TU DARMSTADT HUMVIB-BRIDGE: INVESTIGATION OF THE HUMAN-STRUCTURE INTERACTION ON A FULL-SCALE EXPERIMENTAL PEDESTRIAN BRIDGE

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Abstract: *The simulation of the human-induced vibrations of lightweight footbridges is in general a complex problem where the dynamics of the pedestrian system meets the structural dynamics of the bridge. However, standard methods for numerical analysis of pedestrian bridges deal with this issue by using simplified approaches. The structure is mostly represented either by discretised multi mass systems or through a formulation in modal coordinates, while the excitation is typically described by a moving load. Positive effects of the interaction between the two systems (pedestrian and structure) are usually completely neglected. This paper, which is partially extracted from an actual research report of the Institute of Structural Mechanics and Design (TU Darmstadt), presents an experimental set-up developed for investigations of the human-structure interaction (HSI), as well as results of the preliminary investigations carried out in the same context.*

Key words: *footfall induced vibrations, human-structure interaction, pedestrian bridges.*

1. Introduction

The current trend in the field of footbridge design, generated mainly by the ever more stringent architectonic requirements over the last decades, is veering towards slenderer and lighter structures with greater spans, often consisting of innovative material combinations, as for example the pedestrian glass-steel bridge *Champlimaud Foundation* in Lisbon, Portugal (Fig. 1). Along with the aim for optimised material usage and the advanced design methods which allow the consideration of higher material stress ratios, these aspects lead to the necessity of an accurate simulation of the footfall-induced vibrations in the design phase.

Common methods for numerical analysis of the pedestrian-induced vibrations are mostly based on simplistic approaches which consider the pedestrian as a moving force, i.e. a concentrated (time-dependent) load travelling at a constant walking speed over the investigated structure. However, this approach is likely to overestimate the structural response, especially in case of

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lightweight structures, as it neglects the interaction between the pedestrians and the structure [1–3]. Therefore, various numerical models have been developed recently, in order to take the human-structure interaction into account. The main idea is to define a coupled system (human-structure), which is able to describe the human body by its equivalent dynamic parameters, i.e. mass, stiffness and damping coefficient [1]. The level of detail varies from representing the subject only by its moved mass (MM) towards more realistic assumptions, such as a moved spring-mass-damper (SMD, see also [4]) or even bipedal models [5], which can represent the human body to some extent by its physical biomechanical parameters, i.e. body mass located at the physical centre of mass as well as stiffness and damping coefficients for each leg [6]. Furthermore, some preliminary attempts to include HSI in the analysis of pedestrian crowd loading have been made [1, 7]. A comprehensive overview over various HSI approaches is given in [8].

This paper presents an experimental set-up for investigation of the human-structure interaction developed within an ongoing interdisciplinary research project between the department of Structural Mechanics and Design and the Institute of Sport Science of the TU Darmstadt as well as selected results of the preliminary measurements and of the corresponding numerical investigations. The set-up serves for research purposes both in the field of structural engineering (structural response by means of coupled human-structure systems) and the field of biomechanics (adaptation mechanism of the human body to vibrating underlying structures).

2. TU Darmstadt HUMVIB-Bridge

Within the research projects of the Institute of Structural Mechanics and

Design in the field of footfall induced vibrations, important experimental investigations are carried out on a full-scale pedestrian bridge, built on the campus *Lichtwiese* of the TU Darmstadt (Fig. 2). The main criterion considered in its design was that the first vertical natural frequency lies in a range which is excitable by usual walking frequencies, i.e. 1.4 to 2.4 Hz [9]. Auxiliary conditions referred to the limitation of the static displacement caused by the dead load and to the accelerations induced by walking of a single person, estimated by time history analysis using a moving load approach,

Fig. 1. *Pedestrian bridge Champlimaud Foundation in Lisbon, Portugal, a glass-steel composite structure (sbp GmbH)*

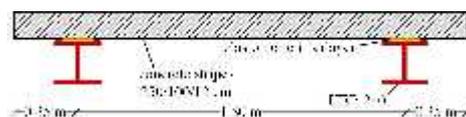Fig. 2. *HUMVIB-Bridge on the campus of TU Darmstadt (covered by a tent)*

