Design, analysis and optimization of the tail bearing housing of jet engine

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Abstract

Tolerance is one of the biggest problems during the production and assembly stages of any product. The focus of this study concerns a new methodology to design and analyze of the tail bearing housing with lowest tolerance, which is located in the rear part of the aero-plane engine and has aerodynamic function to straighten the flow out from the low pressure turbine and also supports the bearing loads from shaft. This work is initiated as a part for ongoing investigations to establish alternative assembly routes where the stability in terms of geometrical robustness is essential to allow for a cost-effective production. The study applied a distribution and a de-coupling of geometrical effects for product assembly to obtain a robust design. The study also presents a methodology that allows assemblies to be evaluated with respect to robustness and geometrical stability. Additionally, robust design and tolerance (RD&T) software, presented in the current study, can evaluate any design and assembly process that are sensitive to variation and may cause problems later on during production. Different types of analyses are performed to study and, later on, to improve the assembly strategy of the tail bearing housing of jet engine. The analyses are very valuable for addressing the sensitivity of different assembly process. Additionally, different assembly rules are discussed, as parallel, series and mixing ones. In the study, twelve assembly models are applied using different techniques, as changing the way parts are located to each other or by using assembly fixtures for gaining positioning with assembly stability. The results from the current study showed that using a series assembly method is not as good as the parallel assembly one; reducing number of assembly parts using the same assembly scenarios can improve the results; using mixing scenarios between parallel and series are usually better than series one. Assembly with fixtures reduces the sensitivity for variation. The best results showed with model using a parallel scenario and a fixture.

Keywords: Jet engine; Design tolerance; Tail bearing housing; Optimization; Analysis

1. Introduction

Typical parts for jet engines of airbus airplanes are very large in size and very complicated in manufacturing, as shown in Fig. 1. All such components are designed at tight tolerances and manufactured in super alloy materials to withstand with jet engine’s environment. In general, design of such products are translated to, or fulfilled by, a set of subsystems, components and manufacturing processes. The compatibility of the products are realized in the end by a number of geometrical features that are produced by a set of manufacturing processes. During production and assembly stages of products, tolerances are shown up as one of the biggest problems for matching them to generate one product. In general, tolerance analysis of different products has been a subject of interest within last few years to try to solve the assembly problems, see e.g., [1–8].

Volvo Aero Corporation (VAC), in Trollhättan, Sweden, is planning to redesign the different parts of Airbus airplane engine by a different way; the new design is based on dividing large parts into small pieces and then assembly such pieces into one large part. Such new design is thought to be in higher quality and lower manufacturing costs, compared to the current design. However, tolerance is one of the biggest problems during the assembly stage of this new design.

As a first step at the ongoing investigations, the VAC is planning to start this new strategy with redesigning the tail bearing housing, as shown in Fig. 2. The tail bearing housing is located in the rear part of the jet engine and has an aerodynamic function to straighten the flow out from the low pressure turbine and support the bearing loads on the shaft. The current work is initiated as a part of the ongoing investigations to establish and examine the alternative design way, especially the stability in terms of geometrical robustness is essential to allow for a cost-effective production. Additionally, tolerance problem is increased by increasing the number of assembly parts because it will be more difficult to fit these parts together.

The purpose of the current study is to examine the new strategy for redesign the engine components. In particular, we should take into account 3D tolerance effects to allow for distribution and de-coupling of geometrical effects in the assembly as well as to allow for a robust design. When it comes to assemblies, robust means that the variation in individual com-
ponents must not be reinforced but instead it should be reduced during assembly.

Figure 1. Volvo aero specialisation components

Figure 2. Tail bearing housing in two views: (a) Front view with assembled parts, (b) Side view with split parts.

2. Methodology descriptions

The methodology applied in the current study to examine the tolerance is called robust design and tolerance (RD&T); the RD&T can handle most of the types of geometrical tolerances, as shown in Table 1 [9−13]. However, it is not able to cover symmetry and angularity types.

