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Turbulence in the Artificial Boundary Layer of Photovoltaic Power Plants

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Abstract

The aeroelastic assessment of turbulence appearing in the artificial boundary layers of photovoltaic power plants is treated in present paper. The approach suggested takes into account multiple functions in the analysis of skew plates of solar panels subjected to laminar and turbulent wind forcing. Analysis and experimental assessments in the wind tunnel are presented. Some results obtained are discussed.

Keywords: aerodynamic tunnel, artificial boundary layer, photovoltaic power plant, mechanics of turbulent wind motion, skew flat plate, solar panel, turbulences.

1 Introduction

The topic of present paper is the assessment of ultimate aeroelastic behaviour of skew plates of solar panels in photovoltaic power plants subjected to laminar and turbulent wind forcing (see Figure 1). The skew flat plates of solar panels are supported by metal structures anchored into terrain. The panels create the active fields of the power plants studied. The photovoltaic power plants are located in territories where the wind loads represent the dominant environmental forcing. The forcing is to be unified into maximal design values for given territory. All structural elements are to be designed in accordance with valid standards and their aeroelastic assessments are required, for example, due to the recommendations of the EUROCODE 1, Loads on Structures, Part 1.4, General Loads, Wind Loads.

Active fields of photovoltaic power plants with a multitude of flat plates with solar panels create artificial boundary layer with laminar and turbulent wind forcing. The aeroelastic response depends on following options:

- wind speed,
- wind direction,

- wind flow (laminar or turbulent),
- wind temperature and humidity,
- snow and ice loads,
- gaps between solar panels,
- geometry and configuration of active fields of solar panels,
- dynamic properties of all structural elements.

Because of the small height of solar panels above the terrain there occur the cataract air flows on edges of the flat plates, which increase the wind speeds and pressures.

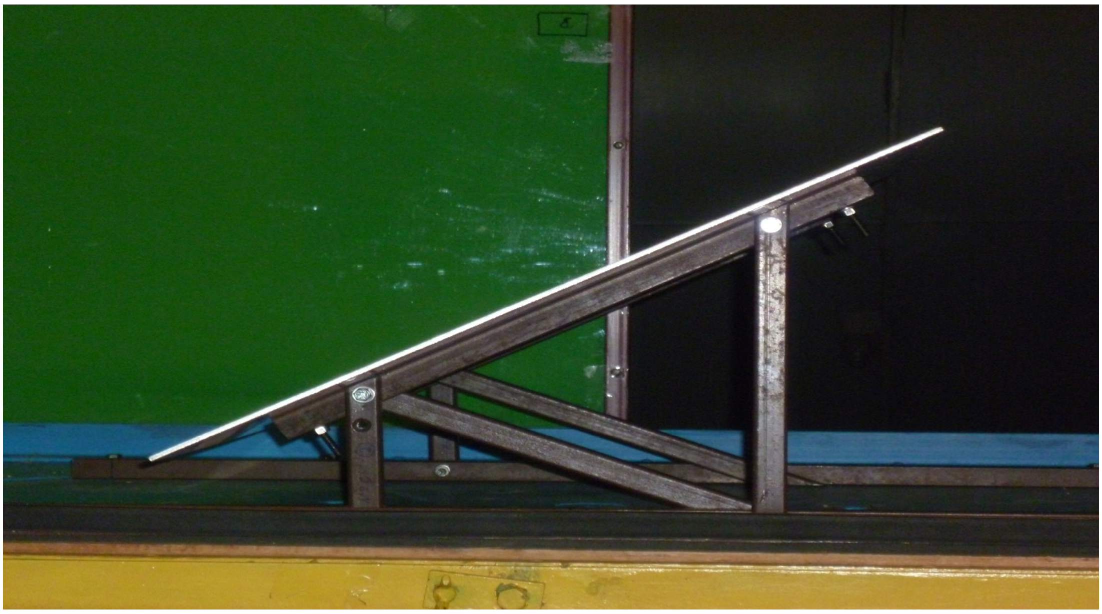

Figure 1. Side view of the skew plate studied in aerodynamic tunnel

In configurations of photovoltaic power plants, with artificial boundary layer in small heights, there appear turbulent wind flows measurable only in the wind tunnel. The measurements in aerodynamic tunnels submit the data required for the analysis of the problem.

