Turbulent wind action on a slender footbridge

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Abstract

This paper concerns analysis of turbulent wind action on a single-span footbridge. Firstly, the issue of the velocity wind field in the boundary layer was mentioned. Then the simplified quasi-steady model of the wind action on a slender object was presented. Procedure of simulation of turbulent wind action was also shown. The specific case without aerodynamic feedback was considered on the exemplary footbridge. Analysis of such action in numerical program was shown as well as the evaluation of its results.

Keywords: turbulent wind field, time domain analysis, quasi-steady model, numerical analysis

1. Introduction

Wind velocity field in the boundary layer is highly random in space and time. Variations in wind velocity and direction are caused by atmospheric turbulence and are dependent on the terrain type and its roughness. Vector of wind velocity has three components: longitudinal V_x, transversal V_y and vertical V_z. Each of them is a sum of static and fluctuation velocity. Static component is a value which is averaged in time period of 10 minutes and it is usually a function of height over terrain. Fluctuation velocity is associated with dynamic features of wind action and it is centered random process of the zero mean value. To sum up, velocity and direction of wind can be presented in the following way:

$$V(\mathbf{r},t) = \bar{V}(\mathbf{r}) + V'(\mathbf{r},t)\ ,\ \alpha(\mathbf{r},t) = 0 + \alpha'(\mathbf{r},t) \tag{1,2}$$

where: $V(\mathbf{r},t)$ – vector of wind velocity in time t and of conductive vector $\mathbf{r}$, $\bar{V}(\mathbf{r})$ – static (mean) wind velocity, $V'(\mathbf{r},t)$ – turbulent wind velocity, $\alpha(\mathbf{r},t)$ – angle of wind onflow, $\alpha'(\mathbf{r},t)$ – dynamic angle of wind onflow.

2. Quasi-steady model of turbulent wind action on slender footbridges

New materials and technologies make the footbridges much lighter, so that they are more vulnerable to dynamic wind action on them [1]. Quasi-steady model can be used to determine turbulent wind action on these structures [2,3]. This approach is based on the assumption concerning formulas which connect wind velocity field in the front of the object with the field of wind action on it. It was assumed that by the extrapolation of the formulas for steady object and stationary air flow in the front of it one can easily obtain these formulas in conditions of disturbed air flow in the front of the object and its movements [4].

Wind action on the footbridge is averaged in the area of a fragment of construction and is reduced to three concentrated wind actions. Wind coordinate system is adopted in such a way that mean binormal component of the wind velocity (V_b) is zero. Tangent wind velocity (V_s) is not taken into account if angle of wind onflow in the horizontal plane (φ) of footbridge is smaller than 30°. In such a situation wind action on slender element of the bridge span is associated with normal wind velocity (V_n).

In aerodynamic analysis of wind influence on buildings, static components of wind field as well as dynamic ones must be taken into account:

$$V_{n1}(z,t) = \sqrt{(\bar{V}_n + V_n')^2 + {V_b'}^2} \tag{3}$$

$$\alpha_{n1}(z,t) = arctg\,\frac{V_b'}{(\bar{V}_n + V'_n)} \tag{4}$$

where: V_{n1} – instantaneous wind velocity perpendicular to the footbridge axis, $\bar{V}_n$ – mean wind velocity, V_n' , V_b' – fluctuation of wind velocity in normal and binormal direction, respectively, α_{n1} – instantaneous angle of wind onflow.

Instantaneous wind velocity (V_{n1}) is the resultant of three components of the aerodynamic wind action: normal wind action, binormal wind action and aerodynamic moment, respectively:

$$w_n(\alpha_{n1}(z,t)) = \frac{1}{2}\rho V_{n1}^2(z,t) C_n(\alpha_{n1}(z,t)) D \tag{5}$$

$$w_b(\alpha_{n1}(z,t)) = \frac{1}{2}\rho V_{n1}^2(z,t) C_b(\alpha_{n1}(z,t)) D \tag{6}$$

$$w_m(\alpha_{n1}(z,t)) = \frac{1}{2}\rho V_{n1}^2(z,t) C_m(\alpha_{n1}(z,t)) D^2 \tag{7}$$

where: ρ – air mass density, $V_{n1}(z,t)$ – as before, $C_n(\alpha_{n1}), C_b(\alpha_{n1}), C_m(\alpha_{n1})$ – aerodynamic coefficients: normal, binormal and torsional, D – characteristic dimension of the footbridge.

The relationships between described quantities are presented in Fig.1 with respect to object local coordinate system ($x_e y_e z_e$).

