FUNCTIONAL TOLERANCING OF A GEARBOX

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ABSTRACT

This paper proposes a scheme for the tolerance specification that uses the features' function information and mating condition attributes in the assembly to derive an appropriate tolerance specification as per the design intents. The proposed mirror method provides a way to locate the critical components. It helps the user identify functional features and group them into clusters. Temporary DRF (Datum Reference Frame) is first generated for each cluster of features on critical components by selecting specific features as datum features. Other features (that are not datum features) present in the same cluster are then toleranced with respect to those datum features. The temporary DRFs as well as the tolerancing scheme are then copied (a mirror image of the critical component) to the other mating components (which are mating with the particular critical component). The final DRFs on the critical components are then decided by analyzing the temporary DRFs and the given functional requirements of each component. Appropriate geometric tolerance types and material conditions for toleranced features are generated following the standards and the industrial practices.

INTRODUCTION

Traditionally tolerances for manufactured parts are specified using symbolic schemes of GD&T as per ASME or ISO standards. Used appropriately, the symbols can give geometric definitions of components that represent design intents. GD&T describes the variational information related to the size, form, orientation, and location of part features. It has a design-dimensioning philosophy that encourages designers to define a part based on how it functions in the final product.

Tolerancing a component as per standards includes 1) datum feature selection, 2) dimensioning between datum features and toleranced features, 3) assignment of geometric tolerance type, value, material condition (for feature of size), and DRF in the feature control frame.

Functional surfaces (edges or points) are normally chosen as datum features. The most important quality of a datum feature is that it must define the orientation and/or location of a part precisely in the assembly. This is particularly true for a primary datum feature. In general, the datum features need to be [MEA 98]: 1) functional (serving a purpose for the part's operation); 2) representative of mating or sitting features and/or alignment edges (to assure that if they are inspected and accepted while oriented to, or located from datums constructed from those features, the controlled features will, indeed, mate and/or sit); 3) repeatable in manufacturing; 4) accessible during manufacturing and inspection operations.

Conditions 1) and 2) are more important than conditions 3) and 4), because conditions 1) and 2) establish direct relationships between functions of the feature to the datum feature. We may add form or orientation tolerance to control datum feature so that they are repeatable in manufacturing and inspection. Some times, a functional feature may not be a good candidate for a datum feature if it has any accessibility problem during manufacturing, assembly and inspection. In that situation, we need to find out other feature that is accessible and whose orientation to the other functional features can be controlled by applying orientation tolerances. Functions and mating conditions must guide the datum selection process. Other practical needs should also be considered in selecting datum features. It should be noted that planar and cylindrical features are the most common features in any component. With sufficiently large surfaces, they are able to control the maximum number of DOFs (degree of freedom) of the orientation of any surface. They are easy to be simulated by surfaces of instruments used in manufacturing and inspection, such as working table of machine tool and inspection machine or surfaces of gages and fixers. Before introducing the proposed mirror method, it is important that we define the function and mating condition attributes of features that will guide clustering of features, selection of tolerance type, and selection of datum features.

FUNCTION AND MATING CONDITION ATTRIBUTES OF FUNCTIONAL FEATURES

In this paper, we differentiated mating condition attributes from function attributes because they serve differently in the tolerance selection process. Details of both attributes are provided in the following.

Functional attributes serve some specific purposes in a part's operation, such as seal, rotate, balance, gearing, fastening, press fit, clearance fit, and sliding etc. They should be used to guide the selection of tolerance types, tolerance values, and material conditions (Maximum Material Condition, Least Material Condition, Regardless of Feature Size - MMC, LMC and RFS).

Let us investigate some of the function attributes and examine how their requirements affect the tolerancing process.

