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Bridge Analysis Structure under Human Induced Dynamic Load

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***Abstract*—**The paper deals with the analysis of the dynamic response of footbridges under human - induced dynamic loads. This is a frequently occurring and often dominant load for footbridges as it stems from the very purpose of a footbridge - to convey pedestrian. Due to the emergence of new materials and advanced engineering technology, slender footbridges are increasingly becoming popular to satisfy the modern transportation needs and the aesthetical requirements of the society. These structures however are always lively with low stiffness, low mass, low damping and low natural frequencies. As a consequence, they are prone to vibration induced by human activities and can suffer severe vibration serviceability problems, particularly in the lateral direction. Pedestrian bridges are designed according to first and second limit states, these are the criteria involved in response to static design load. However, it is necessary to assess the dynamic response of bridge design load on pedestrians and assess it impact on the comfort of the user movement. Usually the load is considered a person or a small group which can be assumed in perfect motion synchronization. Already one person or small group can excite significant vibration of the deck. In order to calculate the dynamic response to the movement of people, designer needs available and suitable computational model and criteria. For the calculation program ANSYS based on finite element method was used.

***Keywords*—**Footbridge, dynamic analysis, vibration serviceability of footbridges, lateral vibration, stiffness, dynamic force, walking force, slender suspension footbridges, natural frequencies and vibration modes, rhythm jumping, normal walking.

I. Introduction

THIS paper deals with the analysis of dynamic response of footbridge which is loaded by the pedestrian movement and then deals with evaluation of response in terms of user comfort. This issue is given special attention in recent years. This is due to several cases of vibration of bridge structure caused by movement of persons. This behavior was very significant to discomfort for the user [4], [5]. The structure was not possible to use by pedestrian in several cases. The problem does not involve just a few structures but the vast majority of footbridges. The structures are designed for static load according to the ULS and the SLS but it should be performed an assessment for the SLS in terms of user comfort. This is the analysis of dynamic load which is modeling the movement of a person or a few persons. The perfect synchronization is assumed and therefore to excite the significant dynamic response of the structure.

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Construction of footbridges is due to span the low-mass structure. The supporting structures may be complex and combined static systems which generate very aesthetically valuable works [4]. Lightweight construction of footbridges may have in terms of dynamic properties small values of damping particularly for the natural frequency located in the interval which includes frequency of human walking. There is no threat in terms of design load but due to vibration of the deck may disrupt the comfort of walking.

Step frequency of vertical pedestrian load is in the range from 1.6 to 2.2 Hz [1]. Standards recommend design structures whose natural frequency does not belong within the range of human walking. For example [9] requires in order to natural bending frequencies were not lower than 3 Hz. This requirement can be difficult to fulfill because many of structures have lower natural bending frequency and still exhibit good dynamic behavior. Construction of suspension footbridges has approximately 1 Hz natural bending frequency [5].

The level of synchronization pedestrians and the stability of step frequency have very significant influence to the dynamic response for crossing a footbridge. Fixed step frequency for crossing a bridge is in the case of an individual or small filling of the bridge when the footbridge is filled by pedestrians the speed of pedestrians decreases. Irregularity of step frequency occurs by the density of 1.5 person/m2 and total dynamic load is reduced [8].

The dynamic analysis was performed by 1 to 16 persons on the selected footbridge. Their movement was thought fully synchronized and the step frequency was chosen according to the natural frequency of the footbridge so that the load representing the movement of people was in resonance [1].

II. Description of the Solution Structure

The footbridge for pedestrians and cyclists is designed as a suspension construction for a field length 84.0 m. Suspension cables are stretched between the pylons which are joined to the foundation by joints and are held at their peaks by the anchor cables. Height of the pylons is 16.490 m from the upper face of the base block. Three meters width steel deck is composed of crossbeams hung on hinges which are connected to the main suspension cable per each 3.0 m. Deck plate is stiffened by longitudinal beams which height is 200 mm [10].

