Thermoelastic Analysis of a Carbon-Fiber Compact Antenna Test Range Reflector

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***Abstract*— Compact antenna test ranges (CATR) are attractive solutions for far-field measurements in a confined space with the single-offset reflector being the most common variation of deployed CATRs. Reflectors in these ranges emit a collimated plane-wave to simulate the far-field condition. This requires that each CATR must be properly focused and undergo careful alignment and validation, as any misalignment would perturb the plane wave. CATRs are normally designed to operate in environments with tight temperature control, however this is frequently impractical to implement in normal test environments. A carbon-fiber CATR reflector designed to be insensitive to temperature fluctuations can be an effective means to prevent thermally-induced deformation, and thus a corruption of the plane wave. This paper will illustrate the performance of this reflector over across a range of temperatures, and use a computational electromagnetic simulation to predict the impact on antenna measurements when the reflector is subjected to different temperatures.**

Index Terms— ***compact antenna test range, reflectors, computational electromagnetics, quiet zone.***

I. Introduction

Indoor far-field measurements were impractical until the advent of compact antenna test ranges (CATR). These ranges are attractive solutions for indoor far-field antenna measurements and are a very robust technology, used since the 1960's. The most common range configuration of a compact range uses a single-offset reflector designed to generate a pseudo transverse electromagnetic wave (TEM). The feed is effectively projected at infinity and the wave incident on the antenna under test if it were at a distance much further than in the actual test environment, which effectively approximates the far-field condition [1].

CATR reflectors are typically 20λ or larger, and require treatment of the reflector edges to minimize the effects of unwanted diffraction within the region where the pseudo plane wave will be illuminating the test antenna which is commonly referred to as the quiet-zone [2]. The size of the reflector is designed to maximize the cross-sectional area of the quiet zone, in which the pseudo plane wave most effectively approximates the far-field condition. The purity of the plane wave in the quiet zone is of utmost importance and is commonly evaluated by calculating the taper and ripple of the plane wave over the designed quiet zone region for both amplitude and phase.

However, the plane wave in a real CATR is a non-ideal entity, and it is influenced by various factors, including reflector surface tolerance, edge treatment, feed pattern and polarization, range geometry and range reflections, among others [3, 4].

The geometry of the range is of particular importance to the generation of plane wave within the finite volume of the anechoic chamber as proper focusing and alignment of the reflector to the feed is crucial to optimize the field within the quiet zone. Any misalignment will result in a deterioration of the quality of the TEM wave in the quiet zone, introducing amplitude and phase errors, which can increase the uncertainty within antenna measurements, especially gain [4].

In practice, some defocusing of the reflector is unavoidable because the phase center of the feed will vary as a function of frequency within the operating band of a particular feed. Furthermore, the phase center of feeds that operate in different bands may vary by differing amounts. As the focal point of the reflector is measured from the phase center of the feed to the vertex of the reflector, the normal variation of the feed's phase center will result in some defocusing of the reflector. Well-designed CATR feeds minimize the movement of the phase center with designs being scaled to maintain a relatively consistent phase center location across a very wide frequency band.

The focal point of the CATR can also change if the reflector body is deformed. Such deformation can occur through thermal changes in the chamber. Normally, CATR reflectors are designed to operate in a narrowly constrained temperature range so as to minimize any thermally induced mechanical deformation. Carbon-composite CATR reflectors are a particularly attractive proposition in this regard, as they offer higher tolerance to thermal variation, as well as higher stiffness to weight ratio when compared to traditional steel reflectors [5]. Nonetheless, it is desirable to determine what deformations will be induced on a carbon-composite CATR reflector due to a wide temperature range.

