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INVESTIGATION OF THE HUMAN-STRUCTURE INTERACTION ON A FULL SCALE EXPERIMENTAL FOOTBRIDGE

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This contribution presents selected results of the numerical and experimental investigations into the effect of human-structure interaction (HSI), performed within a joint project between the Institute of Structural Mechanics and Design and the Institute of Sport Science of the TU Darmstadt (Germany). The project on the one side analyses structural responses of a full-scale experimental footbridge under pedestrian excitation and on the other side identifies human body parameters and adaptation mechanisms during walking of a human on a flexible structure. The test structure was instrumented with biomechanical force plates, a 3D motion capture system as well as several sensors for acquisition of the structural responses. An alternative method for the identification of dynamical parameters for the human body, which is modelled as a single-degree of freedom mass-spring-damper system (SDOF MSD), is proposed.

The method for the MSD parameter identification is based on ground reaction force (GRF) measurements for a subject during walking both on a flexible and on a rigid structure. While the ground reaction force $p_b(t)$ induced by a pedestrian on a perfectly rigid floor depends only on the step frequency and on the pedestrian weight, the contact force $p_p(t)$ in case of a flexible structure depends as well on the interaction between the pedestrian and the structure. It can be expressed acc. to equation (1) as a sum of the ground reaction force exerted on a rigid floor $p_b(t)$ and an interaction force term $p_h(t)$.

$$p_p(t) = p_b(t) + p_h(t) \qquad (1)$$

In order to account for the human-structure interaction, the pedestrian is approximated by a single degree of freedom mass spring damper system (MSD) travelling over the structure at a constant speed, together with a time dependent force, applied externally at the contact point between the structure and the MSD. The moving force depicts the ground reaction force exerted by a pedestrian while walking on a rigid structure and corresponds to the term $p_b(t)$ in equation (1). The spring and damping forces generated by the relative motion between the mass of the SDOF MSD model and the contact point of the structure account for interaction effects by modifying the contact force. They are comprised by the term $p_h(t)$.

Experimental investigations on a test pedestrian bridge allowed both measurements of ground reaction forces in a flexible ($p_p(t)$) and in a rigid configuration ($p_b(t)$), by installing a third support at mid-span. Each of the GRFs measured in the rigid and the flexible configuration was approximated by a Fourier series. Considerable differences (rigid-flexible) were observed only in the case of the first harmonics for walking with resonant frequency. This confirms that the HSI is rather relevant in case of resonant excitation. Using the difference $\Delta p(t)$ between Fourier representations of the GRF in rigid and in flexible configuration (Fig. 1a) and the equilibrium expression of the MSD, the following equation can be formulated.

$$\Delta p(t) = k_p \cdot y_{rel}(t) + c_p \cdot \dot{y}_{rel}(t) \qquad (2)$$

where y_{rel} represents the relative displacement between the COM of the human body and the contact point on the structure (determined by measurements with the 3D motion capture system). By discretising it in time, a linear equation system can be set-up and solved using a least square minimisation, in order to identify the corresponding stiffness k_p and damping coefficient c_p. The stiffness values obtained through an optimisation in a single step over the whole time window (Table 1) are considerably higher for a (near resonant) step frequency of 2 Hz than for the other investigated step frequencies. This effect occurs due to the higher GRF differences, which have to be compensated by the SDOF MSD.

f_s	1.6 Hz	1.8 Hz	2.0 Hz	2.2 Hz	2.4 Hz
k_p [N/m]	1151 ± 151	936 ± 66	5113 ± 469	613 ± 127	2426 ±163
c_p [Ns/m]	152 ± 46	301 ± 30	211 ± 89	62 ± 1	67 ± 7

Table 1. Stiffness and damping coefficient determined for different step frequencies

