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Investigation of peak wind loads on tandem heliostats in stow position

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ABSTRACT

This paper investigates the effects of turbulence in the atmospheric boundary layer (ABL) on the peak wind loads on heliostats in stow position in isolation and in tandem configurations with respect to the critical scaling parameters of the heliostats. The heliostats were exposed to a part-depth ABL in a wind tunnel using two configurations of spires and roughness elements to generate a range of turbulence intensities and integral length scales. Force measurements on different-sized heliostat mirrors at a range of heights found that both peak lift and hinge moments were reduced by up to 30% on the second tandem heliostat when the spacing between the heliostat mirrors was close to the mirror chord length and converged to the isolated heliostat values when the spacing was greater than 5 times the chord length. Peak wind loads on the tandem heliostat were above those on an isolated heliostat for an integral-length-scale-to-chord-length ratio L_u^x/c of less than 5, whereas tandem loads were 30% lower than an isolated heliostat at L_u^x/c of 10. The reduced loads on the tandem heliostat corresponded to a shift to higher frequencies of the fluctuating pressure spectra, due to the break-up of large eddies by the upstream heliostat.

1. Introduction

The concentrating solar thermal (CST) power tower (PT) is one of the most promising renewable technologies for large-scale electricity production. Although the intermittency of solar irradiation is a practical limitation of CST systems, PT plants can be deployed with thermal energy storage or as a hybrid system with existing fossil fuel power plants for a base-line power supply [1]. PT systems consist of a field of heliostat mirrors reflecting sunlight to the top of a beam-up or beam-down tower containing a receiver. Heliostats are arranged in rows on one side of an anti-polar facing cavity receiver in a polar field or surrounding a cylindrical receiver in a surround field. The main limitation of PT systems is their significantly larger levelised cost of electricity (LCOE). The LCOE of a conventional molten-salt receiver PT plant was estimated by NREL [2] to be 0.14 USD/kWh in 2015, but this could be further reduced to 0.1 USD/kWh with near-term advanced heliostats at $97/m^2 in a 2017 tower configuration [3]. In comparison, base-load energy systems, such as fossil fuel power plants, have an LCOE in the range of 0.06–0.13 USD/kWh in 2011 [4]. To reduce the LCOE of PT systems there is a need to lower the capital cost of a PT plant, of which the largest cost is the heliostat field, with an estimated contribution of between 40% and 50% [1,5–7]. During operation heliostat mirrors are inclined with respect to the horizontal and are exposed to large drag forces and overturning moments that are directly proportional to the wind speed with a large projected frontal area to the wind [8]. Heliostats are aligned parallel to the ground in the stow position during periods of high wind speeds to minimise the frontal area and thus the drag forces, as shown for a tandem arrangement in Fig. 1. A cost analysis of quasi-static wind loads by Emes et al. [9] found that the heliostat cost of a PT plant in Alice Springs (central Australia) was reduced by 18% by lowering the design wind speed for stowing the heliostats from 22 m/s to 13 m/s for only a 2% reduction in capacity factor of the heliostat field. While the operating wind load can be reduced by changing the stow wind speed, the survival wind speed that a heliostat is designed to withstand in the stow position cannot be varied based on the maximum site wind speed. Hence, there is a significant potential to minimise the capital cost and LCOE of a PT plant through optimisation of the structural design of heliostats in the stow position. This paper investigates the sensitivity of peak wind loads on a heliostat in stow position (Fig. 1) to: (1) the chord length (c) and elevation axis height

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Nomenclature

A	Heliostat mirror area (m^2)
α	Power law roughness exponent
b	Spire base width (m)
c	Heliostat mirror chord length (m)
c_L	Peak lift coefficient
$c_{M_{Hy}}$	Peak hinge moment coefficient
c_P	Pressure coefficient
D	Spire base depth (m)
D_I	Peak drag force on an isolated heliostat in stow position (N)
D_T	Peak drag force on a second downstream heliostat in a tandem arrangement (N)
d	Separation distance between two tandem heliostat mirrors in stow position (m)
d/c	Longitudinal gap ratio for tandem heliostat mirrors in stow position
δ	ABL thickness (m)
f	Frequency of velocity/pressure fluctuations (Hz)
H	Elevation axis height of stowed heliostat mirror above the ground (m)
h	Spire height (m)
I_u	Turbulence intensity (%)
l_u	Distance to the centre of pressure in the flow direction (m)
L_u^x	Longitudinal integral length scale (m)
L_I	Peak lift force on an isolated heliostat in stow position (N)
L_I	Peak lift force on a second downstream heliostat in a tandem arrangement (N)
M_{HyI}	Peak hinge moment on an isolated heliostat in stow position (N·m)
M_{HyT}	Peak hinge moment on a second downstream heliostat in a tandem arrangement (N·m)
M_{yI}	Peak overturning moment on an isolated heliostat in stow position (N·m)
M_{yT}	Peak overturning moment on downstream heliostat in a tandem arrangement (N·m)
P_i^f	Pressure fluctuations on the upper surface of the stowed heliostat mirror (Pa)
P_i^b	Pressure fluctuations on the lower surface of the stowed heliostat mirror (Pa)
S_p	Power spectrum of pressure fluctuations (Pa^2/Hz)
S_u	Power spectrum of velocity fluctuations (m^2/s^3)
T_u^x	Longitudinal integral time scale (s)
U_∞	Freestream velocity (m/s)
$\overline{U}(z)$	Mean velocity profile (m/s)
u	Streamwise velocity fluctuations (m/s)
x	Longitudinal direction (m)
y	Spanwise direction (m)
z	Height above the ground (m)
z_0	Surface roughness height (m)

