Chapter 18
Some Implications of Human-Structure Interaction

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Abstract On structures, humans may be active which may cause structural vibrations as human activity can excite structural vibration modes. However, humans may also be passive (sitting or standing on the structure). The paper addresses this subject and explores the implications of having passive humans present on the structure. It is not conventional to model the presence of passive humans when predicting structural response, but nevertheless it is instructive to investigate which effect they do in fact have on structural behavior and modal characteristics of structures. Such investigations are made in the present paper.

Keywords Human-structure interaction • Footbridge vibrations • Serviceability-limit-state • Passive damping • Bridge damping

Nomenclature

φ	Mode shape function
α	Dynamic load factor
τ	Integration period
ζ_1	Bridge damping
ζ_2	Human damping
a_{MTVV}	Maximum transient vibration value
a_{VDV}	Vibration dose value
a_{VDV}	Root-mean-square value
e	Ratio
f_1	Bridge frequency
f_2	Human frequency
f_s	Step frequency
G	Pedestrian weight
m_1	Bridge modal mass
m_2	Human modal mass
p	Modal load
T	Observation period
v	Walking velocity

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18.1 Introduction

One type of action of an active person on a structure is walking. This scenario may take place on a footbridge, and this paper considers a footbridge subjected to walking loads; and vertical walking loads in particular.

Basically, the problematic scenario for a footbridge is that the serviceability limit state might not be acceptable. Accelerations levels might be too high rendering the bridge unfit for its intended use. But there are different acceleration properties that might be used for evaluating the serviceability limit state of human-occupied structures. It is not the intention of this paper to evaluate which acceleration property is the right one to use, but at least ISO 2631-1:1997 [1] brings forward acceleration properties such as the RMS-value (root-mean-square-value), the VDV-value (vibration-dose-value), and other values as will be outlined.

One intension of this paper is to evaluate how these properties might be influenced by the presence of a passive person (such as a person passively standing at bridge midspan). Such presence would not be an unlikely event, and the passive person might well be the acceleration receiver potentially finding acceleration levels unacceptable (rather than the active person; the pedestrian).

However, experiments not reported here (but in [2–6]) strongly suggest that the passive person alters the dynamic system brought into vibrations by the pedestrian in that the passive person will act as an auxiliary system attached to the bridge mass. That a passive human may be modelled as a dynamic system is in agreement with findings in biomechanics [7].

Hence, this would be expected to change bridge acceleration levels. It is therefore found of interest to do a parametric study in which bridge response predictions are made for the scenario without the passive person and for the scenario where the passive person is present on the bridge. From the bridge response time series, a set of different acceleration properties defined in [1] (RMS, VDV, etc.), are then extracted for both scenarios allowing an evaluation to made as to how the different acceleration properties are influenced by accounting for the passive person when modelling the dynamic system.

Another scope of the paper is to do a similar parametric study, but whereas the first study focused on the bridge acceleration response at the feet of the passive person, the second study will focus on the bridge acceleration response at the feet of the pedestrian. Generally speaking there are two types of receivers that may be present on a footbridge: The passive person and the pedestrian. As they are not positioned at the same location on the bridge, the vibrations entering at the feet of the two persons will be different. Hence, also the extracted acceleration properties (RMS, VDV, etc) will be different, and the focus of the second study is, as for the first study, to investigate how the different acceleration properties are influenced when accounting for the potential presence of a passive person.

It is believed to be the first published parametric study aiming at quantifying the influence of passive person embracing a number of potential serviceability-limit-state judgement parameters (acceleration properties) and accounting for two potential receivers of vibration.

For the study, a number of assumptions are needed (bridge model, walking load model, and how to model passive persons), and the model assumptions are outlined in Sect. 18.2. Section 18.3 outlines the acceleration properties in focus and how they are extracted from acceleration time series, and Sect. 18.4 presents results of the study followed by a conclusion.

18.2 The Models Considered for the Study

18.2.1 The Footbridge

In order to keep focus on the primary mechanisms for investigation in this paper, it is chosen to employ a quite simplistic bridge for the investigations. In other words it is not the complicity of the bridge model that is to pollute the interpretation of results, which might be the case, if a quite complex bridge was employed.

