Application of a Linear Center Identification Scheme to Deterministic Polar Positioning

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ABSTRACT

In a number of manufacturing applications, parts of circular cross-section must be centered for optimal processing or measurement. However, part form is never perfect, making accurate determination of the "centered" state of a part difficult. Imperfect inputs to the manufacturing process such as rough-processed parts, deformation due to heat treatment, or raw formed materials present difficulty in centering by the traditional manual method. This paper presents a filtering and quantification technique for identifying the true center of an imperfect round part through isolation of the lowest polar frequency component. A low-cost device is presented that centers parts based on this frequency domain identification of center.

INTRODUCTION

Precision convex product shapes occur in all facets of manufacturing industry. A primary example is the manufacture of antifriction bearings. Ball and roller bearing manufacturing comprised $5.1B of US manufacturing gross output in 2003 [BEA 2005]. Due to requirements of center-based or radial manufacturing processes, precision parts such as bearing rings can have a centering requirement before the processing or measurement cycle. Such centering ensures both minimization of single-lobe effects in measurement and form matching of outer to inner diameters in material removal processes (minimization of wall thickness variation).

A number of techniques are currently employed to center manufactured parts. For low precision applications, hard stops or V-blocks with dimensional offset based on nominal radius are employed, and roundness derived from methods such as the inverse matrix method of Okuyama [2001]. Such methods are subject to tool wear and centering error due to part diameter variations. For precision measurement, an axis adjustment based on the measured offset is used. These adjustments can be a standard manual handwheel type or an automatic system such as the microstage of Liu [2004]. These center compensation methods require a larger capital tooling investment or cycle time burdened at a skilled operator rate.

In high-volume measurement or processing applications on the shop floor, manual centering by a skilled operator tapping with a hammer is typically used. A fallacy with manual centering is in the operator's inability to interpret high-frequency signals from surface imperfections and separate the true off-center value. As centering preprocesses are required not only for finished parts, but also for rough cut or even direct raw materials, automating the centering process in an efficient and cost-effective manner can have a profound implication for high-volume manufacturing.

ROUNDNESS

To quantify the benefits of centering out-of-round parts, an understanding of roundness must first be undertaken. The international standard governing out-of-roundness measurement in manufacturing is ISO 1492-1985(E), which gives guidance on measurement and quantification of out-of-roundness [ISO 1985]. The standard defines four methods for centering a given profile.

Minimum Circumscribed Circle (MCC)

The MCC method describes the profile center as equivalent to the center of the smallest circle that contains the measured profile data. This method can be visualized as the smallest rigid ring that will fit over the profile, and is useful for radial external measurements.

Maximum Inscribed Circle (MIC)

The MIC method defines the center of the profile as the center of the largest circle that can be inscribed inside the profile. It can be visualized as the largest plug that will fit inside the profile, and is useful for radial internal measurements.

Minimum Zone Circle (MZC)

The MZC method minimizes the difference between two concentric circles containing the profile data. This is the preferred center measurement method according to the standard, but often requires heuristic or graphical implementation.

This method has been extended analytically to the Minimal Area Difference (MAD) measurement, which minimizes the area rather than diametral differences [Le 1991].

Least Square Center (LSC)

The LSC method minimizes the sum of squares of the radial errors between fitted circle and profile data. This method is considered the most precise quantification of error [Kaiser 1993].

These techniques have traditionally been incorporated into roundness measuring machines in the quality laboratory, but as hardware has become more efficient and inexpensive, geometry measurements have migrated directly to the shop floor [Tabenkin 2002]. Such methods can be applied directly in production machines not only for part measurement, but also for other purposes such as machine tool accuracy [Ramesh 2004]. Centering as a practice is a combination of both part geometry quantification and machine accuracy compensation.

CENTERING

Once the derived center of the data set of a convex part is calculated, it can be used as an input to an actuation system for positioning the part relative to its center. Typically it is desired to bring the geometric center to be coincident within a certain tolerance with the center of rotation for applications such as roundness measurement and material removal processes requiring uniform wall thickness [see Figure 1].

