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ScienceDirect
Solar Energy 105 (2014) 170–180
SOLAR ENERGY
www.elsevier.com/locate/solener

Heliostat drive unit design considerations – Site wind load effects on projected fatigue life and safety factor

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Received 7 October 2013; received in revised form 14 February 2014; accepted 28 February 2014
Available online 5 May 2014

Communicated by: Associate Editor L. Vant-Hull

Abstract

A parametric analysis shows the importance of various effects on heliostat drive unit life, including wind conditions, angles of attack, size, and endurance limits and how these affect predicted safety factors required in terms of fatigue damage. Endurance limit effects are shown to be critical, including "wear and tear" reductions from field exposure and operation, which significantly reduce remaining life. Low safety factors are shown to pose a risk of achieving 30-year life, especially when site wind conditions are considered. Gusts significantly increase the required safety factor, even if they occur for only 10% of the time. Seasonal wind speed variations are also shown to be important, in that speeds during a 3-month period, typically in the Spring, that are above the annual average require a significantly higher safety factor than the predicted value based on the annual average alone. Sites with low annual average wind speeds are shown to be preferable. Having heliostats fully stowed at lower wind speeds than legacy specifications of 50 mph increase life and reduce safety factors required.

Keywords: Fatigue; Winds; Safety factors

1. Introduction

Legacy heliostat requirements are based on use of static wind loads and specify a 30-year life. From the standpoint of fatigue, achieving this life is dependent on the safety factor used. Selection of appropriate safety factors is difficult for any design facing uncertain or highly variable operational conditions. This is especially true of heliostats, which are subjected to cyclic wind loads even when stowed. Over the last several decades there have been examples of heliostats designed with relatively low safety factors incurring premature failures attributed to especially high wind speeds, but, fatigue and dynamic load amplification may have played a role as well. Conversely, there are examples of heliostats surviving for decades at various locations, with little reported damage. Site wind conditions and operational aspects, as well as design aspects, are shown to have a significant effect on life; those effects may help explain observed differences in life of heliostats developed over the last several decades.

It has long been recognized that heliostats can be subjected to tens of millions of wind-load cycles over their required 30-year life and that these cycles contribute to cumulative fatigue damage (Veers, 1987). Recent studies (Ho et al., 2012) of full size heliostats at the Sandia National Laboratories' National Solar Thermal Test Facility

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http://dx.doi.org/10.1016/j.solener.2014.02.045
0038-092X/

(NSSTF) examine the importance of wind loads on fatigue life, especially for certain structural members, and show good comparisons between simulated and measured modes for structural members that are well-characterized. Several of the observed behaviors with the drive units are relevant to this parametric analysis, such as the vortex shedding loads and frequencies, and the wide range of conditions in which they can occur. Other studies have dealt with scale models in wind tunnels, and predicted structural deflections of the reflector and its support structure, but were limited in terms of effects on drive units and their expected life (e.g., Wang et al., 2009; Pfahl and Uhlemann, 2011; Gong et al., 2012). This paper uses a parametric analysis to assess relative effects of wind loads on drive units in terms of the safety factors predicted to achieve 30-year life; the emphasis on drive units is in part because they are the most expensive part of the heliostat (Kolb et al., 2007) and because safety factors often used in their design have been low, primarily to reduce cost, but at the risk of early failure. Drive unit failures can result in severe damage to the heliostat structure, and thus the effect can be compounded.

Load conditions imposed depend on site wind conditions, with wide variations in wind-speed and gust magnitude and frequency, heliostat location in the field, angle of attack, how they are operated and stowed, and design characteristics. Heliostat characteristics that have a major bearing on drive unit life include size, stiffness, moment of inertia, operation and stow wind speed requirements, and damping ratio. Applying conservative safety factors increases life, but also costs, and even this is not necessarily sufficient if the heliostats have low damping, because coupling between the wind-induced forcing function and the heliostat can lead to loads much higher than static design loads. Heliostat developers thus face uncertainty as to what safety factor should be used. The cost implications can be severe, either through over-design or premature failure. The objectives of this parametric analysis are to show the relative importance of these various conditions; to show that use of low safety factors poses a risk; and to outline a method that can be used to estimate the safety factors required as a function of these conditions.