The idea of RD&T is to provide a number of analysis functions at different stages of the design process. In particular, it allows assemblies to be evaluated with respect to robustness and geometrical stability. Such assembly robustness evaluation can detect design and assembly difficulty that are sensitive to variation and may cause problems later on during pro-
duction. It is based on Suh’s independence axiom, which states that in a good and uncoupled design each functional requirement is satisfied by one and only one design parameter [14]. Accordingly, the methodology enables the designer to evaluate the geometrical sensitivity of the assembly, what are the sources of variation and their importance for the overall robustness as well as in what order one can proceed to improve the design. A possible result from the analysis provides the required concepts needed to be changed; such changes are either by changing the way that parts are located to each other or by using assembly fixtures for positioning elements. The methodology is operated by software (called RD&T) and it is implemented in an MS windows operating system and has an IGES interface that enables the designer to import computer aided design (CAD) geometry from arbitrary system; additionally, it can perform assembly robustness analysis. In order to analyze assembly, one should perform the following steps.

**a) Create Parts**
Individual parts in the assembly should be created. Part geometry is imported from a CAD system via the format IGES, or created using points, lines, arcs and primitives.

**b) Create Positioning Systems**
The parts in the previous point are inserted into positioning system. The positioning system for each part is defined as a local P-frame (positioning frame) for the part itself and a target P-frame for the mating part(s).

**c) Define Tolerances**
Tolerances can be defined either globally on the model level and/or by using several points as individual for each. Four different tolerances and available types are: linear, circular, cubic and spherical tolerances. Also the radius of an arc or circle may have a tolerance, which is also included.

**d) Define Measures**
Critical dimensions or points are defined as measures in order to be analyzed. Eight measure types are available: two concerning displacement, two concerning angular measurements and four concerning holes and pins.

**e) Analyze**
Assembly robustness and measure variation are analyzed for the different designs, manufacturing and assembly scenarios. This concerns ”What if” studies, in other words.

### 3. Mathematical modeling

Different models are carried out in the current study to perform different assembly strategies for the tail bearing housing (TBH) of the jet engine. It is important primary to describe the TBH and, hence, discusses the models. The TBH is located in the rear part of the jet engine and has aerodynamic function to straighten the flow out from the low pressure turbine and supports the bearing loads from the shaft. The TBH consists of three mean parts; inner ring, outer ring and struts, as shown in Fig. 2. The inner ring and the outer ring are manufactured as one piece for each, as shown in Figs. 3 and 4; however, to improve the quality and reduce the manufacturing costs, it is suggested to be manufactured as a number of small pieces and then assembled together.

<table>
<thead>
<tr>
<th>Tolerance Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straightness</td>
<td></td>
</tr>
<tr>
<td>Flatness</td>
<td></td>
</tr>
<tr>
<td>Profile of any line</td>
<td></td>
</tr>
<tr>
<td>Profile of any surface</td>
<td></td>
</tr>
<tr>
<td>Perpendicularity</td>
<td></td>
</tr>
<tr>
<td>Angularity</td>
<td></td>
</tr>
<tr>
<td>Orientation of any profile</td>
<td></td>
</tr>
<tr>
<td>Orientation of any surface</td>
<td></td>
</tr>
<tr>
<td>Orientation of any position</td>
<td></td>
</tr>
<tr>
<td>Symmetry</td>
<td></td>
</tr>
<tr>
<td>Taper variation</td>
<td></td>
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<tr>
<td>Step variation</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1. List of different types of geometrical tolerances [9–13].**

![Figure 3. Inner ring](image-url)
In the current study, we keen with the outer ring only, as a first step. The outer ring is divided into twelve equal small pieces as a new proposed design. Each small piece is called a T-Sector, as shown in Fig. 5. The new challenge for this new design is to assembly of such pieces accurately, e.g., performing the design with minimum tolerances to fit the pieces at assembly. The limitation for tolerance values to fit the pieces together is about 1 mm between the T-Sectors in radial direction and 0.45 mm in circumstance direction. One approach to handle this problem is to use RD&T software. In the software, we built twelve assembly models and, then, we check which model will fulfil the requirements, e.g., which one will give the best results. The models are carried out using a different assembly scenario, such as parallel, series and mixing strategies. In the following, the different models are discussed in details and examined via the RD&T methodology.