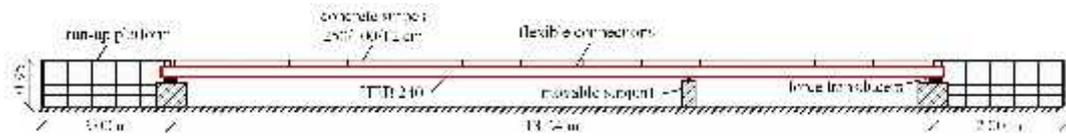Fig. 3. *Cross section of the experimental pedestrian bridge*

Fig. 4. *Sketch of the experimental pedestrian bridge (side view)*

which had to lie in a reasonable range, e.g. below 2 m/s².

Considering the conditions mentioned above, an optimum could be found for a main structure represented by two longitudinal simply supported steel beams (steel type S235JR) with a cross section HEB 240 and a span of 13.24 m (s. Fig. 3 and Fig. 4).

The bridge deck consists of 13 precast reinforced concrete stripes with the dimensions 250 x 100 x 12 cm. It is to be mentioned that there is no shear connection between the concrete elements and the steel girders, as a composite action of the structure (i.e. increased stiffness) had to be avoided, in order to keep the fundamental frequency in the required range. The concrete stripes are simply deployed on the steel beams using an elastomeric interlayer, which prevents the slip between the two components. The gap between the concrete blocks is about 2 cm, small enough for avoiding tripping of the subjects during the investigations, but wide enough to avoid a contribution of the concrete elements to the global structural behaviour.

The total mass of the bridge is about 12000 kg, which leads to a first vertical natural frequency of 2.03 Hz, confirmed also by the experimental investigations. A structural modal damping ratio of 0.3% was determined by measurements.

Furthermore, a third movable support was designed, in order to allow a flexibility of the structural system in the future, e.g. for investigating high-frequency structures. The fundamental frequency of the resulting continuous beam can be tuned according to the specific requirements by installing the

third support at an appropriate location. However, only investigations of the simply supported system will be addressed in the present paper.

3. Structural Analysis

3.1. Structural Models

The structural analysis of the experimental bridge focused on the three aforementioned models: Moving force (MF), moving mass (MM) and moving spring-mass-damper (SMD).

The load $F(t)$ for each of these models is described by a harmonic force approach (Eq. (1)) using the coefficients r_i and phase angles φ_i given in [10], for walking at a step frequency f_p=2 Hz. The step length l_s=0.8 m considered within the numerical analysis was adopted from the literature as well [10].

$$F(t) = G\left[1 + \sum_{i=1}^{m} r_i \sin\left(2\pi \cdot i \cdot f_p \cdot t - \varphi_i\right)\right] \quad (1)$$

This formulation is used as a load for all models and therefore acts as a substitute for the forces humans induce when crossing a footbridge, while the bipedal model presented in [5] creates these forces itself by simulating the human gait.

For the MF approach (s. Fig. 5) a formulation of the beam structure in modal coordinates with a sinusoidal mode shape $\varphi_j(x)$ normalized with respect to the generalised mass M_j according to Eq. (2) was used [1].

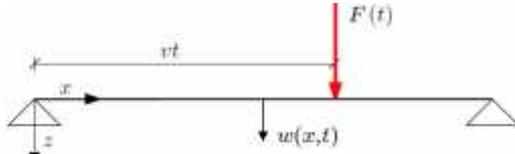The beam is considered to have n degrees of freedom (DOFs) and hence n
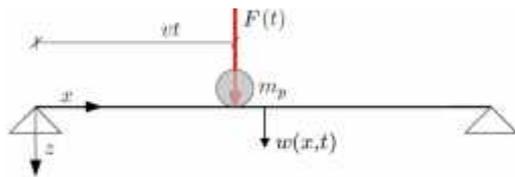
Fig. 5. *Moving force model of a pedestrian*

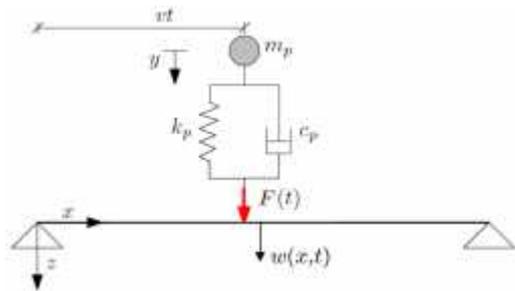Fig. 6. *Moving mass model of a pedestrian*

