An Example of Teaching Geometric Dimensioning and Tolerancing (GD&T) Concepts using 3D Printed Parts

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Abstract

Geometric Dimensioning and Tolerancing (GD&T) is an important tool for engineers to efficiently communicate design intent and requirements. GD&T has several advantages but can be difficult for students to learn due to the inherent 3D nature of the geometric tolerance zones. This paper describes an example of how 3D CAD models and 3D printed parts were used to illustrate several GD&T concepts including position tolerance zones, bonus tolerances, and designing functional gages for part inspection. The example described in this paper was implemented in a sophomore-level CAD course. The example was successfully delivered to a class of 45 students during the Fall 2017 semester. A description of the example is presented and, administering the example, requires simple 3D CAD modeling software and a 3D printer which are common in most engineering schools. Continuous improvements to the example are made based on faculty observations and assessments, as well as an end-of-semester survey administered to the students.

1. Introduction

At the University of Texas at Dallas (UTD), students are exposed to 3D modeling during their freshman year [1-3] but are required to take a more intensive CAD course during the second semester of sophomore year or first semester of their junior year. This CAD course covers 3D part and assembly modeling, parametric curve and surface modeling, preparing fabrication packages for traditional and additive manufacturing, and learning about conventional and geometric tolerancing.

A survey of the literature highlights the importance of Geometric Dimensioning and Tolerancing (GD&T) including reducing costs by decreasing waste, producing components that are interchangeable, and allows designers to more clearly communicate functional relationships between features in drawings [4-7]. However, GD&T concepts can be difficult for students to learn not only because of the many symbols and terminology implemented by this graphical language but also because it may be difficult to comprehend the 3D nature of geometric tolerance zones.

In the rest of this paper, a detailed description of an example to illustrate the concepts of position tolerances and bonus tolerances resulting when MMC is applied is provided. These concepts are illustrated to the students with 3D models, 2D diagrams and 3D printed parts. All necessary calculations are also presented. Finally, results from a student survey are presented.

2. Description of Example Problem

In this problem, a functional gage to inspect a circular hole pattern of the component shown in Fig. 1 needs to be designed. The objective was to create an example to teach the concepts of datum simulators and bonus tolerances. The example also teaches the difference between MMC and LMC, the use of cylindrical datums, position tolerance zones, and basic dimensions. This example was taught to a class of 45 students in Fall 2017 semester. The rest of this section explains how the example was presented in lecture.

To begin, we will assume the size tolerances of the holes and cylindrical surface A have been verified to be within tolerance. What we are trying to determine in this example, is how to determine if the location of the hole pattern is within tolerance. Additionally, in this example the tolerances were purposely chosen to be large in value for illustration purposes. Real-world applications may implement smaller tolerance values but the reasoning and calculations involved would be the same.

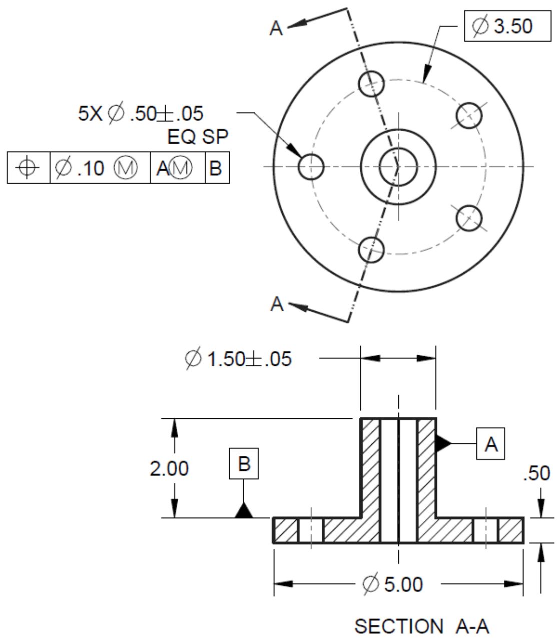

Fig. 1, The component with a circular hole pattern dimensioned in units of inches. Dimensions and tolerances of some features are not shown for clarity.

