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Procedia Engineering 199 (2017) 2856–2863

Procedia Engineering

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X International Conference on Structural Dynamics, EURODYN 2017

Effect of Walking people on Dynamic Properties of Floors

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Abstract

Despite the intensive research that has focused on the dynamic interaction between walking people and slender footbridges, this phenomenon has never been investigated for floor structures. For lightweight floors having mass of 150 kg/m2 or less, where they have relatively low modal masses and damping ratios, this interaction is expected to be more effective than that for normal floors. Such phenomenon, if proven to exist for floors, could explain one of the reasons behind the discrepancy between the measured vibration response of floors due to human walking and the corresponding predicted responses using the currently available models which neglect human-structure interaction for walking humans.
This paper presents the first attempt to investigate the effect of walking people on the dynamic properties of floors. It is based on several experimental tests for groups of people walking on a full-scale but slender laboratory floor structure. For each experiment, a modal test was carried out to identify the dynamic properties of the tested floor. The results showed a significant increase in modal damping for the first vibration mode, while higher modes exhibited less damping increase. A slight increase was also noticed in the natural frequency of the observed modes. These changes in the modal properties are in line with previous observations of the effects of walking people on footbridges. The results presented in this paper can pave the way for future research to model the interaction between walking people and the supporting floor structures in the context of their vibration serviceability.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Human-structure interaction; human-induced vibrations, floors.

1. Introduction

Dynamic interaction between walking people and the supporting civil structures can have a significant effect on human-induced vibrations due to walking [1–4]. This interaction, in both the lateral and vertical directions, has been

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1877-7058
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.561

extensively studied since the high-profile vibration serviceability failures of the Solferino Bridge in Paris and the Millennium Bridge in London 17 years ago. These studies focus on quantifying this phenomenon for people walking on slender footbridges where the existence of walking people can significantly alter the dynamic properties of the supporting structures [5,6]. For building floors, the current trend is to use lighter materials to build slender structures with open plan and long spans. This has resulted in floors with relatively low modal masses and damping ratios, and therefore, they could be prone to the effects of human-structure interaction (HSI) in the vertical direction. The natural frequency and modal mass of building floors are generally higher than that for footbridges, however, this phenomenon of HSI has never been investigated for such floor structures, so its effect on their dynamic properties is unconfirmed. Therefore, this paper aims to assess the effect of walking people on the dynamic properties of slender floors. It analyses the effect of small groups of walking people on the dynamic properties of a full-scale laboratory floor structure.

2. Test structure

2.1. Description of the structure

In this study, a full scale reconfigurable laboratory floor located at the University of Exeter is utilised (Fig. 1). The floor has dimensions of 7.5m by 5.0m and it consists of Sandwich Plate System (SPS) plates [7], which has around 200 kg/m^2 weight, supported by steel beams. A detailed description of the structure is explained elsewhere [8].

Fig. 1. The configurable laboratory floor at the University of Exeter.

2.2. Modal properties of the empty structure

A modal test was carried out to identify the vibration modes of the floor. Two APS400 shakers were utilised to apply a random force on the structure, and 21 Honeywell QA750 accelerometers were used to measure the vibration responses. The grid of the shakers, accelerometers and the test points (TPs) is shown in Fig. 2.

The frequency response functions (FRFs) were measured by dividing the measured acceleration response by the input force. These FRFs were used in the ME'scope software [9] to estimate the modal properties of the structure (natural frequency (f_n), modal damping ratio (ζ), modal mass and mode shape). The mode shapes of vibration modes 1-6 are shown in Fig. 3.