Fig. 7. *SMD model of a pedestrian*

$$\mathsf{w}_j(x) = \frac{\tilde{\mathsf{w}}_j(x)}{\sqrt{M_j}} \tag{2}$$

mode shapes. The differential equation for the *j*-th mode with the corresponding *j*-th generalised load $F(t)\phi_j(vt)$, assumed to be travelling at a constant velocity $v=f_p \cdot l_s$, is expressed as:

$$Q_j = \ddot{q}_j + 2\langle{}_j \check{S}_j \dot{q}_j + \check{S}_j^2 q_j = F(t)\mathsf{w}_j(vt) \tag{3}$$

where q_j denotes the modal coordinate, $_j$ represents the modal damping ratio and $_j$ the *j*-th angular frequency, while $\phi_j(vt)$ describes the modal shape at the location point $x(v,t)=v \cdot t$ of the moving load at the time instant *t*. The MF approach is not able to incorporate any characteristics of the human body or of the human gait besides modelling the movement by the modal force. Therefore the MM was also taken

into consideration for analysing the pedestrian bridge albeit it only adds mass as a parameter of the human body. In this model the mass is positioned right on top of the beam and is, for modelling purposes, described by the same coordinate *w,* as the vertical displacement of the beam (s. Fig. 6). Unlike in the case of the MF approach, the dynamic equilibrium of forces considering the mass of the pedestrian m_p by its inertia yields a modal force of [1]:

$$Q_j(t) = \lfloor F(t) - m_p \ddot{w}(vt,t) \rfloor \mathsf{w}_j(vt) \tag{4}$$

The first and second derivative of the beam's vertical displacement, which is determined through superposition of all the modal components acc. to Eq. (5),

$$w(\mathrm{x,t}) = \sum_{i=1}^n q_i(t)\mathsf{w}_i(x) \tag{5}$$

along with Eq. (4) and the vector $\underline{\mathsf{w}}(vt) = [\mathsf{w}_1(vt) \quad \dots \quad \mathsf{w}_n(vt)]^T$, containing the values of the mode shapes at each time instant *t* can be incorporated in the modal differential equation (Eq. (3)). This results in the following matrices of the system [1]:

$$\underline{M} = I_{n \times n} + m_p \underline{\mathsf{w}}(vt)\underline{\mathsf{w}}^T(vt) \tag{6}$$

$$\underline{C} = diag[2\langle{}_j \check{S}_j]_{n \times n} + 2m_p v\underline{\mathsf{w}}(vt)\underline{\mathsf{w}}'^T(vt) \tag{7}$$

$$\underline{K} = diag[\check{S}_j^2]_{n \times n} + m_p v^2 \underline{\mathsf{w}}(vt)\underline{\mathsf{w}}''^T(vt) \tag{8}$$

The force vector containing $F(t)\phi_j(vt)$ for each equation is the same as considered in the MF approach.

In the final step, a SMD model was implemented in the structural analysis process. In this approach the mass is connected to the bridge via a spring and a damper, mounted on top of the structure, while the harmonic force described in

Eq. (1), simulating the human gait is induced at the contact point (s. Fig. 7). Likewise in the models presented above, the SMD is moving over the bridge system at a constant pace v. As both components, the beam and the SMD are connected, they can be treated as a coupled system, which includes the additional mass m_p, stiffness k_p and damping c_p, as characteristics of the human body. In this approach, the mass is described by the vertical coordinate y as its single DOF while the displacement of the beam structure is still depicted by the coordinate w. The dynamic equilibrium for the mass yields

$$m_p \ddot{y} + c_p (\dot{y} - \dot{w}) + k_p (y - w) = 0 \qquad (9)$$

as the differential equation of motion for the mass m_p. Inserting the vertical displacement of the beam according to the principle of superposition (Eq. (5)), the following equation can be derived, whereas the summation operator from Eq. (5) is expressed as a vector multiplication of $\underline{w}^T$ and $\underline{q}$ or $\underline{w}^T$ and $\dot{\underline{q}}$, respectively:

$$m_p \ddot{y} + c_p \left[\dot{y} - c_p \underline{w}^T (vt) \dot{\underline{q}} \right] \\ + k_p \left[y - k_p \underline{w}^T (vt) \underline{q} \right] = 0 \qquad (10)$$

Using the MM's formulation for the load (Eq. (4)) and substituting y for w in the differential equation Eq. (3) with modal coordinates, describing the displacement of the structure, the system matrices expressed by Eq. (11) to Eq. (13) are obtained [1]. The corresponding force vector is described by Eq. (14).

