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Ultrasonic Self-cleaning Pyranometer Technical Description

1. Background

Solar resource appraisal is undertaken using Pyranometers and Pyrheliometers to precisely measure site-specific solar irradiance. Accuracy is degraded by the presence of water/ice/dust/mud on the glass dome of a Pyranometer, or on the entrance window of a Pyrheliometer. Regular hand-cleaning, on a daily or weekly schedule, is generally necessary to maintain an accuracy of better than 2%.

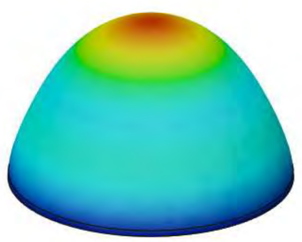
Manual cleaning is labour-intensive and expensive. Hands-free cleaning by water/air spray has been investigated and reported on, as has mechanical cleaning by wiper/brush. These strategies have not been embraced because they require regular service & maintenance and do not eliminate the need for costly labour.

Middleton Solar has devised a fully-automatic self-cleaning technology for pyranometers using ultrasonic vibration of the protective glass dome at two resonant frequencies. The method is an adaption of the 'Ultrasonic Lens Cleaning' technique developed by Texas Instruments for small camera windows.

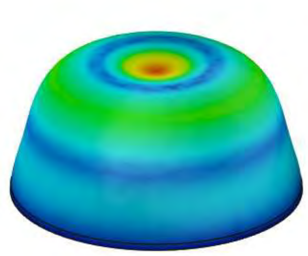
2. Computational Analysis

Finite Element Analysis of a typical Pyranometer outer glass dome, 50mm diameter x 2mm wall thickness, reveals many vibration mode shapes. Mode #3 (≈ 31KHz) and mode #10 (≈ 41KHz) correspond to two natural frequencies that induce significant circumferential displacement of the dome, so are suitable for ultrasonic cleaning.

relative displacement: 0 1



FEA image of mode #3

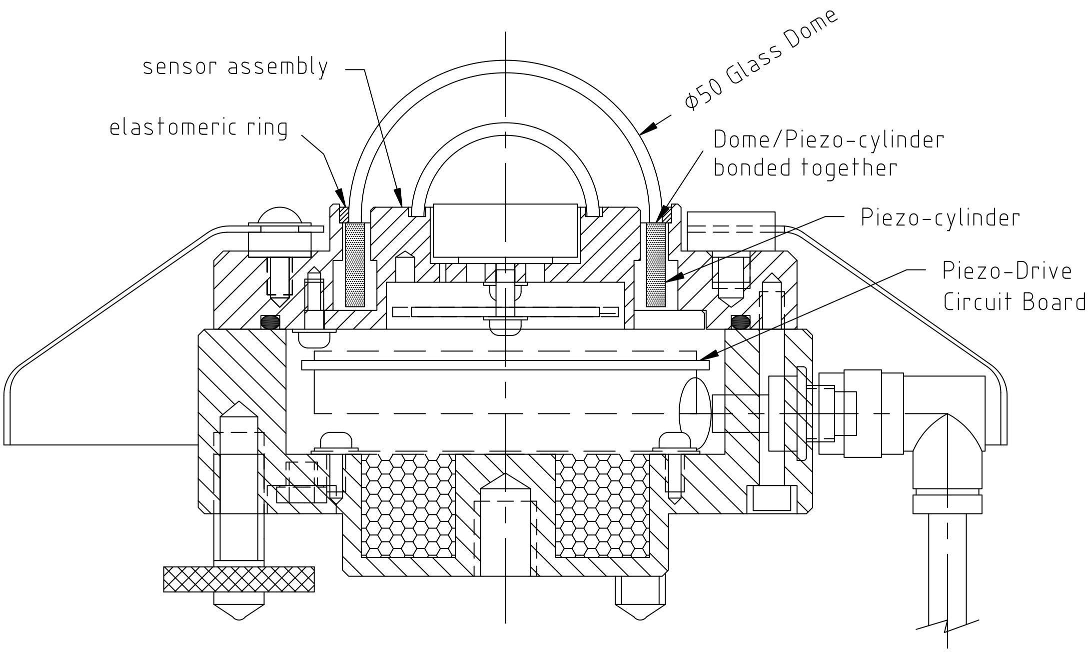


FEA image of mode #10

The two mode shapes in combination include most of the dome surface.

