Chapter 4
Modeling Human-Structure Interaction Using Control Models When Bobbing on a Flexible Structure

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Abstract High performance materials has enabled engineers to design civil structures with smaller dead loads than in the past. However, lower dead loads results in a higher live to dead load ratio and the possibility of excessive vibrations due to human loading. This paper extends a controller theory based model to model the human-structure-interaction (HSI) problem. Prior work focused on modeling a standing individual with bent knees using a proportional, integrative and derivative (PID) controller model. This work extends this idea to a person bobbing or performing short movement up and down by bending his or her knees at the frequency provided by a metronome. Prior work considered the input to the human-structure system was a force applied to the structure. This work consider the bit produced by a metronome as the input to the overall human-structure system. The force applied to the structure is modeled as the output of the human, while the structure's acceleration is fed back into the control human system. Experiments performed at the University of South Carolina using a flexible platform that behaves as a single degree of freedom system are used to test the model. A force plate is installed in the platform to measure the forces exerted by the person on the platform as he or she moves. Model parameters and their corresponding uncertainty are quantified in a probabilistic fashion using Bayesian inference with the force plate forces as well as the acceleration measurements of the structure as observations. The model performance is evaluated by comparing probabilistic predictions with force and acceleration measurements found experimentally.

Keywords Human-structure interaction · Control theory · Human activity · Structural dynamics · Bayes inference

4.1 Introduction

New high performance strength materials have allowed structural engineers to design and construct structures using less material. Slender and lightweight structural members in grandstand, dance floor, malls, and fitness center have the potential to have vibration problems due to a higher live to dead load ratio [1, 2]. There are many examples of excessive vibration induced by human walking, and/or dancing [2]. The Millennium bridge is arguably one of the most well known examples. This structure caught the attention of researchers due to excessive vibration created by people walking [3]. Other examples are the 1831 footbridge failure in Broughton, UK due to unison marching of soldiers [4], and the excessive vibrations of the 30 floor TechnoMart building caused by aerobic exercise in Seoul, South Korea [5]. These excessive vibrations occurred not only because of the small structural damping typical of civil structures but because of the low mass and large spans of the structure.

The interdependence of the structural and human sub-systems cause what some researchers call the human-structure interaction (HSI) phenomenon, where the overall dynamic system might have a new properties [6]. Two remarkable issues appear in human-structure interaction problems: the combined human structure system, such as natural frequency and damping ratio can make the structure prone to excessive vibration due to human dynamic load. The second issue is the synchronization among the people because of the interaction with structure and crowd dynamics that occurred in the London Millennium Bridge[3, 6–8].

These excessive vibrations have captured the attention of scientists and engineers who have developed models to study and explain the combined human-structure system. Classical models such as the mass, damper, spring (MDS) has been widely used. Lasprilla et al. [9], Sachse et al. [10], Wei and Griffin [11], Brownjohn [12]. However, MDS models cannot add energy to the system and therefore, cannot consider other sources of excitation to the overall human-structure system such as sound (or music) excitation. Recently, Ortiz and Caicedo proposed a new model based on the control theory where they

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S. Pakzad (ed.), *Dynamics of Civil Structures, Volume 2*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-030-12115-0_4

used the Proportional, Integrative and Derivative (PID) controller to represent the effect of an individual or a group standing on the flexible structure [1, 9]. The contribution of their work was to frame the human-structure interaction HSI problem as a control problem where the plant is the structure and the controller is modeling the person or people.

In this paper, we expanded the model proposed by Ortiz-Lasprilla and Caicedo [1] where we propose the other use of a controller to include sound (or the bits created by a metronome) as an input to the overall HS system. Experimental data have been collecting for people bobbing (flexing their knees) on a flexible structure behaving as a single degree of freedom system. This experimental data is used to update the parameters of the controller in a deterministic fashion and create a probabilistic model that models the HSI.

This paper is organized as follows. Section 4.2 describes provides an overview of the models overview. A brief discussion of the experimental setup and instrumentation is given in Sect. 4.3. Section 4.4 a comparison between the experimental tests and the predictions of the model is provided. Finally, a brief set of conclusions are discussed.

4.2 Background

Several applications such as robotics, radar antenna, and automobile steering control work based on control theory. Control systems can be classified as open and closed loop control system [13]. Closed loop control of linear system fundamentally uses the concept of feedback. 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.