3. 1. MODEL ONE (M1)

In this model, the T-Sectors are added to each other consequently in one direction, e.g., the T-Sectors number one and two are assembled together; after that the T-Sector three is assembled to T-Sector two; the T-Sector four is assembled to T-Sector three and so on. After assembling all the T-Sectors, they are assembled with the inner ring. The methodology to perform that model in RD&T software is as follows.

a) Create Parts
The model is built using CAD system and applied in the form of IGES files.

b) Create Positioning System
The positioning system for each part is defined as a local P-frame (positioning frame) for the part itself and a target P-frame for the mating part. Since there are four different types of positioning systems, we used 3-point type because it is the easiest one and can give same results as others.

c) Define Tolerances
RD&T is a Monte Carlo based simulation software that uses specified tolerances to generate variation in specific points. Tolerances can be defined in two ways:

- On the global model level where it can be used by (or linked to) any number of points in the model.
- On the local tolerance where it is defined for one specific point only.

Normally, target P-frame points with points and arcs, i.e. the critical dimensions, are applied in the measures. The tolerances for these points can be defined directly from the point edit form or alternatively as described below. For arcs the tolerances have to be assigned (but not necessarily created) from the arc edit form.

The only tolerance used in this model is the linear one where it is added as auto tolerances. The auto tolerance options define an equal normally distributed linear tolerance for all target p-frame points. It is considered 1 mm linear tolerances in the target P-frame points, T-Sector and inner ring as a starting value.

d) Define Measures
Critical dimensions (points) are analyzed and defined as measures. Eight measure types are considered. Two of measures concern displacement, two concern angular measurements and four concern holes and pins. We used only points (point measure) to measure the distance between two points in radial direction and circumstance one. Hence, we can get the distances and tolerances between the first and the last T-Sectors, i.e. T-Sector number one and twelve and also between the T-Sector number twelve and the inner ring. The direction of the measure is defined by pick 2 point method. The three measures obtained are defined as follows.

1. Measure 01 is between two T-Sectors in radial direction.
2. Measure 02 is between two T-Sectors in circumstance direction.
3. Measure 03 is between T-Sector and the inner ring in radial direction.

It is important to note that these measures are performed in the largest tolerance values, i.e. if the tolerance between T-Sector one and T-Sector two is smaller than between T-Sector one and T-Sector twelve, we consider our measure as the larger one.

e) Analysis

RD&T software provides a number of analysis functions in different stages during design processes as: stability analysis, variation analysis and contribution analysis. In the early design stage when manufacturing data is limited, the focus should be set on optimizing the geometrical robustness. The stability analysis can analyze the general robustness of the design that are controlled by the positioning schemes. During product and process integration when real manufacturing data (tolerances and distributions) is available, the focus is set on optimizing the selection of tolerances to meet design, manufacture and cost constraints. The variation analysis can analyze the variation in critical dimensions (measures) of the design. The contribution analysis can present a ranked list of points and tolerances contributing to measure variation. In the following, details about each analysis are explained.

i. Stability Analysis

The stability analysis can analyze the general robustness of the design that is controlled by the positioning schemes (P-frames). The purpose of this analysis is to determine the relative influence of each part in the P-frame as follows:

- Positioning stability of all parts in the assembly (RMS of the variation of all points in a part).
- Defining measures in the assembly.

The analysis is performed using:

- Unit variation to show general robustness and P-frame sensitivity.
- Real tolerances to show actual robustness and P-frame sensitivity.

ii. Variation Analysis

The variation analysis applied Monte Carlo simulation technique to analyze variation in the measures. When the Monte Carlo simulation is finished, the variation results form appears.

iii. Contribution Analysis

The contribution analysis presents a ranked list of all points and tolerances that contributes to measure variation. This analysis is applied for optimizing the selection of tolerances and, in addition, for trouble shooting during the production process.

3.2. MODEL TWO (M2)

The procedure of this model is by assembling T-Sector one with T-Sector two where the T-Sector one is considered to be the ground one. Therefore, the variation will be in the T-Sector two only. The T-Sector three is assembled with T-Sector one and, in turn, the variation in T-Sector two and three will be the same. Note that in the model one, presented early, the T-Sector three was assembled to T-Sector two so that the variation in T-Sector three was doubled approximately. By applying such strategy, all T-Sectors are assembled together and, in turn, we have four sub-assembled parts. Next step is by assembling the four groups together consequently one by one. Then, they are assembled with the inner ring at the end.

The steps to do that model in RD&T software are as same steps as in the model one, i.e. create parts, create positioning system, define tolerances, define measures, and analysis.

