VIBROMETER-BASED MEASUREMENT OF TURNED DIAMETERS

Aaron Cornelius[1], Osian Leahy[2], Burak Sencer[2], Greg Vogl[1]
[1] Production Systems Group
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland, USA
(Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.)
[2] Department of Mechanical Engineering
Oregon State University
Corvallis, OR, USA

Abstract

Producing high-accuracy machined diameters requires the ability to check the part accuracy inside the machine tool so that process corrections can be made. Many different methods have been proposed for *in situ* diameter measurement, including optical inspection with cameras [1], friction rollers to measure the outside circumference of the part [2], and laser velocimetry [3, 4]. However, these methods are difficult to apply to large tight-tolerance parts because of uncertainty limitations or restricted measurement volumes. A common approach in industry is to use a displacement sensor mounted on the toolpost to probe the part diameter. Since this probe is moved using the machine axes, it is subject to the same geometric and thermal errors as the cutting tool. There is therefore a need for a compact, high accuracy sensor which can measure turned diameters *in situ* without relying on the accuracy of the machine tool axes.

Laser doppler vibrometry is commonly applied to measure the vibrations of rotating components. The measured velocities also record some portion of the tangential velocity of the rotating part based on the relative positions of the vibrometer and rotation centerline. When measuring vibrations, this component is treated as a bias on the measurement and significant effort has been put into eliminating it [5]. However, in principle this velocity bias can be used to help calculate the part radius.

This work evaluates the feasibility of a vibrometer-based system for high-precision *in situ* measurement of large meter-scale machined diameters. The approach measures the velocity of the part while it rotates at a fixed rate using a laser Doppler vibrometer, resulting in a measurement that is proportional to the perpendicular distance between the vibrometer beam and rotation centerline [6]. Critically, this measurement is independent of the accuracy of the machine tool axis. A simple displacement sensor (either contact or noncontact) then measures the distance between the part surface and vibrometer. The part diameter is calculated based on these measurements and the calibrated laser angle.

This study has three main sections. First, the theoretical model for laser Doppler measurements of the part diameter is presented. Second, several potential error sources are discussed to analyze their impact on the desired measurements, along with potential ways to mitigate their effects. Finally, the method is tested on a machine tool using a calibrated stepped-diameter part with diameters from 10 mm to 100 mm to evaluate the measurement accuracy.

Ultimately, the vibrometer-based method shows errors of up to 1.4 % of the nominal measurement, which is not sufficient for measuring high-accuracy parts. This large error is assigned primarily to part surface finish and curvature and spindle vibration. Further research on vibrometer behavior and direct current (DC) measurement is required, specifically for cases where the laser is not aimed normal to the surface of the part.

Radius calculation

Figure 1 shows the basic geometry for the vibrometer setup. The laser is aimed at an angle to the part θ and has a unit vector $\hat{L}$ that describes the orientation of the beam. Ideally, it should be aimed at the peak of the part in the X axis, with d_0 being the perpendicular error in this alignment.

The part rotates at a fixed speed ω, measured by a tachometer or encoder. Since the vibrometer's measured velocity is always the component of the part velocity in the direction of the laser, the measured velocity u will always be $u = \vec{L} \cdot \vec{v} = \omega d$, where d is the perpendicular distance between the laser beam and the center of rotation. This measurement is independent of the part size or form, instead reflecting the actual position of the vibrometer relative to the center of rotation (discussed in more detail later).

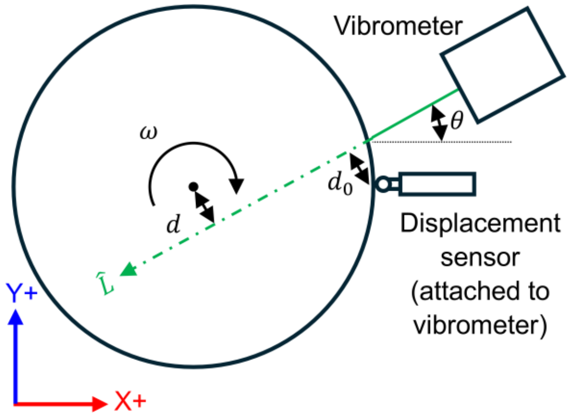

FIGURE 1: Basic layout for measuring the perpendicular distance d using a laser vibrometer.