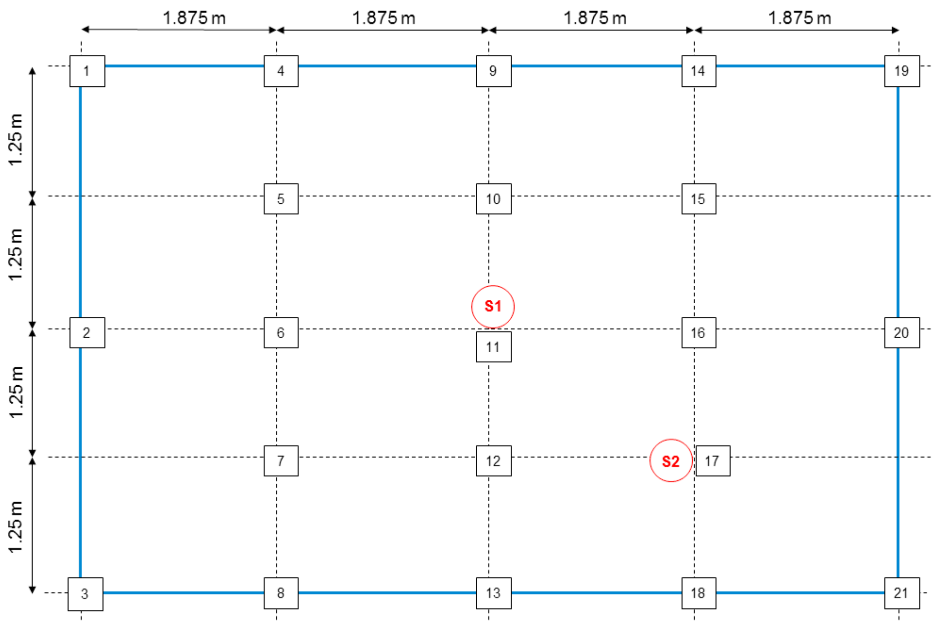

Fig. 2. Position of shakers (red circles) and accelerometers (black squares) on the floor.

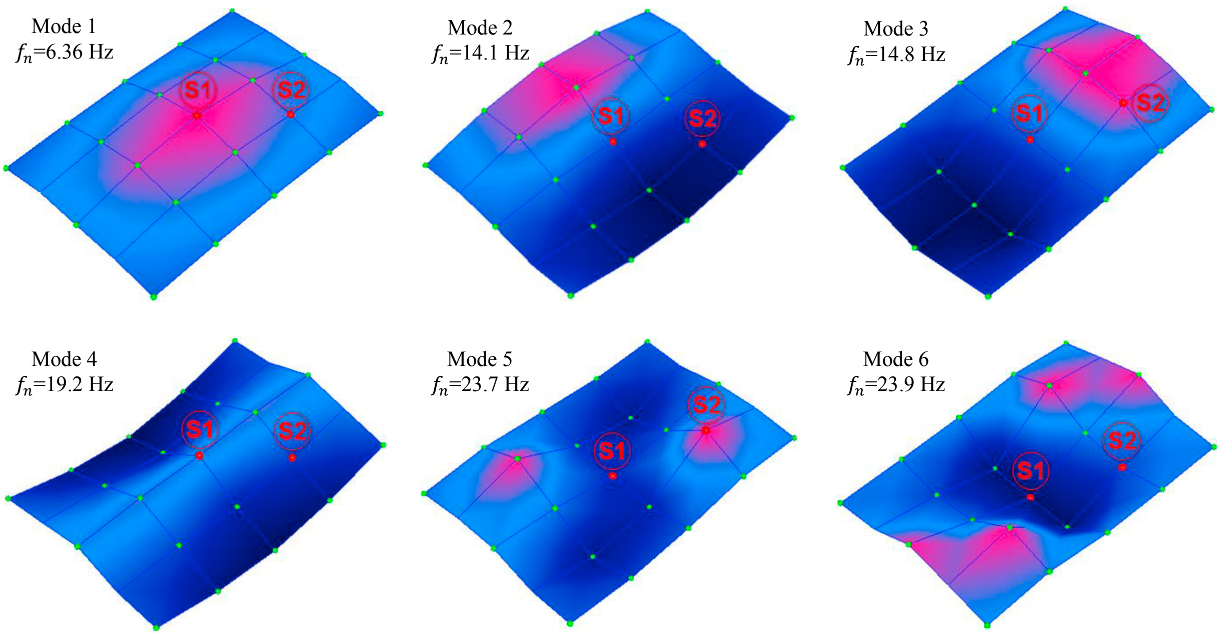

Fig. 3. Mode shapes of vibration modes 1-6. The red and green dots represent the position of the shakers and accelerometers, respectively.

3. Modal properties of the occupied structure

3.1. Walking tests

Before commencing walking tests, all cables were buried within grooves between the SPS plates, or fixed on the floor using adhesive tape to avoid tripping risks. The modal test was repeated, with identical configuration as for the empty structure (section 2.2 and Fig. 2), when small groups of people were walking on the floor. For each test, 2, 4 or 6 people (male and female) were walking on the structure. Bigger groups of walking people were avoided to ensure natural walking due to the limited area of the structure. During each test, the participants were asked to walk randomly around the structure (Fig. 4).