3.3. MODEL THREE (M3)

This model is the same as model two from the beginning until we get the four-subassembly parts. Instead of assembling these parts consequently one by one, they are assembled with the inner ring directly. The steps to do that model in RD&T software are similar to models one and two.

3.4. MODEL FOUR (M4)

We used here a parallel assembly rules to perform the model, you may see appendix for further details about different assembly rules. In this model, we assemble each T-Sector with the ring. Hence, all T-Sectors are not affected by each other, but only by the inner ring. The steps to do that model in RD&T are the same as the previous models.

3.5. MODEL FIVE (M5)

This model applied the assembly rule stated that as small number of assembly parts as low variation obtained, as explained in the appendix. We considered three T-Sectors as one part called big T-Sector. Hence, the numbers of assembled parts are reduced from thirteen to only five (four big T-Sectors and the inner ring). The tolerance for the big T-Sectors will be the same as one T-Sector (1mm). The big T-Sectors are assembled together consequently, i.e. one by one as model one. It is important to highlight that, reducing the number of assembly parts with the same tolerance value will be more difficult for manufacturing and costly. The steps to do that model in RD&T software are the same as the previous models.

3.6. MODEL SIX (M6)

This model is similar as model five except for that the big T-Sectors are not assembled consequently but in the same way as in model two. In particular, big T-Sector one and big T-Sector two are assembled together with considering big T-Sector one as a ground one. Big T-Sector three is assembled with big T-Sector one. Big T-Sector four is added with big T-Sector three. Finally this group is assembled with the inner ring. The steps to do that model in RD&T software are the same as the previous models.

3.7. MODEL SEVEN (M7)
This model is the same as model six, except for that each big two T-Sectors are assembled together. So we have two identical groups; then they are assembled together and finally with the inner ring. The steps to do that model in RD&T software are the same as the previous models.

3.8. MODEL EIGHT (M8)

This model is the same as model seven except for that each big two T–Sectors are assembled with the inner ring instead of assembling with each other. The steps to do that model in RD&T software are the same as the previous models.

3.9. MODEL NINE (M9)

This model is the same as model six except for that each big T–Sector is assembled with the inner ring directly instead of with each other. The steps to do that model in RD&T software are the same as the previous models.

3.10. MODEL TEN (M10)

After comparing the results of the previous nine models, the best result is shown up with the model four, as it will be shown later. Based on that, we used a different technique in the model four to try to improve results of such model. The technique applied is by using a fixture for assembling. In particular, the inner ring is firstly assembled with the fixture so that we locked its six degrees of freedom. Hereafter, each T–Sector is assembled with the fixture. After assembling all the T–Sectors with fixtures, they are assembled with the inner ring. It is allowed for the T-Sectors to move in the radial direction only in order to make the strut to contact with the ring. In this case, we locked the five degrees of freedom for all the T–Sectors. The steps to do that model in RD&T software are the same as the previous models except for the following couple of points.

- We used 6-direction positioning system to assemble the parts. The positioning systems are applied in case of the positioning planes in perpendicular with each other’s. Each of the six positioning points has an individual positioning plane. The positioning system is defined by six locals and six target located points, just as a 3-2-1 positioning system. In addition to these twelve points, the orientations of the target located planes have to be specified.
- We fixed the tolerance values between all parts to be 1 mm.

3.11. MODEL ELEVEN (M11)

Model ten has the best results, as it will be shown later, but it could not fulfil the requirements. The only way to get the planned tolerance is by changing the tolerance values. So model eleven is the same as model ten but with changing the tolerances several times until getting satisfactory results. The differences between this model and the previous one are as follows.

- We used a tolerance between the strut and the corresponding fixture to be 0.05 mm.
- There is no tolerance between the inner ring and the corresponding fixture.
- The tolerance between inner ring and T-Sectors is about 0.4 mm in the radial direction.
- The tolerance between the outer ring and the T-Sector is placed in the measure points to be about 0.2 mm in the circumstance direction.