The basic measurement procedure is now described. First, the vibrometer assembly is positioned at a nominal distance from the crest of the workpiece. Ideally, the vibrometer beam should be aimed at the peak of the workpiece in the X axis (i.e., d_0 should be minimized) to provide a consistent focal distance. A displacement sensor attached to the vibrometer setup measures the actual X-axis distance to the workpiece peak. This measurement Δr is the deviation between the nominal and actual vibrometer/workpiece distance. For this work a high-precision linear variable differential transformer (LVDT) is used, but non-contact solutions can also be used (e.g., laser displacement sensors).

Next, vibrometer measurements are taken as the spindle is run at several different speeds. Figure 2 shows an example dataset, with one minute of data collected at 0 rpm, 300 rpm, 900 rpm, and 1500 rpm.

By assuming that the laser is always positioned at some fixed distance relative to the part radius r, Equation (1) calculates the vibrometer DC velocity u for different part radii r, where d_0 is the perpendicular error from the laser beam to the crest of the part radius, m is a linear scaling factor, and b is a linear offset in the vibrometer signal.

$$u = \omega m(d_0 + (r + \Delta r)\sin(\theta) + Y\cos(\theta)) + b \tag{1}$$

The system parameters m, d_0, b, θ are solved with a least-squares approach. Measurements are taken on a series of calibrated diameters. The matrix setup is shown in Equation (2), where a subscript i indicates the ith datapoint. Solving these parameters requires performing measurements at multiple spindle speeds, multiple part radii, and different Y axis displacements.

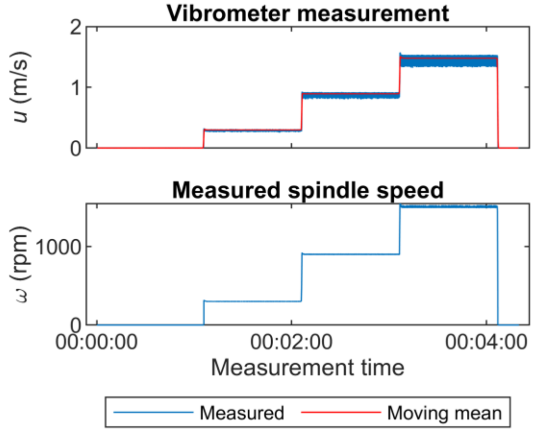

FIGURE 2: Example dataset used for fitting the model and calculating radius. (Top) Vibrometer measured velocity u. (Bottom) Tachometer measured spindle speed ω.

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} \omega_1 & \omega_1(r_1 + \Delta r_1) & \omega Y & 1 \\ \omega_2 & \omega_2(r_2 + \Delta r_2) & \omega Y & 1 \\ & \vdots & & \end{bmatrix} \begin{bmatrix} md_0 \\ m\sin(\theta) \\ m\cos(\theta) \\ b \end{bmatrix} \tag{2}$$

Once the system parameters are known, the system can be used to measure unknown diameters, solving for the part radius using Equation (3). Generally, this is calculated for measurements taken at several different spindle speeds and averaged.

$$r = \frac{u - m\omega d_0 - m\omega Y\cos(\theta) - b}{m\omega\sin(\theta)} - \Delta r \tag{3}$$

Error source analysis and workarounds

This section discusses error sources and their impact on part measurements. When possible, methods are presented to mitigate these errors and improve measurement accuracy.

X axis error motions

As the machine X axis moves the vibrometer setup to measure different diameters, straightness errors in the axis cause error motions in Y, E_{YX}, and rotations around the Z axis, E_{CX}. These error motions affect the measured diameter since they change d as the machine's X axis moves. Equation (4) estimates the error in the measured radius r^* caused by a given Y axis error Y. For small values of θ, E_{YX} and E_{CX} error motions are greatly amplified: for θ = 7 degrees, a 1 µm error in Y axis positioning would change the radius measurement by 8.1 µm. Therefore, the straightness of the machine tool X axis and other sources of error motions pose critical limitations on the accuracy of vibrometer measurements.

$$r^* = -Y/\tan(\theta) \tag{4}$$

These straightness errors are not significant if the error motions are small over the measurement range, which is the case if the vibrometer is calibrated on an artifact with a similar diameter to the measurand. However, for large diameter components this is difficult since a meter-scale calibrated artifact would be prohibitively expensive, and thermal shifts during machining may induce additional error motions which would not be accounted for in the calibration.