3. Functional Description

The outer glass dome of a Pyranometer is bonded directly to one end of a piezoelectric cylinder of equivalent diameter and wall thickness. The dome/piezo-cylinder unit is joined to the Pyranometer body by a ring of elastomeric adhesive/sealant encircling the dome/piezo-cylinder joint. The elastomeric ring provides a hermetic seal and does not unduly damp ultrasonic vibrations.



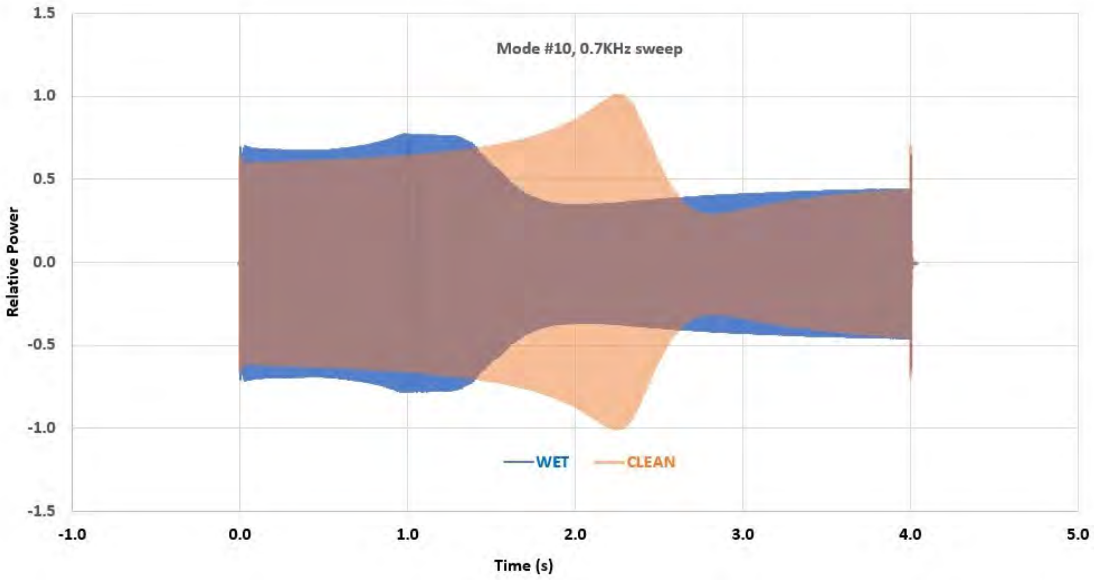
sectioned drawing of USC Pyranometer

A proprietary piezoelectric-drive Circuit Board is located inside the Pyranometer. Cleaning cycle periods can be set on the board, to repeat as necessary depending on the soiling profile at a specific site. Repeat can be every 30 minutes, or every hour, once a day, or some other period. Operation is fully automatic whenever power (nominal 12VDC) is connected to the Pyranometer.

4. Vibration Protocol

The radial resonant frequency of the piezo-cylinder (≈ 22KHz) is determined by diameter & thickness, and material elasticity. Typically piezo-actuators are operated below resonance where displacement is linear with frequency, but the glass dome resonance modes exceed 22KHz so the piezo-cylinder material is optimized to remain effective well above the cylinder resonant frequency.

The piezo-cylinder is activated to vibrate radially by a modified square wave voltage (≈ 150Vpp) in frequency bursts that alternate between the two selected dome resonant frequencies. Dome resonance has a narrow effective bandwidth (≈ 0.05KHz), and changes frequency with temperature and soiling load, so each burst sweeps through a range of ≈ 0.7KHz over ≈ 4 seconds. Multiple sweeps are used, each sweep peaking at ≈ 6W net power. The surface acceleration of the dome reaches a peak at resonance, so dry matter such as dirt is readily ejected. Micro voids are created in water; the voids collapse violently (vacuum bubble cavitation) and cause the water to be ejected from the dome.