It is of great importance that the parameters for the stiffness and damping of the SMD are assumed within a realistic range, so that they can provide reliable insights into the influence of the human body on the time histories of the motion quantities generated during the pedestrian locomotion. In the present investigation analysis, values of 15 kN/m for the stiffness of the spring k_p and a damping ratio $\zeta_p = 0.1$ corresponding to a damping coefficient c_p=219 Ns/m were chosen [6] (slightly higher than suggested in [2]).

$$\underline{M} = \begin{bmatrix} I_{n \times n} & m_p \underline{w}(vt) \\ 0_{1 \times n} & m_p \end{bmatrix} \qquad (11)$$

$$\underline{C} = \begin{bmatrix} diag \left[2\zeta_j \check{S}_j \right]_{n \times n} & 0_{1 \times n} \\ -c_p \underline{w}^T (vt) & c_p \end{bmatrix} \qquad (12)$$

$$\underline{K} = \begin{bmatrix} diag \left[\check{S}_j^2 \right]_{n \times n} & 0_{1 \times n} \\ -k_p \underline{w}^T (vt) & k_p \end{bmatrix} \qquad (13)$$

$$\underline{F} = \begin{bmatrix} F(t) \underline{w}(vt) \\ 0 \end{bmatrix} \qquad (14)$$

3.2. Results of the Structural Analysis

All the aforementioned models were used to evaluate the dynamic structural response of the footbridge under pedestrian loading, whereas the equilibrium equations were integrated using the time-stepping method of Newmark [11] in conjunction with the computer algebra system Matlab®.