4.2.1 *Human-Structure Model*

It is important to highlight that the objective of closed loop controllers are to obtain a desired response of the plant by using feedback and reduce the system error [13, 14]. While in most applications the objective is to reduce the plant output (e.g. reduce vibrations), in this particular application the objective is to mimic the behavior of the combined human-structure system. The block diagram used by Ortiz-Lasprilla and Caicedo [1] consists of a plant $G(s)$ and controller $H(s)$. In this paper we expand this idea by including an additional block to model the response of a person to sound. Figure 4.1 shows the proposed model where $H_1(s)$ represents the dynamics of the person due to floor motion, and $H_2(s)$ represents dynamics of the person due to sound excitation. The excitation force on the structure is represented by the term $B(s)$ whereas the term $C(s)$ represents the output acceleration. $M(s)$ represents the input in form of sound. The combined structure and human system can then be described by the equation

$$TF(s) = \frac{G(s)H_2(s)}{1 + G(s)H_1(s)} \tag{4.1}$$

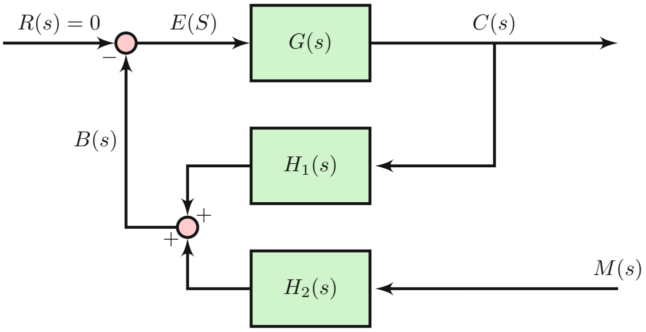


Fig. 4.1 Block diagram of a closed-loop control system

4.2.2 Human Model

Two PID controllers were used in this study, although the idea of close loop control does not limit the models to be PID controllers. The first controller takes acceleration of structure as input and the second takes the sound of a metronome as input. The output of both controller are the force applied to the structure and are added as input to the structure $G(s)$. Each PID controller transfer function has three parameters which are k_p, K_i, and K_d as described in the following equation

$$H_1(s) = K_p + \frac{K_i}{s} + K_d s \tag{4.2}$$

4.2.3 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. 4.2. 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. In this study, the length of the cantilever is 124 inch. The structure can be modeled as single degree of freedom and described by the equation

$$G(s) = \frac{\frac{1}{m}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{4.3}$$

where m, ζ, ω_n are the mass, damping ratio, and natural frequency of 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]

$$p_{1,2} = -\zeta\omega_n \pm \sqrt{(\zeta\omega_n)^2 - \omega_n^2} \tag{4.4}$$

Fig. 4.2 Experimental structure

4.3 Experimental Testing and Model Updating

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 was utilized for experiments. The accelerometer was used to measure the vertical acceleration at the tip of the cantilever and the impact hammer was used to excite the empty structure. In addition, a PCB 130F20 microphone with a sensitivity of 40.2 mV/Pa and a force plate developed in house were utilized to measure the sound created by a metronome and the forces exerted by the person on the structure. The data was collected using an NI 9234 data acquisition system. Data was collected in 20 second 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. The frequency response function of the system was estimated using the equation [16]

$$\mathrm{TF}(f) = \sqrt{h_1(f) * h_2(f)} \tag{4.5}$$

where

$$h_1(f) = \frac{S_{xx}(f)}{S_{xy}(f)}, \qquad h_2(f) = \frac{S_{yx}(f)}{S_{yy}(f)} \tag{4.6}$$

S_{xx} and S_{yy} represent the auto spectral densities for the force and acceleration respectively and S_{xy} is the cross spectral density between the output acceleration and the input force. S_{yx} is the cross spectral density between the input force and the acceleration.

Three different type of experiments were performed. The first test used the empty structure and it was performed with the objective of investigating the structural parameters only. The second and third tests were performed with a person standing with bent knees and a person bouncing (bending their knees) with a specific beat provided by a metronome.

4.3.1 Bayes Inference

Bayesian inference is used to update the parameters of the human and structural models. Bayes theorem is expressed by the equation

$$P(\Theta|D) = \frac{P(D|\Theta)P(\Theta)}{P(D)} \tag{4.7}$$

where $P(\Theta|D)$ is the posterior probability density function of the parameters Θ given the observed data D. $P(D|\Theta)$ is the likelihood, and $P(\Theta)$ is the prior probability density function of the parameters. The prior expresses our knowledge or beliefs about the parameters before updating. Chain Monte Carlo methods (MCMC) are used to sample the posterior [17–19].

4.3.2 Empty Structure

In the empty structure experiments the impact hammer was used to excite the structure. Figure 4.3a shows the input force of the hammer and Fig. 4.3b show the acceleration response.