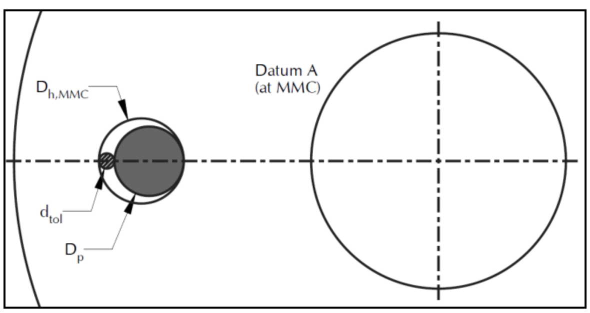

Fig. 2, Diagram used to determine functional gage pin diameter.

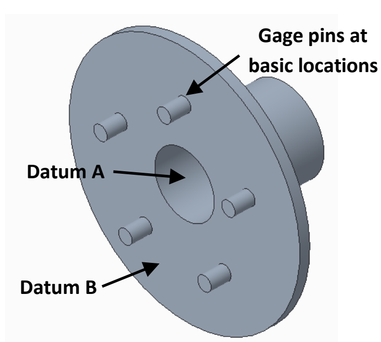

Fig. 3, The functional gage designed for this application with simulated datums A (cylindrical) and B (planar).

The hole positions can be verified to be within tolerance using a functional gage with five pins whose locations are given by the basic dimensions specified in the drawing of Fig. 1. This functional gauge is designed at the lowest end of the tolerance that would allow parts shown in Fig. 1 to still be accepted.

The first step involves determining the diameters of the pins. Looking at the feature control frame, the position of the holes are toleranced relative to the MMC size of the hole and the MMC size of the cylindrical datum A. The MMC of the hole (internal feature of size) is $\phi 0.45\ in$ and the MMC of datum A (external feature of size) is $\phi 1.55\ in$. Next, referencing the diagram of Fig. 2, the pin diameter of the functional gage, D_p, is determined to be

$$\begin{aligned} D_p &= D_{h,MMC} - d_{tol} \\ &= \phi 0.45\ in - \phi 0.10\ in \\ &= \phi 0.35\ in \end{aligned} \quad (1)$$

In Eq. 1, $D_{h,MMC}$ and d_{tol} are the diameters of the hole size at MMC and position tolerance zone specified in the feature control frame, respectively.

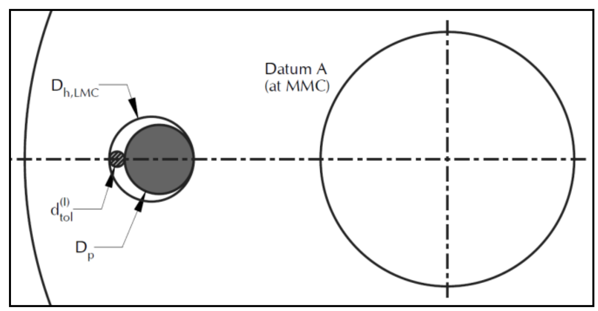

Fig. 4, Diagram used to determine position tolerance for case (I).

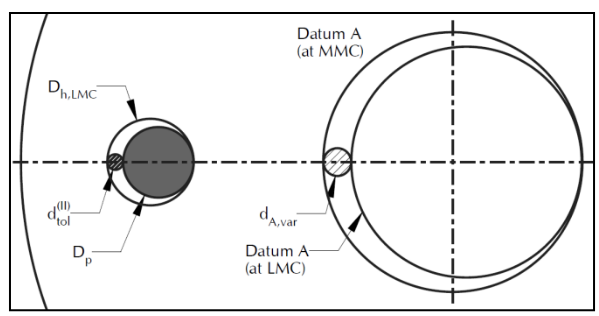

Fig. 5, Diagram used to determine position tolerance for case (II).