II. Range Implementation

A carbon-composite CATR was recently installed that was designed to operate from 2 – 40 GHz with a nominal focal length of 3,658 mm (144”). The CATR performance specifications followed commonly accepted industry standards:

- Amplitude taper: ≤1 dB
- Amplitude ripple: ≤1 dB
- Phase ripple: ≤10° at ≤18 GHz; ≤20° at >18 GHz

The upper frequency of operation of the CATR was primarily limited by the RF subsystem, whereas the lower frequency was constrained by the maximum size of the reflector relative to wavelength, i.e. the need to have an electrically large reflecting surface measuring several wavelengths across, which in this case measured 26 wavelengths vertically and 31 wavelengths horizontally. Figure 1 and 2 illustrate the CATR, which enabled the AUT positioner to be reused within a spherical near-field system, which was intended to address the requirement to test frequencies that were not optimally served by the CATR.

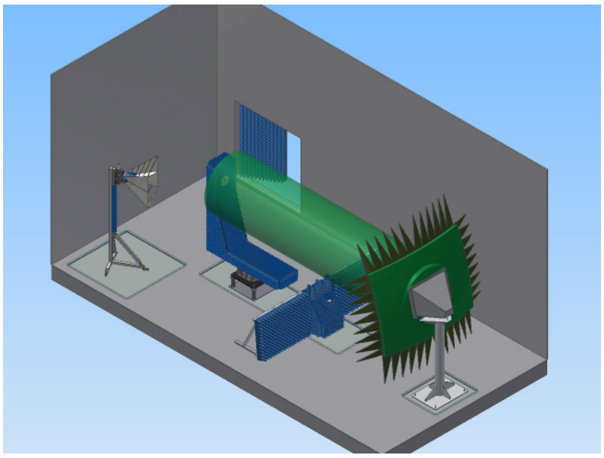

Fig. 1. Mechanical drawing of the combination CATR / SNF range

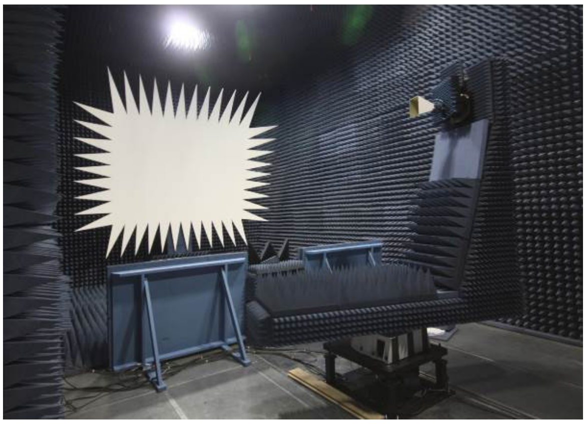

Fig. 2. CATR portion of range; the AUT positioner is shared with the SNF system

Fig. 3. Rear of carbon-fiber CATR reflector; the carbon-fiber support mount can be seen on the pedestal

The CATR parabolic carbon composite reflector was designed and modelled with particular attention being paid to the resistance of the reflector to thermal deformation. The reflector mount serving as the support to the reflector and interface to the pedestal was also manufactured from carbon-composite. This design was selected to avoid any dissimilarity between the coefficients of thermal expansion of the two structures, which could result in an asymmetrical forced deformation of the reflector surface when thermal variations were imposed. This design was evaluated with Finite Element Analysis (FEA), which showed that the paraboloid would deform with temperature, affecting both the focal length and shape. When simulating a change in temperature of the reflector from, 20.5°C to 24°C, FEA predicted the focal length would vary by as much as 4 mm, while the surface quality would vary by as much as 0.2 mm RMS.

As stated previously, the focus of the reflector can be affected by the variation of the phase center of the feed used with normal variations of the phase center defocusing the reflector. The CATR feeds delivered were assessed in the factory to ensure a stable phase center.

