changes the stiffness of the body. Zivanovic et al. (2010) explored the strategy of an arbitrary increase of damping of the system to account for human-structure interaction and pointed out a strong need for further research on quantification of human-structure interaction.

The aforementioned studies provided evidence that in structures subjected to a flow of pedestrians (e.g. footbridges in urban areas), the dynamics of the pedestrian body should be considered in order to define the design load or even to investigate its effects properly. In a previous paper, Silva and Pimentel (2011) presented a biodynamic model for walking pedestrians, in which a single degree of freedom (SDOF) system was employed to represent the dynamics of the human body. The input to obtain the biodynamic parameters was the acceleration measured at the waist of test subjects and forces taken from the literature.

In this paper, a device was developed so both acceleration and applied force can be measured simultaneously. An evaluation of the biodynamic parameters can be obtained according to the walking characteristics of each individual. The plates that compose the force platform were placed side by side in the direction of walking, so that the signal from each foot can be acquired in separate in each plate. The platform is designed in order to be compatible with the frequencies involved in the measurements.

## 2. ANALYSIS OF HUMAN WALKING

The human being moves constantly and one of the most common ways to get movement is by locomotion. Among the various forms of locomotion, walking is one that draws more attention from researchers in the field of motor behavior, probably because it is the most widely used form of locomotion (Barela, 2005). The human walking is a process of locomotion in which the body stands upright and the motion is sustained primarily by a leg and then the other leg, leaving at least one foot in contact with the ground (Inman et al, 1994). This is clearly a different process from running, where both feet do not stay in contact with the ground simultaneously.

## 3. FORCE PLATFORMS

Force plates or platforms are devices designed to measure the forces exerted by a body in an external surface, the contact surface. In 1895 was projected first platform to measure biomechanical forces, composed of spiral tubes of rubber mounted on wood structure to measure the vertical component of the ground reaction force (GRF). Later, Elftman (1938) built a platform to measure vertical and horizontal human walking loads; this had four springs and displacement was measured optically. The first platform for instrumentation using strain gauge force transducers was designed and built by Cunningham and Brown (1952). In 1959 the first platform using force sensors of the Linear Variable Differential Transformer (LVDT) type appeared. Gola (1980) introduced a new platform concept showing that the platform could be suspended by the transducers. Lywood et al (1987) built a platform for research and monitoring of the position of small animals. Other studies may also be cited, for instance, several researchers have designed platforms forces for their own applications: Bagesteiro (1996) and Roesler (1997) used force platforms for underwater applications such as measuring swimmer's jump; Cerutti (2003) used a platform for measuring ground reaction forces due to wind acting on scale models in a wind tunnel.

There are several manufacturers of commercial platforms. But the high cost of these devices makes it difficult to use them in large scale. Depending on the application, the construction of a platform becomes an alternative that may be considered, thus minimizing the costs involved.

## 4. PLATFORM DESIGN AND CONSTRUCTION

For the experimental measurements two instrumented plates were used, being mounted side by side. The platform provides an electrical signal proportional to the force applied to the structure. In the design of the platform it was considered only the acquisition of vertical forces ($F_Z$), because the effect of vertical human action on pedestrian footbridges to the vertical force is the action of interest in this investigation. Fig. 1 shows the acceleration and deceleration plates (these are not instrumented). Fig. 2 shows structural details of the designed device.

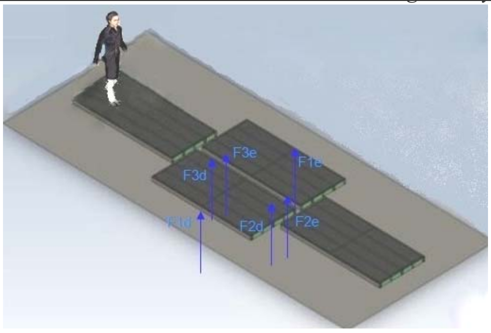


**Fig. 1 -** Force Platform

**Fig. 2 -** Structural details (bottom side view)

As one steps on the force platform (left or right plate), the force applied on them is detected by the load transducers, and the generated electrical signals are amplified and recorded by a data acquisition system. Fig. 3 shows a schematic view of the left platform with the respective load cells and their position in relation to the coordinate axes (x, y).