The idea of application of the flat plate aerodynamics in the field of preliminary structural design was introduced by Bleich [1]. Selberg and Hjorth-Hansen in [2] and [3] carried out an experimental investigation of a number of cross-sections and presented approximate formulae for the flutter velocity of a plate acted upon by Theodorsen´s forces [4]. In their contribution [5] Klöppel and Weber employed the flat plate stability limit as a reference quantity in the same way as Selberg. A general solution of the flat plate equations for a linear model was given by Frandsen [6]. Frandsen showed that a simplified expression by Rocard [7] for the limit state stability of bridges turned out to be a good approximation for the flat plate flutter velocity. Scruton in [8] pointed to apparent similarities of the behaviour of realistic models and flat plate computational model. Buffeting appearing by some forcing conditions was the topic of research of Davenport [9]. Bridge deck flutter derivatives and their action in general aeroelasticity were treated by Scanlan and coworkers in [10], [11], [12] and [14]. Some aspects of non-stationary airfoil theory were dealt with by Sears in [13]. Significant research results concerning the problem are contained also in Refs. [15] – [21].

Slender structures of skew flat plates of photovoltaic power plants are prone to wind-induced vibrations for various reasons. Some issues considered in their wind resistant design are given by:

1. Wind turbulences force the plate with a considerable power and the forced movements owing to turbulence and associated mechanisms are stochastic in nature.
2. There can be produced a strong vortex wake associated with aerodynamic drag force experienced by the plate. Depending on wind speed and cross-section's shape, the shedding of vortices is more or less regular with shedding periods inversely proportional to the wind speed. In resonance conditions the structure's oscillation can control the rhythm of the vortex shedding.
3. Aside the known vortex trail type excitation the more general types of forcing appear in the plate. The possible re-attachement of separated flow, the vortices generated by local geometry and movement of the plate contribute to such periodic forcing.
4. Aeroelastic forces proportional to the movement of the plate can produce self-induced divergent vibrations at some wind speeds.
5. In the design of skew plate is to be avoided that absolute value of negative aerodynamic damping exceeds the positive mechanical damping producing across-wind flexural mode instability. Associated critical wind speed is the flutter velocity while corresponding circular frequency is the flutter frequency.
6. At the onset of divergence the aerodynamic instability of the plate is initiated.

The goal is to develop the approach based on transient dynamics combined with wave propagation forcing and adopted for the analysis of aeroelastic response of skew flat plates of photovoltaic power plants on the basis of results obtained in scope of experimental testing in the wind tunnel.

2 Computational method

The results obtained in scope of testing in the wind tunnel were used as input data in numerical analysis. For calculation of aeroelastic response was adopted the transient dynamics ([22] and [23]). Laminar and turbulent wind forcing was studied adopting the wave propagation approach ([24]).

3 Experimental approach

The testing was made with the model set-up of typical skew flat plate in scale 1:10, developed on the basis of the model similarity with actual structure. The aerodynamic testing was made in the wind tunnel of the Institute of Construction and Architecture of Slovak Academy of Sciences in Bratislava, Slovakia. For testing was used the modul section with cross-sectional dimensions 1200 x 1200 mm and length 6000 mm. Maximal wind velocity obtained was 51 m/sec.

The model of the skew flat plate was made of aluminium with dimensions 1000 x 300 mm and with width 4 mm. The plate was supported by steel supports Jäckl 20/20/2 and anchored into the floor of the tunnel. The view of the experimental set-up in the tunnel is in Figure 1.

In case of the wind forcing there appear the turbulences on upper and lower edges of the plate accompanied by wind gusts and local changes of the wind velocity. The wind velocity influences the standard wind pressure being used in the design of the plate. Required was the specification of actual wind velocities appearing on all edges of skew plate at various wind speeds in aerodynamic tunnel. The speed variations in wind flow are given by aerodynamic coefficient α

$$\alpha = v_{loc}/v_{ave} \quad , \tag{1}$$

with v_{loc} as local velocity of turbulent flow measured on the edge of the plate and with v_{ave} as averaged velocity of laminar wind flow in aerodynamic tunnel. The value v_{ave} corresponds to the standard wind velocity in given territory and was used for the design of all structural elements of skew plates studied. The coefficient α specifies the increase of wind velocity on the edges of the plate. The first goal of experimental testing was therefore the specification of aerodynamic coefficients α on all edges of the skew plate. The values of coefficient α were adopted for specification of resulting stress and deformation states in the plate.