Therefore it was chosen to consider a simple pin-supported bridge, with the dynamic characteristics (natural frequency, damping ratio, and modal mass) of its first bending mode given in Table 18.1.

Table 18.1 Dynamic characteristics

f_1 (Hz)	ζ_1 (%)	m_1 (kg)
Footbridge		
6	0.4	2,500

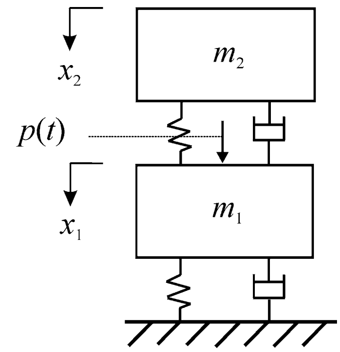

Fig. 18.1 Model of the combined bridge-human system

Table 18.2 Dynamic characteristics

f_2 (Hz)	ζ_2 (%)	m_2 (kg)
Passive person		
7.5	30	60

One item to notice is that it is a bridge, which can resonate as a result of pedestrian traffic, in that the first bending mode can be excited by the third harmonic component of walking loads (with a mean step frequency close to 2 Hz as suggested in [8, 9]).

Another item to notice is that the bridge is very lightly damped making it a bridge which potentially is problematic in the serviceability limit state.

The bridge length, L, was set to 11 m, which is realistic, considering the dynamic characteristics given in Table 18.1.

18.2.2 The Interaction Model

As indicated in the introduction, there are a number of indications that the mass of a passive person present on a footbridge will interact with the footbridge mass, hereby altering the dynamic system and its dynamic characteristics, compared to those introduced in Sect. 18.2.1.

Therefore, for the present studies also an interaction model (combined bridge-human model) is considered, in which a human mass (the mass of a passive person) is attached to the modal mass of the bridge by a linear spring and dashpot.

Figure 18.1 shows the model considered for the present studies as an alternative to the SDOF model of the bridge presented in Sect. 18.2.1. The load $p(t)$ represents the vertical load action of a pedestrian.

The grounded SDOF subsystem represents the bridge and the attached SDOF system represents the dynamics of a passive person.

The dynamic characteristics of the bridge are those already presented in Table 18.1, whereas the values assumed for the passive person (natural frequency, damping ratio and modal mass) are shown in Table 18.2.

These properties are not be interpreted as mean values for a passive (standing) person, but the dynamic properties represent a result (values) derived from tests with an arbitrary standing person. In that sense they are realistic, at least as an example.

18.2.3 Pedestrian Load

A Fourier-series expansion was used to model walking loads from the pedestrian, see Eq. 18.1.

$$f(t) = G + \sum_{i=1}^{3} G\alpha_i \sin(2i\pi f_s t - \theta_i), \tag{18.1}$$

where G represents the static weight of the pedestrian. The properties αi are the dynamic load factors, and for the present study the first three dynamic load factors (harmonics) were considered.

The first dynamic load factor (αi) was modelled as being dependent on step frequency (f_s) as suggested in [10], see the relationship in Eq. 18.2.

$$\alpha_1 (f_S) = -0.2649 f_S^3 + 1.306 f_S^2 + 1.7597 f_S + 0.7613, \quad (18.2)$$

and the two other load factors assumed the values:

$$\alpha_2 = 0.07 \text{ and } \alpha_3 = 0.05. \quad (18.3)$$

The phases were randomly selected. It is a load model by far more reasonable than that found in some design guide lines, although it is possible to make it even more complex and realistic.

The modal load, $p(t)$, associated with the first bending mode (considered to be the dominating mode) is then determined using Eq. 18.4.

$$p(t) = f(t)\varphi, \quad (18.4)$$

where the mode shape function is determined as:

$$\varphi = \sin(\pi vt/L), \quad (18.5)$$

where v is walking velocity and L is the length of the bridge.