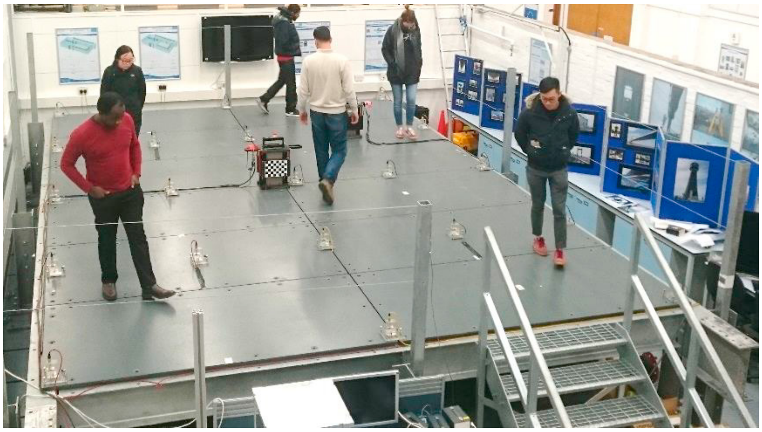

Fig. 4. Modal test of the floor structure occupied by six walking people.

During walking tests, the six vibration modes of the structure (Fig. 3) were excited by a random signal shaker force. Six data blocks, each lasting 80 s, were collected so that each test lasted about eight minutes. The sampling rate of the measured FRFs is 0.0125 Hz, which allows for the detection of small changes in the natural frequencies.

To ensure the validity of the measured FRFs, the test with six walking people was repeated twice. Fig. 5 compares the magnitude of the FRFs for the occupied structure for the two tests. The similarity of the FRFs for the two tests gives confidence about the measured FRFs and utilising them to estimate the modal properties of the occupied structure. The small differences between the two FRFs can be explained by the randomness of the walking paths during the tests.

3.2. Estimation of modal properties

While the effect of walking people on the dynamic properties is obvious for most of the observed modes with natural frequencies up to 40 Hz, this effect is more significant for lower modes (Fig. 5). Hence, this paper focuses on the modes with a natural frequency lower than 25 Hz. Fig. 6 compares the observed magnitude of the FRFs for this range of modes for the tests of both the empty and occupied structure.