Fig. 1 Suspension footbridge

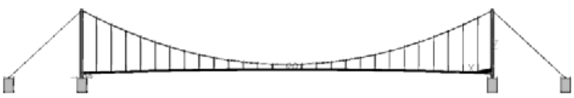

Fig. 2 Side view of footbridge

III. Calculation of Dynamic Response

Solution of the response to the dynamic load requires adequate computational model which takes into account geometrical and physical properties of the structure. Each detail of the connection has not to be modeled in terms of global analysis of structure [14]. The computational model was created for numerical analysis by the ANSYS program system for the purposes of global analysis of static and dynamic load. Modeling of the parts of the structure is described by the types of finite elements which reflect their behavior in real state [11], [12]. The following elements BEAM44, LINK10, LINK8 were used from the library of finite elements of that program. Analysis of the structure is designed as a non-linear and takes into account large deformations. Material characteristics of the structure are described as linear. Dynamic equilibrium of the structure which is described by the general dynamic equation (1) was solved by the Newmark's method.

$$M\ddot{u} + C\dot{u} + Ku = F(t) \tag{1}$$

It is necessary for the solving of dynamic response to perform a modal analysis. Thus we obtain natural frequencies with belonging vibration shapes which show dynamic properties of the structure. The suspension bridges have always few vibration shapes such as lateral, longitudinal, bending and torsion [9]. The vibration shapes are found mainly in combination such as laterally-torsion and torsion-bending. Calculation of natural frequencies was performed using algorithm of method block Lanczos. Subsequently the natural frequency is chosen within the frequency interval of human walking. The selected frequency must belong with the corresponding vibration shape of the structure (e.g. bending, torsion-bending) which can be excited by the load. The slender constructions of footbridges have very low natural frequencies within the frequency interval of human walking [4], [14]. These low natural frequencies and their appropriate natural modes can be excited by the movement of pedestrians.

IV. Dynamic Model Load of Stepping Force

When the human foot treads on the mat the force occurs. This force can be divided into three orthogonal components. The vertical component of the force is the largest and it is shown in Figure 3. The dynamic coefficient of human step is rendered on the vertical axis with the maximum value 1.4 [-]. The value of dynamic coefficient may range in the interval from 1.1 to 1.9 [3]. Dynamic load which is caused by movement of persons can be expressed in periodic functions. The vertical load which is generated by a single pedestrian can be expressed by equation (2) in which the dynamic coefficient is 0.257 [-]. Only the dynamic component of stepping force is taken into account in this equation.

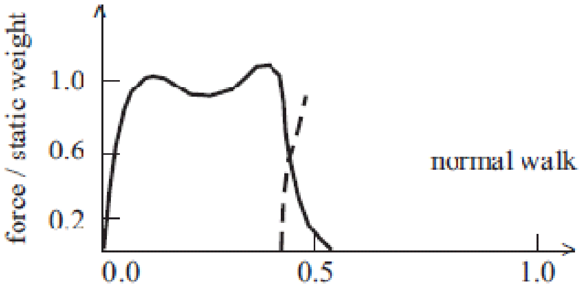

Fig.3 The stepping force at the frequency 1,4 – 2,2 Hz

$$F_{(t)}=700.0,257.\sin(2.\pi.f_0).t \tag{2}$$

The equation (2) can be expressed in the form,

$$F_{(t)}=G+G.0,257.\sin(2.\pi.f_0).t \tag{3}$$

where G is the weight of the person, f_0 is stepping frequency which is identical with the natural bending frequency of footbridge located in the interval of human walking. The expression (3) already takes into account the total weight of person including the dynamic coefficient. The weight of a person is 700 N.

Another variant expression of the vertical component of stepping force is by using Fourier series [3], [6], [7] where it is possible to take into account multiple harmonic frequencies. Expression is a specific case in Figure 3. Stepping force:

$$F_{p(t)} = G + \sum\left(G.\alpha_i.sin\left(2\pi.i.f_p.t - \varphi_i\right)\right) \tag{4}$$

where:

G = 750 N is the weight of the person, α_i is the Fourier coefficient of the i^{th} harmonic component of excitation force (impact factor), f_p is the step frequency (identical to the less important natural frequency of the structure), φ_i is the phase shift between the harmonic components of stepping force.

