Chapter 28
Modeling Human Jumping Force on a Flexible Structure Using Control Models

Ahmed T. Alzubaidi and Juan M. Caicedo

Abstract Live loads on structures such as dance halls, fitness centers, and malls can generate excessive vibrations causing serviceability problems. Several models were used to model force generated by human jumping on a flexible structure such as semi-sinusoidal pulse force, Fourier series, statistical model of the dynamic loads, and pseudo-variable mass models. While these models area able to represent the dynamics of the system in some cases, the human body is a more complex dynamic system. For example, Fourier series model and even other mentioned models are not capable to consider an external excitation like music sound as input to the overall system. This paper expands a prior model of human standing on flexible structure using control theory to a model that consider sound as the excitation to the human-structure system. Energy is added to the system when a person jump or performing short movement up and down at the bit of a metronome. Here, the sound created by the metronome is used as input to overall system.

A flexible cantilever structure, idealized as single degree of freedom system, is used to develop and validate the proposed model. The force exerted by people jumping as well as the acceleration records are used to determine the probability distribution functions of the model parameters. The model is validated by comparing model predictions with additional experimental records.

Keywords Human-structure interaction · Control theory · Human activity · Structural dynamics · Mean square error

28.1 Introduction

In designing a building, the live loads due to human activities such as standing up from sitting, sitting down from rising, moving, bobbing, jumping, and dancing are challenging loads because these actions generate dynamic forces larger than the human body weight. Additionally, the activities sometimes lead to a human discomfort and panic amongst the occupants as they cause excessive vibration in the building [32]. Human force considers the large portion of live load in the designing a commercial, residential building and even stadium, gyms, dance floor and theaters because the structural designers started using a new materials in the designing of lighter and more flexible members of structures above-mentioned [1, 2]. These materials provide a good strength but they are susceptible to human-induced vibration problem. Therefore, in recent years, researchers have been focused on modeling human activities on structures and developing new methodologies to deal with human induced vibration problem. Several examples of excessive vibration induced by individual walking, jumping, and bouncing have been proposed in the literature [3–6]. The oldest one was the failure of footbridge in Broughton, UK 1831 due to the soldiers unison marching [4, 7]. Another well known example is the Millennium footbridge, UK where it had excessive vibration due the people walking during its opening day [6]. The interesting example is in Seoul, South Korea where 39 floor TechnoMart building was shaking because aerobic exercise. The people living there felt the building vibrate vertically for 10 minutes. However, there was no earthquake, explosion, or even high winds. After the detailed investigations, the inspection team found the vibration was caused by people performing an aerobic sport in the fitness center on the 12th floor of the building [5].

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28.1.1 Human-Structure Interaction

When people are performing activity such as jumping or bouncing over a flexible structure, the interdependence of the human and structure dynamic system can cause the phenomenon of human-structure interaction (HSI). Thus, new properties of dynamic system can be resulted by this interdependence [8]. There are two significant issues which should be taken into account. The first one, natural frequency and damping ratio of combined human structure system can make the structure prone to unacceptable vibration due the dynamic force of individual. Second, the synchronization amongst occupants is because of the crowd dynamic and interaction with structure [6, 8–10].

Modeling human-structure interaction has a lack in the fundamental knowledge where most structural engineers have not considered the influence of dynamic load of people in the structure design [11]. Several models were used to model force generated by human jumping on a flexible structure such as semi-sinusoidal pulse force, Fourier series, statistical model of the dynamic loads, and pseudo-variable mass models [12, 13]. While these models area able to represent the dynamics of the system in some cases, the human body is a more complex dynamic system. For example, Fourier series model and even other mentioned models are not capable to consider an external excitation like music sound as input to the overall system.

This study expanded the model proposed by Ortiz and Caicedo [1] to model HSI when individual jumping over flexible structure. New controller have been designed to include the music sound as an input to overall system. We collected experimental data for people jumping to be used in fitting of proposed model. In the Sect. 28.2, we present the methodology while section has a discussion about instruments and experiments setup. The experiments testing is presented in Sect. 28.4 whereas Sect. 28.5 has the comparison between the data points generated by proposed model and experimental data. Finally, the conclusion is presented in Sect. 28.6.