- Seal: arrests any leakage between two components. It requires tight form and size control (assuming no flexible sealing parts used).
- Rotate: preserves the rotation between two components. The feature for "rotate", such as cylindrical features that mate with bearings, requires tight location and form control.
- Balance: preserves balance (symmetry) between two components. The feature for "balance", such as a center hole or a boss to control the relative position of two components, doesn't allow MMC referenced to it if it is chosen as a datum feature.
- Gearing: preserves gear mesh between two components. Requires profile control of the gear mesh.
- Fastening: connects two components. Requires projected tolerance zone consideration and MMC control for interchangeability.
- Sliding: preserves sliding between two components (such as piston assembly). Requires form control on the contacting surfaces.
- Press fit: does not allow any relative movement; The components after press fitted are considered as one single component. RFS is recommended.
- Clearance fit: relative movement allowed. MMC is recommended.

Mating condition attributes serve purposes in part's location and orientation in the assembly. They can be categorized as: locate, sit, contact, align, etc. They can be used in guiding selection of datum features.

- Locate: preserves the relative location of two components, such as a pin interface. The features that are used to locate, such as pin or pinholes, are normally short enough so that they will not control the orientation of component in the assembly but only location. They are not good candidates for primary datum features. However, as they control the position of component in the assembly, they are good candidates for secondary datum features.
- Sit: preserves 3-points contact between two planes, controls 3 DOFs (Degrees Of Freedom): 2 rotations and 1 translation. If the two planes are large enough (for stability purpose), they can be best candidates for primary datum features.
- Contact: preserves 1-point contact between two surfaces, controls 1 DOF: 1 translation. The

surfaces are perfect candidate for tertiary datum feature.

- Align: preserves 2-points contact between two surfaces, controls 2 DOFs: 1 rotation and 1 translation. The surfaces are perfect candidate for secondary datum features.

MIRROR METHOD

The mirror method is based on the observations that: 1) most components in assembly have planar surfaces so that they can sit on each other or just align or contact with each other. Those mating planes that have at least 3-point of contacts (in between them) are called the “strong mirror” in this method; and others that will have less than 3-point of contacts (i.e. 1-point or 2-point case) are called the “weak mirror”. 2) Mating features on two mating components in an assembly are mirrored at those strong interfaces. 3) There are always some important components that sit on or come in contact with more than one component (not including fasteners) in the assembly. 4) Generally the relative position between components is not defined if there is no mirror (strong or weak) between them. 5) Weak mirrors can also be used to locate datum features. 6) Important components have always the maximum number of mirrors on them.

The tolerancing methodology in this work uses these mirrors to locate important component(s) and develop the required DRF(s) on the component(s) first. The mating component’s (which mates with the important component) features are next toleranced. The DRF system of the important component is ”duplicated” (as it is) to the mating components. The common mating features of both important component and its mating components will be then selected as the datum features and their configurations will be same. Tolerancing functional features to this DRF preserves assembliabity and functionality of components. Tolerance types, values and material conditions are decided by industrial practices. Figure 1 shows the recommendations for tolerance type selection in ASME and ISO standards that are normally practiced in industries.

The followings are the steps of the proposed methodology for tolerancing by mirror method:

1. Generate assembly graph of functional features where patterns of features are considered as one feature, and the press fitted components are considered as one component. The function and mating condition attributes of every feature need to be detailed on the assembly graph.

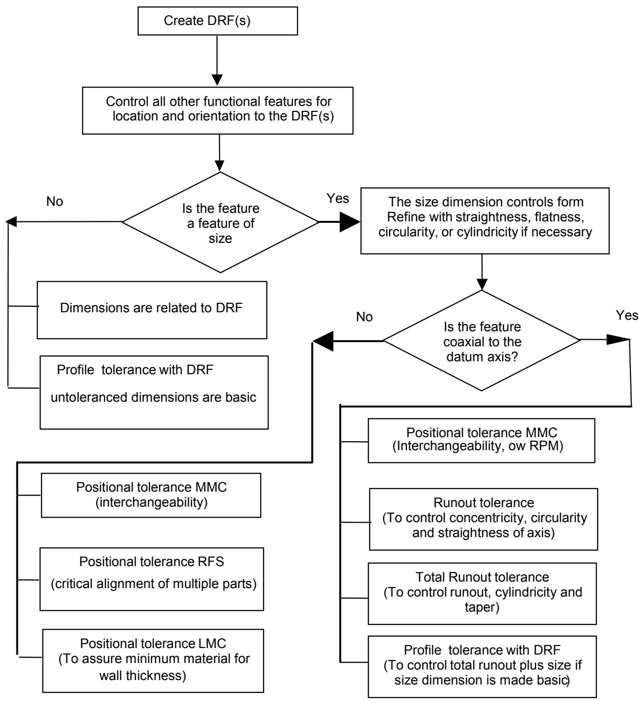
2. Based on the assembly graph, identify component(s) that has/have the maximum number of mirrors (strong or weak). They are the “important” component(s).