The vertical component of stepping force is expressed with the following parameters $\alpha_1 = 0,4$ [-], $\alpha_2 = 0,1$ [-], $\alpha_3 = 0,1$ [-], $\varphi_1 = 0,0$ [rad], $\varphi_2 = \pi/2$ [rad], $\varphi_3 = 3\pi/2$ [rad]. The form function of horizontal component of stepping force is expressed by these parameters $\alpha_{1/2} = 0,005$ [-], $\alpha_2 = 0,01$ [-], $\alpha_2 = 0,01$ [-], $\alpha_3 = 0,01$ [-], $\varphi_1 = \varphi_2 = \varphi_3 = 0,0$ [rad]. The steps frequency is taken according to selected natural frequency of footbridge f = 2.106 Hz, the length of step is considered 0.8 m.

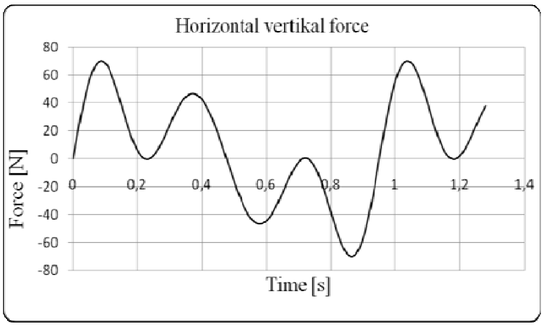

Fig. 4 The horizontal lateral component of the stepping force

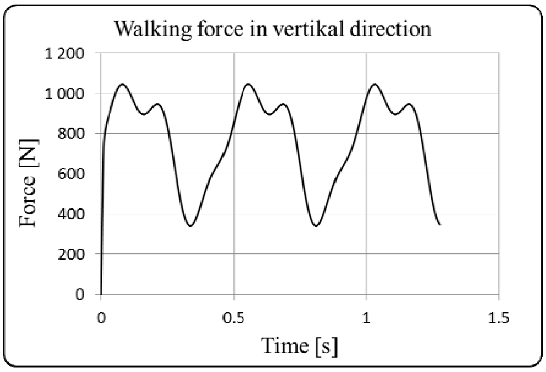

Fig. 5 The vertical component of the stepping force

V. Dynamic Response of Bridge Structure Loaded by the Movement of Pedestrians

Calculation of dynamic response of the structure was carried out for the load simulating the movement of one to sixteen people. Load modeling the movement of people is changing the intensity of load according to (2). Simultaneously the position of force is changing. At the beginning of the calculation the first force that represents a person is located until the next "walker" is placed in the chosen spacing. Spacing was chosen 2.5 m. At a certain moment there are number of 16 forces on the deck and each of them represent the stepping force of one person.

Figure 6 shows the selected eigen vibration of natural frequency identical to the stepping frequency of load. The evaluation is carried out in the places with the greatest deviation. It is assumed in the case of excitation by the frequencies close to or identical to natural frequency of structure that significant vibration will be in the places with the greatest oscillation of appropriate mode shape [15]. Size response depends in addition the load mainly on the time of excitation. In the case of persons crossing the bridge the excitation period corresponds to the time needed to overcome the walkway of the bridge deck.