Fig. 8 exemplarily shows displacement and acceleration time histories at midspan obtained using the three numerical approaches presented above for one person with a weight force of 0.8 kN, walking over the structure with a step frequency of 2 Hz, i.e. very close to the first resonant frequency of the bridge (~2.03 Hz). An overview over the absolute maximal values of the motion quantities (displacement and accelerations) for walking at different step frequencies is illustrated in Fig. 9, whereas the corresponding results from the measurements (presented in section 4) are included in the figure as well, in order to facilitate the comparison.
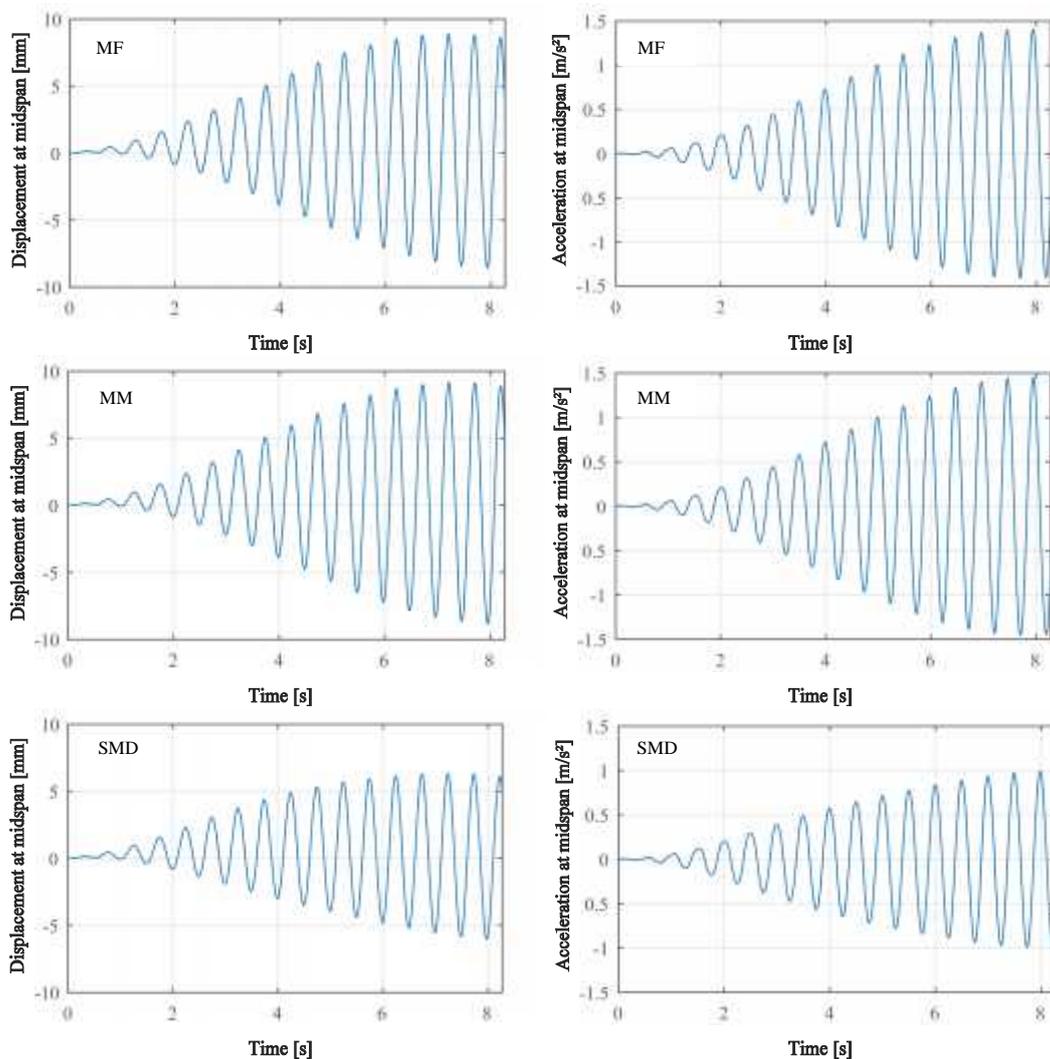
Fig. 8. *Displacement (left) and acceleration (right) time histories at midspan of the bridge: MF (top), MM (middle), SMD (bottom)*

It can be observed that modelling the pedestrian only by its body mass does not produce significant differences of the motion quantities in comparison with the moving force approach. Moreover, the accelerations and displacements of the moving mass model can be, unexpectedly, even slightly higher than the ones generated by the moving force, as for example in case of walking at the resonant frequency (two steps per second). This effect occurs most likely due to the still undetermined changes in the damping of the coupled system over time.

