Alignment and testing of the NIST Calculable Capacitor

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Abstract --- **This paper reports progress on the NIST effort to develop a new calculable capacitor, focusing on improvement of the guard electrode motion control as well as issues associated with the overall electrode alignment. Design of a multi-wavelength Fabry-Perot interferometer which may facilitate testing the calculable capacitor in air is also discussed.**

Index Terms --- **Calculable capacitor, laser alignment.**

I. INTRODUCTION

The main components of the new NIST calculable capacitor (CC) have been manufactured and are now in the initial phases of being assembled and aligned to form a working prototype. The CC's arrangement derives substantially from the classic cylindrical cross-capacitor design described by Clothier [1], but deviates in certain mechanical design and construction details, as well as in the optical systems used for measuring the effective length of the capacitor [2, 3].

II. CAPACITOR MECHANICS AND ASSEMBLY

The general arrangement of the assembled prototype is shown in the cross-section view of Fig. 1. The standard consists of four equal right circular cylinders that serve as the main cross-capacitor electrodes, with a pair of tubular guard electrodes along the central axis, one fixed and one movable, defining the variable effective length.

Main bar assembly. The main bars mount to a circular base plate that has four cones at 90° intervals at a fixed radius from the plate's center. Three of the cones are machined directly into the base plate. The fourth cone is an adjustable insert (Fig. 1). This insert is constructed similar to a cap head screw, where the cap has a cone machined in the top. The threaded shaft of the insert penetrates the baseplate through an oversized hole, and the insert is secured to the base plate using a nut and washers. Thus, the precise location of this cone can be adjusted simply by tapping on the nut with a mallet.

A precision silicon nitride sphere seats in each cone to make a ball and socket pivot (Fig. 1). The socket is machined into the base of each bar, so that the final assembly is similar to having four ball bars mounted symmetrically about the center of the plate and housed in a concentric canister. Fine screw adjusters driven by Picomotors are included at the top of the canister to adjust the alignment of the bars with respect to a vertical axis orthogonal to the mirror surface on the cylinder base.

Movable guard electrode. The guard electrode is a hollow tube suspended at its upper end from an adjustable gimbal joint that couples to a shaft guided by a pair of Teflon impregnated plastic bushings seated at opposite ends of the center bore of

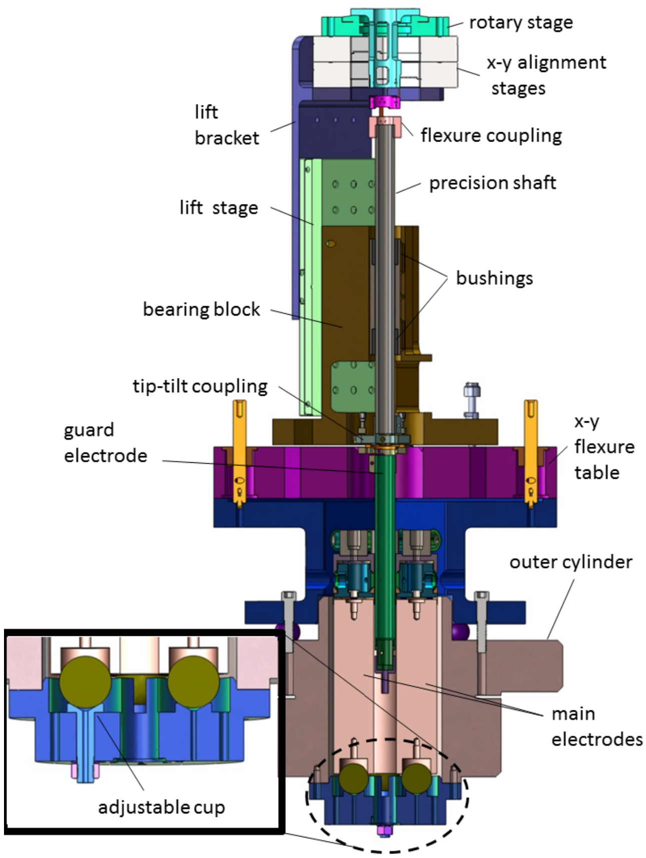

Fig. 1. Cross-section of NIST prototype. Capacitor bars (peach) pivot on silicon nitride spheres. Bars can be aligned using laser light reflected off of their mirror end faces.

the bearing block. The adjustable gimbal joint allows the axis of the guard tube to be made precisely parallel to the axis of the bearing shaft and provides an electrical break between the guard and the bearing shaft. In a significant departure from [1], the guard is not guided or supported by the main electrodes.