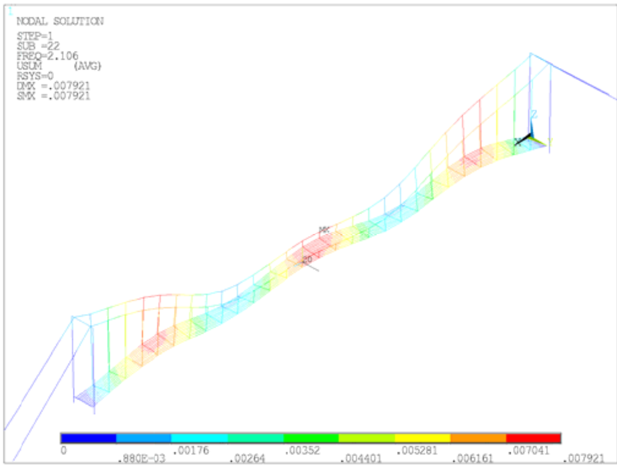

Fig. 6 Selected shape natural vibration of the structure

The graphs in Figure 7 show the change of dynamic response vs. the number of pedestrians. Evaluation is made for the point of deck located in the middle of span. The place with the greatest oscillation is located for appropriate frequency in this point. The time of readout is in the middle of the total time required to move all people. Dependence of the size of the shift point to the number of pedestrians is initially almost linear [13]. This phenomenon was more pronounced in the case of a smaller spacing between pedestrians. Mitigating the relationship between the number of people and size of deflection is the result of uniformly distributed load of persons when the load does not work locally but causes more uniform deflection with the less total value on a larger area than small group of pedestrians centered around one location.

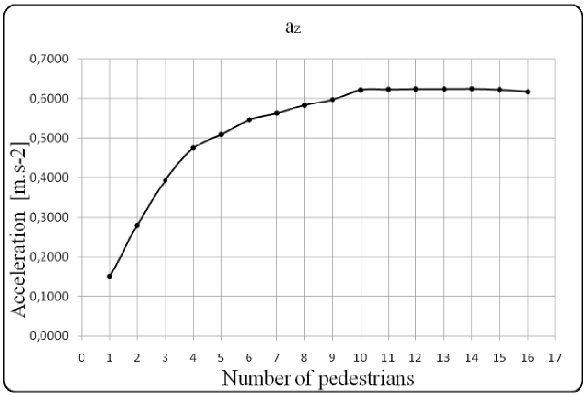

Fig. 7 Change of dynamic response of the structure on the number of pedestrians – acceleration in vertical direction

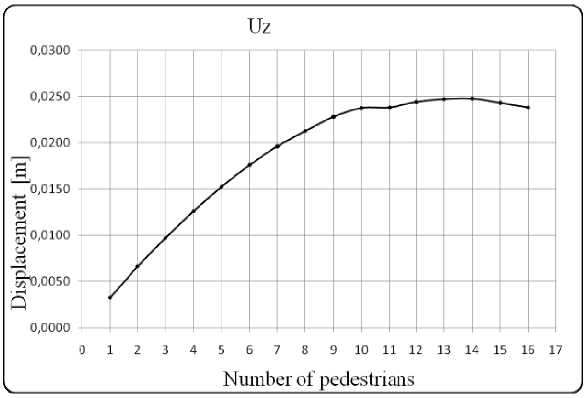

Fig. 8 Change of dynamic response of the structure on the number of pedestrians –displacement in vertical direction

The course of displacement and acceleration in the point at L/2 is shown above. Cases for one, eight and sixteen pedestrians are shown. Acceleration in the case of one and eight pedestrians clearly shows how the structure oscillates in the relevant natural shape. There is the increasing value of the acceleration at a time when pedestrians are approaching the point with the greatest oscillation that is approximately L/4 and L/2. It occurs to deck oscillation with a greater acceleration than in previous case when the sixteen pedestrians are walking (0.71 m.s-2) but no longer so significant excitation in the appropriate mode shape. Difference disappears completely when the load is transferred from the largest deflection through node (a place with almost no deflection).