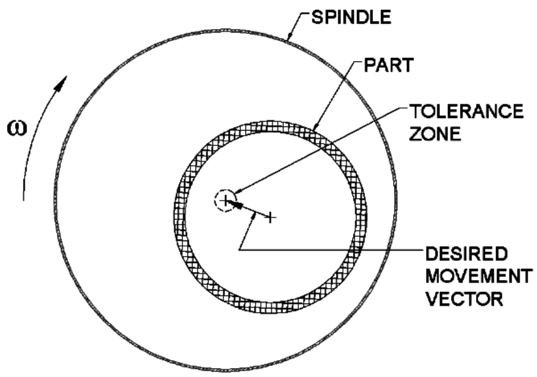

FIGURE 1. ALIGNMENT OF PART CENTER WITH ROTATIONAL CENTER BY DEFINING A MOVEMENT VECTOR

The need for manual and automated centering devices has been addressed through novel application of general principles. The general methods for centering are divided between physical actuation of the part relative to its supports and adjustment of the overall reference frame.

Centering by adjustment of the reference geometry is widely used in industry today, mainly in high-precision measurement applications. Centering may be done through hardware as in Cartesian axis adjustments on a roundness-measuring machine [Tokyo Seimitsu 2001], or through software, as in a programmed offset in a 3-dimensional coordinate measuring machine.

Centering by actuation of the object with respect to a fixed reference has recently seen wider development, since, as better-performing hardware becomes available, high-precision centering can be achieved at a lower cost and therefore applied to a wider range of processes. Classic pick-and-place robotic mechanisms have been used to position parts, but can be lacking in positional precision for parts with high variation.

Newer methods include vibratory or impulsive actuation to position parts quickly and precisely. Yamagata [1995] addressed actuation by impact in micropositioning using piezoelectric elements. Huang and Mason [2000] applied the theory of balancing impact energy with frictional dissipation to positioning. Siebenhaar also applied impact actuation practically with electromechanical hammer control [2004]. Such effective methodologies can also be adapted to actuation on a dynamic rotating part.

CENTER IDENTIFICATION: A LINEAR APPROACH

If we consider an application of center identification of a rotating part at constant radial velocity, the signal may be “unwrapped” around the center of rotation from a polar to rectangular representation in the time domain. This representation may be fitted through a Cartesian least squares fitting algorithm by a curve of the following form:

$$y = b_0 + b_1 \cos(x) + b_2 \sin(x) \quad (1)$$

where

$$y \equiv \mathit{radial\ position}$$
$$\mathit{through\ rotational\ center}$$
$$x \equiv \mathit{rotational\ position}\,[\mathrm{deg}]$$
$$b_i \equiv \mathit{fit\ coefficients}$$

This form is a limaçon equation of an offset circle of radius b_0 and center point (b_1, b_2). The usefulness of this form is in its linearity, whereas fitting a circle to the same data may require a more computationally intensive algorithm.

From the fit curve, the off-center distance and angle are extracted from

$$B = \sqrt{{b_1}^2 + {b_2}^2} \quad (2)$$

$$\phi = \tan^{-1}\left(\frac{b_2}{b_1}\right) \quad (3)$$

Figure 2 shows radial profile data of a rotating part with the least squares fit limaçon function of the form given in (1).

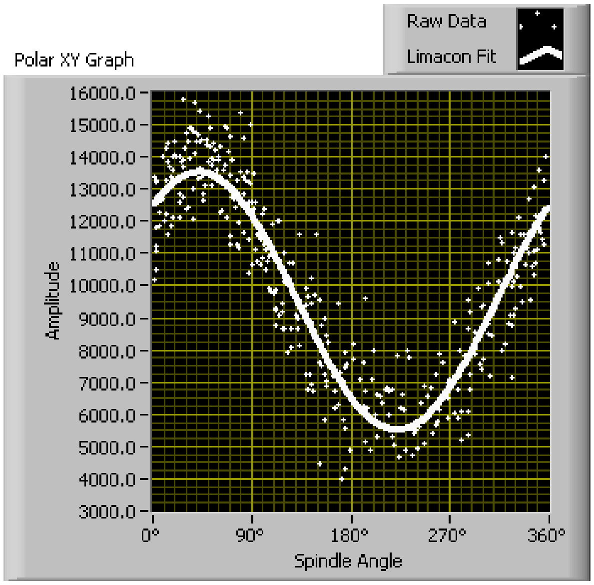

FIGURE 2. SIMULATED NOISY DATA WITH LIMAÇON FIT (R = 10000, σ_{NOISE} = 1000, OFF-CENTER DISTANCE = 2000)

