METROLOGY ARTIFACT DESIGN
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INTRODUCTION
Coordinate Measuring Machines (CMMs) are widely used to measure the shape of machined parts. Their availability, speed, resolution and flexibility have pushed them into many new applications. Laboratories and manufacturing facilities alike use them to assess the quality of fabricated parts. However, to reap the full benefits of a CMM, there is a need to “qualify” its measuring capabilities and compare it to other CMMs available. Through the years, there have been a number of calibration artifacts developed including ball bars, ball and hole plates, ring gauges, and hole bars [1]. After considering these artifact standards, a ring gauge was chosen for further development. The overall features of the ring gauge (OD, ID, width and wall thickness) can be used to exercise multiple axes of a CMM. In addition, small features can be added to the ID and OD to assess the capability of the machine to deal with small temporal and spatial variations in surface features. The ring gauge can also be measured in different orientations and positions on the CMM to cover the entire working volume. Figure 1 shows the ring gauge geometry on the Diamond Turning Machine (DTM) during machining.

RING GAUGE FEATURES
The first prototype of the ring gauge was created in 6061-T6 aluminum. It has a 6” (152.4mm) ID with 1” (25.4mm) square cross section and all surfaces of the gauge have been diamond turned. Reference surfaces were created on the OD and ID in the form of 0.5” (12.7 mm) wide grooves that are 30 µm deep. The OD is a smooth ring but the ID has a swept sine wave with ± 2.5 µm amplitude and spatial wavelength range from 1/80” (0.317mm) to 1/4” (6.35mm). A swept sine wave is a sine wave that continuously varies its frequency. In this case, the wave begins at the long wavelength and progresses to a short wavelength in the first 90 degrees. To produce a continuous wave, the wave is “flipped” to line up with the last wave and then the wavelength increases to the starting point as it reaches 180 degrees. From 180 to 360 degrees, the wave is a mirror image of the first 180 degrees. Figure 2 illustrates these features. The small surface features will assess the capability of the CMM to respond to small surface anomalies and to characterize the dynamic performance of the CMM as it traverses the varying wavelength features.

DESIGN AND FABRICATION PROCEDURE
The design of the ring was selected for a convenient size with sufficient stiffness to be usable and machinable. Significant thought went into the mounting system and machining procedure to
guarantee a cylindrical shape post-machining. Figure 1 shows the ring mounted in the diamond turning machine. It is supported on a vacuum chuck with 3 one-inch diameter posts. The procedure was to machine the back of the flat vacuum plate and mount it on the spindle. The posts are installed and machined flat. The ring was bolted to the posts and the front side was machined and then flipped over and the back side is machined. Next, the ID and OD of the ring were machined. Finally, the finished reference shapes were machined: a flat cylinder on the OD and the swept sine wave on the ID.

**Fabrication of Swept Sine Wave**

The wave features of the artifact were fabricated using a Fast Tool Servo (FTS) shown in Figure 3. An 18 mm long, hollow cylindrical piezoelectric actuator (25 mm OD and 12 mm ID) drives the device to a maximum displacement of 18 µm. A capacitance gage provides feedback on the position of the tool holder by looking at the back of it through the hollow actuator. A commanded position is turned into a positive input voltage and sent to a high voltage amplifier where it is amplified by 100 before being sent to the FTS.

![Figure 3. Fast Tool Servo.](image1)  
![Figure 4. System dynamics of the FTS.](image2)

The open-loop dynamics of the FTS as a function of the frequency of a sine wave command is shown in Figure 4. The top graph is the amplitude ratio of the output voltage from the capacitance gage to the input voltage to the amplifier. It shows a slight decrease in amplitude with frequency up to about 400 Hz and a strong increase to the first natural frequency of 5 kHz. This frequency is a result of the first bending mode of the cylindrical plate that serves as the base for the tool holder. The phase difference between input and output shows a small offset (4°) at DC that grows to about 27° at 1000 Hz. These dynamics need to be compensated using a closed loop control system.