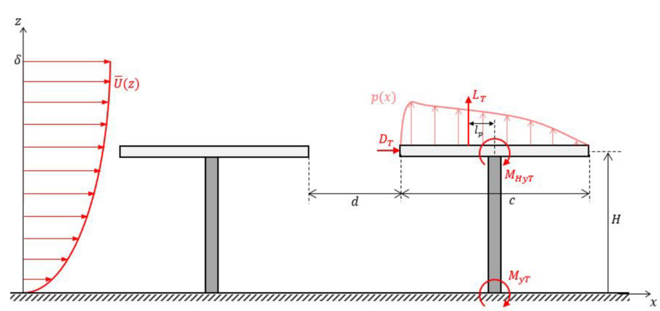

Fig. 1. Peak wind loads due to a non-uniform pressure distribution p on a second stowed heliostat in a tandem arrangement with identical mirrors of chord length c and elevation axis height H separated by a gap distance d and exposed to a logarithmic mean velocity profile $\overline{U}(z)$ in the ABL.

(H) of a single heliostat mirror and spacing (d) between two heliostat mirrors in a tandem arrangement; (2) the turbulence characteristics in the ABL.

Static wind loads on isolated heliostats in operating and stow positions have previously been calculated using mean and peak wind load coefficients derived from experimental data in systematic wind-tunnel studies. Peterka et al. [10] found that the peak lift and hinge moment coefficients on a 1:40 scale heliostat modelled as a thin flat plate were approximately 10 times their mean values in stow position at a longitudinal turbulence intensity I_u, defined by the ratio of the root-mean-square of fluctuating velocity to the mean velocity, of 18% commonly observed in the open country terrain surrounding heliostat fields [11]. This indicates the significance of gust and amplification effects on survival high-wind conditions for heliostats in stow position. Peterka et al. [10] and Pfahl et al. [12] showed that peak wind load coefficients increase significantly at I_u above 10%. Analysis of peak wind loads obtained from wind tunnel experiments has previously yielded the most realistic results by matching turbulence intensities [13], however the sizes of the relevant eddies also significantly affect the peak wind loads on heliostats. Emes et al. (2017) found that the peak lift coefficient and peak hinge moment coefficient on an isolated heliostat in stow position increased linearly and approximately doubled when the ratio of the longitudinal integral length scale to the mirror chord length L_u^x/c increased from 5 to 10 at a constant turbulence intensity. Previous experimental studies have focused on the effects of the temporal characteristics of ABL turbulence on isolated heliostats in stow position, but further knowledge of the relationships between the temporal and spatial characteristics of ABL turbulence and the peak wind loads on isolated and tandem heliostats is required. Hence, the first objective of this study is to improve the understanding of the peak wind loads on an isolated heliostat in stow position and two stowed heliostats in tandem. The sensitivity of the peak wind loads on a second downstream heliostat in a tandem arrangement, relative to an isolated heliostat, to L_u^x/c is investigated to determine the effect of the critical scaling parameters of the upstream heliostat on the sizes of the turbulent eddies in the ABL that reach the second downstream heliostat.

The design and layout of heliostat fields have previously been optimised with respect to the optical efficiency of heliostats in operational positions, however static wind loads have also been found to be highly dependent on the spacing between heliostats relative to mirror chord length, defined by the longitudinal gap ratio d/c and the heliostat field density, defined by the ratio of mirror area to land area. Peterka et al. [14] measured mean and peak wind loads on 1:60 scale-models of a tandem arrangement of five consecutive heliostats in rows of a high-density region of the Barstow heliostat field. In addition, Pfahl et al. [15] measured peak wind loads on 1:20 scale-models of a tandem arrangement of four