# RING GAUGE FOR EVALUATION OF CMM DYNAMICS

**Kenneth P. Garrard[1], Thomas A. Dow[1], and Karalyn F. Folkert[2]**
**[1]North Carolina State University, Raleigh, North Carolina, USA**
**[2]Consolidated Diesel Company, Whitakers, North Carolina, USA**

## BACKGROUND

An artifact has been designed and built to assess the static and dynamic performance of a Coordinate Measuring Machine (CMM). CMMs can measure a wide variety of component shapes and have accuracy and repeatability comparable with most manufacturing operations. The Y-12 National Security Complex manufactures precision parts for the government and private companies. Part acceptance is generally based on dimensional inspection and comparison with tolerance specifications. The goal of this project was to design and fabricate an artifact that can be used to expose the measurement errors in a CMM due to static (error motion of slides, control system) and dynamic sources (following error, probe dynamics). With this information, a measurement strategy for a part shape can be developed that will limit the errors to an acceptable value. If the artifact includes a broad band of excitation sources, the measurement will show how the actual gauge motion is transformed by the dynamic environment to produce a new motion with amplitude and phase errors. A ring gage was found to be the best artifact geometry for Y-12 and the addition of small sine wave features allow both static and dynamic calibration.

## RING GAUGE GEOMETRY

The ring gauge has a 200 mm OD, a 150 mm ID and a thickness of 25 mm. The material was 17-4 PH stainless steel, heat treated for maximum dimensional stability and electroless nickel plated. Diamond turned flat surfaces on the top and bottom as well as circular sections on the ID and OD can be used as a standard ring gauge to measure machine geometry and the effectiveness of control systems and error correction schemes. The OD and ID have raised sections on which a sine wave features were machined to measure the dynamic response of the machine and probe.

### Swept Sine Wave

The small features on the surface of the ring are designed to create a range of excitation frequencies to evaluate the response to a dynamic environment. A number of different geometries were investigated and the best candidate was a swept sine wave with constant amplitude. A swept sine wave is a sine wave with a continuously varying wavelength; that is, each point on the swept sine wave has a different wavelength. For the ring gauge, the wave begins at a 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. Four quadrants of the same wavelengths allow a smaller section to be measured. Figure 1 illustrates these features.

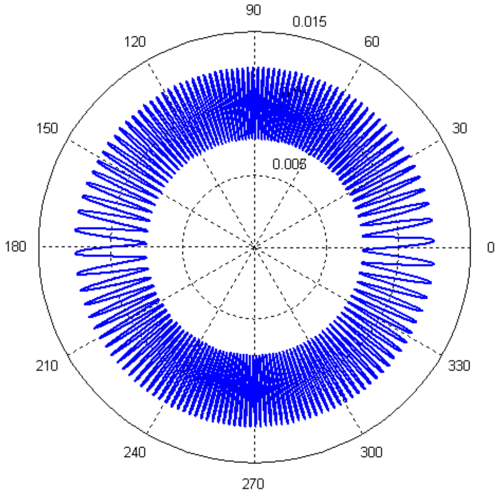

*FIGURE 1. A continuous swept sine wave in polar coordinates.*

The allure of the swept sine wave is that it contains a wide range of wavelengths and thus excitation frequencies. Different measurement speeds change the frequency range for the transfer function while the spatial wavelength remains the same. The linear swept sine wave from 0º to 90º is given by Equation 1 where *A* is amplitude, *t* is circumferential distance, *d* is the modulation parameter and *f* is the base wavenumber. The total number of waves over length *L* is *d*+*f*.

$$y = A \cdot \sin\left(\frac{2\pi t}{L}\left(\frac{d}{L}t + f\right)\right) \qquad (1)$$

## Swept Sine Wave Excitation

The swept sine wave creates a frequency-rich environment that reveals the dynamics of the CMM, its ability to respond to small surface anomalies and the performance of the CMM as it traverses the varying wavelength features. The values of the swept sine wave were selected based on desired minimum and maximum spatial wavelength. Because the wavelengths can be considered as individual frequencies, a Fourier transform can be performed on the data set. With sampled data, the units on the frequency spectrum plot are in terms of Hertz.