For the measurement of the wind velocities were used the anemometers positioned in the axis of the tunnel (measurement of velocities v_{ave}) as well as on the edges of the skew plate (measurement of velocities v_{loc}). The anemometers for the measurement of velocities v_{loc} were adopted in various positions in order to find the variability of wind velocities on all edges of the plate studied.

The time records were made on channels measuring three accelerations A1, A2, A3, four strains T1, T2, T3, T4 in the centres of all four edges of the skew plate as well as the wind velocities in the tunnel. The accelerations A1, A2 a A3 were measured on upper (A1), lower (A2) and side edges (A3) of the plate. The testing was made for:

a) model in horizontal attitude 0° and located perpendicularly to the direction of the wind flow – the assessment of the shear wind along the plate,

b) model in horizontal attitude and turned -180° compared with the wind flow – the assessment of the air sucking on the plate,
c) model in horizontal attitude and turned +90° compared with the wind flow - the assessment of the wind pressure on the plate.

In accordance with the measurements made in critical points there was stated that response of the plate is dominated by deformations with turbulent components of pressure and sucking of wind which are irregularly distributed along the surface of the plate. Turbulent wind flows initiated the ultimate aeroelastic response of the plate. The values of aerodynamic coefficients α, obtained in aerodynamic tunnel, are summed up in Tables 1, 2 and 3. There are contained the wind speeds on the edges of skew plate, specified in scope of measurements 1 until 9 at various wind speeds.

In tables are summed up automatically established wind speeds 10 - 50 m/sec in the aerodynamic tunnel, averaged actual wind speeds v_{ave} in the wind tunnel as well as the local wind speeds v_{loc} on all edges of the plate. In tables are also corresponding aerodynamic coefficients $\alpha=v_{loc}/v_{ave}$ on all edges of the plate. In Table 4 are some comparisons of calculated and measured data.

Wind speed [m/sec]	Measu-rement Nr. 1 v_{loc} [m/sec]	Measu-rement Nr. 1 v_{ave} [m/sec]	Measu-rement Nr. 1 $\alpha=v_{loc}/v_{ave}$	Measu-rement Nr. 2 v_{loc} [m/sec]	Measu-rement Nr. 2 v_{ave} [m/sec]	Measu-rement Nr. 2 $\alpha=v_{loc}/v_{ave}$	Measu-rement Nr. 3 v_{loc} [m/sec]	Measu-rement Nr. 3 v_{ave} [m/sec]	Measu-rement Nr. 3 $\alpha=v_{loc}/v_{ave}$
10	14.5	10.1	1.4356	18.8	10.1	1.8614	15.8	10.1	1.5643
20	28.8	20.2	1.4257	35.6	20.2	1.7624	30.6	20.2	1.5148
30	39.9	30.1	1.3256	48.9	30.1	1.6249	42.9	30.1	1.4252
40	51.4	40.1	1.2817	59.7	40.1	1.4888	55.7	40.1	1.3890
50	65.2	50.2	1.2988	74.8	50.2	1.4900	69.8	50.2	1.3904

Table 1. Results of measurements Nr. 1, 2 and 3 in wind tunnel

Wind speed [m/sec]	Measu-rement Nr. 4 v_{loc} [m/sec]	Measu-rement Nr. 4 v_{ave} [m/sec]	Measu-rement Nr. 4 $\alpha=v_{loc}/v_{ave}$	Measu-rement Nr. 5 v_{loc} [m/sec]	Measu-rement Nr. 5 v_{ave} [m/sec]	Measu-rement Nr. 5 $\alpha=v_{loc}/v_{ave}$	Measu-rement Nr. 6 v_{loc} [m/sec]	Measu-rement Nr. 6 v_{ave} [m/sec]	Measu-rement Nr. 6 $\alpha=v_{loc}/v_{ave}$
10	13.5	10.1	1.3366	18.8	10.1	1.9603	14.0	10.1	1.7129
20	26.8	20.2	1.3267	34.6	20.2	1.8119	27.5	20.2	1.5742
30	36.9	30.1	1.2259	47.9	30.1	1.6578	40.9	30.1	1.3588
40	49.4	40.1	1.2319	56.7	40.1	1.4638	52.7	40.1	1.4389
50	61.2	50.2	1.2191	66.8	50.2	1.4103	63.8	50.2	1.3506