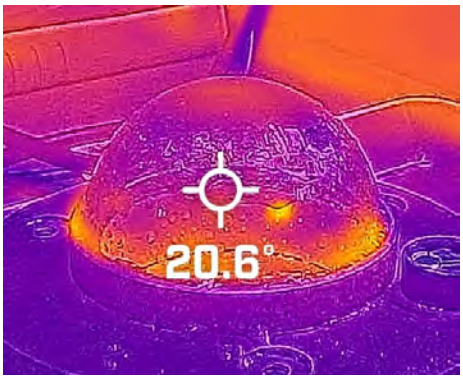


frequency shift of Mode #10 due to water load on dome

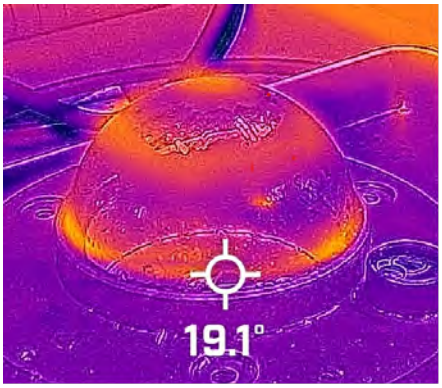
The power peaks at dome resonant frequency. Two 4-second sweeps are overlaid to illustrate that the resonant frequency changes with water load on the dome. The wet-dome resonant frequency is displaced ≈ - 0.2KHz from when the dome is clean and dry.

5. Visualization of Dome Resonance

The glass dome wall exhibits small thermal gradients between regions of high and low displacement, at the resonant frequencies. Thermal imaging of a resonating dome reveals the mode shapes.



thermal image of mode #3



thermal image of mode #10

The two thermal images confirm that the actual mode shapes are consistent with the shapes anticipated by Computational Analysis (page 1), but also exhibit significant displacement where the dome base is attached to the piezo-cylinder.

6. Visualization of Ultrasonic Self-Cleaning

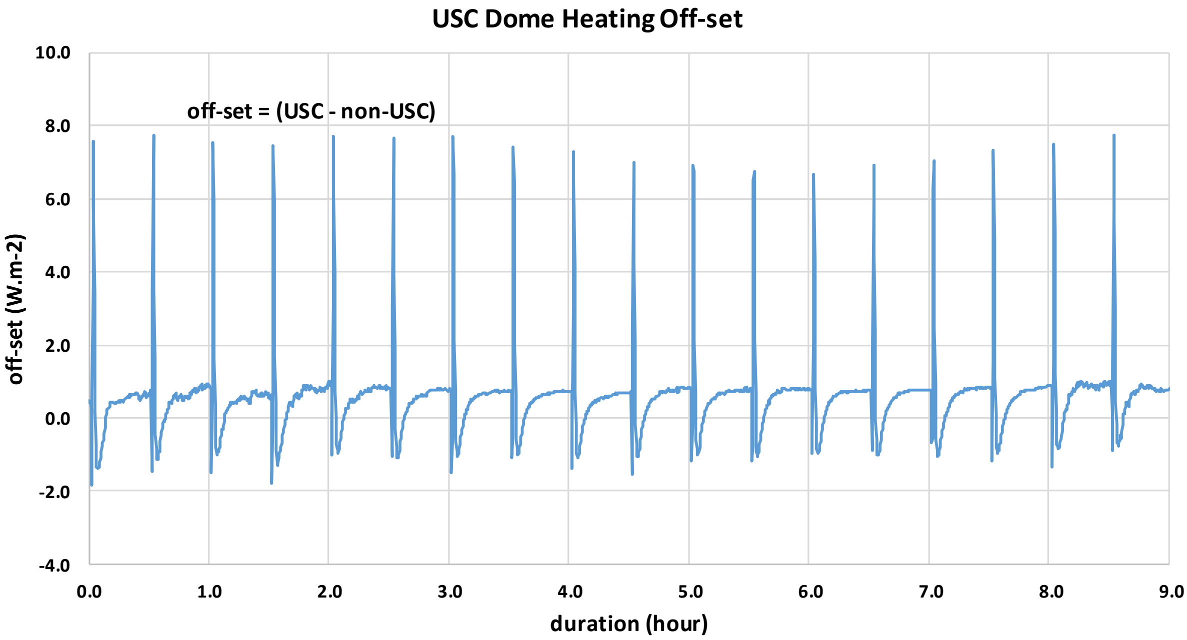
Left Photo: USC pyranometer outdoors on a rainy day, resonating at mode #10, clearly showing water mist shedding from the dome surface.