3. Functional features in each important component are grouped into one cluster if they are physically connected to the mirrors. Datum features are selected in each cluster based on function and mating condition attributes of features. One DRF is generated from those datum features for each cluster. Validity of the DRFs is important and the establishment of the DRF must conform to the ASME standard (refer to tables 4-2, 4-3 and 4-4 in ASME Y14.5.1 [ASME94b]). Other features in the cluster that are not datum features are the features to be toleranced to the DRF. If there exist any features that belong to more than one cluster, then, those features should be toleranced only once with respect to a DRF of either one of those clusters. Functional features that do not belong to any cluster will be toleranced to any DRF as selected by user.

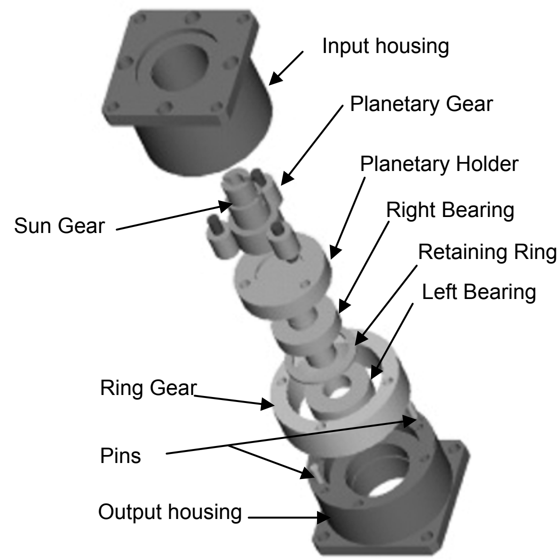
4. Any important component may have more that one cluster and thus more than one DRF. However, if any two clusters have contacts with the same mating component, those two clusters need to be merged into one so that they will have only one DRF.

