MODEL TESTS TO INVESTIGATE THE EFFECTS OF GEOMETRICAL IMPERFECTIONS ON THE NIST CALCULABLE CAPACITOR

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Abstract

A calculable capacitor links the U.S. capacitance unit to the SI unit and has a relative standard uncertainty of 2×10^{-8}. Geometrical imperfections are one of the largest sources of this uncertainty. Tests with a model calculable capacitor have been done to better evaluate and reduce this uncertainty.

Introduction

The calculable capacitor is a cross-capacitor whose value can be found from a single length measurement [1]. The National Institute of Standards and Technology (NIST) calculable capacitor consists of four vertical cylindrical bars arranged at the corners of a square. The length of the capacitor which determines its value is defined by cylindrical blocking electrodes partially inserted between the four bars at their top and bottom. The actual measurement made is a difference measurement with the moveable upper blocking electrode in two different positions for each measurement. The NIST calculable capacitor is described in Ref. [2].

One of the largest sources of uncertainty in the calculable capacitor experiment is due to geometrical imperfections in the bars and the alignment of the bars with each other and with the blocking electrodes. Recent linearity tests, which consisted of measuring 0.1 pF increments along the length of the calculable capacitor, have resulted in the assignment of a larger uncertainty for geometrical imperfections [3]. We believe that two of the main contributors to this uncertainty are the eccentricity of the central blocking electrodes and local imperfections along the main bars.

Clothier [4] performed a series of tests with a model capacitor to evaluate these effects. Clothier investigated the effect of eccentricity of the blocking electrode, the effect of local imperfections on the bars, and the effect of a uniform taper of the bars. His tests showed that a small spike at the ends of the blocking electrodes reduces the effect of local imperfections in the bars and compensates for the effect of a uniform taper in the bars. There is a still a change, however, in capacitance when the spike is near a local imperfection. If a measurement is made when the movable blocking electrode is in such a position and the capacitance change is large enough, there will be an error.

We have repeated these tests for our geometry to check that our spike's compensation is adequate. In this work we also looked at the effect of tilt of the blocking electrodes and the effect of a uniform taper of three or fewer bars. The tilt of the blocking electrodes is of interest, because in our calculable capacitor their tilt is different for the two positions used in the calculable capacitor difference measurement. Also, all four main bars do not have a uniform taper; one has more of an outward taper than the others.

We have also tried changing the shape of the tip of the blocking electrodes using a cone shape instead of the usual spike. It was anticipated that a cone-ended blocking electrode would be less sensitive to local imperfections.

Experiment and Results

The tests are performed with a model calculable capacitor that has the same dimensions as the NIST calculable capacitor. In order to remove the effect of capacitance change as the blocking electrode is moved, a short double-ended blocking electrode is used. In this way the blocking electrode can be moved along the length of the bars without changing the capacitance. Other effects can then be observed.

Eccentricity tests The double-ended blocking electrode was centered between the four bars. This probe was then moved in 0.2 mm increments towards the gap between two adjacent bars, and the change in cross capacitance measured. The probe was also moved towards a bar from the central position to see if the effect was the same as movement towards a gap. Following Clothier's analysis [4], the change ΔC in the capacitance due to the probe being off center can be expressed as $\Delta C = k\varepsilon^2$, where k is a constant and ε is the displacement from the central position. Our value for k is 2×10^{-4} aF/μm^2 for both the spike-ended electrode and the cone-ended electrode. This agrees with Clothier's value for k. Displacement towards a bar gave the same results as displacement towards the gap between bars.

Tilt tests To create a tilt, one end of the double-ended electrode was kept centered using a Teflon ring while the other end was displaced by 0.2 mm increments and the change in cross capacitance measured. The change in

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capacitance ΔC obtained from the tilt tests can be predicted from the eccentricity of the ends using the k from the eccentricity measurements. This allows us to estimate the effect of tilt in our calculable capacitor.