The prior probability density function PDF distribution of structure mass is assumed to be a normal distribution P(mass) $\sim N(600, 25)$. The prior PDF of the natural frequency of the empty structure is assumed to be a normal distribution P(ω_n) $\sim N(18.85, 1.0)$. The prior PDF for the damping ratio was assumed as P(ζ) $\sim N(0.006, 0.004)$. The likelihood function was assumed as a Normal distribution with a standard deviation modeled by an Inverse Gamma with shape $\alpha = 4$ and scale $\beta = 0.2$. A Markov Chain Monte Carlo MCMC algorithm was utilized to sample P($\Theta = \{\text{mass}, \omega_n, \zeta\}|D$). The posterior distributions for mass, ω_n and ζ were used as prior distributions for the model of the human-structure system of the person bouncing.

4.3.3 Person Standing with Bent Knees

The structure was tested again with a single occupant standing over the structure with bent knees and not moving. The structure was excited by the impact hammer similar to the excitation of the empty structure. The experimental transfer function of occupied structure was calculated using Eq. (4.5) and it is shown in Fig. 4.4. The parameters of the closed

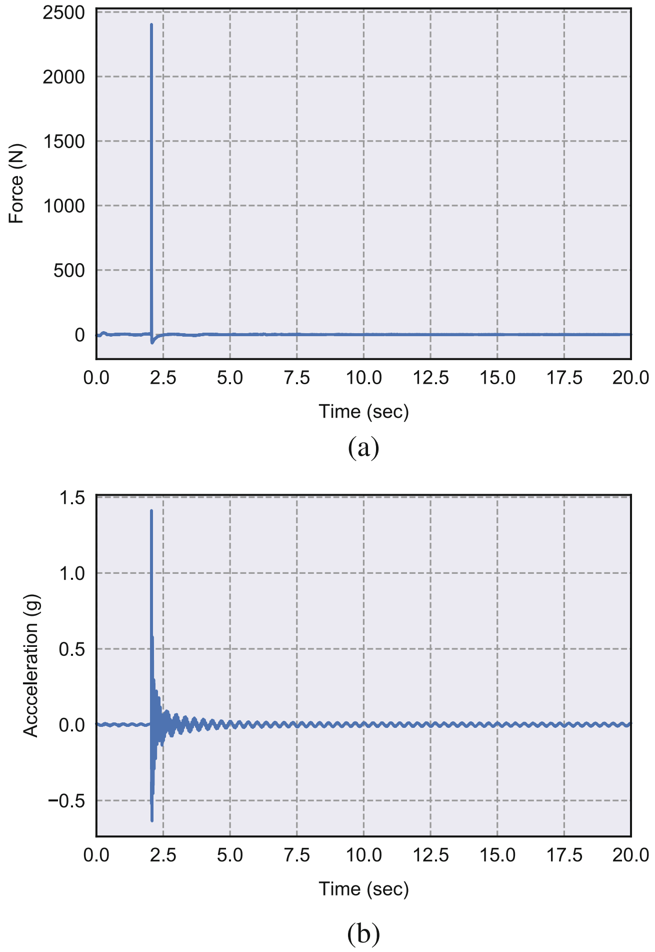


Fig. 4.3 Acceleration and impact force-time history of empty structure. (**a**) Impact force-time history. (**b**) Acceleration-time history