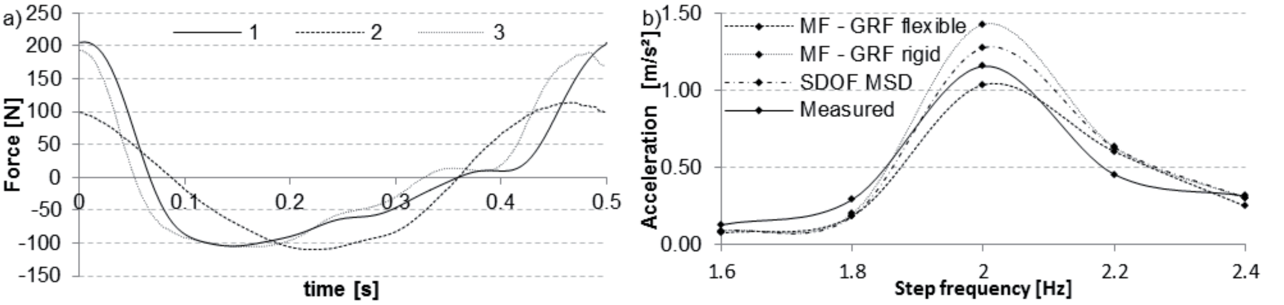

Fig. 1. a) GRF difference for a pedestrian having a body mass of 73.31 kg, walking with 2 Hz: 1- measured, 2 – reconstructed acc. to equation 2 and table 1 (least square optimisation in a single step over the whole stance), 3 – reconstructed using time variable stiffness and damping; b) Maximal accelerations at mid-span of the bridge: computational and measurement results

The reconstruction of the GRF difference according to the values in Table 1 and equation (2) underestimates the measured GRF difference (Fig. 1a). Hence the structural response generated by a computation with the SDOF MSD approach (defined by the parameters in Table 1) is higher than the measured one (Fig. 1b). However the maximal relative difference lies at about only 10% (at resonance), while the moving force approach (with GRF measured in the rigid configuration) overestimates the measured acceleration by up to 23%. This indicates that the assumption of the human-body as a “vibration absorber” is justified. The numerical analysis with the moving force approach using GRF measured at the mid-point of the flexible structure resulted in underestimated structural responses. This effect can be attributed to the assumption of the mid-span GRF as load for the whole walking length on the bridge, which is likely to be erroneous, since the GRF reduction due to the interaction effects is directly influenced by the vibration amplitude.

In order to check if the MSD result can be improved, the time histories introduced in equation (2) were split in 100 time windows of equal length. Subsequently, a least square optimisation problem was solved for each window. This results in time dependent stiffness and damping coefficient (Fig. 2). Fig. 1a shows that the consideration of time variable parameters significantly improves the approximation of the reconstructed GRF difference. The implementation of time dependent MSD parameters in the numerical analysis revealed a maximum acceleration of about 1.21 m/s², i.e. a relative difference to the measured response of about 4.3%. Hence the assumption of time dependent MSD parameters is justified in case a high accuracy is required.

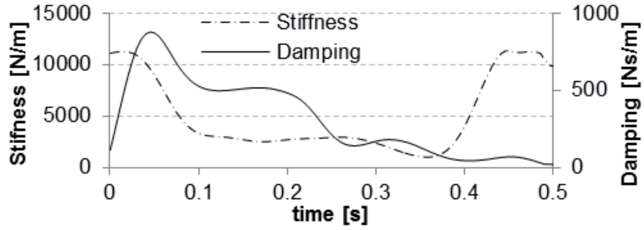

Fig. 2. Time histories (moving average) of the stiffness and damping over a complete stance for f_s = 2 Hz

The methodology for identification of human body parameters introduced in this contribution was validated through comprehensive numerical and experimental investigations with human subjects walking at different step frequencies over a full scale experimental pedestrian bridge. However, since only a reduced number of subjects has been considered yet, the statistical influence for the varying stiffness and damping coefficients for the adopted SDOF MSD model will be the goal of further investigations. Furthermore, the insights gained from the investigations of single persons have to be extended and adapted for human crowd loading, where the HSI plays an even more important role.