However, with the generated spatial data, it is more useful to plot the results in terms of wave number[1]. The wave number is the reciprocal of the normalized spatial wavelength. Figure 2 shows the FFT of the first quadrant of the ideal wave for the ID. The magnitude is largest near the shortest wavelength at wave number 223/λ which translates to a wavelength of 0.537 μm. The phase values accumulate for half of the wavelengths and then returns to zero.

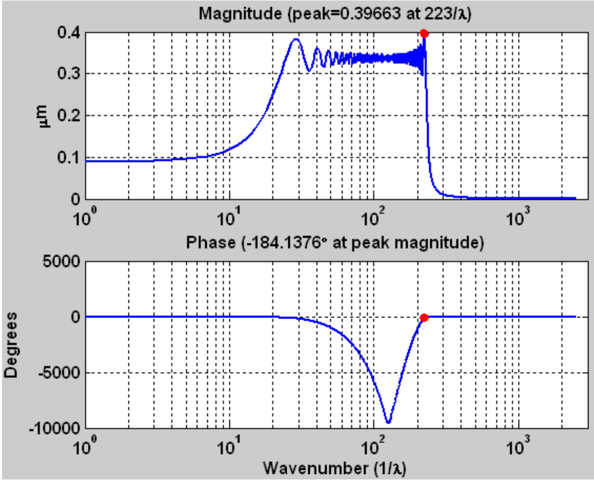

*FIGURE 2. Spatial frequency spectrum of the first quadrant of the swept sine wave in Figure 1.*

The FFT of the swept sine wave is more difficult to interpret than a single frequency sine wave due to the constantly varying nature of the wavelength. Rather than strictly interpreting the ideal FFT and directly comparing it to an FFT of an actual measurement, the data analysis may be simplified. A CMM has dynamic characteristics that will influence the overall measurement of the artifact and the ability of the probe to detect small perturbations changes with the radius of the probe, measurement speed, radius of the part and size of the feature. Since the swept sine wave on the surface of the ring has an 'accepted' value[2] and the CMM measurement will generate another data set, the CMM's dynamics, or transfer function, may be found by comparing these measurements using a form of deconvolution. Convolution in the time domain is the multiplication of the swept sine wave and the impulse response of the dynamic system to construct an output that shows the influence of these dynamics. Since the dynamics of the CMM are not known, the inverse of convolution, or deconvolution, is used; the CMM measurement is divided by the accepted swept sine wave. To expedite calculations, deconvolution may be executed in the frequency domain. The magnitude and phase components in the frequency domain are separated to create a Bode plot of the CMM's dynamics. Multiple measurements with different speeds can be used to create the desired frequency range of the Bode plot to determine the dynamics of the system. The transfer function of the CMM provides a significant amount of information about the machine. It specifies the natural frequency as well as the machine's performance within a frequency range. If a measurement speed is specified, the speed may be converted to frequencies present in the swept sine wave data and an appropriate CMM operating speed determined based on the transfer function and an acceptable amount of error.

## ARTIFACT FABRICATION

A Fast Tool Servo (FTS) was used to machine the swept sine wave on the ring[3]. The piezoelectric stacks of the FTS are excited by the signal from a high voltage amplifier. The frequency and voltage signal affect the movement of the tool on the FTS. Feedback control from the built in cap gauge can correct for position error at low frequency. The closed loop controller uses position feedback with a proportional-integral control algorithm to correct position error. Gains are selected to shape the response of the system, to prevent overshoot

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[1] The number of waves per unit distance (one quarter of the ring circumference).

[2] The actual swept sine wave may not be exactly equal to the designed shape.

[3] K. Folkert, T. Dow, K. Garrard. Metrology Artifact Design. ASPE Proceedings, 34, 462-465 (2004).

and to correct for the following error. Although the system dynamics of the FTS are improved with closed loop control, there is still significant phase error in the system at higher frequencies. Since the FTS will operate at close to 600 Hz when machining at 20 rpm, deconvolution is applied to the swept sine wave before it is input into the controller. Deconvolution uses the magnitude and phase characteristics of the FTS with the information of the desired wave output to adjust the amplitude, phase and shape of the command signal; that is, it alters the input to produce an expected output[4]. This technique greatly decreases the error to about 300 nm in the fabrication of the swept sine wave.