Effect of local imperfections and uniform taper in the bars For this series of tests three double-ended blocking electrodes, one flat-ended, one spike-ended and one cone-ended, all of the same length, were used. To simulate the effect of a local imperfection on the bars, a narrow strip of foil is wrapped around each of the four bars. A uniform taper in the bars is simulated by wrapping a wider metal foil strip around 4, 3, 2 or 1 bars near their ends. The wider strip also simulates the effect of a local imperfection as the electrode approaches the edge of the foil. In each case, the double-ended blocking electrode is moved along the bars until its front edge is 2 cm past the front edge of the foil. The average cross capacitance is measured as the electrode is moved along the bars.

The results from these tests are shown in Fig.1 and are similar to Clothier's results [4]. The magnitudes of the changes in capacitance are equivalent to those observed by Clothier when the difference in thickness of foil used is accounted for. Our bars and blocking electrode have approximately twice the diameters as Clothier's but the effect from imperfections on the bars should be the same.

One of the differences we observed from Clothier's work was for the spike-ended electrode in case (c) in Fig. 1. Our spike produces an increase in capacitance instead of a decrease. This opposite effect is also seen for the narrow strip of foil in case (d) in Fig. 1. We have observed that this difference is due only to the relative diameter of the spike, ours being larger. We experimented with several diameters to determine if there was one between these two cases that produced no change in capacitance. The in-between case showed an increase and then a decrease in capacitance with the overall change being similar in magnitude to the two other cases. The advantage is that the change in capacitance from the initial value is halved, reducing the effect of a local imperfection.

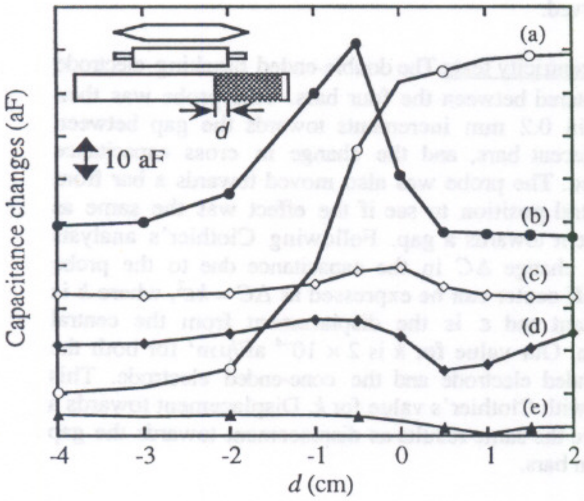

Figure 1. Capacitance changes as the blocking electrode is moved along bars. The different cases are: (a) the flat-ended electrode with 102 mm wide, 50 µm thick foil and (b) with 3 mm wide, 127 µm thick foil, (c) the spike-ended electrode with 102 mm wide, 50 µm thick foil and (d) with 3 mm wide, 127 µm thick foil, and (e) the cone-ended electrode with 3 mm wide, 127 µm thick foil. The foil was applied to all four bars.

The tests with foil on three or fewer bars had to be done with very thin foil (25 µm) since second-order effects were significant at greater thickness. Initial tests appear to indicate that the spike will still compensate in these cases.

The cone-ended electrode showed smaller changes in capacitance for both the narrow (Fig. 1, case(e)) and the wider strip of foil than the spike-ended electrode. The capacitance does not return to its initial value implying that the angle of the cone's apex in not correct. Because of the difficulty in varying this angle, obtaining the correct angle was not pursued. In any case, a cone would not be practical since the tip of blocking electrode has to be wide enough for the laser used in the length measurement to pass through. A modified cone shape (a cone with a short spike on top) would have to be used. While initial tests with this modified cone show smaller changes in capacitance than with the spike, the difference is not enough to warrant changing the spike end. More testing will be done with this new shape.

Conclusions

Our eccentricity tests agreed well with Clothier's results and the tilt tests will provide a way to evaluate the tilt effect in our calculable capacitor. The other results indicate that only small improvements in the effects from local imperfections will be gained from changes to our present blocking electrode. Our spike, however, appears to be adequate and compensates even for the taper of 3 or fewer bars.

References

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