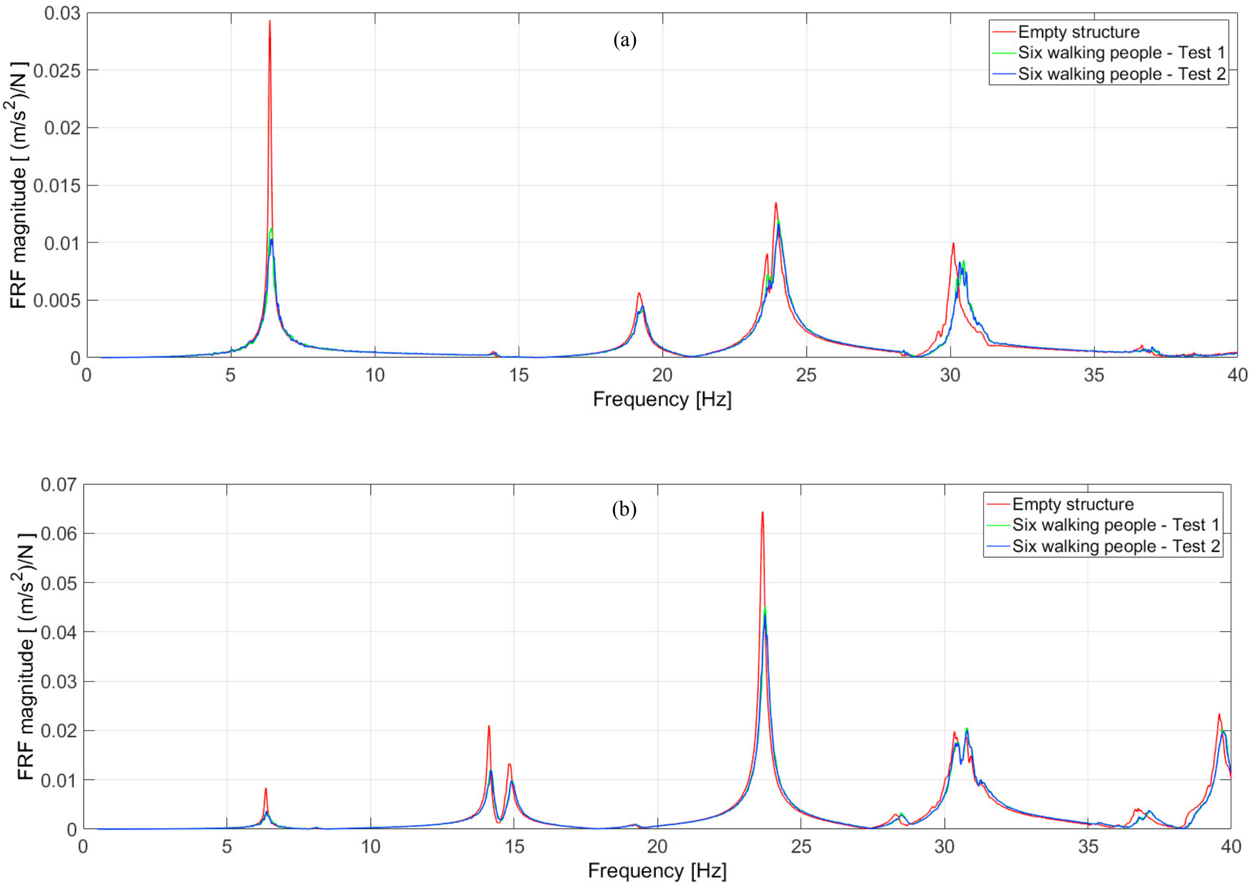

Fig. 5. Point accelerance FRFs magnitude at (a) TP11 and (b) TP17.

For each test, the modal properties of the occupied structure were estimated using ME'scope software in the same way as for the empty structure (section 2.2). However, the process of estimating the modal properties using this software depends on subjective decisions regarding the curve fitting of the measured FRFs. Hence, another method to estimate the modal properties using the measured FRFs was utilised. For each mode, the parameters defining an analytical FRF that resembles its measured counterpart were optimised. The optimisation process of these parameters (natural frequency, damping ratio and modal mass) was based on a genetic algorithm (GA) model developed for this purpose using Matlab software. The GA model is designed to minimise the objective function described in Eq.(1).

$$F(f_n, \zeta, m) = \sum_{f=f_1}^{f_2} [FRF_a(f) - FRF_m(f)]^2 \ , \qquad (1)$$

where, $F(f_n, \zeta, m)$ is the objective function ($[(m/s^2)/N]^2$), m is the modal mass (kg), f_1 and f_2 are the lower and upper bound frequencies around each mode (Hz) and $FRF_a(f)$ and $FRF_m(f)$ are the analytical and measured FRF magnitudes, respectively ($(m/s^2)/N$).

In the GA model, the lower and upper bounds of the damping ratio and modal masses were between 50% and 200% of their estimated counterparts using ME'scope software. However, for the natural frequency, those bounds were $f_n - 0.2$ Hz and $f_n + 0.2$ Hz, respectively.