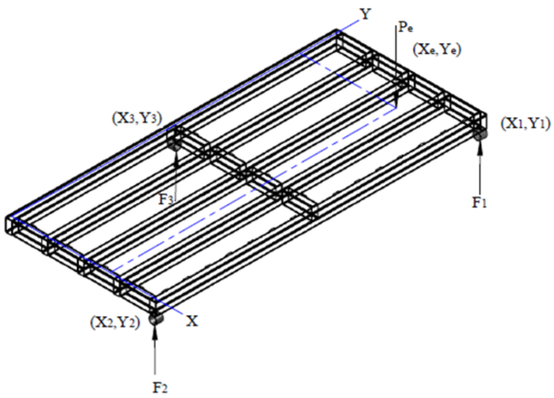


**Fig. 3 -** Positioning of the load cells in the left force platform

According to the scheme in Fig. 3, the static equilibrium equations allow writing:

$$P_e = F_1 + F_2 + F_3 \tag{1}$$

$$F_2 y_e + F_3(y_e - y_3) - F_1(y_1 - y_e) = 0 \tag{2}$$

$$F_3 x_e - F_1(x_1 - x_e) - F_2(x_2 - x_e) = 0 \quad (3)$$

Solving the previous system for the variables, P, x and y one has:

$$P_e = F_1 + F_2 + F_3 \quad (4)$$

$$x_e = \frac{F_1 x_1 + F_2 x_2}{P_e} \quad (5)$$

$$y_e = \frac{F_1 y_1 + F_3 y_3}{P_e} \quad (6)$$

Thus, knowing the F1, F2 and F3 loads, the coordinates x and y of the applied load is obtained using Eq. (5) and (6). Inversely, knowing P, x and y, one can obtain the values of the forces in the three load cells:

$$F_1 = \frac{P_e(x_2 y_e + x_e y_3 - x_2 y_3)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \quad (7)$$

$$F_2 = \frac{P_e(x_e y_1 - x_1 y_e - x_e y_3 + x_1 y_3)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \quad (8)$$

$$F_3 = -\frac{P_e(x_e y_1 - x_1 y_e + x_2 y_e - x_2 y_1)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \quad (9)$$

Similar equations to the above ones can be developed for the calculation of the $P_d$ force and $x_d$ a $y_d$ positioning for the right platform.

## 5. FORCE TRANSDUCERS

The ring type load cells were used because of their easier construction and low cost. All load cells are designed according to the needs of application. It should be considered the nominal capacity which is the magnitude for which the mechanical transducer is provided to work without damaging it. In the design of the transducer the sensitivity of the load cell should be considered in order to have a high sensitivity. Taking this into account, a specially designed load cells becomes advantageous compared with load cells which have a fixed commercial sensitivity defined by the manufacturer. The design of this device may be made to cover a wide range of loads, by varying parameters such as radius (R), thickness (t) and the ring length (L). Fig. 4 presents these design variables.

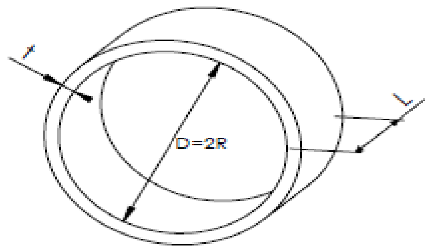


**Fig. 4 -** Cell type load ring

For the instrumentation of each load cell four strain gauges were used (PA-06-125AA-120-LEN with gauge factor of 2.02 and 120 of electrical resistance, Manufacturer: Excel Sensores Ltda). In this case, two strain gauges are subjected to tensile stress and the other two compression stresses, so that the deformations occurring in the device can be summed into the equation below:

$$\frac{\Delta E}{V} = \frac{k}{4}(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4) \quad (10)$$

They were instrumented and connected in a circuit known as a Wheatstone bridge. As there is a variation of strain gauge's electrical resistance due to the deformation occurring in the ring, there is an imbalance in the bridge. The following equation provides the tension on the ring type load cell (Dally et al., 1993):

$$\sigma_\theta = 1{,}09\frac{FR}{Lt^2} \quad (11)$$

Where: $\sigma_\theta$ is the tension on the load cell wall, F is the applied force, R is the radius of the ring, L is the length and t is the thickness. The equation which provides the deformation is given by $\varepsilon = \sigma_\theta / E$. For metallic materials like steel and normal strain gauges made of constantan, the value of deformation should be about 1000µm/m (micro-strain). This sensitivity is appropriate for most applications. By selecting the external diameter (D) and thickness of the tube (t) and allowing to vary the length (L), one obtains the optimum design of the load cell.

