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High-concentration solar dishes based on pneumatic reflecting membranes

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Abstract

The ability of pressurized circular membranes to approximate a paraboloid of revolution is investigated with the goal of designing a high-precision and lightweight solar dish concentrator. The optical performance of elastic and elasto-plastic deforming membrane materials is thoroughly analyzed by means of finite element structural modelling combined with Monte Carlo ray-tracing simulations using the yield strength, elastic modulus, and tangent modulus as parameters. The simulation results are verified experimentally by accurate scans of PET and aluminum membranes. They reveal that elasto-plastically deforming membranes can reach a peak concentration ratio of 3070 at a rim angle of 20° – a 14-fold value vis-à-vis that of conventional elastic membranes – while keeping strains at reasonable low level. Anisotropy detrimentally affects the aluminum membrane's performance, but optimal overstretching in the plastic regime can further boost its peak concentration ratio.

Keywords: Solar dish; Membrane; High concentration; Elasto-plastic deformation

1. Introduction

Because of their lightweight and easy packing, pneumatic (inflated) membranes are applied as concentrators in space applications for antennas and telescopes (Jenkins, 2001, 2006), and in solar energy applications for parabolic trough (Bader et al., 2009, 2011) and dish systems (Schlaich, 1999; Zanganeh et al., 2012). For example, a 3 MW solar pilot plant in Ait Baha, Marocco, uses 6000 m^2 of active surface with pneumatic membranes for parabolic trough concentrators (Airlight Energy, 2015). In the standard approach, a reflective film is clamped to a circular support frame and a slight vacuum is applied to deform it as close as possible to a paraboloidal shape. However, the shape obtained by this procedure is in general not parabolic and leads to serious spherical aberrations (Meinel and Meinel, 2000). Current 3D solar concentrators based on pneumatic membranes suffer from limited concentration beyond very small rim angles, and thus require multiple facet designs (Zanganeh et al., 2012). This article discusses challenges encountered with these kind of solar concentrators and presents a novel avenue with elasto-plastic membranes, which significantly improves their performance. To evaluate each design, the deflection of the membranes is simulated using finite

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Nomenclature

Latin characters

A	area
c	constant in parabola equation $c = 1/(4f)$
$\mathbf{c}$	clamping point
$C_{g,95}$	geometric concentration ratio at 95% intercept
D	membrane diameter
E	Young's modulus
f	focal length
h	membrane thickness
p	pressure
r	radius
R	membrane radius
w	vertical displacement
z	vertical axis
z_{rec}	vertical distance between rim and receiver

Greek characters

ε	strain
ε_0	prestrain
θ	angular subtense of sun (4.65 mrad)
σ	stress
σ_0	prestress
ν	Poisson's ratio
ϕ_{rim}	rim angle

Subscripts

c	center of membrane
g	geometric
i	at inner side
o	at outer side

element structural analysis with ANSYS® Mechanical APDL (ANSYS Mechanical APDL Release, 2013). The optical characteristics are then determined by Monte Carlo (MC) ray-tracing using an in-house software code (Petrasch, 2010). A prototype solar dish is used to experimentally validate the simulation model by measuring the shape of PET and aluminum membranes with a high-precision optical scanning system. The performance of the different designs is compared by means of the solar concentration ratio.

2. Pneumatic membrane as solar concentrator

The schematic of a single reflective membrane clamped to a circular supporting frame under vacuum is illustrated in Fig. 1. Indicated are the radial r and vertical z axes, dish radius R ($D = 2R$), membrane area A_1, central deflection w_c, rim angle ϕ_{rim}, shortest distance between rim and center along the membrane l, and half sun angle subtended by incident sunrays $\theta = 4.65$ mrad. ϕ_{rim} is defined as the angle between the axis of revolution z and the line connecting the receiver center and concentrator rim. If $D/h \geqslant 80$, the membrane is devoid of bending rigidity (Ventsel and Krauthammer, 2001). If $w_c/h > 5$, in-plane stresses are predominant and bending moments become negligible (Ventsel and Krauthammer, 2001). These criteria hold for $\phi_{rim} > 1°$ for all membranes discussed in this work, provided some restrictions are considered for the clamping of the membrane as discussed in Section 4. Previous studies (Lyman and Houmard, 1963; Vaughan, 1980; Barton and Winger, 2009; Zanganeh et al., 2012) considered reflective plastic films, especially metallized PET films, because of their low cost and robustness. They exhibit a purely elastic behavior for most of the rim angles usually obtained in membrane concentrators. For small deflections, isotropic membranes in the elastic regime generate a profile shape – the so-called "Hencky surface" – that can be described analytically by a series expansion derived by Hencky (1915). Generalizations were derived for initially tensioned membranes (Campbell, 1956; Wilkes, 1998) and for large deflections (Fichter, 1997).

2.1. Difference to the paraboloid of revolution

The paraboloid of revolution provides the theoretical maximum concentration ratio for a concave concentrator $C = \sin^2(2\phi_{rim})/\sin^2(2\theta)$ (not including obstruction by receiver) (Harper et al., 1976; Winston et al., 2005). It is thus of interest to compare the 3D shape of pneumatic

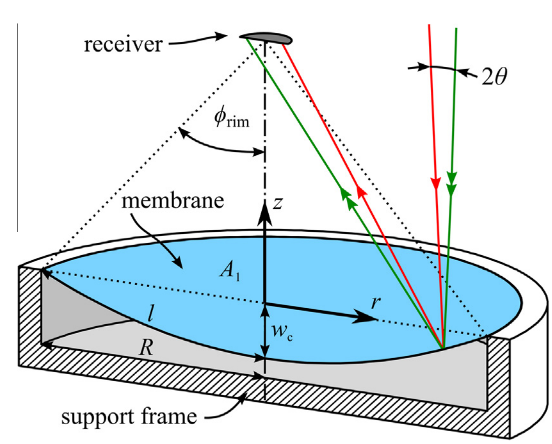

Fig. 1. Cross-section of a membrane dish concentrator. Indicated are the radial r and vertical z axes, dish radius R, membrane area A_1, central deflection w_c, rim angle ϕ_{rim}, shortest distance between rim and center along the membrane l, and half sun angle of incident sunrays θ.