There are various ways to model the walking velocity, but it seems established that it depends on step frequency (f_s), even though some design guides do not recognise this to be the case. So as to employ realistic relationships for the studies of this paper, a relationship between step frequency and walking velocity was monitored for a walking person. The relationship is shown in Eq.18.6.

$$v = 0,386 f_s^2 - 0,1217 f_s + 0,381. \quad (18.6)$$

I can be shown that the monitored relationship has much resemblance with findings in [11], but the monitored relationship was used for later numerical studies of this paper.

18.3 The Response Parameters

A later section will explain how bridge response time series to the action of a pedestrian was calculated. However, in this section focus is on how bridge acceleration time series were processed to obtain the response parameters introduced in ISO 2631-1:1997 [1].

The bridge acceleration properties in question are those given below.

$$a_{PEAK} = \max\left[a_w(t)\right] \quad (18.7)$$

$$a_{RMS} = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2}, \quad (18.8)$$

$$a_{VDV} = \left[\int_0^T a_w^4(t)dt\right]^{1/4}, \quad (18.9)$$

$$MTVV_\tau = max\left(\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)dt\right]^{1/2}\right). \quad (18.10)$$

It is apparent that the acceleration time history is weighted quite differently in the respective calculations, which also explains why there is an interest in focusing on how they are influenced when the dynamic system is altered by the presence of a passive person.

The VDV-approach uses a power of 4, thus placing high focus on peak values in the acceleration time history. The MTVV-approach employs a running integration period, τ (which for the present studies is set to 1 sec), but it eventually places focus a maximum value. Placing focus on the maximum response is certainly the case for the PEAK-approach (by definition), and the RMS-approach is special in the sense that the result (the a_{RMS}-value) is influenced by the observation period T (which is a choice to be made).

As for the observation period T, it was chosen to a value of 30 sec for any RMS-calculation. The choice is solely motivated by the fact that it found to be the time between on-set of bridge vibrations until bridge vibrations had vanished in the most severe resonant case. Another choice could have been made, and results in terms of the RMS-values would then have been different from those presented in this paper.

Generally, [1] focuses on the structural vibrations experienced where they enter into the human body (for the present study at the feet of vibration receivers, as humans are either standing or walking), and for all scenarios the primary resonant vibrations would be in the 4–8 Hz frequency band.

Only vertical components of acceleration response are considered (which is reasonable for the footbridge in focus in this paper), but had horizontal components also been present there would be more processing to do.

18.4 Results

18.4.1 Accelerations at Feet of a Passive Receiver

As previously mentioned, the acceleration properties in Eqs. (18.7, 18.8, 18.9, and 18.10) were calculated at bridge midspan:

(A) Using the 2DOF interaction model in Fig. 18.1.
(B) Using a SDOF model for the bridge (i.e. without attaching a SDOF model for the passive person).

For the calculations of midspan bridge accelerations, a Newmark time integration scheme was employed using time steps of 0.01 sec.

The acceleration properties were identified using a number of different step frequencies of the pedestrian (stepping through the range of 1.7–2.3 Hz, being realistic step frequencies). It is to be understood in this way that first the pedestrian was modelled to excite the bridge with a step frequency of 1.7 Hz, then 1.75 Hz etc. For each step frequency two time series were derived (one for assumption A and another for assumption B) and for both, the acceleration properties were calculated.

This gave frequency response curves for all acceleration properties. From these curves, the resonant frequencies were identified along with the associated resonant (max) values of each property in the frequency range of 1.7–2.3 Hz. For example, for the property a_{vdv}, the following resonant properties were identified:

$$a_{VDV}(A) \text{ and } a_{VDV}(B), \tag{18.11}$$

representing the absolute maximum a_{vdv}-value found on assumption A and on assumption B, respectively.

For the presentation of results, the ratio e_{VDV} defined in Eq. 18.12 is introduced.

$$e_{VDV} = a_{VDV}(A)/a_{VDV}(B). \tag{18.12}$$

When this ratio obtains a value below unity it indicates that the maximum VDV-value derived on assumption A is smaller than the maximum VDV-value derived on assumption B. In other words that the passive person has had a damping effect on the bridge (has reduced the VDV-value).