3.12. MODEL TWELVE (M12)

This model is the same as model eleven except for changing the place of the positioning system, i.e. handle the parts from other points. The positioning system for model eleven is the best place according to the stability analysis of the software. But we have to consider the tolerance of the thickness of the struts. To avoid the thickness tolerance, it is proposed to handle the struts from other points. Although the new points of that positioning system effect the stability of the parts since each part is more sensitive to variation in this case; however, it is preferable than considering a tolerance in the thickness of the struts, as it will be discussed later. The tolerance values for the inner ring and the outer ring of the T-Sector are the same as model eleven. The only difference is the tolerance of the strut with the fixture, e.g., zero tolerance.

4. Results and discussions

In this section, the results from the twelve assembly models are presented and discussed. The RD&T software is used for analyzing and evaluating the different models. In the following the results are presented firstly and, hereafter discussion of results are introduces.

Results M1

The results of the variation analysis, contribution analysis and stability analysis are as follows. Please note that, for all results, measure 01 is between two T-Sectors in radial direction, measure 02 is between two T-Sectors in circumstance direction, and measure 03 is between T-Sector and the inner ring in radial direction.

- Measure 01 361 mm.
- Measure 02 631 mm.
- Measure 03 258 mm.

Results M2

The results of the variation analysis, contribution analysis and stability analysis are as follows:
Results M3
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 398 mm.
- Measure 02: 582 mm.
- Measure 03: 393 mm.

Results M4
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 109 mm.
- Measure 02: 30 mm.
- Measure 03: 28.9 mm.

Results M5
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 216 mm.
- Measure 02: 355 mm.
- Measure 03: 103 mm.

Results M6
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 247 mm.
- Measure 02: 361 mm.
- Measure 03: 278 mm.

Results M7
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 236 mm.
- Measure 02: 315 mm.
- Measure 03: 76.8 mm.

Results M8
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 245 mm.
- Measure 02: 189 mm.
- Measure 03: 18 mm.

Results M9
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 10.1 mm.
- Measure 02: 8.61 mm.
- Measure 03: 2.27 mm.

Results M10
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 1.12 mm.
- Measure 02: 1.53 mm.

Results M11
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 0.431 mm.
- Measure 02: 0.426 mm.

Results M12
The results of the variation analysis, contribution analysis and stability analysis are as follows:
- Measure 01: 0.441 mm.
- Measure 02: 0.245 mm.

As shown from the above results, using a series assembly method is of inferior quality than a parallel assembly; in particular, tolerance of model one is not as good as model four. Reducing the number of assembly parts with using same assembly scenario and tolerance values can improve the results significantly, see models one and five. On the other hand, reducing the number of assembly parts with same tolerance will be more difficult for manufacturing point of view.

Using mixing scenarios between parallel and series ones are usually better than series one only, you may see for example, models one and three. In case of models one and two, the tolerance of model two is a little greater than that of model one because the assembly in model two makes the parts more sensitive to variation. Accordingly, the series scenario is not always as good as the mixing one but it depends on the mixing scenario itself and the assembly parts as well. Models six, seven, eight and nine are all assembled according to a mixing technique between series and parallel ones. However, the results are different because of the different scenarios only. The models from one to nine show that the best strategy is the parallel one. By applying this strategy using a fixture during the assembly, the results show that assembly with fixtures reduces the sensitivity to variation. Model ten is the best tolerance results among all models (from one to ten) but it is not fulfilling the requirements (the requirements are Measure 01=1 mm and Measure 02= 0.45 mm). So that the tolerance is changed until getting the acceptable limit in models eleven and twelve.

Model eleven is built with tolerance 0.4 mm for inner ring in radial direction, 0.2 mm for outer ring in circumstance direction, and 0.05 mm between fixture and the T-Sectors. The variations in results are 0.431 mm between the T-Sectors in radial direction and 0.426 mm in circumstance direction. Model twelve is built as the same as model eleven except for changing the positioning points of the T-Sector in order to avoid the tolerance between the T-Sector and the fixture. It is built with tolerance 0.4 mm for inner ring in radial direction, 0.2 mm for outer ring in circumstance direction, and no tolerance between fixture and the T-Sectors. The variation in re-
results are about 0.44 mm between the T-Sectors in radial direction and 0.245 mm in circumference direction. As seen from these values, the variation in circumference direction is almost half of radial direction, i.e. 0.2 mm in circumference direction and 0.4 mm in radial direction. The difference between the results of the two positioning systems for models eleven and twelve is big for the measure 02 but small for the measure 01. The reason may refer to the difference for positioning points of the both models. The positioning points for model twelve are not distributed as same as model eleven, so that the measure 01 increases, while the measure 02 decreases.

