Creating Measurement Fixtures for Verifying Geometric Tolerances

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Abstract

In the Mechanical Engineering Department at the University of Texas at Dallas (UTD), a senior-level elective course on Geometric Dimensioning and Tolerancing (GD&T) was developed to provide our students with an in-depth understanding of GD&T so they are able to apply and interpret GD&T in engineering drawings to guarantee design intent. This paper describes measurement fixtures that were created to bridge the gap between theory and practice and explain the geometric tolerances of form (circularity and cylindricity) and orientation (angularity). The fixtures are easy to implement, cost effective, and the measurement activities are scalable to large classes. Samples of student work demonstrate they can compare measurements to the geometric tolerances defined in an engineering drawing, make direct connections to the tolerance zones produced by each symbol, and determine the conditions for a fabricated part meeting or failing the design requirements specified in an engineering drawing. Students who participated in the course indicate in an end-of-semester survey how the measurement activities relying on these fixtures can bridge the gap between the symbols in the engineering drawing and their physical meaning.

1. Introduction

Geometric Dimensioning and Tolerancing (GD&T) is a complex language using numbers, letters, and special symbols implemented in engineering drawings to control a part's geometry. It can be used to control the form (shape), size, location, and orientation of part's features [1], [2]. Controlling these geometric attributes is fundamental to GD&T. GD&T is implemented in the design and manufacture of precision parts and assemblies, and it is important to effectively communicate design intent and requirements [3].

GD&T can be difficult to comprehend and learn due to all the symbols involved and the inherent three-dimensional (3D) nature of geometric tolerance zones produced [4]. Comparing the symbols/letters/numbers on a drawing to hands-on measurement can help students better understand their meaning (and use) within a drawing and learning this complex language can be facilitated by translating it into real-world, hands-on applications [4]. However, the tools and equipment to do so can be numerous and expensive. This can pose a barrier for engineering departments that have many students or limited budget but want to introduce GD&T into their curriculum.

In the Mechanical Engineering Department at UTD, students are exposed to the basics of GD&T during a junior-level Computer-Aided Design (CAD) course [4], [5], [6]. This course covers basics like limitations of conventional tolerancing and a few essential applications with GD&T such as locating a hole. In surveys conducted in this course, students expressed having difficulty relating the symbols to the 3D tolerance zones produced. This was addressed by developing computer models and 3D printed parts which had a positive effect on student learning experiences [4].

In Spring 2024, an advanced elective course on GD&T was offered for the first time to senior-level students with the CAD class as a prerequisite. The elective course covers dimensioning and tolerance methods and practices defined by ASME Y14.5-2018. The learning outcomes of the GD&T elective course are:

- Be able to apply and interpret GD&T symbols in engineering drawings.
- Explain the tolerance zones produced by geometric tolerances and the modifiers that can be used with them.
- Understand the effects of geometric tolerances to ensure drawings guarantee design intent.

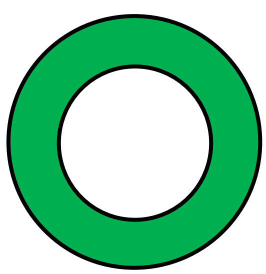
The topics covered in this course include:

- Tolerance format, material conditions, material envelopes, allowances, and other basic terms associated with dimensioning and tolerancing.
- Key terms, symbols, modifiers, and rules associated with GD&T.
- Form (circularity, cylindricity, straightness, flatness).
- The datum system.
- Orientation (parallelism, perpendicularity, angularity).
- Location (position).
- Runout (circular, total).
- Profile (line, surface).
- Tolerance stack-up analysis.
- Gauge design and implementation.

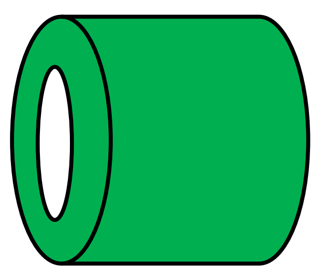
To aid the students taking the new elective course, a series of measurement fixtures were developed to address challenges associated with visualizing 3D tolerance zones and relating the various symbols, letters, and numbers to the physical meaning for actual parts.

In this paper, we demonstrate how measurement fixtures can be fabricated from inexpensive acrylic sheets using laser cutting. These fixtures were implemented in measurement activities at various times during the semester to check geometric tolerances of 3D printed or machined parts in the senior-level elective course on GD&T. The fixtures are designed for use with a dial indicator and a granite surface block.

Fixtures and measurement activities for circularity, cylindricity, and angularity are discussed. Samples of student measurements and the results of an end-of-semester survey conducted by the university and observations from the implementation of the measurement activities are also presented.