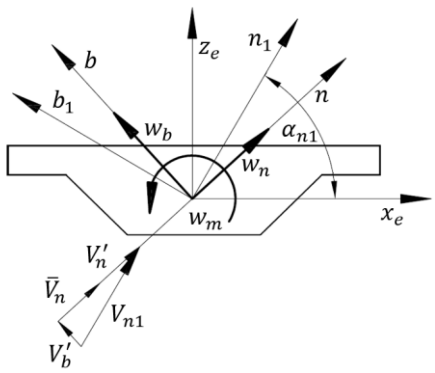

Figure 1: Wind action on the footbridge cross-section

3. Procedure of wind action on footbridge

The procedure of the determination of dynamic wind action on footbridge is illustrated in scheme (Fig. 2).

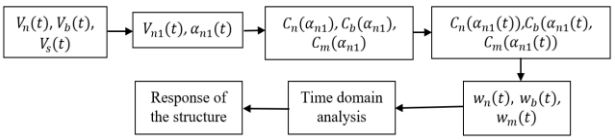

Figure 2: The procedure of simulation of turbulent wind action

The first step is the simulation of turbulent wind field, so components $V_n(z,t)$, $V_b(z,t)$ and $V_s(z,t)$ are determined. Then instantaneous wind velocity perpendicular to the footbridge axis ($V_{n1}(z,t)$) and angle of wind onflow ($\alpha_{n1}(z,t)$) are calculated. The next step is to adopt aerodynamic coefficients C_n, C_b and C_m for the analysed footbridge cross-section. These coefficients are determined for typical cross-sections, but for uncommon ones it is recommended to assume values from literature or from model tests of such objects in wind tunnel. Therefore, one can have these coefficients as a function of the angle of wind attack in time domain. So, three components of the wind action in assumed nodes of footbridge can be obtained. Then the simulation of dynamic wind action can be made which is resulted in time variable response of a structure.

4. Calculation example

Analysed case concerns specific wind action without aerodynamic feedback on a single span footbridge. The object was modelled as a simply supported beam of 27 m length and 3,6 m width of the cross-section. It consists of two plate girders and concrete deck.

The following characteristics of the wind action on the footbridge were assumed according to [5]: wind load zone – I, terrain category – 2 (which corresponds to localization of the object over the express road), mean wind velocity – 22m/s.

It must be pointed out that in presented example, local coordinate system of wind (nsb) coincides with local coordinate system of the footbridge elements ($x_e y_e z_e$) and the angle of wind onflow in horizontal plane (φ) is assumed as smaller than 30°.

Aerodynamic coefficients for the analysed footbridge were adopted as for Tacoma Narrows Bridge [6], because their cross-sections are similar (Fig. 3). Turbulent wind velocity field was simulated with use of the program WINDSYM elaborated in the Department of Structural Mechanics at the Lublin University of Technology [7]. It was made for eleven points of the footbridge located in main axis of the object.

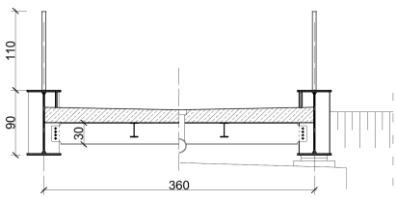

Figure 3: Cross-section of the analysed footbridge

On the basis of simulation results and assumed data, time variable wind action on a structure was determined. Three components were applied in each of 11 footbridge nodes: horizontal force acting perpendicular to longitudinal cross-section of the footbridge (w_n), vertical force (w_b) and aerodynamic moment (w_m). Then the time history analysis was conducted in Autodesk Robot Structural Analysis which allowed to obtain time variable structure response. Critical damping ratio was assumed as $\gamma = 0.006$ for mass-stiffness model of damping and Newmark method was chosen in further calculations.

5. Results of calculations

As calculations results, series of time-varying quantities were obtained. Figure 4 shows an example of vertical displacements (u_{ze}) for node 6 which is localized in the middle of the footbridge span. In Tab.1 extreme displacements under different types of actions are summarized.

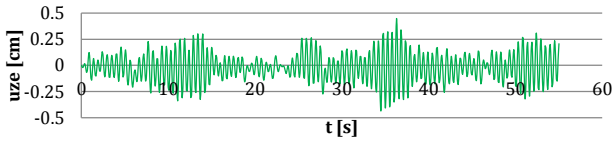

Figure 4: Displacements in z_e direction

Table 1: Displacements under different types of actions

Displacement	Dead weight	Live load	Wind action
u_{xe} [cm]	0	0	0
u_{ye} [cm]	-0.58	-0.44	-0.03
u_{ze} [cm]	-8.74	-6.62	-0.44

On the basis of obtained results analysis, the following conclusions can be drawn:

- Extreme displacements appear in vertical direction (z_e), i.e. in direction of the lowest stiffness of the structure;
- Displacements in horizontal directions (x_e, y_e) are negligibly small;
- High stiffness of the analysed object causes that the wind action is a secondary problem in this case;
- Moreover, human vibrations comfort criteria (taken from [4]) for this footbridge are fulfilled.

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