The load cell was designed for a load of 1600 N. The 1020 steel was the material used for the machining cell. The cell has a diameter of 47 mm, length of 40 mm and is 2 mm thick. Using Eq. (11) the tension value of the load cell is obtained as 245.2 MPa and, considering the modulus of elasticity of the steel as 210 GPa, the total deformation of the transducer is found as $\varepsilon = 0.00116$. Using Eq. (10) and the values of gauge factor, the calculated sensitivity of the load cell is: $\Delta E/V = 2{,}35 mV/V$. The supply voltage is 5 volts, and then the output voltage of the load cell is 11.78 mV for a load of 1600 N. Fig. 5 shows the instrumented load cell. Fig. 6 shows the load cell assembly in the force platform.

**Fig. 5 -** Instrumented Ring-type load cell.

**Fig. 6 -** Load cell assembly on the platform.

## 6. SIGNAL CONDITIONING, FILTERING CIRCUIT AND DATA ACQUISITION BOARD

The output signals from the load cells are small, so it is necessary to increase the value of these signals. The signal conditioner serves to amplify, filter and equalize the signal in order to get the proper voltage levels, with good signal to noise ratio and minimal distortion. The design of the signal conditioner is quite simple, as just one amplifier per channel and it is designed to measure six channels. The signal conditioner is powered by 110/220V AC power and using a switching power supply and voltage regulator gave the symmetrical voltages of +12 V -12 V to power the operational amplifiers and voltage of 5V DC to power the Wheatstone bridge. The circuit has variable resistors to the balance of the bridge. Starting from 11,78 mV it is desired to amplify the signal to a range of +/-7,5 V. Thus, the conditioner amplification was designed to a 594x gain. All circuits of the device are placed in a metal box in order to reduce external electro-magnetic interference and minimize the noise. The designed signal conditioner can be viewed in Figs. 7 and 8.

**Fig. 7 -** External view of the conditioner/amplifier

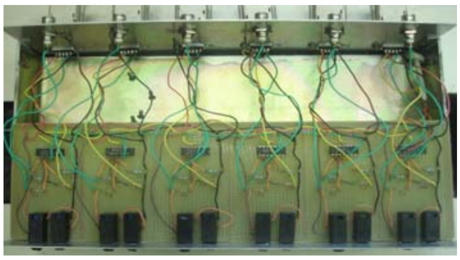

**Fig. 8 -** Internal view of the conditioner/amplifier

The measured signal may contain undesirable frequency from the load cells. Then, knowing the frequency range of interest a low-pass filter may be designed. Therefore, it is essential to the development of a filtering circuit, allowing only the frequency components in the range of interest to remain in the signal. Thus, a low-pass filter with resistors $5{,}11 k\Omega$ and capacitors $0.22 \mu F$ was used.

A data acquisition board model USB 1616FS (Measurement Computing) commercially available was used to make experimental measurements. This is an analog/digital converter device of 16 bits based on USB communication and 16 measuring channels. The maximum input voltage is 15 V. The operating temperature range is 0 – 70 $°C$ (manufacturer's data Measurement Computing).

## 7. EXPERIMENTAL MEASUREMENTS

### 7.1 Natural frequencies of the force platform

According to Toso and Gomes (2011) force platforms should allow the measurement of loads compatible with the frequencies involved in its application, that does not produce a resonant dynamic response, thus amplifying the values of loading and inducing measurement errors. The platform must have sufficient stiffness to prevent any unwanted vibration that may influence the measurement. For measuring natural frequencies of the platform an unidirectional accelerometer was used (model 8312B10 nominal sensitivity of 200 mV/g measuring frequency range 0-180 Hz, Kistler company's data). The structure was subjected to an excitation by an impact hammer, and a value of 30.1 Hz was found for the frequency corresponding to the first vibration mode.