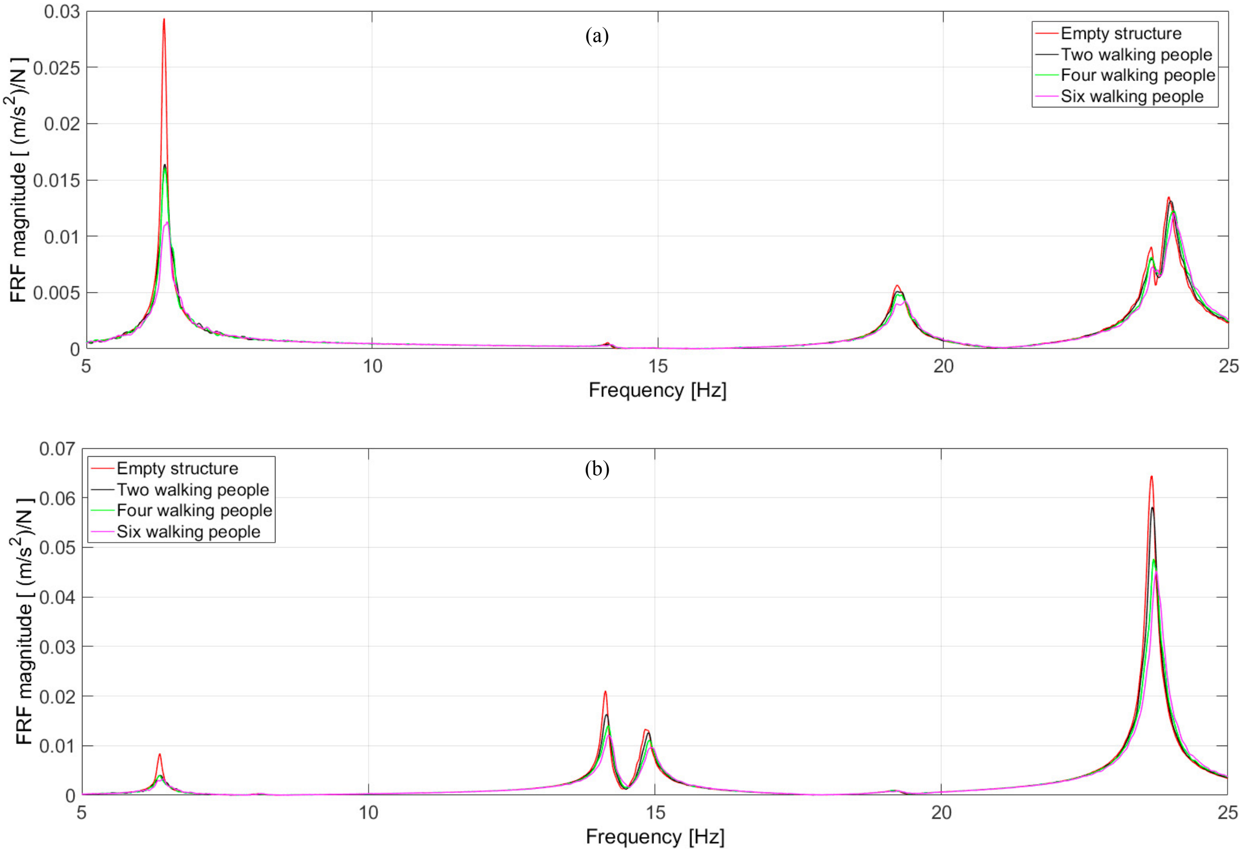

Fig. 6. Point accelerance FRFs magnitude at (a) TP11 and (b) TP17 for the empty and occupied structure with 2,4 and 6 walking people.

For each mode, the utilised FRF in the optimisation process was measured at the test point where the maximum FRF magnitude was obtained. Fig. 7 compares the optimised and measured FRFs for the first mode when the structure is empty or occupied by six walking people.

The estimated modal parameters of the six identified vibration modes using both methods are comparable (Table 1). Despite the differences between them, the general trend is that the more people walk on the structure, the more increment is obtained for natural frequencies, damping ratios and modal masses.

4. Discussion and conclusions

The results show that the existence of walking people has increased the damping ratio and slightly increased the natural frequencies of the observed vibration modes (Table 1 and Fig. 8). This effect has reduced for vibration modes with higher natural frequency. Interestingly, there are small differences between the modal properties of the first mode when the structure is occupied by two or four walking people (Table 1 and Fig. 8). This could be explained by the random distribution of walking people around the floor during the tests with respect to the mode shapes (Fig. 3).

The results presented in this paper are in line with previous findings for people walking on footbridges [1,3]. However, it is notable that only six people walking about a relatively lightweight SPS floor (200 kg/m^2) resulted in three times greater damping ratio compared with the empty floor. This may be relevant when checking vibration serviceability of assembly structures, such as large concourses.