5. If repeatability is a necessity, form and orientation tolerance must be considered for the datum features.

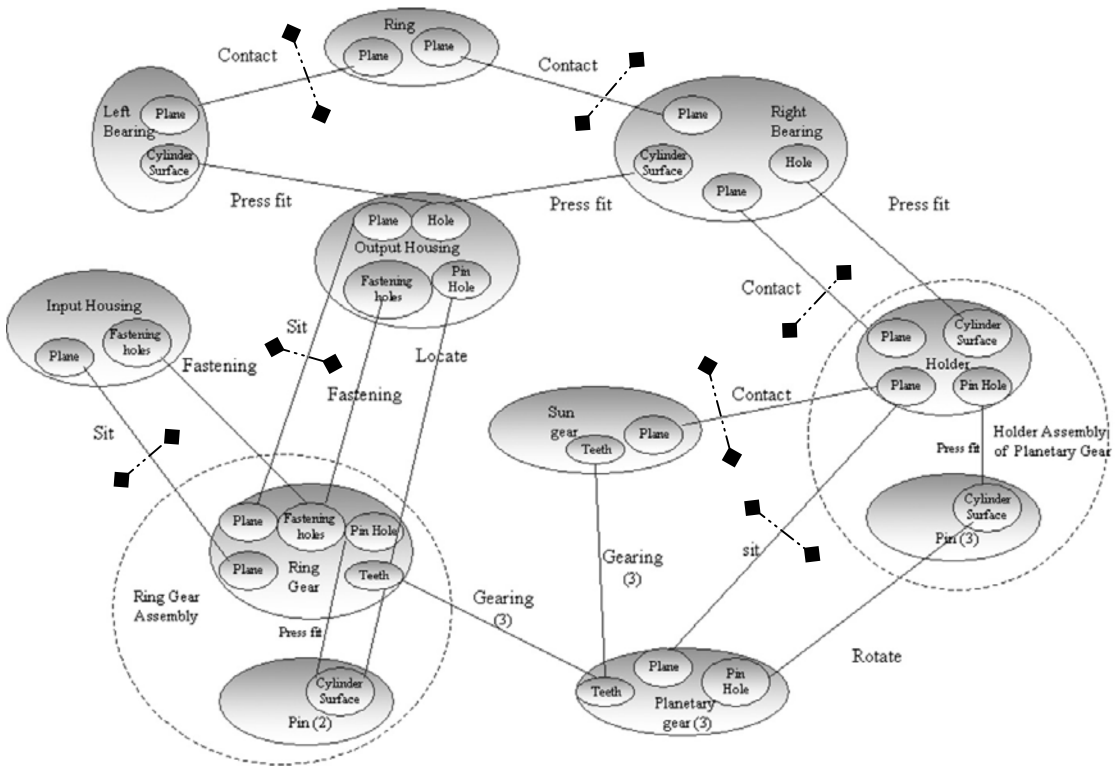
6. Select appropriate tolerance types of other features’ (which are not datum features) location with respect to the established DRF as per figure 1. If necessary, additional orientation or form or both tolerances need to be added to a feature for a stricter control as per its functional requirements. Tolerance values are inferred from size tolerance and fitting requirements (if there is no specific requirements about size tolerance of features, tolerance value is initialized to zero in order to have a maximum size tolerance). Material conditions are determined as MMCs or LMCs based on functional requirements.



1. TOLERANCING FLOW CHART [ASME94a]



2. EXPLODED VIEW OF A GEARBOX ASSEMBLY



3. ASSEMBLY GRAPH OF THE GEARBOX WITH MIRRORS

7. Once the features of important components are toleranced (which has been established temporarily at this stage), we need to focus on the other mating components (that are mating with important components). First, the DRFs of the mating components are established by “duplicating” the corresponding DRFs of the important components. Then the same rules of tolerancing as shown in figure 1 are applied to all other functional features of each of the mating components to establish the tolerance specification.

CASE STUDY: TOLERANCING OF A PLANETARY GEAR SET

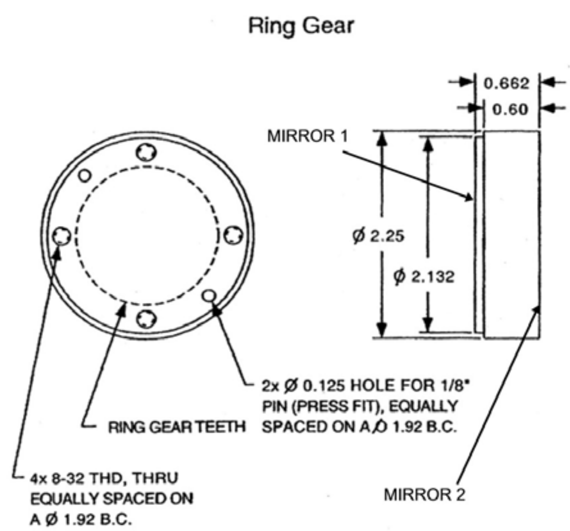
This section describes an assembly model of an industrial device – a planetary gear set (i.e. a gear box) as shown in figure 2.
The figure 3 is the assembly graph of the gearbox with the function and mating condition attributes shown on it. Please note that ◆---◆ represents a mirror between components.