Note that since the limaçon approximation to the offset circle is linearized about the data center, a larger offset will give a larger error in the estimation of the offset. However, in a centering operation, the need for a precise estimate increases as the part becomes more centered.

For example, given an off-center distance of 10 mm, high accuracy in modeling is not a great requirement, as other unmodeled or linearized effects such as friction and part resilience will have a much higher effect than model inadequacies. However, if an actuation of 10 µm is required, accurate modeling is a necessity. The limaçon approach gives a lower computational intensity than true circle fitting, but provides the highest accuracy to the centering process when needed.

PART GEOMETRY CONDITION

Manufactured parts are never perfect. Typical variations include periodic deviations due to the manufacturing process and roughness defects. These features' effect on the data may influence the calculated center position.

Periodic Defects

Periodic defects can be caused by variables within the manufacturing process itself. Harmonic noise from grinding or finishing machines can manifest itself as waviness in the finished part.

The limaçon estimation fit is unaffected by periodic defects of an integer number of lobes about the circumference.

Roughness

Surface roughness appears as random noise within the data signal.

Due to the random nature of roughness geometry, its effects average to zero, and have little effect on the center position calculation.

FIXTURING

A simplified and effective centering approach can affect the available fixturing options for a manufacturing operation.

Two major fixturing methods in manufacturing are fixed-jaw chucks and magnetic force systems. Jaw chucks impart inherent elastic deformation due to clamping forces, especially problematic for highly compliant workpieces. Satyanarayana [2002] addressed a technique for minimization of these forces.

However, these forces and their effect on workpiece geometry may be avoided entirely by changing to a magnetic-based chucking scheme without jaws in cases where the machining forces are within the magnetic workholding capability. The availability for production use of this chucking option is made possible by automated part centering.

APPLICATION TO CENTERING

The process of identifying a part center with respect to center of rotation, and using that offset vector to drive an actuation mechanism has been practically applied to a bearing ring centering device.

System Description

A system has been developed whereby a round artifact on a rotating spindle table is measured, and its center point identified with respect to the center of rotation. This off-center distance is used to plan a motion path for an actuation arm to push the part to the center of rotation. The analysis system incorporates frequency-domain filtering to identify the magnitude and phase of the off-center distance.

Hardware. The automated centering system is comprised of an air bearing spindle and a linear motor air bearing pusher arm that carries a digital length probe (see Figure 3). The system is driven by a deterministic controller utilizing a DSP motion control card (MCC).

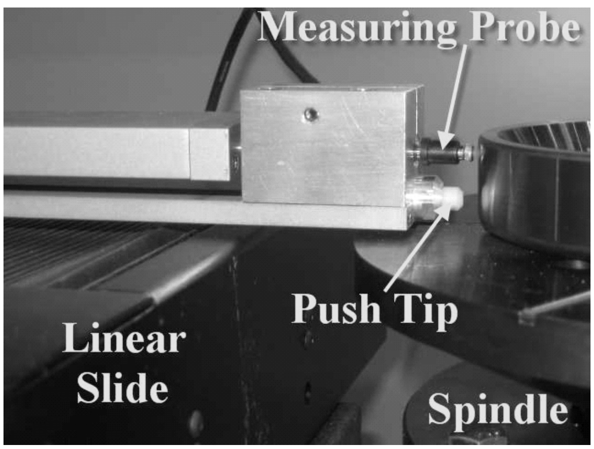

FIGURE 3. MAJOR COMPONENTS OF PROTOTYPE CENTERING SYSTEM.