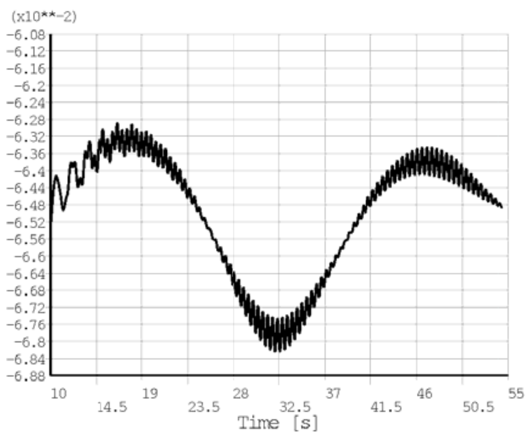

Fig. 9 Displacements in the point at L/2 – vertical, case for one pedestrian

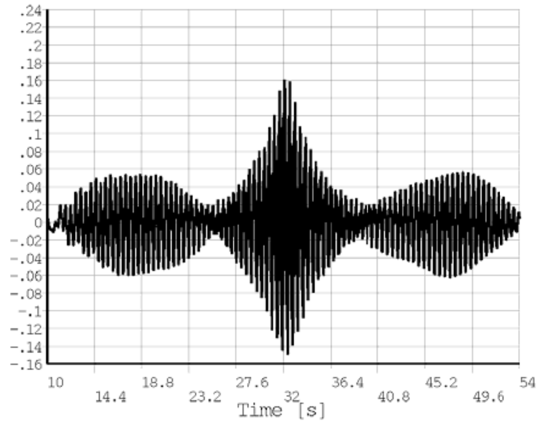

Fig. 10 Acceleration in the point at L/2 – vertical

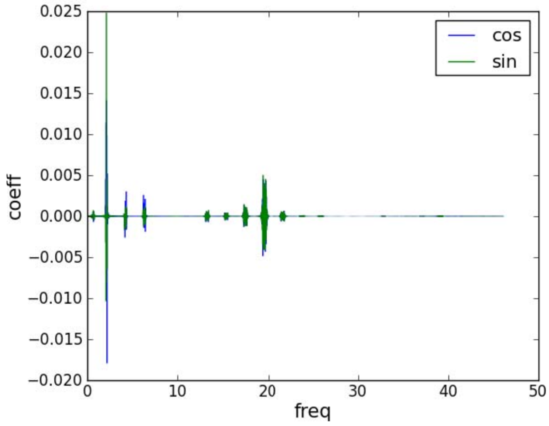

Fig. 11 Frequency and Fourier coefficient, case for one pedestrian

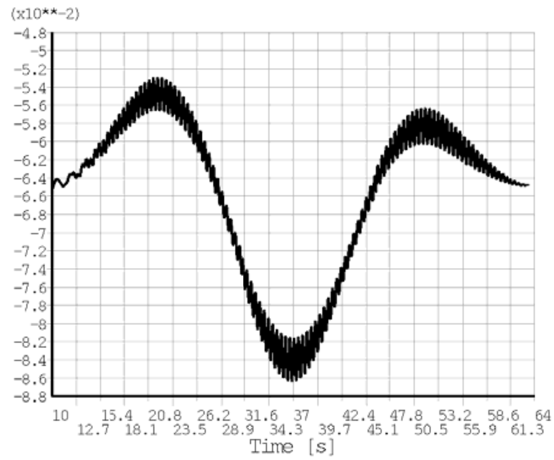

Fig. 12 Displacements in the point at L/2 – vertical, case for eight pedestrians

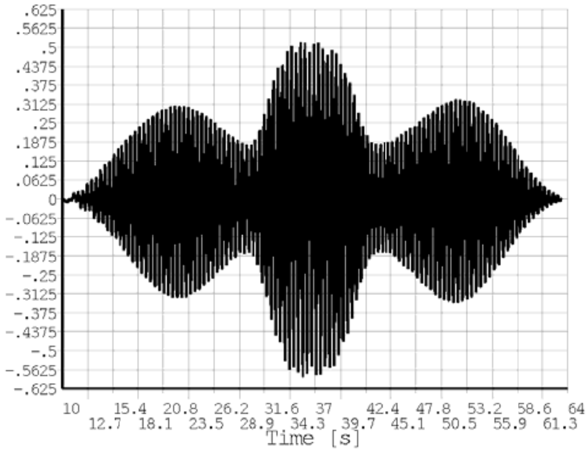

Fig. 13 Acceleration in the point at L/2 – vertical

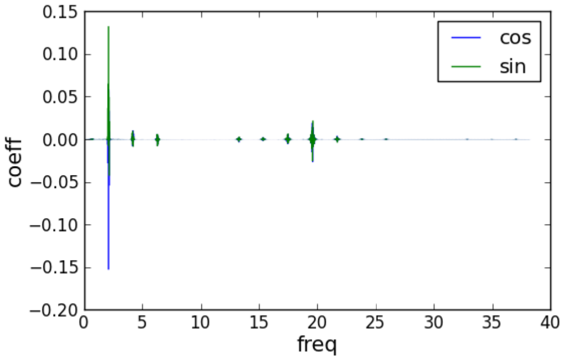

Fig. 14 Frequency and Fourier coefficient, case for eight pedestrians

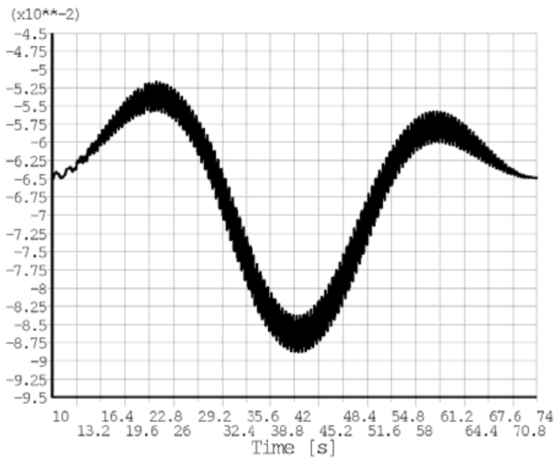

Fig. 15 Displacements in the point at L/2 – vertical, case for sixteen pedestrians