28.2 Proposed Approach

Control theories are divided into three essential categories which are classical, modern and robust control theories. Several applications such as robotics, space-vehicle systems, radar antenna, and automobile steering control work based on control theory [14–16]. In 1940, the researchers developed the frequency-response methods which allow engineers to design linear control system [15]. One of these systems is a closed-loop control which fundamentally uses the concept of feedback. Classical control theory developed for single input single output system and based on frequency-domain whereas modern control theory developed for multiple input multiple output system and deals with time-domain analysis of the differential equation [14, 15]. The simplicity of designing control system comes from the fact that modern control theory is based on the model of real control system. The principle of the feedback control was developed for engineering and non-engineering fields and found to reduce the difference between output and input system. Control systems can be classified as open and closed-loop control system (feedback control system). The idea of using feedback is not new. The Greeks used feedback in 300 B.C. in developing the float regulator mechanisms [14, 16]. More than 50% of industrial controllers that have been used are PID controllers. The usefulness of the PID controller is to provide satisfactory control [15].

Many authors in different disciplines have been modeling the human body using a control system in last three decades [17–22]. For example, Kimura and Jiang have applied the control system to robotics and compared it with human body performance in terms of keeping stability for different activities, such as standing and jumping [19]. In the same scope, they have proposed and developed PID controller in modeling the balance, keeping control of humans, and found that a PID controller can be utilized to understand the standing process [17]. Result shows that the Derivative term (Kd) is remarkably lower when the humans close their eyes. However, the controller models are not main stream in HSI problems.

Ortiz et al. were the first researchers to utilized a closed-loop control system to represent a model of the interaction between the human and structure.

28.2.1 Human-Structure Model

Control systems are not only applied in the mechanical and electrical engineering fields but also in civil, chemical, and environmental engineering [14]. The fundamental concepts of control system were developed for linear systems using feedback concept. Control systems are based on input and output relationship and could be open or closed-loop control systems. In this research, we focused on a closed loop control system to model human-structure interaction.. Closed loop control systems use an output of the plant (system to be controlled) and a feedback loop to achieve the desired behavior [14].

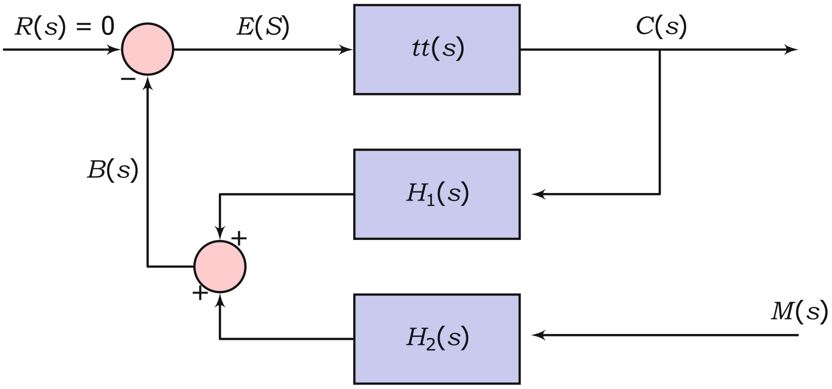


Fig. 28.1 Block diagram of a closed-loop control system

The underlying aim of the feedback concept is to reduce the error between the input and output in the system. Figure 28.1 shows the block diagram of the proposed model. The term G(s) is the transfer function of the structural system whereas the terms H1(s) and H2(s) are the transfer function of the first and second controllers respectively. The input force for empty and occupied structure is represented with terms R(s) whereas the second excitation when people are jumping on the structure which is the sound of music is represented by the term $M(s)$.The output acceleration is represented by the term $C(s)$ whereas the terms B(s) and E(s) represent the force utilized to control the structure and the actuating error. A measure from the plant is used as input to the controller and control device which provides an additional input to the plant. In this study, we modeled HSI using the same concepts where the structure is modeled as the plant of the system and the human is modeled as the controller. Equation (Eq. 28.1) describes the combined structure and human system.