Right photo: a frame-grab from a slow-motion video of a wet glass dome indoors, resonating at mode #10, showing water being energetically expelled from the dome surface.

7. Self-Cleaning Limitations

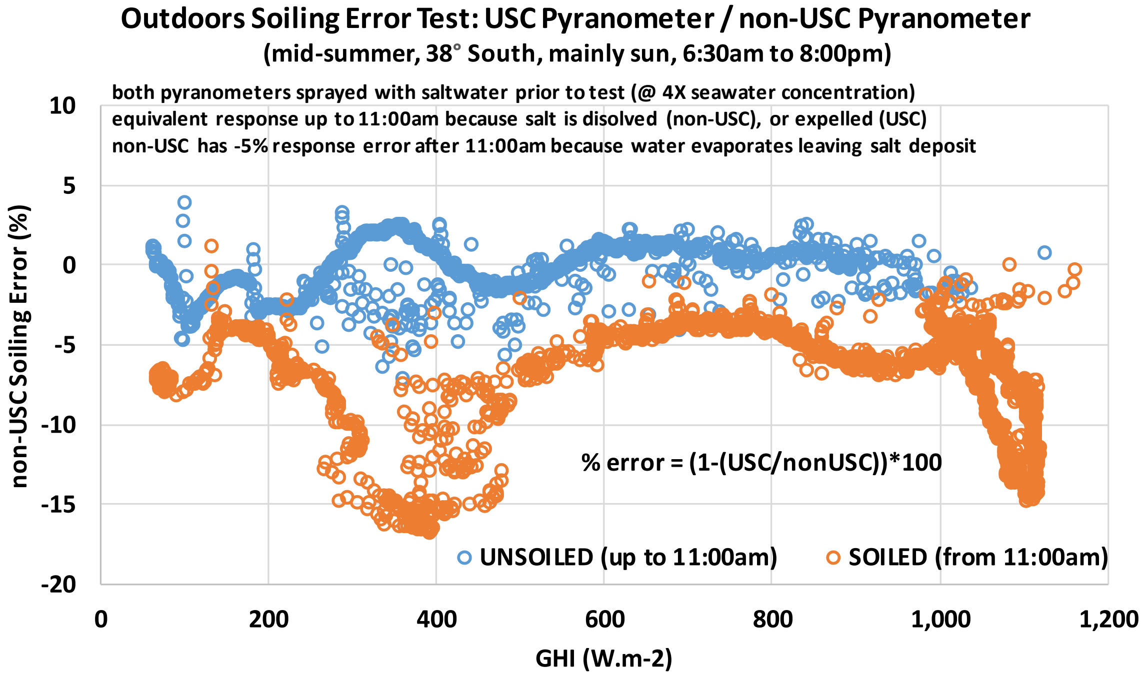
Ultrasonic self-cleaning is effective at removing water and particles, but not effective at removing material that has bonded to the surface of the glass dome.

Ultrasonic self-cleaning induces a momentary (≈10 sec) increase in the dome temperature resulting in ≈ 7.5 W.m-2 pyranometer response off-set spike due to IR radiation exchange, via the inner dome, with the exposed black sensor surface. This off-set is not evident in Fast-Response Pyranometers that use concealed sensor thermopiles.



8. Self-Cleaning Validation

Middleton Solar has undertaken field testing of ultrasonic self-cleaning Class B Pyranometers.



The salt-soiling tests show that a non-USC pyranometer can exhibit significant daily soiling error, whereas a coextensive USC pyranometer remains error free.


non-USC: before test


non-USC: after test


USC: before test


USC: after test

The photos show that sea-salt soiling is effectively removed from the USC dome, but persists on the non-USC dome. The salt has been dissolved by dew during the test, and subsequently dried out, so the salt deposit pattern transforms.

9. Development Timetable

Middleton Solar plans to provide sample units, to selected Users, for independent field evaluation in early 2024. Production release is anticipated for later in 2024.

10. Other Solar Instrument Applications

Middleton Solar will over time apply ultrasonic self-cleaning to other solar instruments we manufacture such as Class A & Fast-Response Pyranometers, Pyrheliometers, Sunphotometers, and Tracker Eyes.