Software. The base software used for automated centering is National Instruments' LabVIEW Real-Time with Motion. The program consists of parallel loops for:

- Data collection
- Data filtering and fitting
- Actuation (push) control
- Arm servo following motion control when not under a deterministic push command

System Operation

The system rotates the spindle to a constant rotation rate upon start command. The slide advances until the measurement probe makes contact with the part surface, at which time a proportional-integral-derivative (PID) motion control scheme is employed to maintain a constant distance from the part surface to the arm. Part surface data is continually taken from the probe and arm axis encoders, generating a raw part profile.

This polar profile is then analyzed using limaçon curve fitting to determine its off-center vector and phase. The derived parameters are used to drive a deterministic actuation toward the center of rotation with a magnitude equal to the off-center distance. The (follow, model, actuate) process is repeated until the part is centered within the required tolerance, currently 2.5 µm.

System Performance

The current system centers parts in the range of 0.8 – 20 kg in under one minute. Average times from sample runs of n=100 for different mass parts are given in Table 1.

TABLE 1. CENTERING RESULTS OVER THE PART RANGE (ABSOLUTE TOLERANCE = 2.5 µm)

Mass [kg]	Part Diameter [mm]	Average Centering Time [s]
0.77	123.9	47.6
0.88	88.9	49.9
1.20	170.0	93.7
1.25	90.5	58.2
20.0	179.0	45.8

Due to the fitting algorithm used, the surface condition of the part outer diameter has very little effect on centering performance. All higher frequency components are removed from the signal, leaving the derived model as a single limaçon curve.

A sample round part of unfinished surface (rough turned with surface rust) was centered, then the surface was turned at feed of 0.04 mm/rev, and the centering process repeated (see Figure 4). For each condition, the workpiece out-of-roundness was independently measured on a Rondcom 30A roundness tester using the Minimum Zone Circle (MZC) method.

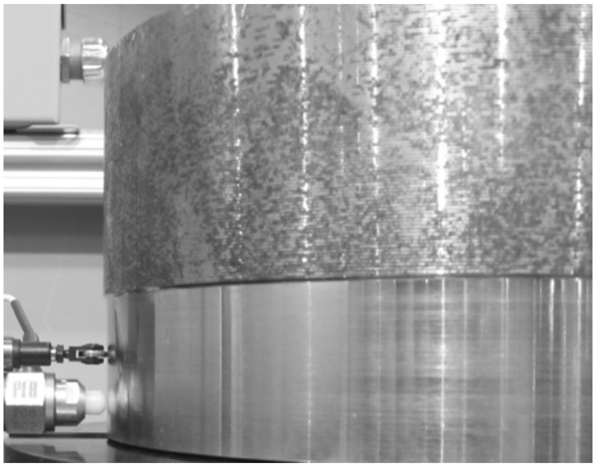

FIGURE 4. LARGE MASS PART (M = 20.0 KG), SHOWING UNFINISHED (UPPER) AND FINISHED (LOWER) SURFACES.

Results of centering operations for both finished and unfinished surfaces are given in Table 2.

TABLE 2. CENTERING RESULT FOR LARGE MASS PART (M = 20.0 kg, TOLERANCE = 2.5 µm)

Part Condition	Out-of-Roundness [μm_{p-p}]	Average Centering Time [s]	Average No. of Actuations
Unfinished with rust	115	50.2	8.9
Finish turned	6	45.8	8.3

Note that the unfinished part is able to be centered within 10% of the time achieved with the finished part of the same mass and diameter.

CONCLUSION

Current standards and definitions for out of roundness are described, and derived conditions for centering are presented. A linear method for identification of the center of a rotating circular profile through isolation of the lowest rotational frequency component is described.

The method is implemented in a bearing ring centering application utilizing low-cost components and control hardware. The system is successfully applied both to a range of parts, and to two similar parts with different surface conditions. Performance of the system is robust to signal input noise for poor finish of the measured surface.

The benefit of this method comes from its ability to center parts with higher order waviness or poor surface quality, parts that may be difficult or impossible to center by hand. Such centering ability leads directly to manufacturing process improvements such as stock reduction, alternative chucking and improved part quality or measurement ability. The given application is applicable in a wide range of operations on the shop floor as a feasible and viable alternative to current manual centering operations.

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