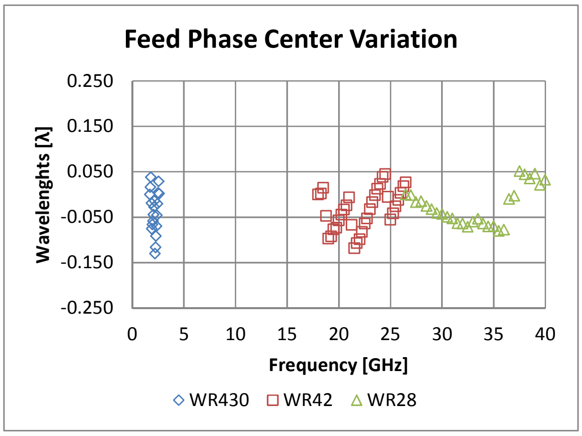

Fig. 4. Variation of phase center with frequency

This is a 90° corrugated horn, and the location of phase center does not move much in longitudinal direction with frequency, only varying by 0.1 wavelengths across the band.

III. Measurement Results

A. Test Configuration

As encouraging as the FEA results were, it was important to test the thermal effects on the reflector in a measurement environment following its installation. During installation, the reflector surface was measured using a laser tracker to assess any deformations of the shape due to the change in environment or the addition of the serrated edge treatment, which were not installed at the factory. While this analysis was performed in a relatively stable thermal environment, the temperature was not completely controlled by the heating ventilation and air-conditioning (HVAC) system and therefore varied slightly. Most HVAC systems have comparatively long time constants, particularly for the case of physically larger chambers, resulting in some thermal instability. As can be seen in Figure 5 the measured focal length of the reflector varied by less that 0.01% relative to its nominal value over a temperature range of ca. 2°C. The results on site compared favorably to measurements taken at the factory, though the factory was not temperature controlled and at a nominally higher temperature.

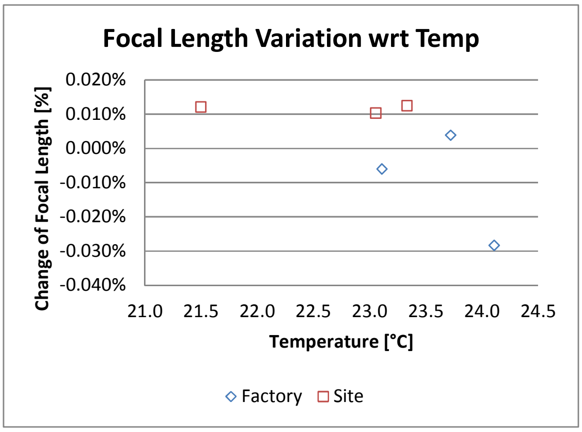

Fig. 5. Variation of reflector focal length with respect to temperature

As the temperature range observed was fairly small, it was desired to examine the performance of the CATR over a large temperature range, and in particular analyze the effects of temperature on the quiet zone.

To do this, the chamber was cooled overnight to 17°C providing sufficient time to have the temperature reach steady state. The same process was repeated, heating the chamber to 26°C, which was the maximum attainable temperature with the installed HVAC system at the time of the test. This represented a 9°C temperature variation. The CATR was allowed to reach thermal equilibrium at both extreme ambient temperatures.

The quiet zone was probed with an NSI field probe 1828 mm (72”) long, mounted on a rotary positioner allowing for 360° motion with the probe scanning radially. The field probe was collocated with the AUT positioner structure and was in thermal equilibrium during measurements. The test was conducted at two bands, 10-15 GHz and 26.5-40 GHz with the CATR quiet-zone field probe presented in Figure 7 below.

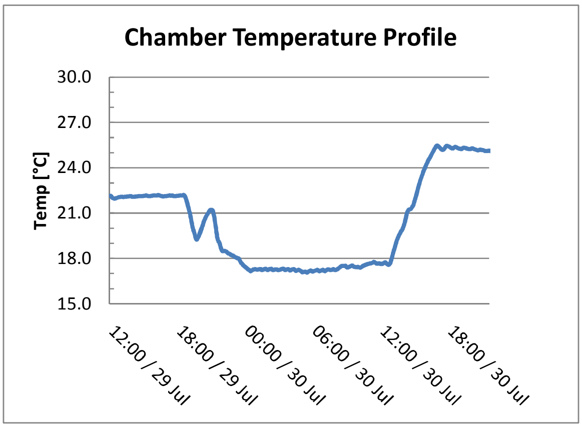

Fig. 6. Chamber temperature was cycled from 17 – 26°C allowing for the chamber to achieve thermal equilibrium in both temperature extremes