From the assembly graph as shown in figure 3, we can detect seven mirrors between components; between every pair of those components, there is a planar interface. Three components can be considered as important components: the ring gear with two pins (pressed and considered as one component), the planetary holder with 3 pins (pressed and considered as one component) and the retaining ring. The retaining ring will not be considered here because it is a standard component. So the important components in this gearbox example are the ring gear and the planetary holder. Following the procedure of the proposed mirror method as described in the last section, we first need to group functional features on each important component into clusters. Then, identify datum features and features to be toleranced to the datum features in each cluster. Tolerance type and material conditions are then decided by the flow chart as shown in figure 1. Determination of tolerance values has not been specifically addressed in this paper; it is itself a research problem and it has been addressed by our research group elsewhere [NISTIR02]. At this stage, all the location tolerances will be specified 0.00 if the material condition is either MMC or LMC, so that we can have maximum bonus tolerance of the toleranced feature of size. Otherwise, if material condition is RFS, some low positive values are specified. The dimensioning of the components is not shown for simplicity. The tolerancing of important components cannot be completed until all their mating components have been toleranced. So we have called the tolerancing of important component before completion of tolerancing of its mating components as “temporary tolerancing” in the following.

<u>Temporary Tolerancing of Ring Gear</u>

From figure 3, we can see that there are two mirrors on the ring gear. One is between the ring gear and the output housing, and the other is between the ring gear and the input housing. Both mirrors have mating attributes of “sit”. It means that we need a three-points contact between the two contact planes of the two components. So the mirrors are strong mirrors. Generally, strong mirrors will be considered for the primary datum features and the weak mirrors will be considered for the secondary or tertiary datum features.

Because we have two mirrors on our important component --- ring gear, we can group functional features on it into two clusters.

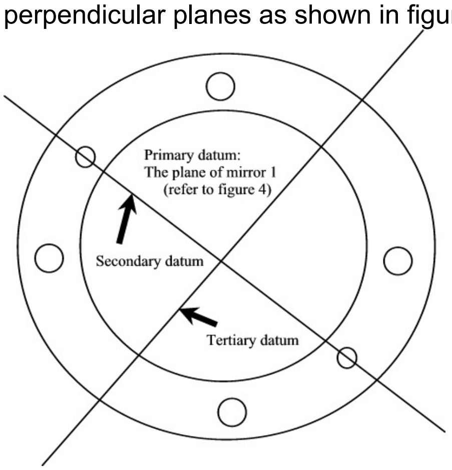


4. FUNCTIONAL FEATURES ON RING GEAR

All functional features of ring gear are shown in figure 4. The mirror 1 connects with the $2\times\phi0.125$ pinhole pattern and the $4\times$8-32 THD THRU hole pattern and the ring gear teeth. The mirror 2 connects with the $4\times$8-32 THD THRU hole pattern and the ring gear teeth. So cluster #1 includes mirror 1, the $2\times\phi0.125$ pin hole pattern, the $4\times$8-32 THD THRU hole pattern and the ring gear teeth, and cluster #2 includes the

mirror 2, the 4×8-32 THD THRU hole pattern and the ring gear teeth.
Since the mirror 1 is a strong mirror, we choose it as the primary datum feature in cluster #1. Among the rest of functional features in cluster #1, we choose the 2×ϕ0.125 pinhole pattern as the secondary datum feature because it has a mating condition attribute of "locate".