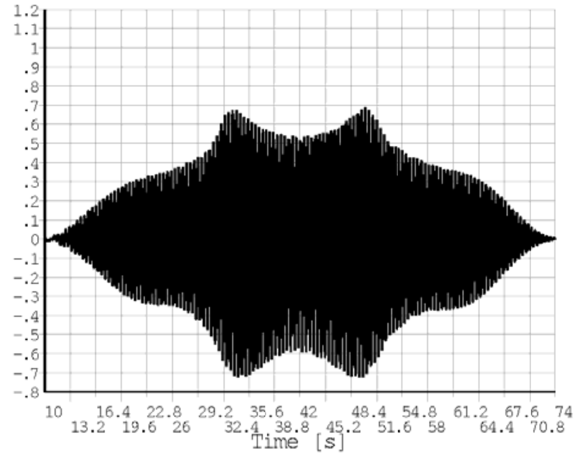

Fig. 16 Acceleration in the point at L/2 – vertical

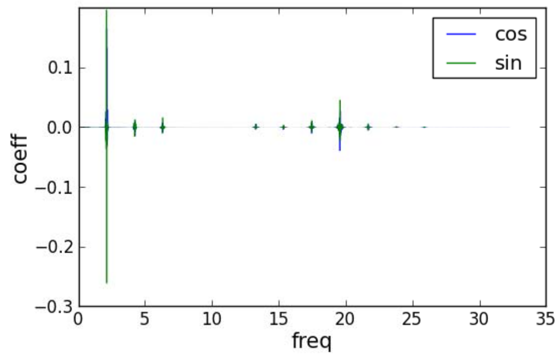

Fig. 17 Frequency and Fourier coefficient, case for sixteen pedestrians

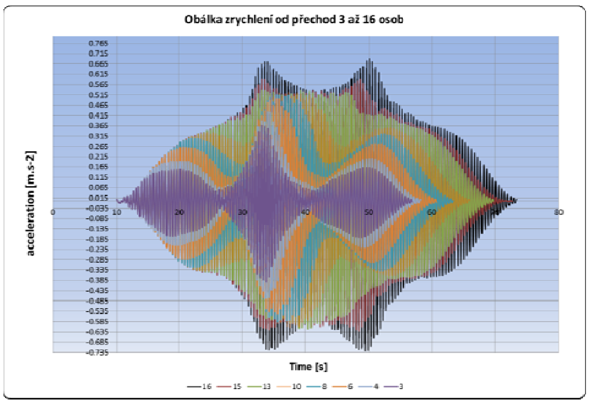

Fig. 18 Cover of acceleration by transition from 3 to 16 persons [$m.s^{-2}$]

VI. Conclusion

This study deals with the dynamic response of the footbridge loaded by the movement of persons. The dependence of the increasing dynamic response was studied on the number of synchronized pedestrians crossing the footbridge. Synchronized group of people going in the frequency identical to the natural frequency of structure can excite vibration of the structure in the corresponding mode shape.

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