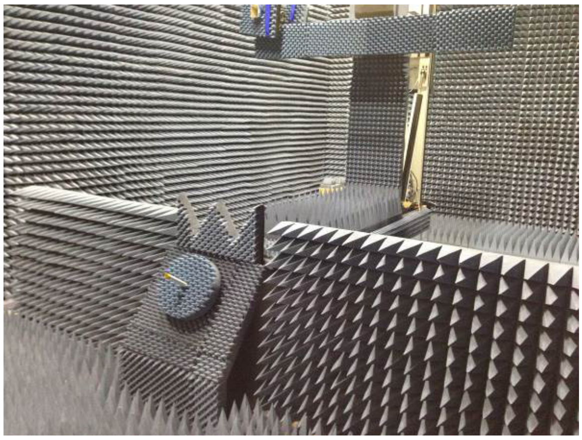

Fig. 7. Test setup with the field probe can be seen in horizontal orientation and mounted on the AUT positioner

B. Quiet Zone Performance

When examining the quiet zone characteristics for the horizontal cut and horizontal polarization, the amplitude taper and amplitude ripple showed excellent agreement, when comparing the measurements at high and low temperature. Phase ripple showed excellent agreement at both temperature extremes for the 10 – 15 GHz case. However, the phase results at 26.5-40 GHz were offset by as much as 3.5° at the higher temperature. Nevertheless, the parameters measured met the design specifications of the range at all temperatures.

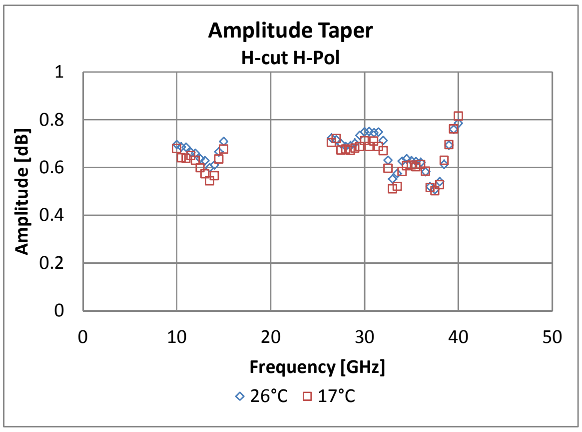

Fig. 8. QZ amplitude taper comparison at 26°C and 17°C

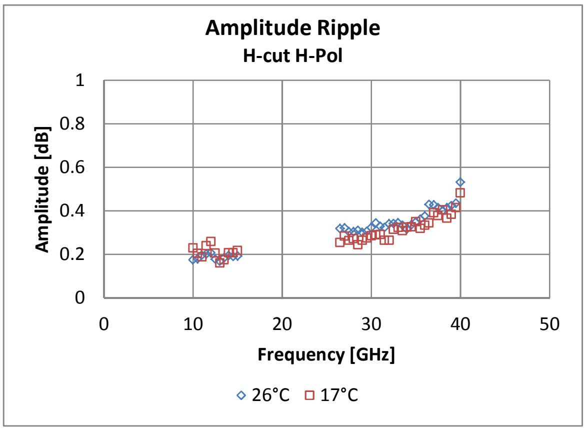

Fig. 9. QZ amplitude ripple comparison at 26°C and 17°C

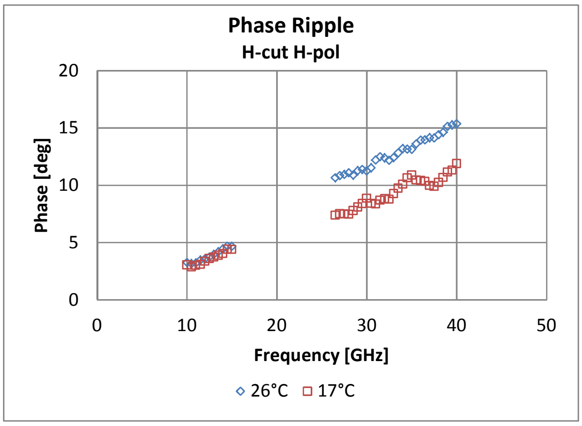

Fig. 10. QZ phase ripple comparison at 26°C and 17°C

For the case of the vertical cut and horizontal polarization, there was little discernable difference between the two temperature extremes for amplitude and phase parameters.