This can be mitigated by adding a second vibrometer, as shown in Figure 3. Since these vibrometers measure the part from opposite sides, a shift in Y or rotation in C will cause an increase in one vibrometer reading and a decrease in the other.

Each vibrometer is calibrated using the same procedure described previously. When both measurements are used to measure a given diameter, they are averaged using Equation (5) to give the final radius estimate $\bar{r}$, where subscripts indicate which vibrometer position the value is for. Simulations of ideal systems show that this correction theoretically eliminates the impact of E_{YX} error motions and reduces the impact of E_{CX} errors to well below 1 nm for a part with a diameter of 1 m.

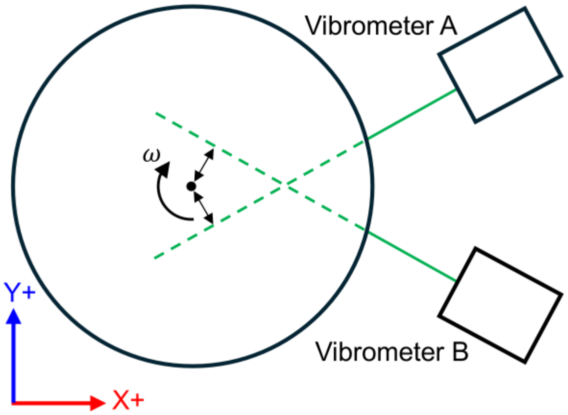

FIGURE 3: two vibrometer setup to reduce the sensitivity to E_{YX} *and* E_{CX} error motions.

$$\bar{r} = \frac{\cos(\theta_B)\, r_A + \cos(\theta_A)\, r_B}{\cos(\theta_A) + \cos(\theta_B)} \tag{5}$$

Part runout and shape effect

Laser Doppler vibrometer measurements are theoretically insensitive to the shape and alignment of rotating workpieces [6]. This insensitivity occurs because the vibrometer only measures the component of velocity in the laser direction. For a rotating object, this component of the velocity is always proportional to the perpendicular distance between the laser and center of rotation, giving $u = \omega d$. Large runouts may still cause some difference in measurement due to changes in the reflection angle and focus. However, this effect should be minimal when inspecting turned parts *in situ*.

Nonetheless, part runout or non-circular forms will cause different Δr values to be obtained depending on the orientation of the spindle when the LVDT displacement measurement is taken. These errors directly add to the measured part radius. A simple workaround is to take multiple measurements from the LVDT at different spindle orientations and take the average value. For round parts, the average of the maximum and minimum LVDT measurements provides a consistent measurement, e.g., with a 10 µm circularity error contributing at most 10 µm of error to the measured part diameter depending on the alignment of the part eccentricity and roundness. When the part is significantly out of round, additional measurements can be taken and averaged as shown in Figure 4.

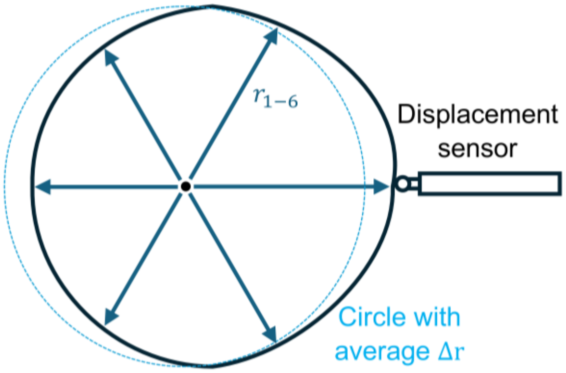

FIGURE 4: Diagram illustrating how to find the average Δr for eccentric circular parts

Vibrometer stability

The vibrometer signal is not perfectly stable over time. Figure 5 shows a 1-hour measurement taken on a static part, starting when the vibrometer is first turned on. The vibrometer shows a clear warmup period, with the signal shifting by up to 1 mm/s and a bias of 1 mm/s.