Since MMC was implemented in the component of Fig. 1, a functional gage can be designed to verify the positions of the holes. The functional gage designed for this application is shown in Fig. 3. For simplicity in this undergraduate class, we assumed the variation of the simulated datums A and B was much less compared to the variation of the surfaces of the component making contact with the simulated datums of the functional gage.

Next, we wanted to show what happens to the position tolerance zone if the hole and datum A were manufactured at their respective LMC values instead of their MMC values. This was addressed incrementally in two cases:

I) Hole at LMC and datum A at MMC
II) Hole and datum A at LMC

The scenario of case (I) is detailed in Fig. 4. In this case, the allowable variation of hole position, $d_{tol}^{(\mathrm{I})}$, is

$$\begin{aligned} d_{tol}^{(\mathrm{I})} &= D_{h,LMC} - D_p \\ &= \phi 0.55\ in - \phi 0.35\ in \\ &= \phi 0.20 in \end{aligned} \tag{2}$$

where $D_{h,LMC}$ is the diameter of the hole at LMC. Hence, the bonus tolerance for case (I), $d_{bonus}^{(\mathrm{I})}$, is

$$\begin{aligned} d_{bonus}^{(\mathrm{I})} &= d_{tol}^{(\mathrm{I})} - d_{tol} \\ &= \phi 0.20\ in - \phi 0.10\ in \\ &= \phi 0.10\ in \end{aligned} \tag{3}$$

Since the position tolerance zone is defined relative to the hole's MMC size, when the hole size deviates from it's MMC value a bonus tolerance results up to $\phi 0.10\ in$.

The scenario of case (II) is detailed in Fig. 5. In this case, the additional variation of the cylindrical surface A, $d_{A,var}$, needs to be taken into account. This is determined as follows:

$$\begin{aligned} d_{A,var} &= d_{A,MMC} - d_{A,LMC} \\ &= \phi 1.55\ in - \phi 1.45\ in \\ &= \phi 0.10\ in \end{aligned} \tag{4}$$

where $d_{A,MMC}$ and $d_{A,LMC}$ are the MMC and LMC values of datum A, respectively. The allowable variation of the hole position is now

$$\begin{aligned} d_{tol}^{(\mathrm{II})} &= D_{h,LMC} + d_{A,var} - D_p \\ &= \phi 0.55\ in + \phi 0.10\ in - \phi 0.35\ in \\ &= \phi 0.30 in \end{aligned} \tag{5}$$

This yields a bonus tolerance of

$$\begin{aligned} d_{bonus}^{(\mathrm{II})} &= d_{tol}^{(\mathrm{II})} - d_{tol} \\ &= \phi 0.30\ in - \phi 0.10\ in \\ &= \phi 0.20\ in \end{aligned} \tag{6}$$

Hence, when the hole size and cylindrical surface A deviate from their MMC values, the allowable variation of the hole size is up to 3 times the position tolerance specified by the designer in the feature control frame.

Since MMC condition is typically implemented in drawings when components are to be fabricated using conventional subtractive manufacturing techniques/tools to reduce scrap, the bonus tolerance should be determined and the functional requirements of the component should be assessed with this additional allowance in variation.

3. 3D Printed Parts

For some students, the 3D models of component and functional gage and the diagrams shown in Fig. 2, Fig. 4 and Fig. 5 may not be sufficient to understand the concepts of datum simulators, position tolerance zones, and bonus tolerances due to the inherent 3D nature of these concepts. To help with this, a 3D printed functional gage and two 3D printed components were developed and passed out to the students during lecture. One 3D printed component was designed so that the hole pattern would pass inspection while the second component was designed so that it would not. Both 3D printed components were designed with all features within tolerance except, in the second component, the location of one hole was purposely selected to be slightly beyond the boundary specified by the allowable variation calculations (Eq. 2 and Eq. 5). To the author's eye, there was no visual difference between the two 3D printed components. The students used the functional gage to inspect the hole pattern implementing the datum priority set in the feature control frame.