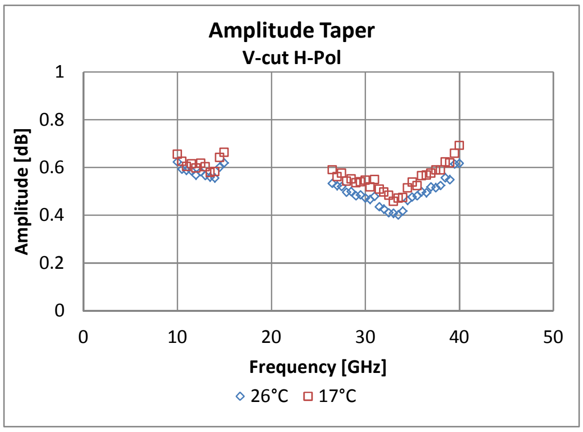

Fig. 11. QZ amplitude taper comparison at 26°C and 17°C

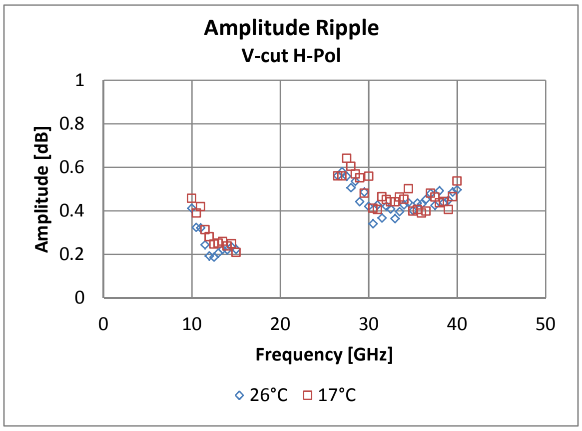

Fig. 12. QZ amplitude ripple comparison at 26°C and 17°C

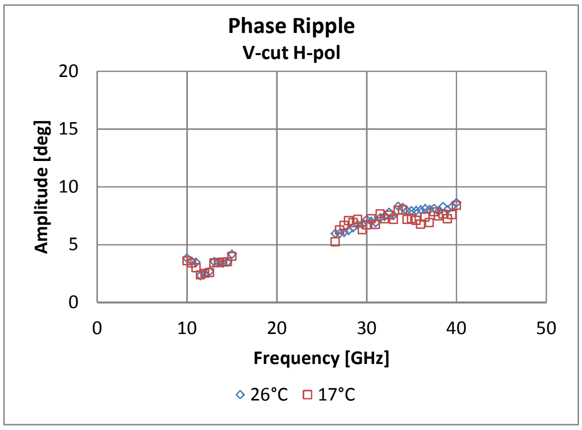

Fig. 13. QZ phase ripple comparison at 26°C and 17°C

C. *Effect of Thermal Fluctuations on Antenna Patterns*

The measurements shown above show that the focal length of a carbon-composite reflector remains unchanged over a small temperature range. Furthermore, the performance of the quiet zone remains relatively invariant over a larger temperature range. However, due to limitations with which the facility could be heated or cooled, it was unclear from the measurement results how a larger temperature variation would affect the focal length, and in turn how the corresponding focal length change would affect the performance of the quiet zone.