$$TF(s) = \frac{H_2(s)}{1 + G(s)H_1(s)} \tag{28.1}$$

28.2.2 *Structural Model*

A cantilever structure was built at the Department of Civil and Environmental Engineering at the University of South Carolina and has been used to experimentally test the proposed model. This structure consists of a steel frame and concrete blocks as shown in Fig. 28.2. This structure has a mobile support and masses which are used to change the dynamic properties of the system and the live to dead load ratio. For simplicity, the structure G(s) has been modeled as a single degree of freedom system. The transfer function of structure G(s) is defined as:

$$G(s) = \frac{\frac{s^2}{m}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{28.2}$$

where m**,** ζ**,** ω_n are the mass, damping ratio, and natural frequency of the system. The poles which are the root of denominator of transfer function are expressed in terms of the natural frequency (ω_n) and damping ratio ζ of the structure as shown in the following equation [15]

$$p_{1,2} = -\zeta\omega_n \pm \sqrt{\left(\zeta\omega_n\right)^2 - \omega_n^2} \tag{28.3}$$

Based on the SDOF model shown in (28.5), the model parameters for the structure are $\Theta = \{m, \omega_n, \zeta\}$.

Fig. 28.2 Experimental structure

28.2.3 *Controller of the Model*

Proportional, Integrative, and Derivative (PID) controller is one of the most widely utilized in industry. A PID controller is supported by Laplace transform and has operation form in time domain. Each term of the controller can shape the response of the system and change response characteristics such as overshot. The wide availability and ease of use are the two main reasons to make the PID controller a significant control tool [23]. PID has been used in most of the engineering fields such as electrical [24], biochemical [25], aerospace [26], and civil engineering [27, 28]. A PID controller has three terms which are Proportional, Integrative, and Derivative, and has two derivations which are PI and PD controller. PID controller has transfer function:

$$H_1(s) = K_p + \frac{K_i}{s} + K_d s \tag{28.4}$$

In this research, $H_1(s)$ which represents the dynamics of the person due to floor motion is represented by PID controller, and $H_2(s)$ represents dynamics of the person due to sound excitation as shown in Fig. 28.1. We designed new controller which is denoted by the following equation:

$$H_2(s) = \frac{\alpha s + \beta}{s^2 + \gamma s + \psi} \tag{28.5}$$

28.2.4 Optimization Process

Optimization is one of the deterministic numerical methods where it used to estimate the parameters value of complex model [29]. One of optimization technique is the Mean Square Error (MSE) which was used to estimate the model parameter by using the model parameter that give a minimum mean square error [30]. MSE is to measure the mean square different between the experimental data points and the data points generated by proposed model. MSE is denoted by equation Eq. 28.6.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y - \hat{Y}\right)^2, \tag{28.6}$$

where the Y is the experimental data points and $\hat{Y}$ is the data points generated by proposed model. The parameter which gave a minimum mean square error were used to fit the model the experimental data.

28.3 Experimental Testing

28.3.1 Lab Specimen

The structure utilized in the experiments has been designed, built, and retrofitted in structural lab of the Civil and Environmental Engineering Department in the University of South Carolina. This structure has steel frame and concrete blocks where they are used to inspect the dynamic properties of flexible slabs. The concrete blocks are made using normal concrete whereas the steel frame which is composed using 5 × 4 × 1.4″ steel tube is a cantilever truss shown in the Fig. 28.3.

The structure is a cantilever slab and has four supports. Two supports are hinge support which allow the rotation about y-axis cannot move along x-axis. The other two which are mobile supports are roller supports and can move along x-axis to change the cantilever length which in turn can change the structure dynamic characteristics. However, the concrete blocks can also change the dynamic properties of structure.

Fig. 28.3 Experimental structure

The dynamic properties of the structure are modify from rigid ($\omega_n = 62$ rad/s) to flexible structure ($\omega_n = 18.5$ rad/s) by changing the mass and stiffness. The actual live to dead load ratio of structure susceptible to human-induced vibration is represented in the lab specimen by making the structure light and flexible. The length of the cantilever used in this study is 124 in as shown in the Fig. 28.3.