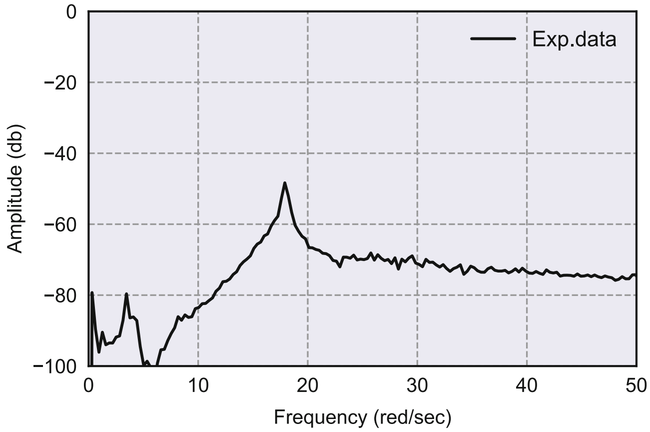
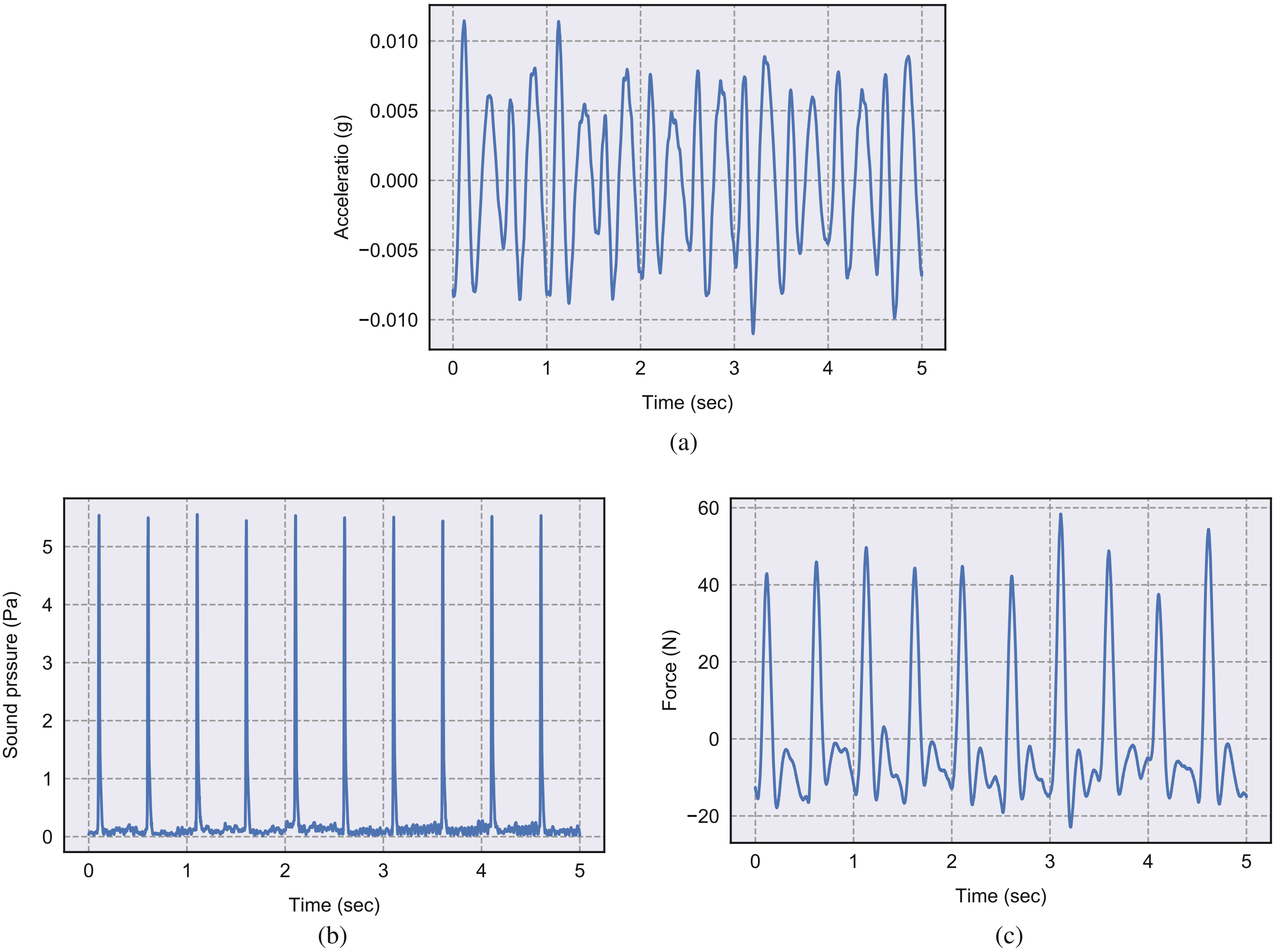


Fig. 4.4 Experimental transfer function of occupied structure

loop control system were updated, finding the posterior distribution of the parameters $\Theta = \{\text{mass}, \omega_n, \zeta, K_p, k_d, k_i\}$. The posterior $P(\Theta|D)$ from the previous experiment was used to inform the structural parameters.

4.3.4 Individual Bouncing on Flexible Structure

A test using the force plate was used to understand the interaction between the human and the flexible structure. Here the force generated by the person bobbing was measured to update the second PID controller ($H_2(s)$ in Fig. 4.1). During bouncing the subject move her/his body up and down with his/her knees bent and keeps fully contact with the floor. In other words, the person is not jumping. Bouncing is a simpler activity to model than jumping and it is the focus of this paper [20, 21]. A metronome was set to 120 bpm and the person standing in the structure was asked to excite the structure with his/her feet 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. 4.5. The prior probability density function PDF distributions of a person bouncing model are shown in Table 4.1. The parameters of the structure and both PID controllers were updated using experimental data.