To this end, the quiet zone performance of the CATR was simulated at 12 GHz using a NSI's computational electromagnetic modelling software [2, 3]. The focal point of the reflector was progressively defocused by an amount up to 2% of the focal length or 73 mm, corresponding to temperature changes much larger than the 9°C seen during measurements. The corresponding quiet zone field was calculated. It was assumed that due to the reflector being designed with a uniform CTE, any thermally induced deformation of the reflector would be symmetrical and would primarily result in a change of the focal length. The effects of any asymmetrical deformation that substantially changes the paraboloidal shape or that induce ripple on the reflector surface were therefore not considered. The simulation results are presented below.

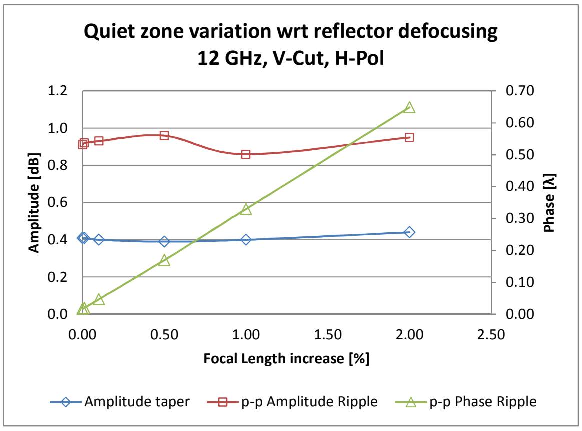

Fig. 14. Simulated variation of quiet zone performance with progressive defocusing of the CATR reflector, vertical cut, horizontal polarization

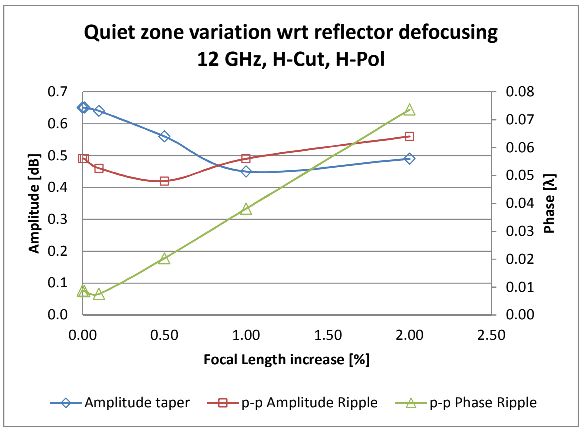

Fig. 15. Simulated variation of quiet zone performance with progressive defocusing of the CATR reflector, horizontal cut, horizontal polarization

As can be seen, despite a large forced change in the focal length corresponding to 2.5 λ – nearly 20 mm – the amplitude taper and ripple largely remain unchanged. The phase ripple shows a large linear slope that largely corresponds to a phase taper of the quiet zone. Within these simulations the location and orientation of the feed was held fixed corresponding to the practical case. The location of the vertex of the parabolic reflector was also fixed so as to ensure that the thermoelastic deformation of the carbon-composite reflector would be as prominent as possible corresponding to an upper-bound estimation of the thermal effects.

IV. Summary and Conclusion

This paper has presented an analysis of the sources that can contribute to a defocusing of a compact range reflector. In particular, the performance of a CATR outfitted with a carbon-fiber reflector was considered over a large temperature range.

The reflector focal length was determined using surface profile data obtained from coordinate measurements taken using a precision laser tracker and was found to vary comparatively little over a smaller temperature range. Results of the probing of the quiet zone in horizontal and vertical orientations have been presented showing that the reflector is insensitive to comparatively large temperature variations and the quiet zone performance remains largely unaffected.

Even though it was evident that the focal length of the reflector analyzed changed little, it was desired to examine the effect of a larger change in focal length to the performance of the CATR quiet zone. Simulation results were presented that showed that even a large 2% defocusing of the reflector resulted in relatively small changes in of the amplitude taper or peak-to-peak ripple. However, the effect on the phase ripple was more substantial with the introduction of a progressive linear phase taper.

The analysis presented shows that the performance of the compact antenna test range examined is largely unaffected over a larger temperature ranges, and in general, minor defocusing of the CATR reflector does not substantially impact the performance of the compact range.

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