28.3.2 *Instrumentation and Experiments*

In the practical aspect, we used a PCB 096D50 impact hammer with a sensitivity of 0.2198 mV/N and a PCB 333B50 accelerometer with a sensitivity of 1019 mV/g. We used the accelerometer to measure the vertical acceleration at the tip of the cantilever whereas the impact hammer was used to excite the empty structure. In addition, we developed a force plate to measure the force exerted by the individual jumping on the flexible structure. A PCB 130F20 microphone with a sensitivity of 40.2 mV/Pa and was utilized to measure the sound created by a metronome and.The data was collected using an NI 9234 data acquisition system. Data was collected in 20 s records at a sampling frequency of 6400 Hz. While this frequency is high for the structure, it was required to correctly describe the pressure captured by the microphone.

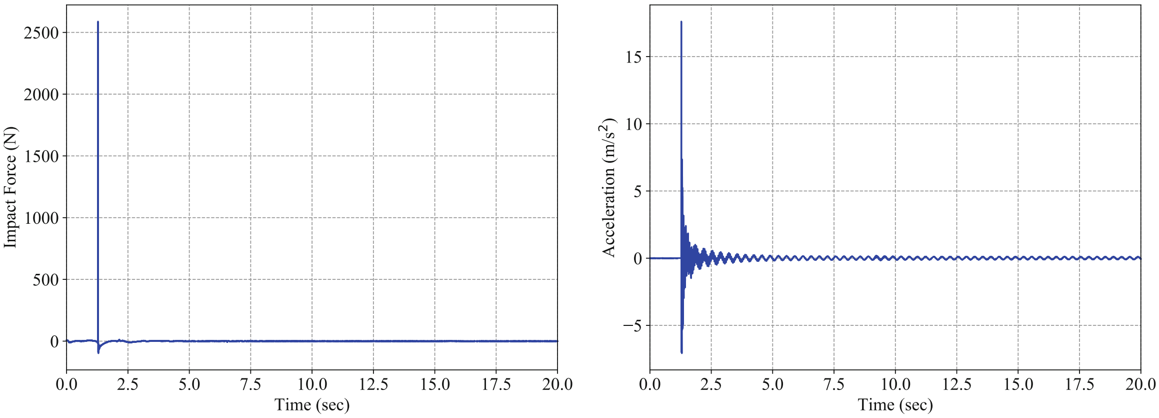
28.4 Modeling the Jumping Force

To compare the force generated by person jumping over the flexible structure and force predicted by the proposed model, we conducted three experiments described below where the experiments involved empty, occupied structure and individual jumping on the flexible structure.

28.4.1 *Empty Structure*

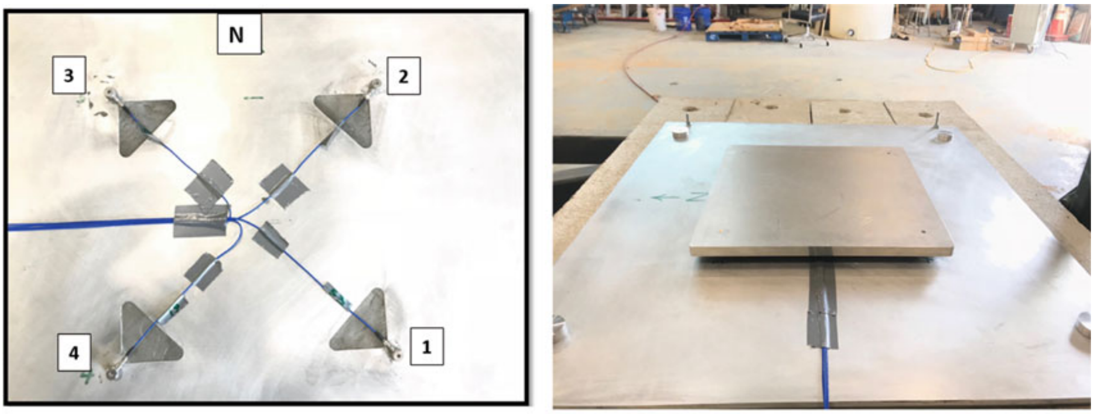
The impact hammer is used to excite the structure. Figure 28.4a shows the input force of the hammer and Fig. 28.4b shows the acceleration response. The structure is modeled as single degree of freedom and this model has three parameters (ω_n, ζ, m).