The frequency spectrum of the signal from the accelerometer is shown in Fig. 9. Another way of measuring the natural frequency of the platform was using the signals from the load cells; Fig. 10 shows the force load cell signal in the frequency domain. Note that the value obtained (30.1 Hz) is the same value measured previously with the use of the accelerometer. There is a smoothness of the force spectra due to the mechanical filtering of the platform system. In the case of the accelerometer spectra, local plate mode of vibration was also captured by the accelerometer due to its location.

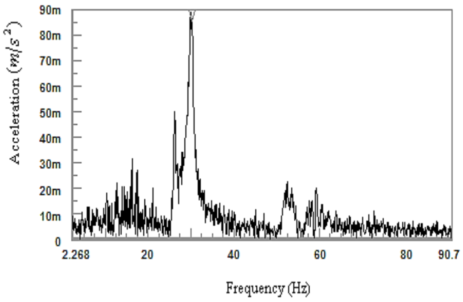


**Fig. 9 -** Acceleration frequency spectrum

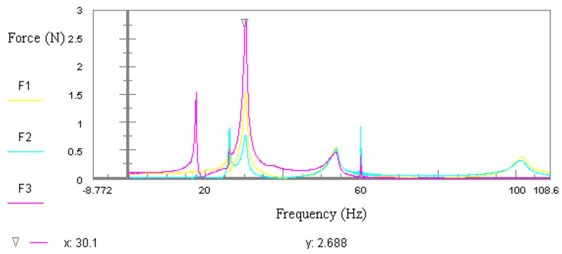


**Fig. 10 -** Force frequency spectrum

### 7.2 Ground Reaction Force (GRF) and acceleration

One of the measured variables was the force that is related to the vertical component of the GRF due to body weight and the vertical acceleration and /or deceleration acting on the body. The platforms have a length of 2010 mm and thus, a person can walk normally stepping with one foot on a platform once and twice on the other platform. Several people of several ages and both sexes participated in the experimental measure-ments, seeking thereby a higher variability of biotypes, with their walking patterns and thus finding a model that best represents the phenomenon of human walking. A sampling frequency of 500 Hz was used and the data acquisition time was 10 s. Fig. 11 shows the data of the GRF during the measurements, considering a person with a body mass of 75 kg and 1.81 m tall, in normal walking.

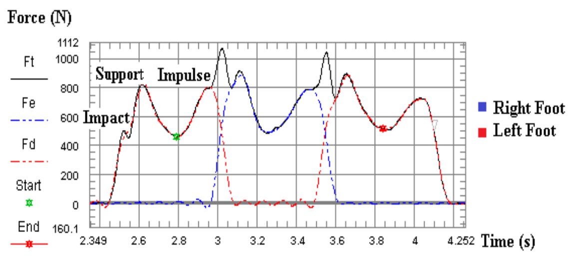


**Fig. 11 -** Data for Ground Reaction Force (GRF)

The vertical component of the GRF is characterized by two peaks and a valley, and usually these peaks have a magnitude greater than the body weight. For each leg, the first peak is observed during the first half of the support and features the support leg receiving all body weight. This occurs after the contact of the foot with the ground (Larish *et al*. 1988). The second peak is observed in the existing end of the support and represents the impulse against the ground to begin the next step. The valley between two peaks is slightly smaller in magnitude than the body weight and occurs when the foot is in flat position at the ground (Hamill and Knutzen, 1999). Also, there is a peak in the first milliseconds (ms) of the support, and this peak is not always evident. This refers to the impact force, which results from the collision between two bodies (the foot and the ground) and reaches maximum magnitude before 50 ms after initial contact of the two bodies. The magnitude of the peak impact force can be influenced by several factors: speed of locomotion and footwear (Barela, 2005).

The acceleration of the pedestrian was also one of the variables measured. Using a unidirectional accelerometer, as previously specified, above and connecting it to a signal conditioner also positioned on the waist of the person, it was possible to measure the acceleration of the pedestrian while walking. Fig. 12 shows the device developed for measuring acceleration.