(a) Annulus

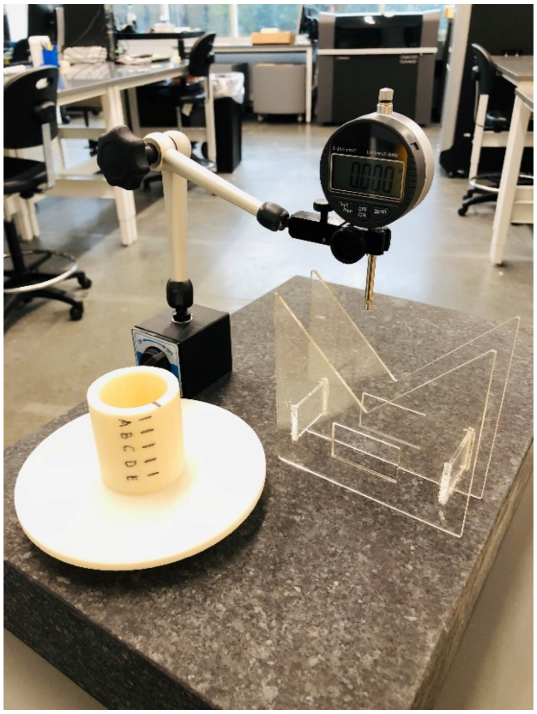


(b) Hollow Cylinder

Fig. 1, Tolerance Zones Produced by Circularity and Cylindricity

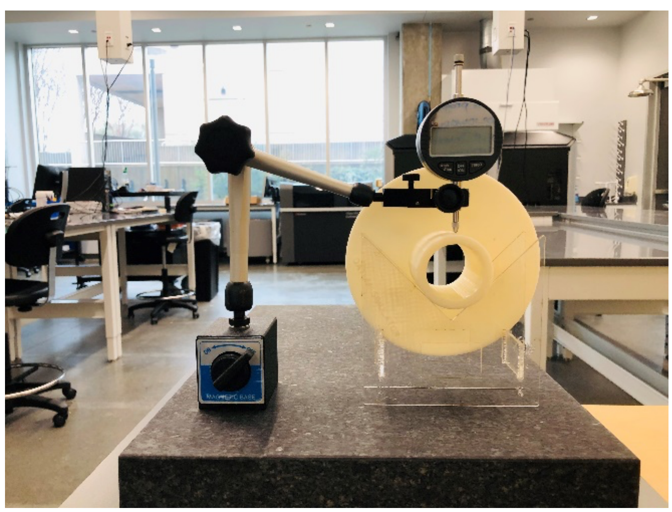
2. Measurement Fixture for Circularity and Cylindricity

Circularity or roundness is a cross-sectional check resulting in a planar (2D) tolerance zone [2]. The tolerance zone is the space between two concentric circles (the annulus shown in Fig. 1a) and if the surface of the feature's cross-section is contained within this space, the feature will pass inspection. If the surface exceeds the space, the feature will be rejected.



(a) Parts and tools needed to check circularity and cylindricity

(b) 3D printed part showing the rotation and cross-section guides.



(c) Setting up the part for measurement.

Fig. 2, Circularity and Cylindricity Measurements

Circularity is a check on the feature's form and is independent of any other features. Hence, no datums are provided in the Feature Control Frame (FCF). The tolerance value in the FCF controls the difference in radius between the two concentric circles defining the tolerance zone. Since the difference between the maximum and minimum distances from the axis are controlled, circularity does not check the feature's size (i.e., diameter). Since circularity is a cross-sectional check, it can be applied to any axisymmetric (revolved) shape including cylinders, tapered cylinders, spheres, etc.

Cylindricity checks the entire surface of the feature resulting in a 3D tolerance zone. The tolerance zone is the space between two concentric cylinders (the hollow cylinder shown in Fig. 1b). Like circularity, cylindricity checks a feature's form independently of any other features and no datums are provided in the FCF. The tolerance value in the FCF is the difference in radius between the two concentric cylinders. Cylindricity can only check cylindrical features.

To check circularity and cylindricity, a measuring system that uses computer technology is required [1], however, this can be expensive. One assessment method for circularity and cylindricity is Minimum Radial Separation (MRS) [1] which requires the radial distance between the highest and lowest points (i.e., the distance from the axis to the surface) and then subtracting these values and comparing them to the value in the FCF. If the difference is less than or equal to the value in FCF, the part passes. It is rejected otherwise. A solution to checking these tolerances is to use a v-block. When rotating a cylindrical part on a v-block, the part might move up and down and an axis may not be established. This can result in either a conservative measurement (i.e., the measured variation is higher than the actual variation) or it might result in an under measurement (i.e., the measured variation is less than the actual variation). The latter scenario would be an issue especially if tight tolerances are specified. If tight tolerances are required, a more advanced measurement system is required. For larger tolerances, a v-block can be used and that is what is implemented in our measurement activity.