The 3D printed functional gage and components were fabricated using a Dimension Elite 3D printer with a layer thickness of $0.007\ in$. This 3D printer implements Fused Deposition Modeling (FDM) with support material removal [8]. Since the sizes and tolerances implemented were large compared to the layer thickness, the components and functional gage performed as intended.

4. Results of a Student Survey

Students were asked to provide anonymous feedback on the activity in a survey administered at the end of the course. The survey includes the student's perception of their understanding of the example topics and if the 3D printed components and functional gage helped them understand some of these topics. The students were asked to respond to the following statements based on a 5-point Likert scale where a value of 1 meant they strongly disagreed and a value of 5 meant that they strongly agreed with the statement.

1) I understand why the geometric tolerances controlling position require the use of datums.

2) I understand why a bonus tolerance can result when position geometric tolerances and MMC are applied.
3) I understand why a functional gage can be used to check position geometric tolerances at MMC.
4) The 3D printed components and functional gage shown in class helped me understand the concept of bonus tolerance.
5) The 3D printed components and functional gage shown in class helped me understand how a functional gage can be used for part inspection.

The results of these are plotted in a diverging staked bar chart [9] as shown in Fig. 6. The raw data is given in Table 1. Out of 45 students in the class, 28 students responded to the survey and allowed their anonymous responses be used for research purposes.

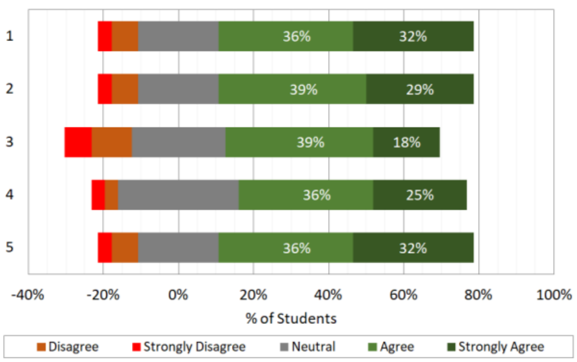

Fig. 6, Student responses to survey questions.

Table 1, Number of students who strongly disagree (SD), disagree (D), agree (A), strongly agree (SA) and where neutral (N) with the statements.

Statement	SD	D	N	A	SA	Total
1	1	2	6	10	9	28
2	1	2	6	11	8	28
3	2	3	7	11	5	28
4	1	1	9	10	7	28
5	1	2	5	12	8	28

As can be seen from Fig. 6, over 57% of the students who responded to the survey either agreed (A) or strongly agreed (SA) with each of the statements. Homework assignments and exam questions also indicated understanding of the concepts.

Students were also asked to provide free-response comments on the difficulties they faced learning about geometric tolerances. Some students could have benefited from more lectures (only an introduction is intended in this course): "need more practice," and "not solving enough problems." Some students had difficulty understanding the tolerance zones: "the shape of tolerance zone," and "location tolerances." A student mentioned difficulty with "all the symbols and their meanings." Some students explained they benefited from the examples: "I think it was hard visualizing this but the examples helped," and "lecture slides and examples were helpful."

After reviewing the student's comments and positive feedback on the example with 3D printed parts, introducing more examples like this would be greatly beneficial. To this end, one or more examples with detailed calculations, diagrams, 3D models, and 3D printed parts will be created for future semesters.

5. Summary

In this paper, an example to illustrate GD&T concepts using 3D models and 3D printed parts was described. The example is considered simple to implement only requiring CAD software and a 3D printer and was successfully administered to 45 students. Results from a student survey (28 respondents) indicate the example had a positive effect on the student's understanding of the concepts.

Acknowledgement

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