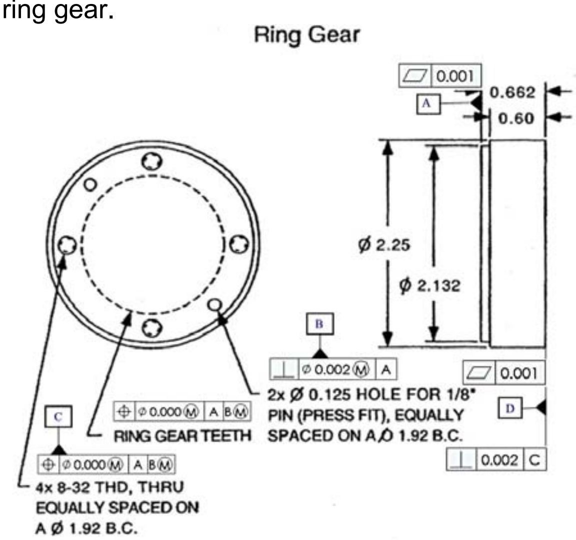
A pattern of holes/bosses at MMC may be used as a group to establish a datum [ASME94a]. In our case, individual datum axes are established at the true position of each hole. These are the axes of true cylinders (such as hard gages) that simulate the virtual condition of the holes/bosses. So we have three datums: datum A --- a plane (from mirror 1) and datum B and C --- two axes (from the 2×ϕ0.125 pin hole pattern). From the table in appendix-1 which is the table 4-4 in [ASME94b], we find our case is similar to the case 3.11 where the validity condition is $(A \perp B) \wedge (B \neq C)$. It ensures the validity of our chosen datums. The resultant DRF generated from the three datums has three perpendicular planes as shown in figure 5.



5. DATUMS THAT FORM THE DRF OF CLUSTER #1

In cluster #1, there are 2 features (the 4×8-32 THD THRU hole pattern and the ring gear teeth) that need to be dimensioned and toleranced to this DRF. Positional tolerances are required to control these two features (refer to figure 1). We want interchangeability of the 4×8-32 THD THRU hole pattern; so we choose MMC as its material condition. The position of the pitch circle of the ring gear teeth need to be controlled so that it can mesh well with gear teeth on planetary gear and sun gear; so we choose RFS as its material condition.

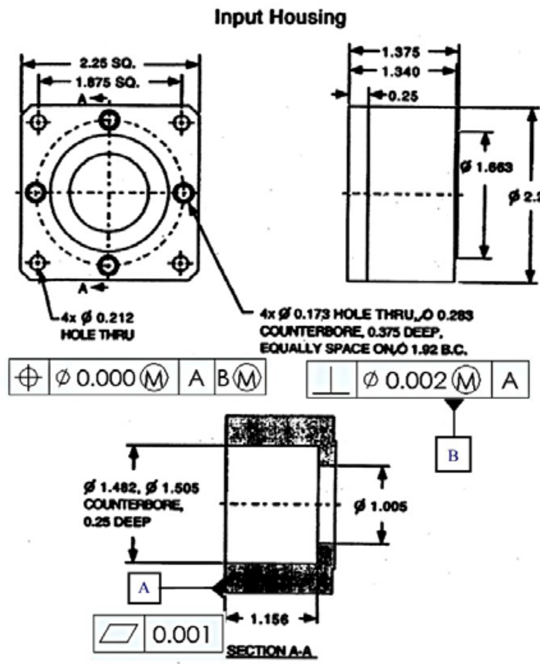
In cluster #2, the mirror 2 is selected as the primary datum feature and the 4×8-32 THD THRU hole pattern is selected as the secondary datum feature. Since the ring gear teeth belongs to both cluster #1 and cluster #2 and it has been toleranced in cluster #1, it will not be toleranced in cluster #2 (refer to the step#3 of the mirror method). All datum features need to be specified with the form or orientation tolerances for repeatability purpose. The mirror 1 and mirror 2 are controlled by flatness tolerances. The 2×ϕ0.125 pinhole pattern is controlled by using a perpendicularity tolerance. Since the 4×8-32 THD THRU hole pattern has been toleranced in cluster #1, the mirror 2 need to be controlled by a perpendicularity tolerance with the 4×8-32 THD THRU hole pattern as the datum feature. Figure 6 shows the temporary tolerancing of the ring gear.



