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Wind gust distribution analysis and potential effects on heliostat service life

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Abstract

Intense gust conditions associated with storms are shown to occur in the range of heliostat natural frequencies and can thus induce high dynamic coupling loads. Wind data taken during a severe storm on an instrumented tower at Savannah River National Laboratory shows that conservative wind speed differences of at least ±4.5 m/s (±10 mph) relative to the average speeds occurred a substantial fraction of the time over periods of the order of 1 s. Although these results were determined for a specific site and a particular storm, they are representative of storm conditions, which are governed primarily by buoyancy effects, as opposed to essentially boundary layer shear effects associated with time-averaged winds speeds that dominate meteorological site data sets. Since heliostats typically have relatively low damping ratios and natural frequencies of the order of 1 Hz, resonant dynamic coupling could occur with significantly higher loads than those predicted from design requirements for steady state winds. This effect reduces service life and impacts reliability through both possible near-instantaneous failures for excessively high dynamically coupled load and the additional high-load cycles that increase cumulative fatigue damage, even if relatively few in number, given the characteristics of fatigue life and loads. Therefore, the effect of these gust-induced cyclic dynamic effects on fatigue life and survival deserve consideration as part of heliostat design and operation. In particular, increased damping of heliostats to mitigate dynamic coupling deserves consideration.

Keywords: Heliostat; Vortex shedding; Wind gusts

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1. Introduction

There is a potential issue with transient wind conditions that can subject solar collectors, in particular, heliostats, to dynamically-coupled loads greater than the traditional static load requirements used for decades in their design. Typical static operational and survival wind speed requirements, such as for the Second-Generation Heliostat, are summarized in Kolb et al. (2007). However, heliostats are damped spring-mass systems, subjected to forcing functions from transient winds, and thus are subject to dynamic coupling. In particular, shedding vortices and wind gusts, if they are near the natural frequency associated with the heliostat drive unit, can, within only a few cycles, cause a resonant oscillation with loads of the order of five to ten times the static load for typical low damping ratio

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heliostats (e.g., ~5–15% of critical damping), and thus contribute to premature failure. Vortex shedding has been the usual concern, in part because the frequency over a range of wind speeds and reflector angles of attack is of the order of typical drive unit natural frequencies over a wide range of heliostat areas. Vortex shedding load effects were considered as part of the Phase 1 DOE study (Kusek, 2012) and the effect of static loads from vortex shedding on heliostat fatigue life relative to these loads and a range of safety factors are presented in Blackmon (2014). However, we have also determined that wind gust fluctuations vary such that comparable near-resonant frequencies can occur a significant percentage of the time. Our analysis of data taken during a severe storm shows that these wind conditions impose additional forcing functions; this increase in the total number and amplitude of cyclic loads imposed on heliostats further contribute to reduced service life.

2. Transient wind effects

First we briefly outline vortex shedding effects on heliostat dynamic response and then summarize the gust transients associated with a severe storm and how these are related to heliostat natural frequencies.

2.1. Vortex shedding

Consider the vortex shedding effect. The frequency, f, for a wind speed, U, and square heliostat of side (chord), h, and projected chord, $h\sin\alpha$, at the incidence angle, α, can be approximated using,

$$f = StU/h\sin\alpha, \tag{1}$$

where St, the Strouhal number, is of the order of 0.15–0.2 for flow incidence angles, $\alpha > 30°$ (Stahl and Mahmood, 1985). Below 30°, flow conditions were such that although vortices were observed, Stahl and Mahmoud were not able to "construct a unique, coherent picture of the wake region." Their Reynolds number was approximately 10^5, and thus below turbulent transition. However, Bourgoyne et al. (2005) show that for Reynolds numbers from 1×10^6 to 50×10^6, shedding vortices occur, as with struts. Although their experiments with an NACA airfoil shape are different from a canted "flat plate" heliostat, these results give further support to potential dynamic coupling loads from vortex shedding. Furthermore, they showed that "These spectral peaks occur at different normalized frequencies, with differing heights and widths, but always near the anticipated Strouhal number, St, for near-wake vortex shedding from foils and struts: $St = \approx 1/2\pi$." They showed a variation of the Strouhal number multiplied by 2π as a function of Reynolds number that ranged from about 1 to 1.5; that is, the conventional Strouhal number was about 0.16 to 0.24. There are comprehensive wind tunnel tests of model heliostats (e.g., Peterka et al., 1989), CFD models (Wang et al., 2009), and field tests (Strachan and Houser, 1993; Ho et al., 2012) that address various aspects of heliostat wind induced loads together with the wind speeds and their transients.

The maximum static azimuth moment is typically determined for near-vertical heliostats canted into the wind with angles of attack in the range of about 20° (Heller and Peters, 1989). This static moment can have a higher dynamic coupling load with vortex shedding that can induce stresses on the drive unit that exceed its ultimate strength, especially with low safety factors and damping coefficients. It is assumed in this analysis that the frequency for a given wind condition can be approximated using a Strouhal number of the order of 0.15–0.2. When the frequency is in the range of the drive unit natural frequency, dynamic coupling becomes an issue, especially for low drive unit damping ratios. The tests of two heliostat designs at the Sandia National Solar Thermal Test Facility (Ho et al., 2012) showed that these damping ratios can be low. The Sandia results indicated drive unit damping of their NSTTF heliostats and a commercial heliostat to be low for areas in the range of 37, 60, and 80 m^2. Ho, et al., state: "*For the NSTTF heliostat, damping was found to be in the range of* 5–15% *of critical damping, although the estimates of damping were found to have greater uncertainty at the low end of this damping range. The other modes of the heliostat were less than* 1% *damped even for high wind speed cases with increased aerodynamic damping. For the commercial heliostat configurations, damping was found to be in the range of* 7–10% *of critical damping and was not found to be significantly affected by the change in mirror area size.*"

An earlier test conducted at Sandia (Strachan and Houser, 1993) shows the heliostat dynamic response to winds for the 200 m^2 SPECO heliostat; the reported beam movement for that test showed a beam centroid variation of about ±4.65 milli-radians. The design requirement was that the heliostat have a pointing error of the beam less than about 1.5 milli-radians for winds less than 10 mph (4.47 m/s) and 2.0 milli-radians for winds up to 35 mph (15.6 m/s). Strachan and Houser's results were for an angle of attack of 150° (wind from the back, or, effectively, 30°), which is not as severe a condition as the 20-degree case and the average wind speed was 18 mph (8.04 m/s). The data points were over a total duration of ~6 s. Fig. 1 is a re-plot of their data showing an approximate sine wave with a period of about 4 s, or about a 0.25 Hz frequency. Using Eq. (1) with $St = 0.2$, 18 mph (8.04 m/s) average wind speed, 150° angle of attack, and the approximate width of the 200 m^2 heliostat of 46.4 ft (14.1 m) gives a frequency of 0.23 Hz. The Excel trend line was used to develop a 6th order polynomial curve fit; also, a simpler sinusoidal fit is shown for comparison. These data indicate vortex shedding loads caused a dynamically coupled response. However, the drive unit stiffness, moment of inertia, and thus natural frequency of that heliostat at that angle of attack are not known and can no longer be