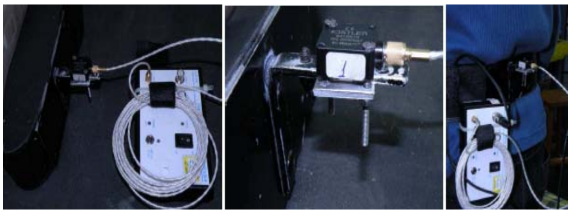

**Fig. 12 -** Belt, accelerometer, signal conditioner and its attachment to the waist of the person.

The values of frequency identified from the accelerometer signals were consistent with literature values. According to Zivanovic *et al*. (2005) the mean rate of steps for a person walking is about 2 Hz which characterizes the frequency involved during human walking. A frequency spectrum measured by this apparatus is shown in the figure below, indicating the frequency of 2.008 Hz.

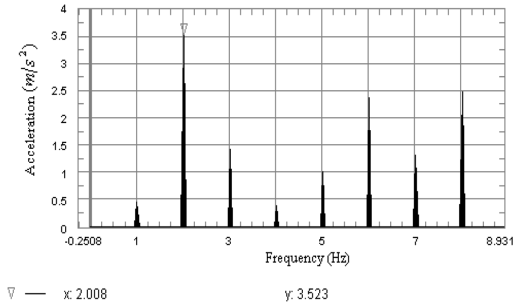


**Fig. 13 -** Vertical acceleration spectrum measured at the waist of a pedestrian.

## 7.3 Evaluation of measurement uncertainty

The measurement uncertainty is the parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the physical value. For uncertainty evaluation of the designed and built platform, the propagation of uncertainties involved in the assembled system was calculated. As input for the analysis one has the uncertainty in each of the load cells, $\pm\Delta F_1 \pm \Delta F_2 \pm \Delta F_3$ obtained by the calibration process of the load cells. Another source of uncertainty is the position of each of the cells to each other relative to the platform $\pm\Delta x_1 \pm \Delta x_2 ; \pm\Delta y_1 \pm \Delta y_3$. These measures can be taken directly from the platform. Using the equations of static equilibrium presented above and the method of uncertainty propagation of Kleine and McClintock, it yields:

$$P_e = 900N \;\; e \;\; \Delta P_e = \pm 14,54N = \pm 1,61\% P_e \quad (12)$$

$$P_d = 900N \;\; e \;\; \Delta P_d = \pm 22,85N = \pm 2,54\% P_d \quad (13)$$

$$x_e = 0,805m \;\; e \;\; \Delta x_e = \pm 0,0077m = \pm 0,95\% x_e \quad (14)$$

$$x_d = 0,805m \;\; e \;\; \Delta x_d = \pm 0,0136m = \pm 1,68\% x_d \quad (15)$$

$$y_e = 0,974m \;\; e \;\; \Delta y_e = \pm 0,0128m = \pm 1,31\% y_e \quad (16)$$

$$y_d = 0{,}974m \ \ e \ \ \Delta y_d = \pm 0{,}0186m = \pm 1{,}91\% y_d \quad (17)$$

where: $P_e$ and $P_d$ are the reaction forces of the left and right platforms, $x_e$ $y_e$ $x_d$ $y_d$ are the coordinates referring the application of feet force.

The platform on the right shows bigger errors than the left platform for both the values of ground reaction forces and coordinate values (x, y) of force application. This is because the load cells that compose the right platform have higher values of uncertainty.

## 8. NUMERICAL MODEL OF THE PLATFORM

A finite element model was developed to evaluate the natural frequencies of the platform. These values were compared with experimental data obtained from the spectra of signals from accelerometers and load cells as shown previously. Through the modal analysis the fundamental frequencies and corresponding mode shapes of the structure were obtained.

The software ANSYS was employed in the modeling. The finite element mesh was composed of 187158 tetrahedral elements with 10 nodes and the Lanczos method was used for the extraction of eigenvalues and eigenvectors. Fig. 14 shows the final numerical model mesh for evaluation of the natural frequencies. In turn, Fig. 15 shows the values of the natural frequencies and their respective modes of vibration.