On the contrary, the spring-mass-damper model reveals in general considerably lower displacements and accelerations than the MF and MM approaches. The highest relative differences, of about 40-80%, occur in case of walking with step frequencies close to the first resonant frequency of the structure, (e.g. for 2.0 and 2.1 Hz, s. Fig. 9). This indicates clearly an "absorber effect" of the human system, i.e.
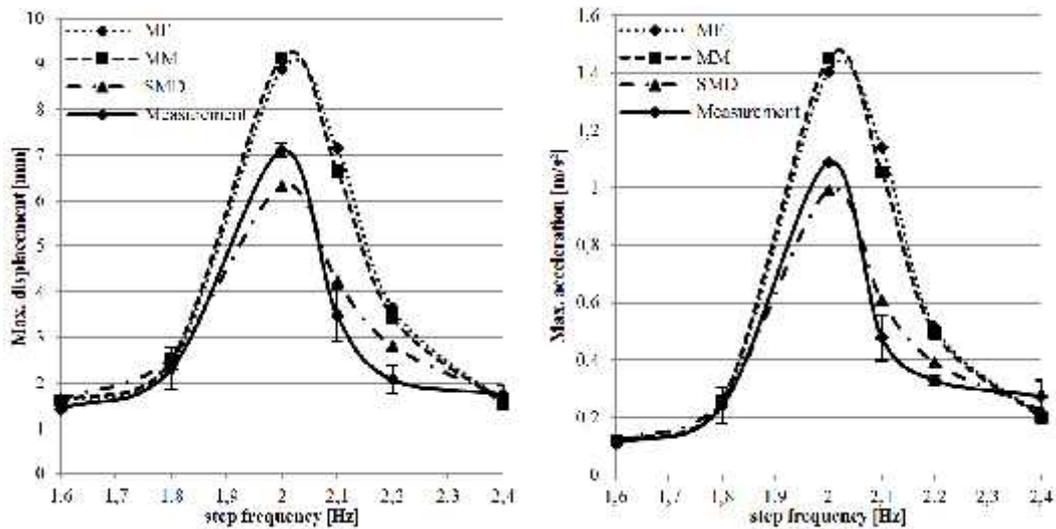
Fig. 9. *Maximal displacements (left) and accelerations (right) at midspan of the bridge*
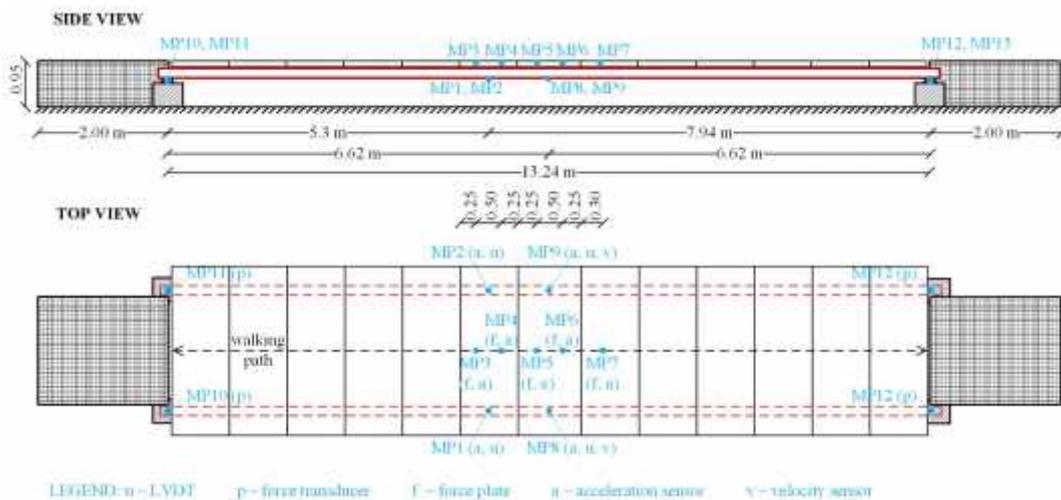

Fig. 10. *Measurement set-up*

an increasing overall damping of the system over time, observed also by Caprani et al. [1].

4. Experimental Investigations

4.1. Measurement Set-up

Subsequent to the structural analysis, the pedestrian bridge presented in section 2 and considered in the numerical models, was subjected to the first preliminary experimental investigations in order to verify if the computationally obtained effects of human-structure interaction occur in the experiments as well. For this, the same scenarios as in the structural analysis, i.e. one person walking on a predefined path (longitudinal axis of the structure, s. Fig. 10) in the step frequency range 1.6-2.4 Hz, were considered.

Fig. 10 schematically shows the location of all the sensors used in the measurement. As the experimental set-up serves both for

investigations concerning the mechanics of the structure and the biomechanics of the human body, the measurement set-up is very complex, employing nine very sensitive acceleration sensors, four linear variable displacement transducers (LVDT), two velocity sensors, four force transducers for measurement of the support forces as well as five biomechanical force plates for acquisition of the ground reaction forces signals. In addition, a biomechanical motion capture system (MCS) was utilised for a high-frequent recording of the movement for individual body segments. The analysis of the MCS data can be used either for determining of the human body parameters, e.g. stiffness and damping or to reconstruct the ground reaction forces by means of the second Newton's law of motion [12]. However, only displacement and acceleration data of the midspan point MP8 are addressed in this paper. As only loading scenarios along the longitudinal axis were planned, the analysis of MP8 was sufficient, as it is expected that all the points of the cross-section experience similar movement behaviour. This aspect was checked by means of comparison between MP8 and MP9.

4.2. Measurement Results and Discussion

The fundamental frequency of 2.04 Hz determined through ambient measurements

and subsequent Fourier analyses matches the computed result of 2.033 Hz very well. The higher measured natural frequencies are as well in a very good agreement with the corresponding values from the numerical analysis. The modal damping ratio was determined to 0.3%, using the logarithmic decrement approach on several free decay signals. The acquisition rate was 2400 Hz for the LVDTs and 2000 Hz for the acceleration sensors. However, a low pass filter with the cut-off frequency of 35 Hz was applied within the signal processing. The same frequency content was considered as well in the structural analysis.