The experimental transfer function of empty structure which is calculated using frequency response function [31]. where the value of first single predominant peak is 18.5 rad/s. The parameters (ω_n, ζ, m) were calculated using optimization technique to be used for the model of the human-structure system of the individual jumping.



(a) (b)

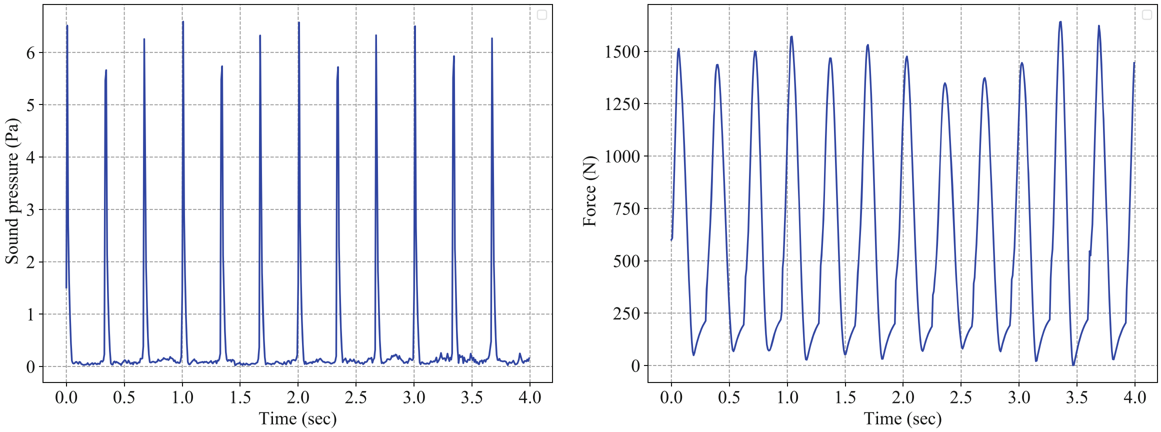
Fig. 28.4 Acceleration and impact force-time history of empty structure. (**a**) Impact force-time history. (**b**) Acceleration-time history



(a)

(b)

Fig. 28.5 Force plate for jumping. (**a**) Force sensor. (**b**) Top part of the force plate



(a)

(b)

Fig. 28.6 Sound and dynamic load-time history of jumping at 3 Hz. (**a**) Sound pressure-time history. (**b**) Dynamic load-time history

28.4.2 Occupied Structure

Single individual was standing over the structure with bent knees to test the flexible structure where the test was similar to that of the empty structure. The experimental transfer function of occupied structure is calculated using frequency response function [31]. The parameters of the occupied structure (ω_n, ζ, m, K_p, K_d, K_i) were calculated using optimization technique to be used for the model of the human-structure system of the individual jumping.

28.4.3 Individual Jumping on Flexible Structure

To understand the interaction between the human jumping and the flexible structure, we conducted a test using the force plate. Figure 28.5 shows the force plate designed and developed in Civil and Environmental Engineering Department at University of South Carolina. Here the force generated by the person jumping is measured to compare with theoretical force produced by the proposed model in Fig. 28.1. During jumping the subject move her/his body up and down and loss the contact with the floor.

A metronome or music beats was set to 180 bpm and the person standing in the structure was asked to excite the structure by moving his/her body at the frequency of the sound. The sound pressure produced by the metronome, acceleration, and load applied by the person were acquired using data acquisition system and shown in Fig. 28.6.