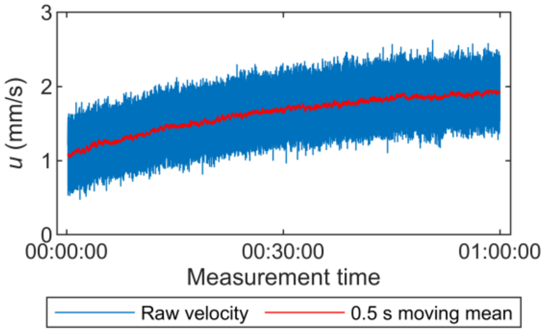

FIGURE 5: Vibrometer stability over 1 hour

To compensate for this, the data collection program records a short period of data with the part not spinning at the beginning and end of the program (visible in Figure 2). Linearly interpolating between these values gives estimated vibrometer biases for the duration of the data collection, which is then removed from the signal. Therefore, only non-linear drift over the course of a single vibrometer measurement (< 5 minutes) affects the measurement, which should reduce the total effect of vibrometer warmup to less than 0.05 mm/s. Alternatively, the vibrometer can be allowed to reach steady-state before measurement.

Spindle vibration

Vibrometer measurements are affected by linear and angular displacements of the spindle axis while rotating. This effect depends on surface finish, laser spot size, and vibration amplitude. Vibrometer measurements on mirror surfaces are affected solely by vibrations parallel to the beam of the vibrometer, while measurements on retroreflective surfaces with pure diffuse reflection are sensitive both to parallel and perpendicular vibrations. Parts with intermediate surface finishes transition between the two effects, with more polished parts showing less cross sensitivity [5]. However, note that the studies which show this have all assumed that the laser is oriented normal to the surface of the part, and none have examined the DC component of the signal. For this application, the laser is necessarily not normal to the surface, which may result in different behaviors.

Surface finish

Vibrometer measurements on rotating parts have been widely studied, and it is known that the surface finish of the part has a strong impact on the measured vibrations [5-7]. Micro features in the part surface finish cause localized specular reflection to the sensor, generally referred to as speckle noise, which varies as the part rotates and different areas of the part surface enter the laser beam. Studies have demonstrated that speckle noise causes the vibrometer to measure pseudo-vibrations, which are difficult to separate from real part vibration and which vary in amplitude based on the surface finish of the workpiece. However, these studies have focused on measuring part vibration. To date, the effect of surface finish on the DC velocity measurement has not been extensively studied.

Part curvature

When measuring a round part, the laser spot has some finite size and thus wraps around some portion of the part surface. This means that the laser does not have a single fixed d value and will see a range of different Doppler shifts based on the instantaneous velocity of each surface point. The measurement reported by the vibrometer is based on the mean Doppler shift observed by the photosensor. Ideally, this mean Doppler shift should be the same as the shift at the laser beam centroid, but for a curved surface some portions of the surface may be more likely to return the beam than others, resulting in a biased signal. This could result in nonlinearities since smaller diameter parts have higher curvatures and may have higher biases, but this has not been studied.

This would be less significant on large diameter parts where the surface the vibrometer is projected on would be close to planar.

Experimental setup

Error! Reference source not found. shows the experimental setup used in this work. The setup is located on a Hurco VMX24 vertical machining center. A calibrated stepped artifact made from Grade 304 stainless steel, with diameters ranging from 10 mm to 100 mm, is clamped in the machine spindle. Vibrometer measurements are taken with a Optomet Nova laser vibrometer with a 10 mW, 1550 nm measurement laser and a 520 nm targeting laser. The vibrometer is tilted at an angle of roughly 7 deg relative to the X axis. A Solartron D6T/2/S LVDT probe (0.05 µm repeatability, 1 µm full-range accuracy) is used to measure Δr. Since the LVDT interferes with the laser path, it is mounted on a kinematic coupling so it can be removed before the vibrometer measurements.

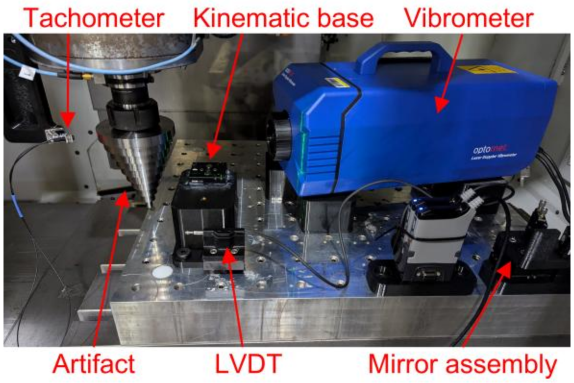

FIGURE 6: Testbed for initial vibrometer performance testing. The laser is tilted at an angle of about 7 deg relative to the X axis.