(a)

(b)

(c)

Fig. 4.5 Acceleration, sound, dynamic load-time history of bouncing at 2 Hz. (**a**) Acceleration-time history. (**b**) Sound pressure-time history. (**c**) Person dynamic load -time history

Table 4.1 Prior PDF for model of structure excited by the person

Parameter	PDF	Mean	Standard deviation
ω_n	Normal	$\mu = 18.85$	$\sigma = 1.0$
ζ	Normal	$\mu = 0.005$	$\sigma = 0.00025$
Mass	Normal	$\mu = 600$	$\sigma = 25$
K_p	Normal	$\mu = 1299$	$\sigma = 130.0$
K_d	Normal	$\mu = 42$	$\sigma = 8.0$
K_i	Normal	$\mu = 495.0$	$\sigma = 25.0$
K_{p1}	Normal	$\mu = 75{,}240$	$\sigma = 7524$
K_{d1}	Normal	$\mu = 3179.0$	$\sigma = 320.0$
K_{i1}	Normal	$\mu = 802{,}800$	$\sigma = 80{,}280$

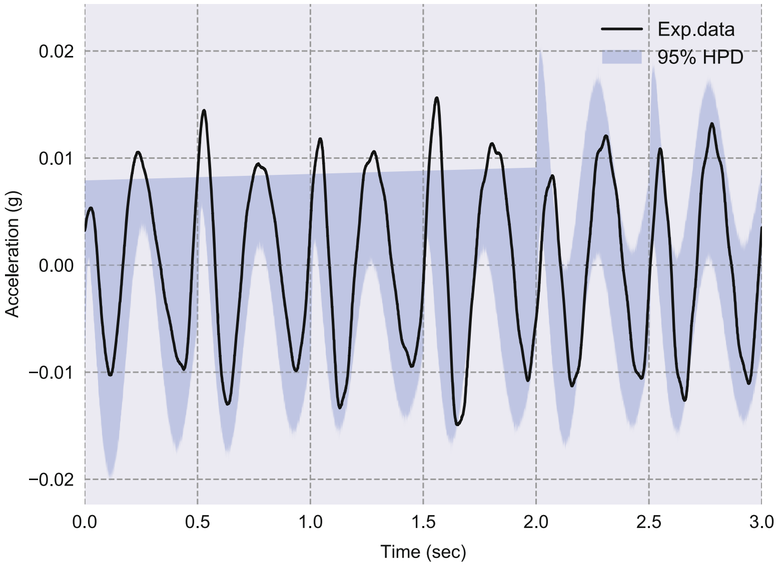


Fig. 4.6 Posterior predicative check

Table 4.2 Moments of random variables describing the parameters of the human, music and structure

Parameter	ω_n [red/s]	ζ	Mass[kg]	K_p	K_d	K_i	$K_p 1$	$K_d 1$	$K_i 1$
Mean	18.21	0.006	634	−1341	115.979	1128	84624	8217	2,838,127
St. Deviation	0.0.198	0.003	11.08	54.4	2.19	175.5	4119	182.8	63,490
95% HPD	(17.98, 18.89)	(0.001, 0.009)	(609.5, 654.6)	(−1465, −1269)	(112.7, 120.09)	(789.5, 1503	(70,666, 89,047)	(6091, 7262)	(2,739,917, 2,952,269)

4.4 Results and Discussion

Because of the type of experiments performed, different parts of the model were updated with each data set. The parameters of the structure (plant) were updated with the empty structure. Then, the parameters for $H_1(s)$ were updated with the experiment of the person standing with bent knees. Finally, the complete system was updated with the sound excitation. The posterior PDF of the parameters were sampled using Metropolist Hasting algorithm. A posterior prediction check was performed by using the model to predict the acceleration of a structure with a different experiment as shown in Fig. 4.6. Table 4.2 shows the posterior of mean, standard deviation, and 95% of HPD interval of each parameter of the final model.

4.5 Conclusions

This paper presents a new model to represent the human-structure interaction phenomenon to simulate the complete system when an individual flexes their knees on a flexible structure. The proposed model uses two Proportional, Derivative, and integrative (PID) controllers to model both the feedback from the structure and the excitation due to sound. Model parameters were updated using Bayesian inference. Posterior predictions of the model match well with experimental results for a single person. However, additional research needs to be performed to verify the validity of the model with other individuals.

Acknowledgement The author would like to acknowledge the higher education and scientific research ministry of Iraq to support this research.

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