The v-block's parts used in the GD&T class are laser cut from an acrylic sheet, and they are assembled with acrylic adhesive. The total cost of the acrylic and adhesive used is less than $5. Due to the precision of laser cutting, this fixture is stable and flat when placed on a granite surface block as shown in Fig. 2a.

Table 1, Recording Circularity and Cylindricity Measurements

X-Sec	MAX Measurement	MIN Measurement	Circularity
A			
B			
C			
D			
E			
Cylindricity (based on sections A-E only):			

A 3D printed part is used for taking measurements (Fig. 2a,b). The part has markings that can be used as visual guides to ensure a full rotation is made and others to locate the probe along the axis of the cylinder for cross-sectional checks. The complete measurement setup is shown in Fig. 2c. A digital probe is used, and the students measure the highest and lowest points for each cross-section. The students check circularity for each cross-section and cylindricity is checked considering all cross-sections (i.e., using the overall highest and lowest points). The entire measurement is conducted on a granite surface block and students recorded measurements (in units of inches) in Table 1.

3. Measurement Fixture for Angularity

Angularity is a check on a feature's orientation. It requires a datum reference in the FCF. Angularity can be used to check the orientation of a plane, or it can be applied to a Feature of Size (FoS) to control the orientation of an axis [2].

Angularity of a plane is checked in the measurement activity. For this case, the tolerance value in the FCF controls the distance between two parallel planes which are oriented at an angle relative to the datum plane specified using a basic dimension (Fig. 3). The resulting tolerance zone is the space between two parallel planes and the variation in the part's surface must be contained within this space. It is important to note that surface angularity directly checks the orientation of the surface, but it is also indirectly checking the surface's flatness.

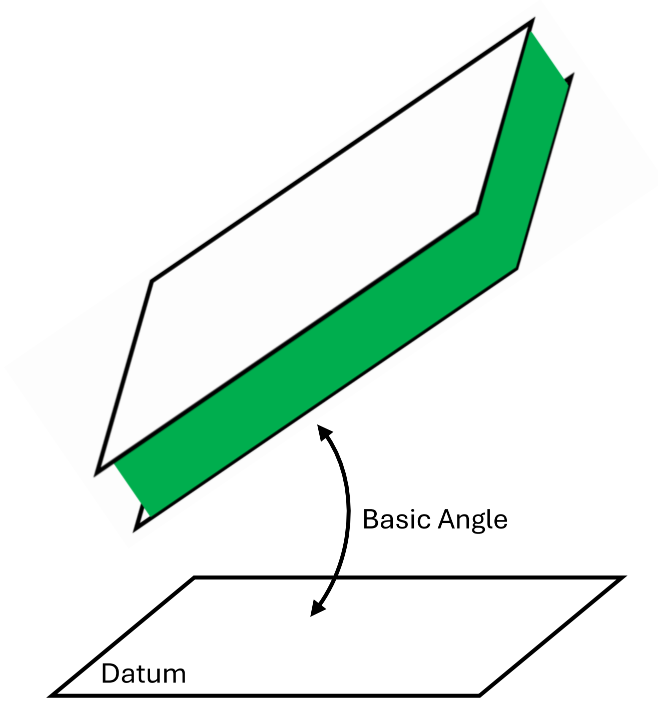
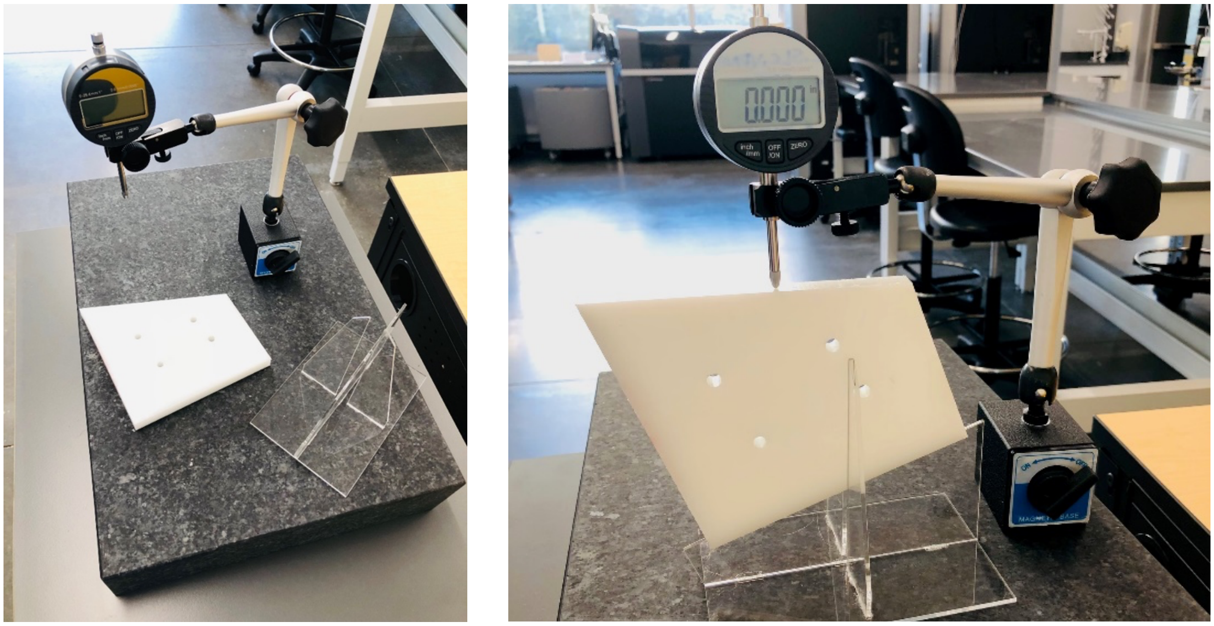