Table 2. Results of measurements Nr. 4, 5 and 6

Wind speed [m/sec]	Measurement Nr. 7 v_{loc} [m/sec]	Measurement Nr. 7 v_{ave} [m/sec]	Measurement Nr. 7 $\alpha=v_{loc}/v_{ave}$	Measurement Nr. 8 v_{loc} [m/sec]	Measurement Nr. 8 v_{ave} [m/sec]	Measurement Nr. 8 $\alpha=v_{loc}/v_{ave}$	Measurement Nr. 9 v_{loc} [m/sec]	Measurement Nr. 9 v_{ave} [m/sec]	Measurement Nr. 9 $\alpha=v_{loc}/v_{ave}$
10	13.7	10.1	1.3564	17.8	10.1	1.7623	14.3	10.1	1.4158
20	26.8	20.2	1.3267	36.6	20.2	1.8119	28.7	20.2	1.4208
30	38.9	30.1	1.2923	49.9	30.1	1.6578	40.4	30.1	1.3422
40	52.4	40.1	1.3067	60.7	40.1	1.5137	52.6	40.1	1.3117
50	66.2	50.2	1.3187	76.8	50.2	1.5299	67.7	50.2	1.3488

Table 3. Results of measurements Nr. 7, 8 and 9

Wind speed [m/sec]	Measurement Nr. 7 v_{loc} [m/sec]	Measurement Nr. 7 v_{ave} [m/sec]	Measurement Nr. 7 $\alpha=v_{loc}/v_{ave}$	Measurement Nr. 8 v_{loc} [m/sec]	Measurement Nr. 8 v_{ave} [m/sec]	Measurement Nr. 8 $\alpha=v_{loc}/v_{ave}$	Measurement Nr. 9 v_{loc} [m/sec]	Measurement Nr. 9 v_{ave} [m/sec]	Measurement Nr. 9 $\alpha=v_{loc}/v_{ave}$
10	13.7 (13.5)	10.1 (10.0)	1.3564 (1.3500)	17.8 (17.5)	10.1 (10.2)	1.7623 (1.7157)	14.3 (14.5)	10.1 (10.5)	1.4158 (1.3809)
20	26.8 (26.9)	20.2 (20.4)	1.3267 (1.3186)	36.6 (36.9)	20.2 (21.1)	1.8119 (1.7488)	28.7 (29.3)	20.2 (20.8)	1.4208 (1.4086)
30	38.9 (39.4)	30.1 (31.1)	1.2923 (1.2669)	49.9 (51.3)	30.1 (32.2)	1.6578 (1.5931)	40.4 (42.8)	30.1 (32.1)	1.3422 (1.333)
40	52.4 (53.3)	40.1 (41.9)	1.3067 (1.2721)	60.7 (63.0)	40.1 (42.7)	1.5137 (1.4754)	52.6 (55.1)	40.1 (42.8)	1.3117 (1.2874)
50	66.2 (68.8)	50.2 (54.3)	1.3187 (1.2670)	76.8 (79.2)	50.2 (55.4)	1.5299 (1.4296)	67.7 (70.4)	50.2 (56.1)	1.3488 (1.2549)

Table 4. Comparison calculation vs measurements Nr. 7, 8 and 9
(calculated values are in brackets)

4 Conclusions

The averaged increase of speeds and pressures of wind flows on upper, lower and side edges of the plate are given by aerodynamic coefficients α=1.4255, 1.6532 and 1.4080, respectively. The averaged increase of the wind pressure on the plate due to change of wind direction and turbulences appearing is given for wind sucking by the multiplicator –1.65 and for the wind pressure by the multiplicator 1.43 of the standard values valid for the face action of the wind on the model. Due to appearance of wind gusts the ultimate response of the model was forced. There appeared to be combined axial and shear amplitudes of vibration parallel with the plane of the skew plate studied.

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