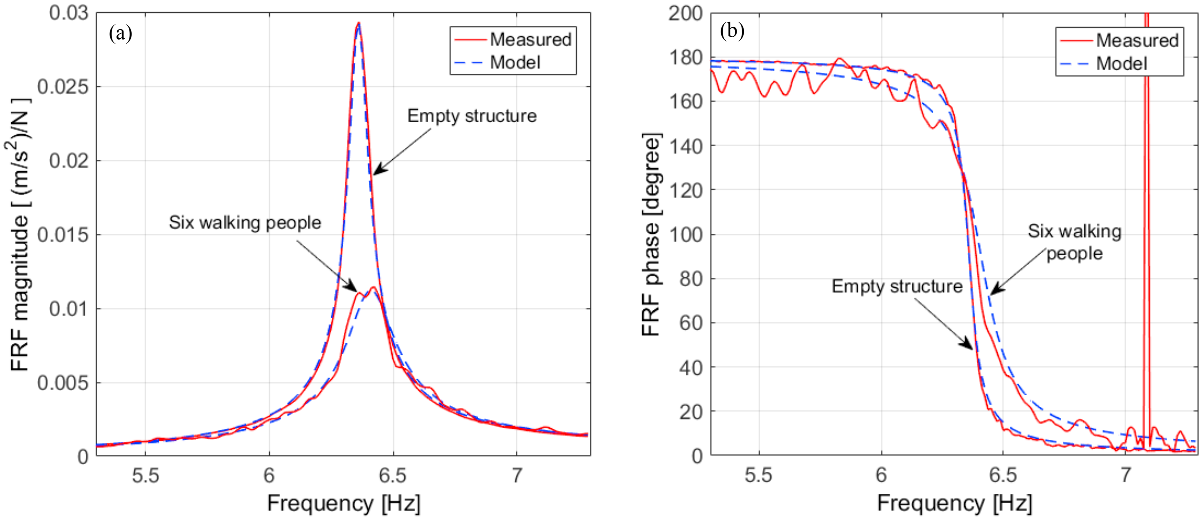

Fig. 7. (a) Magnitude and (b) phase of the measured and modelled FRFs (at TP11) of the first vibration mode when the structure is empty or occupied by six walking people.

Table 1. Identified modal properties (red is natural frequency, blue is damping ratio and green is modal mass) of the six vibration modes (Fig. 3) using GA optimisation of the FRFs and ME'scope software (between brackets).

Mode	Empty structure			Two walking people			Four walking people			Six walking people		
	f_n (Hz)	ζ (%)	m (kg)	f_n (Hz)	ζ (%)	m (kg)	f_n (Hz)	ζ (%)	m (kg)	f_n (Hz)	ζ (%)	m (kg)
1	6.36 [6.36]	0.584 [0.521]	2920 [3019]	6.377 [6.38]	0.997 [0.946]	2973 [3086]	6.378 [6.38]	1.011 [0.988]	3007 [3086]	6.409 [6.4]	1.459 [1.38]	3057 [3156]
2	14.14 [14.1]	0.376 [0.339]	3531 [3629]	14.165 [14.2]	0.456 [0.445]	3575 [3858]	14.189 [14.2]	0.539 [0.535]	3599 [3858]	14.215 [14.2]	0.659 [0.602]	3634 [3858]
3	14.84 [14.8]	0.615 [0.591]	5230 [5176]	14.869 [14.9]	0.641 [0.637]	5233 [5251]	14.892 [14.9]	0.741 [0.715]	5282 [5328]	14.923 [14.9]	0.817 [0.849]	5390 [5569]
4	19.204 [19.2]	0.668 [0.636]	3065 [3156]	19.223 [19.2]	0.694 [0.662]	3079 [3191]	19.238 [19.3]	0.749 [0.715]	3097 [3265]	19.27 [19.3]	0.798 [0.803]	3121 [3265]
5	23.663 [23.7]	0.324 [0.318]	2346 [2403]	23.686 [23.7]	0.361 [0.37]	2366 [2358]	23.717 [23.7]	0.43 [0.428]	2420 [2451]	23.75 23.7]	0.457 [0.478]	2430 [2451]
6	23.941 [23.9]	0.553 [0.581]	4584 [4328]	23.979 [24.0]	0.576 [0.594]	4618 [4217]	23.013 [24.0]	0.61 [0.65]	4680 [4628]	24.02 [24.0]	0.666 [0.673]	4711 [4823]