6. TEMPORARY TOLERANCING OF RING GEAR

Tolerancing of Input Housing

The input housing mates with the ring gear on the mirror 2 (which is a strong mirror, figure 7). This input housing is a mating component (whereas the ring gear is the important component). As described in the proposed mirror method, the DRF of the input housing should be an image of the DRF of cluster #2 on the ring gear. The DRF should be duplicated on the input housing.
Other functional features will be dimensioned and toleranced with respect to this DRF. The primary datum feature on the input housing is the mirror 2 and the secondary datum feature is

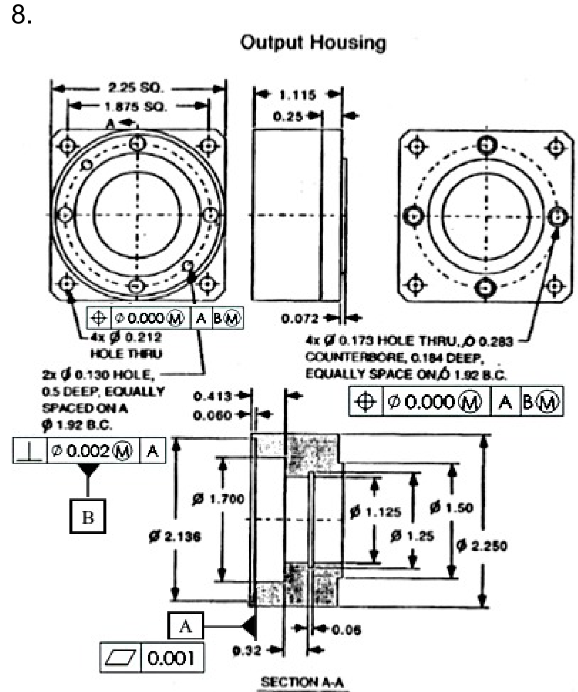


7. TOLERANCING OF INPUT HOUSING

the 4×Φ0.173 hole pattern (figure 7). Tolerancing of its datum features is same as that of the ring gear: a flatness tolerance on the mirror 2 and a perpendicularity tolerance on the 4×Φ0.173 hole pattern. Following the flow chart of figure 1, other functional features, such as the 4×Φ0.212 hole THRU pattern will be controlled (with respect to this DRF by a positional tolerance at the MMC material condition. The toleranced input housing is shown in figure 7.

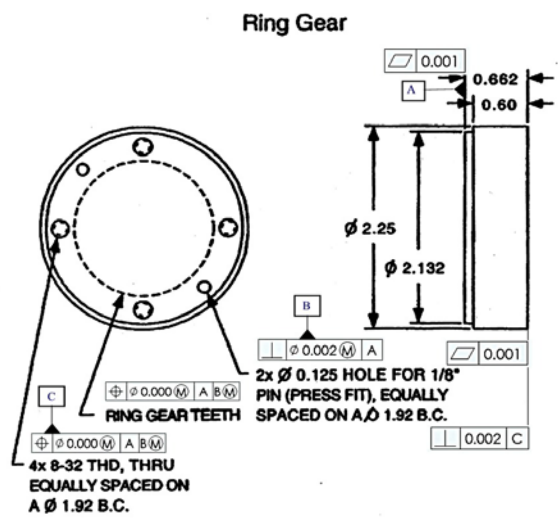
Tolerancing of Output Housing.

Like the input housing, the output housing is also a mating component to the ring gear. The tolerancing procedure is also similar. The output housing mates with the ring gear on the plane of mirror 1 (figure 8). The DRF on the output housing is an image of the DRF of cluster #1 on the ring gear. Other functional features of the output housing are dimensioned and toleranced with respect to this DRF. The primary datum feature on the output housing is the mirror 1 and the secondary datum feature is the 2×Φ0.130 hole pattern (figure 8). Tolerancing of datum features is same as that of the ring gear: a flatness tolerance on the mirror 1 and a perpendicularity tolerance on the 2×Φ0.130 hole pattern. Other functional features, such as the 4×Φ0.173 hole THRU pattern and the 4×Φ0.212 hole THRU pattern are toleranced with a positional tolerance at MMC material condition. The toleranced output housing is shown in figure 8.