The result shows frequencies values very close to those obtained in the experimental analysis. The numerical model shows 30.9 Hz for the first vibration mode while the experimental test indicates 30.1 Hz. The platform is designed in order to be compatible with the frequencies involved in the measurements which are in the range of 0.5-10 Hz. So, it was confirmed numerically and experimentally that the design presented a resonant dynamic response far from the range of walking frequencies, thus minimizing the chances of measurement errors due to load amplification (Toso and Gomes, 2011).

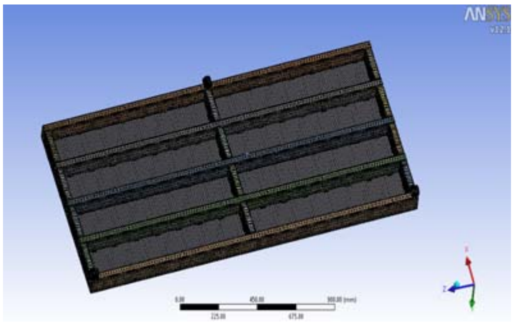


**Fig. 14 -** Numerical model mesh used in the modal analysis

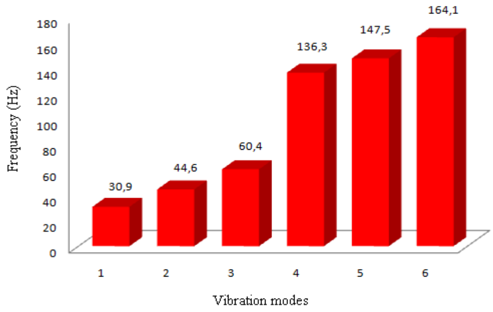


**Fig. 15 -** Natural frequencies from modal analysis

## 9. EVALUATION OF BIODYNAMIC PARAMETERS

In a previous paper (Silva and Pimentel, 2011), a biodynamic model for walking pedestrians was presented, in which a single degree of freedom (SDOF) system was employed to represented the dynamics of the human body. The highlights of the model are presented here, together with the new results obtained from the tests using the platform. More details about the procedure can be found in the aforementioned reference.

In essence, the whole body of a walking person was conceived as a SDOF model (Fig. 16).

The dynamic parameters m, c and k of the model do not have a direct relationship with parts of the human body. Since the contact between the pedestrian and surface is always maintained, by isolating the pedestrian, the equation that represents the up and down motion of the center of gravity of the pedestrian is given by:

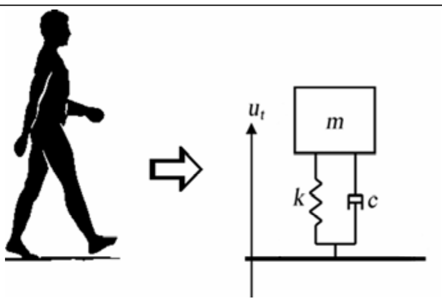


**Fig. 16 -** SDOF biodynamic model

$$m\ddot{u}_t + c\dot{u}_t + ku_t = P_{Gnd} \quad (18)$$

In Eq. (18), $u_t$ is the displacement of the degree of freedom with respect to a fixed reference point, a dot on top of it indicating a derivative with respect to time, and $P_{Gnd}$ is the ground reaction force. Such a force also varies with time, being measured together with the acceleration at waist level. The center of gravity of the body was considered to be around the point in which accelerations were measured.

The biodynamic parameters were obtained by solving a system of three non-linear equations (Eq. 19), which is the expression of the accelerance frequency response function of a SDOF model described by Eq. (18). Eq. (19) represents the stationary response of a SDOF system. Since the measurement at the platform represented a few cycles of motion of the pedestrian, the acquired signals were replicated in time so as to represent a signal from a continuous movement. This also made it possible to obtain acceleration and force spectra with appropriate frequency resolution for the processing.

$$A(\omega_i) = \frac{\omega_i^2 P_{Gnd0}(\omega_i)}{\left|k - \omega_i^2 m + j\omega_i c\right|} \quad (19)$$

In Eq. (19), the parameters m, c and k are the unknowns, j is the square root of (-1), and $P_{Gnd0}(\omega_i)$ and $A(\omega_i)$ are the input values, being respectively the amplitudes of the harmonic components of the ground reaction force obtained from the spectra of the signals measured from platform and from the acceleration at waist level for the frequency $\omega_i$, with $i$ varying from 1 to 3. This led to a system of three nonlinear equations that were solved by using the conjugate gradient algorithm.