Fig. 3, Tolerance Zone Produced by Angularity

One method of checking an angularity tolerance implements a sine bar. The datum feature (actual part surface) would contact the top surface of the sine bar. The height of the bar on one end would be adjusted to achieve a desired angle. This angle would make the angled surface on the part horizontal, and a dial indicator can then be used to measure the amount of variation in the surface and ensure it is within the tolerance specified in the FCF.

The tools and the part used for this measurement are shown in Fig. 4a. The part measured is made by machining an angled surface on an ABS block. The resulting surface has some imperfections that could be detected by the dial indicator. The total cost of the ABS block, acrylic, and adhesive was less than $10. The resulting fixture was stable on the granite block and the supports added to the fixture stabilized the ABS part.



(a) Parts and tools needed to check the angularity of a flat surface

(b) Setting up the part for measurement

Fig. 4, Angularity Measurements

The measurement setup is shown in Fig. 4b. The acrylic fixture acts like a sine bar. The angle of the fixture is set to 20° which is the basic angle of the part's surface. Once the block is in the fixture, the angled surface on the block is checked to be horizontal using a bubble level. Keeping the probe fixed, the fixture is slowly moved to ensure the probe contacts the part's surface. The difference between the highest and lowest values over the entire surface are checked against the value in the FCF. Students are asked to repeat the measurement 5 times, and they recorded measurements (in units of inches) in Table 2.

Table 2. Recording Angularity Measurements

Measurement #	MAX Measurement	MIN Measurement	Angularity
1			
2			
3			
4			
5			
Angularity (based on measurements 1-5):			

4. Results and Observations

In the Spring semester of 2024, the course had a total enrollment of 12 students and they were required to complete the measurement activities as part of the course requirements of the elective

GD&T course. The students were divided into 4 teams of 3. The circularity and cylindricity measurement activity was completed in an average of 20 minutes by each team and all students were required to perform at least one circularity check. The angularity measurement activity was completed in an average of 10 minutes. The most time-consuming aspect of the measurement activities was setting up the dial indicator. Since the theory was explained during lecture, the students were very independent during the activities.

Fig. 5 shows a sample of student work for the circularity and cylindricity measurement activity. The students were instructed to zero the probe at the start of each measurement which resulted in positive values when the probe moved over surface protrusions or negative values over recesses. Circularity is determined for each cross-section, therefore, the largest actual circularity measurement of 0.0265 (corresponding to cross-section D) would be compared to the value in the FCF.

Cylindricity is over the entire surface, therefore, the cylindricity is determined by the overall largest and smallest measurements which the student has boxed. This resulted in an actual cylindricity value of 0.0315 which would be compared to the value in the FCF. Once the students had the actual values resulting from measurements and could compare them to a value in the FCF, they made a direct connection to the tolerance zones produced by each symbol (i.e., an annulus vs a hollow cylinder) and how all the probe measurements must lie within these tolerance zones if the part is to pass inspection. It was beneficial for the professor to see the students making these connections and hearing directly from them. This was also a great opportunity for the professor to ask the students questions regarding the lecture content such as: “How would the tolerance zone change if the shaft diameter was smaller or larger?”; “How would the results change if the actual shaft diameter is at its MMC value?”; or, “How can Rule #1 be overridden?”