## CONTACTING PROBE MEASUREMENTS

### Determining Probe Dynamics

The dynamic transfer function of the air-bearing probe depends on the dynamics of the probe/gauge interface contact and any filtering built into the cap gauge electronics. Typical air-bearing probes capture some of the exhaust air and use it to preload the probe against the surface. This preload is a constant force independent of the deflection of the probe.

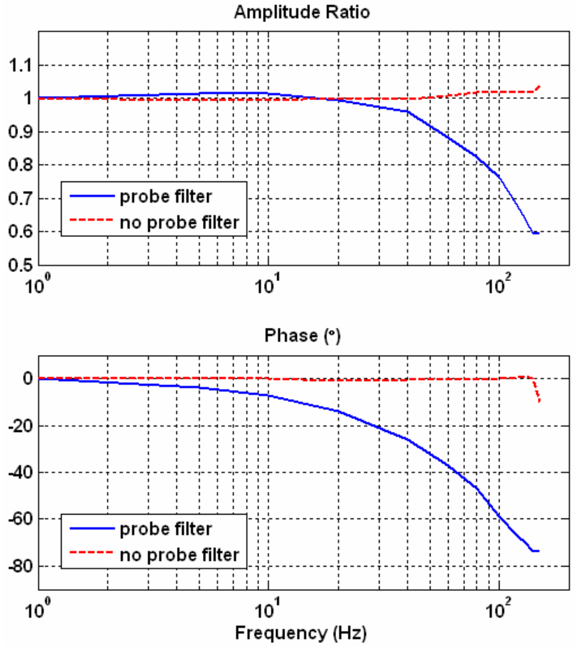

*FIGURE 3. Transfer function of the air-bearing capacitance gauge with and without filtering.*

When confronted with the dynamic forces from the ring gauge motion, the probe will follow the surface until the dynamic forces exceed the preload and then it will leave the surface. The initial conditions, mass and damping will determine its motion and it will bounce when it returns to the surface depending on the relative speed and interface.

Electronic filtering will change the apparent position of the probe by reducing the amplitude and introducing phase lag. An example of the probe response when excited with a sine wave motion with and without the electronic filtering is shown in Figure 3. A preload of 3.4 grams keeps the 7.4 gram mass of the probe in contact until about 150 Hz. The filtered amplitude ratio (air-bearing probe motion divided by excitation) drops as expected and is down about 3 dB (0.707) and lags the input by 64° at 113 Hz due to the filter. If the filter is removed the bandwidth is 20,000 Hz and the probe measures the motion up to the acceleration limit of 150 Hz after which it 'bounces' and contacts the surface sporadically.

The motion of the probe when it exceeds its acceleration limit will become a part of the dynamic measurement. This motion will depend on the dynamics of the probe (the friction, damping and spring constant) but not the shape of the part. A model of the motion of an air-bearing cap gauge was developed and corroborated by experimental measurements.

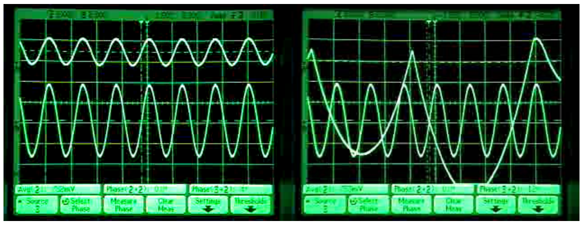

*FIGURE 4. Motion of the probe (top) and gauge (bottom) in contact (left) and bouncing (right).*

An example of the probe motion is shown in Figure 4 from an oscilloscope measuring probe and excitation motion at 50 Hz. The preload was reduced in the right to allow bouncing. Because of the range of the cap gauge, there is a 2.5x gain difference in the two signals. Notice that the amplitude of the probe motion grows significantly when bouncing occurs but the frequency is much lower than the excitation. The response changes depending on the gauge velocity and direction when the probe contacts it.