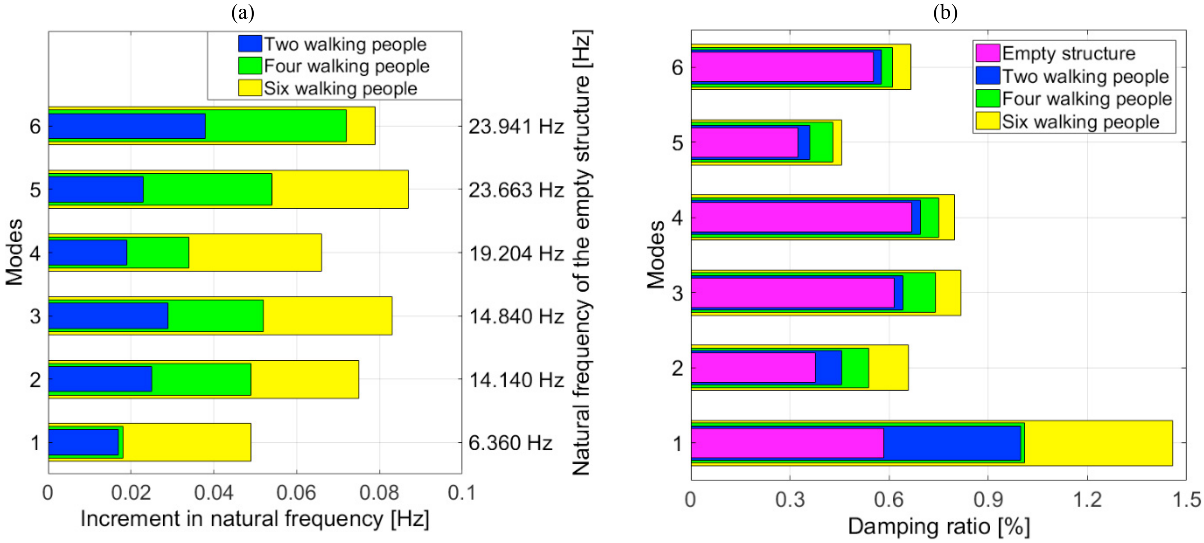

Fig. 8. Effect of walking people on the (a) natural frequency and (b) damping ratio for the six identified vibration modes of the structure.

Acknowledgements

The authors are grateful for the College of Engineering, Mathematics and Physical Sciences in the University of Exeter for the financial support they provided for the first author and his PhD program. The authors would also like to acknowledge the financial support provided by the UK Engineering and Physical Sciences Research Council (EPSRC) for grant reference EP/K03877X/1 ('Modelling complex and partially identified engineering problems-Application to the individualised multiscale simulation of the musculoskeletal system').

References

[1] Shahabpoor E, Pavic A, Racic V, Zivanovic S. Effect of group walking traffic on dynamic properties of pedestrian structures. J Sound Vib 2017;387:207–25. doi:10.1016/j.jsv.2016.10.017.

[2] Van Nimmen K, Maes K, Živanović S, Lombaert G, De Roeck G, Van den Broeck P. Identification and Modelling of Vertical Human-Structure Interaction, Springer International Publishing; 2015, p. 319–30. doi:10.1007/978-3-319-15248-6_34.

[3] Zivanovic S, Diaz IM, Pavic A. Influence of walking and standing crowds on structural dynamic performance. 27th Int Modal Anal Conf 2009.

[4] Jiménez-Alonso JF, Sáez A. A direct pedestrian-structure interaction model to characterize the human induced vibrations on slender footbridges. Inf La Constr 2014;66:1–9. doi:10.3989/ic.13.110.

[5] Shahabpoor E, Pavic A, Racic V. Interaction between Walking Humans and Structures in Vertical Direction: A Literature Review. Shock Vib 2016;2016:12–7. doi:10.1155/2016/3430285.

[6] da Silva F, Fernandes B, Pimentel R. Modeling of crowd load in vertical direction using biodynamic model for pedestrians crossing footbridges. Can J Civ Eng 2013;40:1196–204. doi:dx.doi.org/10.1139/cjce-2011-0587.

[7] SPS: the Sandwich Plate System heavy engineering composite from Intelligent Engineering n.d. http://www.ie-sps.com/ (accessed February 1, 2017).

[8] Hudson EJ, Reynolds P. Design and Construction of a Reconfigurable Pedestrian Structure. Exp Tech 2016. doi:10.1007/s40799-016-0144-3.

[9] Vibrant Technology Inc. ME'Scope VES 6.0 2015.