The kinematic coupling can also mount a set of mirrors that redirect the vibrometer beam to measure the part from a different angle, illustrated in Figure 7. This simulates the two-vibrometer setup to cancel out Y-axis error motions. While the no-mirror and mirror measurements cannot be taken simultaneously, the approach requires only that the two measurements are of the same setup, not that they are taken contemporaneously.

Table 1 shows dimensional information for each of the steps on the calibrated artifact, as well the measured runout when installed in the machine tool spindle. The diameter and circularity for each step was measured using a coordinate measurement machine (CMM) with a maximum permissible error of 2.5 µm. The runout was measured using the LVDT probe.

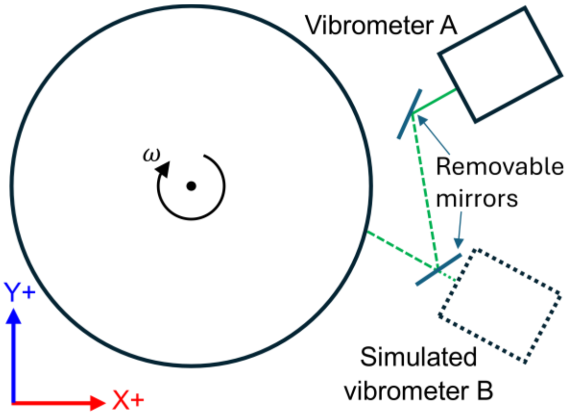

FIGURE 7: Diagram showing how removable mirrors redirect the vibrometer to approach the part from a different angle

Table 1: Calibrated artifact dimensions/runout

Nominal diameter (mm)	Calibrated diameter (mm)	Circularity (µm)	Runout (µm)
100	100.037	7.9	3
90	90.020	7.1	17.3
80	80.013	10	25.8
70	70.004	7.9	34.3
60	60.026	12.8	42.8
50	50.017	10.1	55.8
40	40.010	10.3	54.5
30	30.029	12.5	74
20	20.026	8.5	84
10	10.030	23.1	93.7

Results

Table 2 shows the measured diameters for this approach, measuring the 10 mm, 30 mm, 50 mm, 70 mm, and 90 mm diameter sections of the part. This dataset took roughly 1 hour to collect. The same dataset was used to fit m, d_0, θ, and b. Therefore, this situation represents the best possible case for the vibrometer measurement, where the surfaces used for calibration are the same as those for the vibrometer measurement. Even under this best-case situation, the measurements show errors of up to 1.4 % of the nominal diameter. While the worst performance is observed on the 10 mm diameter section, omitting this case still results in errors over 1 %.

The vibrometer stability and warmup may contribute to this error; that is, the errors after bias compensation would significantly affect tight-tolerance diameter measurements but do not explain the large measurement errors. Artifact form also contributes since the average of the maximum and minimum LVDT readings were used to obtain Δr for this initial study. However, the peak circularity error affects the diameter measurement by at most 23.1 µm (17% of the actual measurement error for the 10 mm diameter section) and is therefore not the primary error source. Similarly, while these measurements were not done in a temperature-controlled environment, thermal expansion of the artifact is not the most significant error source.

Table 2: Part diameter measurement results

Calibrated diameter (mm)	No mirror diameter estimate (mm)	Mirror diameter estimate (mm)	Weighted average (mm)	% error
10.030	9.882	9.902	9.892	-1.38
30.029	30.179	29.844	30.011	-0.06
50.017	50.079	50.017	50.048	0.06
70.004	69.171	70.157	69.664	-0.49
90.020	89.654	90.725	90.190	0.19

Currently, these errors are assigned primarily to the part surface finish and spindle vibrations. As discussed previously, the specific case of DC vibrometer measurements on rotating parts where the vibrometer is not oriented normal to the part surface has not been studied in literature. As such, it is difficult to quantify this effect, but it likely accounts for most of the remaining errors.

Conclusion

This study has evaluated the feasibility of a vibrometer-based system for measuring part diameters. The initial results do not show the capability for high-precision measurements, with relative errors on the order of 10^{-2}. Since several other sources of error (runout, machine tool error motions, and vibrometer warmup) have been accounted for, these errors are attributed to the part surface finish, spindle vibration, and part curvature. Further work is necessary to understand the fundamental behavior of vibrometers for DC measurements on rotating parts, particularly when the laser is not oriented normal to the part surface, as well as methods for compensating for vibrometer stability via continuous calibration.

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