8. TOLERANCING OF OUTPUT HOUSING

Revisiting Ring Gear to Finalize its Tolerancing



9. FINAL TOLERANCING OF RING GEAR

After tolerancing two mating components (input and output housings) which mate with the ring gear (which is the “important component” here), we need to revisit the ring gear once again and finalize its tolerancing. It is evident that the ring gear has two clusters (which were formed with two mating components). However, those two clusters do not mate with the same component (cluster #1 of ring gear mates with output housing and cluster #2 of ring gear mates with input housing). So, we do not need to merge the two clusters into one and their DRFs are also not merged. Let us now examine other features that need to be toleranced in both clusters #1 & #2. There exist no other functional features in cluster #2 other than the datum features. So, there is no need to have an extra DRF for cluster #2 since it serves no purpose. We delete the datum D. Datum C is kept because it is used as the datum for the perpendicularity tolerance. The final tolerancing of the ring gear is shown in the figure 9.

CONCLUSIONS

The objective of this paper is to establish a scientific and logical method of tolerancing. A mirroring technique based on feature's functional and mating conditions has been proposed. It helps users identify appropriate datum features and other functional features that are required to be toleranced (with respect to those datum features). It suggests how to establish the tolerance types in a systematic way, so that assembliability and functionality of the assembly can be satisfied. The proposed mirror method differentiates the mating condition attributes from the functional attributes and uses them differently for tolerancing. It utilizes the mating condition attributes in locating datum features while it buses functional attributes in the selection of tolerance types and material conditions. The techniques for determining specific tolerance values will be next coupled with this proposed mirroring method to fully synthesize a tolerance specification for a functional assembly. We are now implementing a rule-based system in a CAD environment using the proposed scheme. The function and mating condition attributes are either retrieved directly from solid model in CAD system or specified by users. This system can generate assembly graph automatically and locate all the mirrors and important components. The rules for determining the tolerance types as shown in figure 1, are encoded in a knowledge base.

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APPENDIX –1: RECOMMENDATION FROM ASME*

Case	Datums			Free xfrms	Invariants	Validity Conditions
	A	B	C			
3.1	PL	—	—	x, y, w	z, γ_z	—
3.2	PL	PT	—	w	z, γ_z, ρ_z	—
3.3	PL	PT	PT	—	all	$C \not\subset \{\sqcup B : \sqcup \perp A\}$
3.4	PL	PT	AX	—	all	$C \neq \{\sqcup B : \sqcup \perp A\}$
3.5	PL	PT	PL	—	all	$\neg (A // C)$
3.6	PL	AX	—	—	all	$\neg ((A // B) \vee (A \perp B))$
3.7	PL	AX	—	w	ρ_z, z, γ_z	$A \perp B$
3.8	PL	AX	—	x	y, z, u, v, w	$A // B$
3.9	PL	AX	PT	—	all	$(A \perp B) \wedge (C \not\subset B)$
3.10	PL	AX	PT	—	all	$A // B$
3.11	PL	AX	AX	—	all	$(A \perp B) \wedge (B \neq C)$
3.12	PL	AX	AX	—	all	$(A // B) \wedge \neg (B // C)$
3.13	PL	AX	PL	—	all	$(A \perp B) \wedge \neg (B \perp C)$
3.14	PL	AX	PL	—	all	$(A // B) \wedge \neg (B // C)$
3.15	PL	PL	—	x	y, z, u, v, w	$\neg (A // B)$
3.16	PL	PL	PT	—	all	$\neg (A // B)$
3.17	PL	PL	AX	—	all	$\neg (A // B) \wedge \neg (C // \{\sqcup (A \cap B)\})$
3.18	PL	PL	PL	—	all	$\neg (A // B) \wedge \neg (C // \{\sqcup (A \cap B)\})$

* Recommendation for Datum Validity (Refer to the Table 4-4 in ASME Y14.5.1)

(Note: PL—plane, AX—axis, PT—point)