A dSPACE DSP control system was used to drive the actuator and compensate for the dynamics shown in Figure 4. A PI control loop was created and the results using the most appropriate gains are shown in Figure 5 up to 600 Hz. The plots of Figure 5 also compare a 1µm and 5µm input to the closed loop system to demonstrate the amplitude dependence of the FTS. The gain at low frequency has been improved (equal to approximately 1) and the phase is nearly zero from DC to 70 Hz for the 5 µm amplitude input. The step response in Figure 6 indicates the improved amplitude response and settling time using the controller.
To create the swept sine wave, the FTS is commanded to provide a range of sinusoidal outputs that depend on the wavelength of the feature and the spindle speed. The minimum speed for the spindle on the DTM is about 20 RPM, which makes the sinusoids of interest range from 25 to 500 Hz on the ring gauge dimensions described in Figure 1. Therefore, based on the characteristics of the FTS shown in Figure 5, the waveform at the highest frequency will be distorted in both amplitude and gain compared to the lowest frequency.

One technique that can be applied to correct the phase and gain is called Deconvolution [2]. In this technique, the dynamics of the FTS are measured, inverted and applied to the desired tool motion to create a modified input command. This command will provide the correct tool motion when applied to and distorted by the FTS dynamics. A sample swept sine wave has been fabricated on the outside of a aluminum cylinder (110 mm OD) to test the quality of the machined sine waves and the results are shown in Figure 7.

Figure 7 was measured using an air-bearing LVDT mounted to the base of the DTM. The spindle was driven at a low speed (2 RPM) and the resulting data was modified to compensate for the 1 mm diameter of the LVDT tip. Because the tip radius is not that much smaller than the radius at the base of the shortest wavelength sine wave, the data from the LVDT will provide a distorted picture of the machined sine waves. The tip radius will appear to increase the width of the sine waves and reduce the distance between them. However, the data was corrected by finding the actual contact point between LVDT tip and sine wave (assuming the tip is a perfect sphere) and modifying the data to show the actual surface features.

MEASUREMENTS
The first prototype of the ring gauge was measured at the Precision Engineering Center (PEC) as well as at the Oak Ridge Y-12 Facility. The measurements at the PEC were performed using an
LVDT on the spindle of the DTM rotating at approximately 2 RPM. Similar measurements were made at Y-12 using a CMM as shown in Figure 8. The ring gauge was measured in a horizontal orientation mounted on a rotary table and a scanning probe. The CMM measurement showed two errors: one is reduced amplitude at the shortest wavelength (highest frequency) sine wave and the second is a lobed profile that matches the number of hold-down bolts. The former problem has been solved with a larger minimum feature size along with the deconvolution/closed loop control and the second is being addressed with a new support during machining.

Figure 8. Measurement setup with a CMM at Y-12.  
Figure 9. CMM measurement.

CONCLUSIONS
The final ring gauge design will be a useful addition to the artifacts available to calibrate CMMs. Improvements in the fabrication technique have reduced the amplitude and phase errors of the different frequency sine waves from 5 to 0.6 µm based on an amplitude input of ± 5 µm. A new design of the ring support is underway and a second prototype will be fabricated with features on both the ID and the OD of the ring. The mounting of the ring in a CMM is another issue that must be addressed to utilize the ring gauge in different orientations. The final phase of the project involves measurement and uncertainty. The accepted measurement data can then be used in the assessment process of the CMMs. The CMM will measure the artifact, and the data will be compared to the accepted measurement data through uncertainty analysis. The Guide to the Expression of Uncertainty in Measurement [3] will be the primary source for the uncertainty analysis. However, the non-linearity of the features may pose a problem with the uncertainty model. Finally, this procedure will use decision rules to make a final assessment on the uncertainty associated with a specific CMM of whether it is fit to perform measurements on real parts.

REFERENCES