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[4] W. Panusittikorn. Error Compensation Using Inverse Actuator Dynamics. PhD Disseration, North Carolina State University, (2004).

## RING GAUGE MEASUREMENT

Measurement of the swept sine wave on the ring gauge (Figure 5) provides a rich dynamic input to assess the response of the structure, controller and probe of the CMM. The advantage of the ring gauge is that the entire CMM structural loop is included. This is also a problem because any bouncing behavior of the probe is measured.

*FIGURE 5. Setup of a CMM probe measurement of the swept sine waves.*

As the probe moves from the low frequency region to higher frequencies, the magnitude and phase of the measured shape will be modified by the dynamics of the CMM. This change can be quantified by comparing the measured shape to the 'accepted' shape of the surface. However, the data must be modified before analysis to eliminate the non-contact regions. If the probe leaves the surface the observed system behavior will not be LTI (linear time invariant).

An algorithm has been developed to compute the CMM/probe transfer function given the gauge shape, a measurement data set and the circumferential speed of the measurement. The algorithm detects probe bounce in the measurement signal and windows the data appropriately before performing a transfer function calculation in the frequency domain.

To demonstrate the capability of this measurement technique, the air bearing probe with and without the electronic filter was used to measure the ring gauge shape. The air-bearing preload was set for contact up to about 80 Hz and a linear sine sweep was sent through a FTS to the probe. The data was collected using XPC Target and a National Instruments 6052E multifunction board at a 20 kHz sample rate. The results are shown in Figure 6 and can be compared to the probe transfer function in Figure 3. Without the filter the probe behaves as expected with unity gain and flat phase response until it loses contact. Attenuation and phase lag with the probe filter are in good agreement up to about 50 Hz.

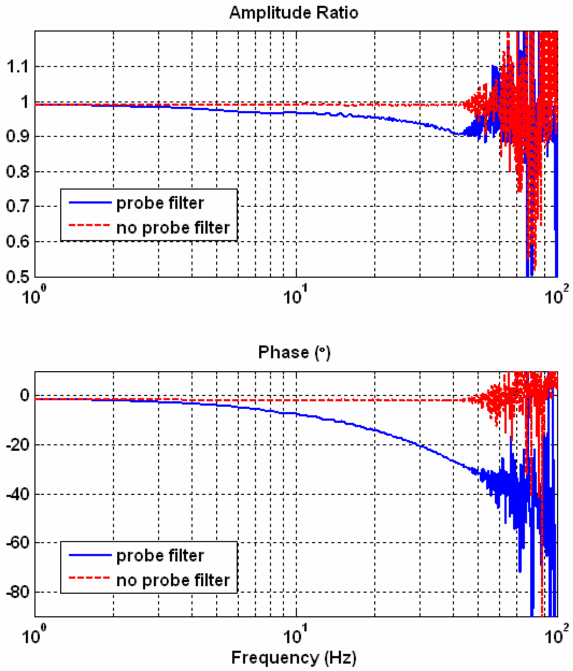

*FIGURE 6. Probe transfer function derived from measurement data with and without probe filter.*

## CONCLUSIONS

- A ring gauge artifact with cylindrical and cylindrical with swept sine wave features has been designed and fabricated.
- Error of the ± 5 µm amplitude features is 300 nm PV and the ring is round to 120 nm PV with a surface roughness of 37 nm RMS. The swept sine wave contains spatial frequencies on the OD from 6.384 mm to 0.383 mm corresponding to 1.6 to 27 Hz at 1 rpm.
- Changing the transfer function of an air-bearing cap probe was used to demonstrate the effectiveness of the swept sine wave to measure dynamic performance.
- Algorithms were developed to extract the dynamics of the probe from the swept wave measurement. Dynamic errors change the shape and add uncertainty to the result.
- Probe dynamic response from the ring gauge measurement will allow a CMM operator to devise a measurement strategy to limit dynamic errors to a specified range.

## ACKNOWLEDGEMENT

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