X-Sec	MAX Measurement	MIN Measurement	Circularity
A	0.006	-0.0075	0.0135
B	0.0045	-0.010	0.0145
C	0.0185	-0.002	0.0205
D	0.0215	-0.0050	0.0265
E	0.0110	-0.0070	0.0180

Cylindricity: 0.0315 (only based on cross-sections A-E)

Fig. 5, Sample of Student Measurements for Circularity and Cylindricity

Fig. 6 shows a sample of the angularity measurements. The measurement over the entire surface was repeated 5 times and the largest and smallest measurements for each were recorded. In this table, students determined the angularity considering each individual measurement (i.e., measurement 1 resulted in an actual angularity of 0.0165 while measurement 2 resulted in an actual angularity of 0.0120) as well as an actual angularity of considering all measurement data. The intent was to make them think about which value would be compared to the FCF. The actual angularity considers all measurement data and was 0.0235 which is obtained from the overall largest measurement recorded in measurements 2 and 5 and the overall smallest measurement recorded in measurement 5. Some questions a professor can ask his students are: “What is angularity applied to a surface indirectly controlling?”; or, “How would the measurement fixture need to be adjusted if the basic angle changes?”

	MAX Measurement	MIN Measurement	Angularity
1	.0075	-0.009	0.0165
2	.01	-0.002	0.012
3	.007	-.0045	0.0115
4	.0055	-0.005	0.0105
5	.010	-.0135	.0235

Angularity: .0235 (based on 5 measurements above)

Fig. 6, Sample of Student Measurements for Angularity

The goal of the measurement exercises was for students to associate the symbols and values in the FCF to the measurements required. This required students to think about the measurement errors which can be introduced if the probe is misaligned relative to the part and rotating/moving the part slowly so they take proper measurements (an analog dial indicator would be better, so they visually see the dial’s movement). Another consideration was to ensure there were no debris on the granite block, the parts, and the probe. Students were also tasked with maintaining a clean and orderly working environment and returning all tools and parts.

Overall, the measurement activities were easy to implement, inexpensive, and they can be scaled to larger groups of students. In an end-of-semester course survey conducted by the university, students commented: “I genuinely feel like I learned a lot about the course because of the measurement activities”, “the measurement activities relating to the recent presentation were great to cement the information”, and “I think the hands-on experience of using measurement tools for the measurement activities should remain the same.” The university course survey had 100% participation (i.e., all 12 students participated) and the following ratings were given:

- Overall, the course was excellent: **4.83**/5.00
- I discussed ideas from this course with others outside the classroom: **4.75**/5.00
- This course has been (or will be) of value to me: **4.90**/5.00
- The course inspired me to learn more: **4.75**/5.00

The comments and ratings reflected the comments the students made during and after the measurement activities. They found the activities useful to relate the theory to practical, hands-on applications and they were able to associate them to applications they were currently working on.

5. Conclusion

This paper presents easy to implement and inexpensive measurement fixtures that can be used to verify the geometric tolerances of circularity, cylindricity, and angularity. The fixtures are implemented at various points in the semester in measurement activities as part of a senior-level elective course on GD&T. The measurement activities helped the students tie the theory to practical applications. The fixtures are made of acrylic and fabricated using laser cutting and the measurement activities can be scaled to larger groups.

6. References

[1] A. Krulikowski, *Fundamentals of Geometric Dimensioning and Tolerancing 2018: Using Critical Thinking Skills, Revised Edition*, SAE International, 2021.
[2] *Dimensioning and Tolerancing: Engineering Product Definition and Related Documentation Practices*, ASME Y14.5-2018 Standard, 2018.
[3] J. D. Meadows, *Geometric Dimensioning and Tolerancing: Applications, Analysis & Measurement [per ASME Y14.5-2009]*, James D. Meadows & Associates, Inc. and ASME Press, 2009.
[4] O. Rios, "Teaching Geometric Dimensioning and Tolerancing Concepts using 3D Computer Models and 3D Printed Parts," ASEE Annual Conference and Exposition, 2018.
[5] O. Rios, “Forming a Strong Association Between Dimensional Data in Sketches and Engineering Drawings,” ASEE Annual Conference and Exposition, Online, 2020.
[6] D. Fadda, and O. Rios, “Work In Progress: Online Computer-Aided Design Class,” ASEE Annual Conference and Exposition, 2019.