Fig. 11 illustrates typical displacement and acceleration time histories measured at the point MP8, generated by a subject walking with 2 Hz. As the subject weights 0.76 kN, the results had to be normalized to a subject weight of 0.8 kN, the same value as assumed in the computations. As the step frequency lies very close to the fundamental frequency of the unloaded structure, built-up resonance effects are clearly visible, i.e. the response from one footfall is amplified by the next step. This effect also occurred in the structural analysis (s. Fig. 8).

The absolute maximal displacements and accelerations (as average values from all the trials) and the corresponding error bars, representing one standard deviation of uncertainty, are shown in Fig. 9 along with
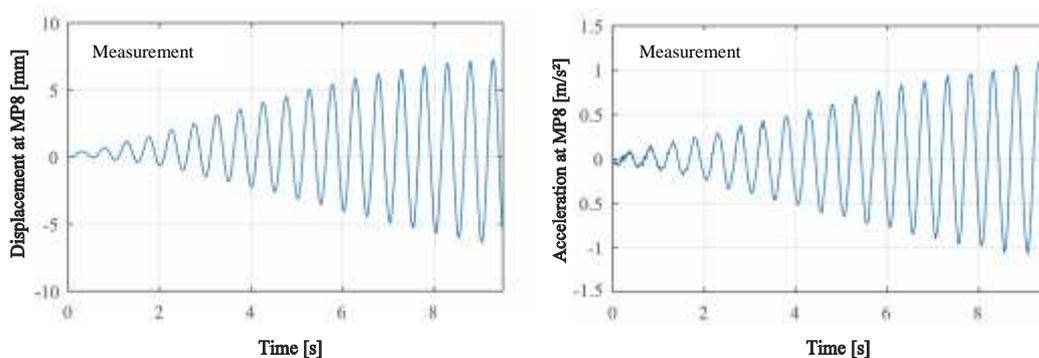

Fig. 11. *Displacement (left) and acceleration (right) time histories measured at MP8*

the results of the structural analysis for all investigated walking step frequencies. The MF and MM approaches obviously overestimate the structural response by about 30% in case of quasi resonant excitation (step frequency of 2 Hz). On the contrary, a good correlation between the measurements and the results of the SMD approach can be observed. The relative differences lie at about 10% for the maximal accelerations and 12% for the corresponding maximal displacements in the worst case scenario of resonance excitation. The differences can be explained by the assumption of literature values for the parameter set of the human system (k_p=15 kN/m and c_p=219 Ns/m) as well as for the moving load definition instead of using real values of the investigated subject.

5. Conclusions and future work

The TU Darmstadt HUMVIB-Bridge was subjected to numerical and experimental investigations concerning the human-structure interaction. It was shown that the classical approach of modelling the human action by a moving load and the simplified interaction model of a moving mass can overestimate the measured responses from a human excitation by about 30% at resonance excitation. The comparison of the results for a more complex spring-mass-damper model with the corresponding measured values revealed a very good correlation between the respective quantities. This indicates that the assumption of the human system acting as a "vibration absorber" is justified and hence it can be further investigated.

However, the parameter set for the mechanical system of the human body as well as the load definition were adopted from the literature, which might represent an error source, as they are in reality subjected to a high inter-subject variability.

Hence, further investigations are planned, which will try to eliminate this error source by considering the real stiffness and damping parameters of the investigated subjects as well as measured time histories of the ground reaction forces within the numerical analysis, in order to better isolate the interaction effect.

Furthermore, similar experimental investigations are envisaged for pedestrian crowd loading, as it is expected, that the interaction effect becomes even more relevant in this case. This requires as well the analysis of the variation of dynamic system properties (damping and natural frequencies) over time, as significant changes are expected due to the higher ratio between the mass of human-systems and structural mass.

Further research topics at TU Darmstadt deal with the link between biomechanics and structural mechanics. In this context, a reliable implementation of common biomechanical bipedal models for gait simulation in the structural analysis is intended.

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