Table 28.1 The parameters value of the human, music and structure

Parameter	ω_n [rad/s]	ζ	m [kg]	K_p	K_d	K_i	α	β	γ	ψ
Values	18.0	0.04	730	34	2000	6	11,000	10	11	300

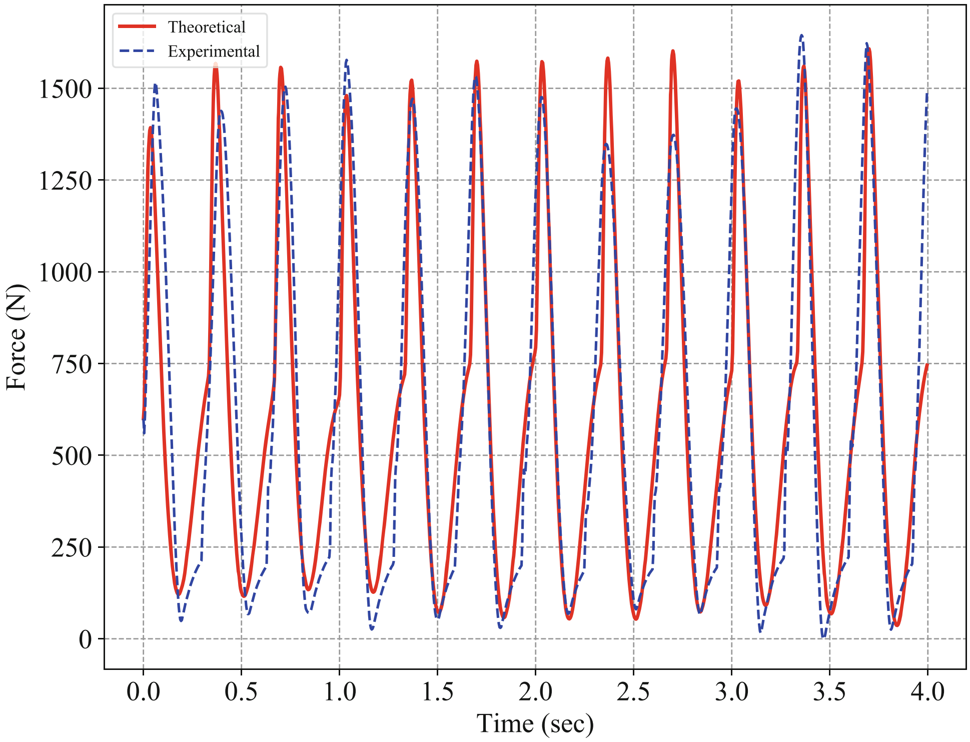


Fig. 28.7 Fitting theoretical to experimental response of dynamic force

28.5 Results

The parameter of the empty structure was optimized with the empty structure data whereas the parameter of PID controller was optimized using the data of person standing. Then, the overall system was optimized using the data of individual jumping over flexible structure. The beat of metronome was assumed to be 180 bpm and the force generated by person jumping was calculated to compare with model. Mean square error technique was used the estimate the parameters of proposed model. The parameters of model were (ω_n, ζ, m, K_p, K_d, K_i, α, β, γ, ψ). The parameters K_p, K_d, *and* K_i belong the PID that simulates the dynamics of the person due to floor motion whereas the parameters α, β, γ, *and* ψ belong to the new controller H_2 that simulates the dynamics of the person due to sound excitation.

Table 28.1 shows the parameters values which gave minimum mean square error. Figure 28.7 shows the fitting model to the experimental data of dynamic force of individual jumping one flexible structure.

28.6 Conclusion

This paper presents a new deterministic force model for a person jumping on flexible structure and to understand the interaction between the human and structure. The overall model is based one control theory and has two controllers. The first controller is PID and used to represent the dynamic of person due to floor motion whereas the second was designed to represent the dynamics of the person due to sound excitation. Not only the feedback between the structure and individual was included by the model but also the additional input (Music sound) to human. The parameters of the overall model were estimated using optimization process by taking the parameters that minimize the mean square error. The data points of individual force generated by deterministic model match well with experimental data points.

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