The following treats various factors that impact heliostat life using a parametric analysis of quasi-static wind loads and basic heliostat characteristics. A method is developed that shows how the 30-year life requirement and safety factor for the drive unit can be estimated from site conditions using representative fatigue curves for a range of endurance limits (i.e., knee in the curve of the fatigue strength vs. number of stress cycles, Shigley and Mischke, 1989). One purpose of this analysis is to provide insight into the relative importance of various factors such as site wind conditions (e.g., average wind speed, gust effects, and seasonal wind speed variations); endurance limits; heliostat size; angles of attack; and vortex shedding. The parametric analysis shows how safety factor and predicted life are related to these factors.

The analysis first considers how life is affected by safety factor and cumulative fatigue damage for low, medium, and high annual average wind speeds representative of solar sites. Both a large (148 m^2) and a relatively small pedestal-mounted heliostat (9.2 m^2) are considered. The larger size is the DOE baseline pedestal-mounted elevation–azimuth ATS heliostat (Kolb et al., 2007). The smaller size lies in the mid-range of current production heliostats, such as the eSolar heliostat (1.14 m^2 mirrors, multiples of which are ganged on a common frame, Schell, 2011) and the Brightsource heliostat (~14–15 m^2). The 9.2 m^2 heliostat is based on a pedestal-mounted elevation–azimuth design developed under the US/Israel Science and Technology Foundation, conducted during the mid-to late1990s as part of a US Department of Commerce cost-shared program led by McDonnell Douglas Aerospace, with Ortem Industries, Rotem Industries, and the Weizmann Institute of Science in Israel (Yogev et al., 1999). That project was continued under a DOE grant (Blackmon, 2008). A variant of that design is in the final development stages as part of the phase 2 low cost heliostat development project, funded by the DOE SunShot program with HiTek Services as prime contractor (Kusek, 2012); that approximate size was found to be optimum based on the heliostat cost/area vs. area analysis developed in that program for a practical, achievable set of cost factors (Blackmon, 2012, 2013).

A representative fatigue curve is used with a range of endurance limits varied from the maximum strength at about 50% of ultimate for the laboratory tests of pristine, polished materials, to a low of 10% for the case of actual machined components with severe degradation. The range in endurance limits illustrates the effects of "wear and tear" on drive unit life. Life is estimated using Miner's rule for quasi-static loads imposed over a range of wind speeds that impose moments corresponding to stresses above the endurance limit. The number of cycles over 30 years is estimated using vortex shedding frequencies for two angles of attack and a Weibull distribution for a range of average wind speeds. Effects of increased loads due to wind gusts and/or seasonal wind speeds are estimated parametrically.

Consideration of fatigue is an important criterion, but strength and stiffness requirements and dynamic coupling effects are also important. Legacy requirements have long imposed a stiffness requirement for pointing accuracy, but often the stiffness requirement has not been used, because design for stiffness was considered to be overly conservative and costly. Instead, various legacy heliostats have been designed for strength (Dietrich et al., 1982; Heller and Peters, 1989). Dynamic coupling is not addressed here, but has been shown to have a major effect on life and survival for heliostats having low damping ratios (Kusek, 2012). In this analysis the heliostat is assumed to have sufficient damping to avoid dynamic load amplification. The vortex shedding load is assumed to be reversed and essentially sinusoidal. The quasi-static load at each wind speed is determined from the wind speed squared for a given angle of attack relative to the maximum design load; the design load for this analysis is azimuth torque, based on the ATS 148 m^2 heliostat and its drive unit (Heller and Peters, 1989), and