The bearing shaft is a precision ground and polished anodized aluminum tube (approximately 10^{-6} m/m straightness) that slides through the bushings to define the vertical translation axis. In order to drive the shaft and minimize errors due to moments and off axes actuation forces, the upper end of this bearing shaft is clamped to a flexure coupling that nests inside a set of stages that provide precision x-y positioning as well as gradated rotation of the clamp with respect to and about the bearing axis. A crossed-roller bearing stage mounted to the bearing housing and actuated by a vacuum compatible motorized screw drive is used to raise and lower the entire assembly as shown.

The bearing housing sits on three adjustable feet that rest atop a sturdy x-y flexure table mounted at the top of the main bar canister to facilitate the centering of the guard tube between the cylinders. The tip and tilt of the bearing axis is adjusted using the cylinders as reference through capacitive and optical measurements.

III. ALIGNMENT

We have developed a two-step alignment procedure that combines optical and capacitive measurements. A novel feature of our design is the inclusion of alignment mirrors machined into the main electrodes. The orientation of each alignment mirror with respect to the associated cylinder axis can be measured on the NIST M48 coordinate measurement machine. Due to finite alignment tolerances in the diamond turning machining, the end mirror of each cylinder exhibits a conic shape with an angle of the order of 100 µrad with respect to the plane perpendicular to the cylindrical axis. The bottom plate of the assembly has three 6 mm apertures in form of an equilateral triangle that is aligned with the mirror ring of each electrode. The optical alignment system consists of an optical lever arm with an angular sensitivity of the order of 1 µrad. As reference for the alignment, the laser beam is adjusted to be collinear with the travel axis of the movable guard electrode. In the first alignment step, the laser beam is sequentially guided to the three apertures under each electrode, and the positions of the reflected beam, forming an equilateral triangle, are measured. The electrode is then adjusted such that the triangle center is aligned with the guard electrode travel axis. In the second alignment step, we use the capacitive measurements between the main electrodes and the movable guard electrode at the two end positions of the travel range, to match these capacitive readings to a few parts in 10^5, corresponding to a few 100s nm. The resulting cross-capacitances between the main electrodes have been matched to levels below 100 ppm.

IV. MULTI-WAVELENGTH INTERFEROMETER

The uncertainty of the Fabry-Perot interferometer designed for the CC operation in vacuum is on the order of 1 pm, limited by the extent to which we can reliably interpolate the cavity resonances [3] and uncertainty in the cavity Gouy phase [4]. In initial testing, however, it will be of interest to employ the CC in air, with refractive index n. In this case, the interferometer measures the optical path length $D = nL$ associated with the physical length L. The measurement uncertainty in the length L of interest is then severely compromised by uncertainty in the index of refraction, which varies with pressure, temperature, and humidity.

In order to determine the physical cavity length L, we are comparing two different approaches. The straightforward approach involves simply measuring the pressure, temperature, and humidity in close proximity to the capacitor, and subsequently inferring the index of refraction of air by means of an empirical formula. In the NIST Advanced Measurement Laboratory, where the calculable capacitor is housed, the thermal stability of the room is $\pm 0.1^{\circ}$ C, while the relative humidity is stable to $\pm$ 1%. Pressure is more difficult to control as it is correlated to external atmospheric pressure; we have found from day to day the value can deviate by as much as $\pm$ 1000 Pa. The second approach involves using multiple wavelengths, relaxing the requirements for accurate measurements of atmospheric parameters [5]. We are currently using dielectric cavity mirrors that are highly reflective at λ_1 = 780 nm, λ_2 = 1064 nm, and λ_3 = 1560 nm. The optical path lengths $D_i = n_i L$ are then slightly different for the three wavelengths, on account of the dispersion of air. The actual physical length L can be deduced from a pair of measurements at two different wavelengths as

$$L = D_1 - A(D_1 - D_2)$$

where

$$A = \frac{n_1 - 1}{n_1 - n_2}$$

The advantage of this approach is that the quantity A exhibits very little sensitivity to the temperature and pressure. We are currently supplementing the light at 1560 nm with a second optical drive at 780 nm derived by passing amplified light from a 1560 nm fiber laser through a PPLN doubling crystal. This beam is independently phase modulated and a second Pound-Drever-Hall signal is obtained. The frequency metrology is carried out by comparing all of the lasers at 1560 nm to a frequency comb.

V. CONCLUSIONS

Progress is being made towards realizing a new CC. The novel translation mechanism of the guard electrodes completely avoids direct contact with the main electrodes. System alignment is achieved by combined optical and capacitive measurements.

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