Ten pedestrians took part in the tests and each of them crossed the platform ten times. For every walk of each person, the biodynamic parameters were obtained by solving the Eq. (19). The relevant characteristics of the movement and the results obtained for the biodynamic parameters are shown in Table 1, together with respective mean and standard deviations (STD). Out of the 10 participants in the experiment, the results of one of them was withdrawn for not performing well when solving Eq. (19), leading to parameters with very large errors.

The Dynamic Load Factor (DLF) is the ratio of the static weight of the pedestrian and the amplitude of dynamic force component of a particular harmonic. The values observed for this factor for the first three harmonics are also shown in Table 1.

The results obtained showed a significant variation of the values of some biodynamic parameters, in particular the modal mass and stiffness. In a previous test campaign in which only measured accelerations at waist level were employed to obtain such parameters (Silva and Pimentel, 2011), the variation observed was not that significant. This requires that tests with a larger number of pedestrians than the ones involved up to now are necessary. In sequence, regression expressions could be inferred for the biodynamic parameters so as to be used in design.

## 10. CONCLUSIONS

A platform was constructed in order to simultaneously measure acceleration and ground reaction force (GRF) of test subjects while walking, aiming to obtain the parameters of a single degree of freedom (SDOF) biodynamic model representing a walking pedestrian. A numerical model of the platform showed dynamic behaviour (natural frequencies) similar to measured ones. The GRF parameters, like frequency and corresponding amplitude spectrum and walking frequency, were gathered to fit the

**Table 1 -** Biodynamic parameters of test subjects

| Pedestrian | M (kg) | Fp (Hz) | M (kg) | C (Ns/m) | k (N/m) | DLF1 | DLF2 | DLF3 |
|---|---|---|---|---|---|---|---|---|
| **1** | 75.2 | 1.81 | 21.51 | 419.76 | 9570.40 | 0.261 | 0.016 | 0.035 |
| **2** | 69.7 | 1.92 | 23.28 | 476.37 | 10166.49 | 0.261 | 0.034 | 0.050 |
| **3** | 71.4 | 1.91 | 17,19 | 493.00 | 7578.48 | 0.308 | 0.064 | 0.052 |
| **4** | 97.5 | 2.03 | 25.06 | 608.28 | 15196.28 | 0.318 | 0.030 | 0.050 |
| **5** | 81.3 | 1.89 | 54.58 | 712.11 | 4967.40 | 0.316 | 0.040 | 0.039 |
| **6** | 80 | 1.88 | 49.80 | 566.52 | 10193.53 | 0.380 | 0.044 | 0.048 |
| **7** | 60.9 | 2.17 | 32.61 | 534.51 | 11084.42 | 0.366 | 0.027 | 0.033 |
| **8** | 99.2 | 1.94 | 48.77 | 492.72 | 14095.68 | 0.230 | 0.027 | 0.049 |
| **9** | 64.3 | 1.92 | 39.24 | 573.87 | 8348.05 | 0.303 | 0.050 | 0.033 |
| **Mean** | 77.72 | 1.94 | 34.67 | 541.91 | 10133.41 | 0.305 | 0.037 | 0.043 |
| **STD** | 12.67 | 0.10 | 13.12 | 81.02 | 2962.00 | 0.046 | 0.013 | 0.008 |

SDOF model. The efficacy of the measuring system and data processing was confirmed by evaluating the uncertainty of the measurements, which were less than 2%. Relevant characteristics of GRF like the peaks of support force and impulse, and also the impact force, could be observed from the data. As for the acceleration values, they were consistent with measured values presented in the literature. The biodynamic parameters could be obtained from the procedure employed. However, a significant variation of the values of some parameters was observed, requiring additional tests with more pedestrians to provide statistical significance for the results.

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