In similar manners, the ratios given in Eqs. (18.13, 18.14, and 18.15) were computed.

$$e_{RMS} = a_{RMS}(A)/a_{RMS}(B), \tag{18.13}$$

$$e_{MTTV} = MTVV(A)/MTVV(B), \tag{18.14}$$

$$e_{PEAK} = a_{PEAK}(A)/a_{PEAK}(B), \tag{18.15}$$

Table 18.3 Acceleration ratios

e_{PEAK}	e_{RMS}	e_{VDV}	e_{MTVV}
0.55	0.44	0.51	0.55

Table 18.4 Acceleration ratios

e_{PEAK}	e_{RMS}	e_{VDV}	e_{MTVV}
0.49	0.64	0.64	0.64

The results in terms of the four ratios are given in Table 18.3.

First it can be noticed that a single passive pedestrian is suggested to be capable of reducing bridge responses quite significantly (by a factor of about 2). One reason for this is that the bridge has quite low inherent damping, whereas the damping inherent in the human body is quite high, and much higher than that normally seen in pure structural systems.

Another observation is that the damping effect of the passive person to some degree depends on which acceleration property is considered. Hence, the damping effect is not a unique property, as it is seen to depend on the parameter chosen for the serviceability limit state evaluation.

Thirdly, it is worth noting that if acceleration properties are computed in order to evaluate the serviceability limit state related to the passive receiver (vibration comfort of the standing person) quite different results are obtained whether or not his presence is modelled when setting up the dynamic system. In reality, he needs to be there (on the bridge) to judge whether the vibration comfort is acceptable or not.

18.4.2 Accelerations at Feet of the Pedestrian

Having focused on the passive receiver, focus is now turned to the active receiver of vibrations (the pedestrian). He will not experience the same bridge vibration time history as the passive receiver standing at mid-span, as he is moving. Particularly, he well not experience bridge vibrations after he has passed the bridge (which the passive receiver might).

As was the case for the passive receiver, bridge vibrations at his feet were calculated, prior to identifying the acceleration properties and ratios here from. Again this was done on both assumption A and on assumption B (with and without accounting for the presence of the standing person).

The results in terms of the four ratios are given in Table 18.4.

Again it is seen that the presence of the passive person is expected to attenuate bridge vibrations (as experienced by the pedestrian), as the ratios attain values less than unity.

By comparing the values in Table 18.4 with those in Table 18.3, it can also be found that the attenuation of the different acceleration properties (induced by a passive person) is not the same.

In other words, the impact of introducing a passive person on the bridge has different effects on the accelerations entering the passive person and those entering the pedestrian. Hence, the “damping effect of a passive person on structural vibrations” is not a unique property. The results suggest that it depends on which receiver of vibrations that is considered, and on which acceleration property that is used for quantifying the damping effect.

It is not shown here, but by adding a passive person on the bridge, not only its damping characteristic will change, but also its natural frequency.

18.5 Conclusion

For a pin-supported footbridge, scenarios with a single (active) pedestrian and the potential presence of a passive (standing) person on the bridge were studied (with and without the passive person). Both persons (the pedestrian and the passive person) might be receivers of vibration and might feel discomfort.

It was found that the passive person had the effect of mitigating structural vibrations (and quite significantly in the studied case), but it was also found that “the damping effect of a passive person on structural vibrations” is not a unique property.

For one, it was shown that is it somewhat dependent on the acceleration property (derived from bridge acceleration time histories) chosen for consideration (PEAK, RMS, VDV, MTVV, being the properties considered in this paper).

Secondly, “the damping effect” also depends on whether focus is placed on the accelerations entering the feet of the passive receiver of vibrations (the standing person) or the pedestrian (the active person).

All in all the study has quantified some effects of human-structure interaction. Perhaps the study has also brought about some questions as to whether exciting codes of practice handle the problem of evaluating the serviceability limit state quite right. It is not always as simple as it means.

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