It is important to clarify that the only difference between model four and ten is the fixture. Model ten uses fixture for assembling and that gives about 2 mm less tolerance than model four. On the other hand, using the fixture increases production costs. If one is not interested in fixture, one can reduce the tolerance values of model four until obtaining the acceptable results. The new tolerance values in this case will be about 0.01 mm between the T-Sectors themselves and 0.005 mm between the T-Sectors and the inner ring; the variations in results, in this case, will be about 0.287 mm between the T-Sectors in radial direction and 0.455 mm in circumference direction. In order to manufacture the parts in such tolerance values, the manufacturing costs will be high. Accordingly, designer should choose between these two strategies.

<table>
<thead>
<tr>
<th>Models</th>
<th>Assembly scenario</th>
<th>Strategy</th>
<th>Results (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model one</td>
<td>- T-Sector connected to the next in one direction</td>
<td>Series assembly</td>
<td>Ms1</td>
</tr>
<tr>
<td></td>
<td>- All T with ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model two</td>
<td>- 3T-Sector together</td>
<td>Series and parallel</td>
<td>398</td>
</tr>
<tr>
<td></td>
<td>- Each 3T-Sector to next</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model three</td>
<td>- 3T-Sector together</td>
<td>Series and parallel</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>- Each 3T-Sector with ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model four</td>
<td>- T-Sector to ring directly</td>
<td>Parallel</td>
<td>3.47</td>
</tr>
<tr>
<td>Model five</td>
<td>- 3T-Sector as one part</td>
<td>Series and parallel with reducing number of parts</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>- Each 3T-Sector to next in one direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model six</td>
<td>- All T-Sector with ring</td>
<td>Series and parallel with reducing number of parts</td>
<td>247</td>
</tr>
<tr>
<td></td>
<td>- 3T-Sector as one part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model seven</td>
<td>- T-Sector in both directions</td>
<td>Series and parallel with reducing number of parts</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>- All T-Sector with ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model eight</td>
<td>- 3T-Sector as one part</td>
<td>Series and parallel with reducing number of parts</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>- Assembly 2 T-Sector by 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model nine</td>
<td>- 3T-Sector as one part</td>
<td>Parallel with reducing number of parts</td>
<td>10.1</td>
</tr>
<tr>
<td>Model ten</td>
<td>- As model four but with fixtures</td>
<td>Parallel</td>
<td>1.53</td>
</tr>
<tr>
<td>Model eleven</td>
<td>- As model ten but with changing the tolerance values</td>
<td>Parallel</td>
<td>0.431</td>
</tr>
<tr>
<td>Model twelve</td>
<td>- As model eleven but with changing the positioning system</td>
<td>Parallel</td>
<td>0.44</td>
</tr>
</tbody>
</table>

5. Summary and conclusions

Geometry-related quality problems, or so called tolerance problems, generated during functional and physical domain of products are often shown up in many industrial processes. This problem is difficult to be recovered since it is shown up during assembly stage, e.g., the parts are already manufactured. The current work aims at presenting a methodology that allows assembly to be evaluated with respect to robustness and geometrical stability during the early stage of the design process. The assembly robustness evaluation can detect design and assembly difficulties that are sensitive to variation and may cause problems later on during production.

In the current study, tail bearing housing of airbus airplane engine, which is manufactured by Volvo Aero Corporation in...
Sweden, is planned to be designed as a number of small parts instead of one large part only; the idea behind this new design is to get better quality and lower manufacturing costs. However, this new design is facing a new challenge regarding the tolerance problem. The aim of the current work is to solve this problem and find out solution(s) with least amount of tolerance. Twelve different assembly models using different strategies are proposed, some of them without using fixtures and some by using fixtures.

Different types of analyses are performed to study and to improve the assembly strategy of the tail bearing housing of the jet engine. In particular, the stability analysis can analyze the general robustness of the design, which is controlled by the positioning schemes. The variation analysis can analyze a variation in critical dimensions (measures) of the design. Finally, the contribution analysis can present a ranked list of all points and tolerances, which contribute to measure variation. The results of these analyses are a very valuable for the assembly sensitivity. Knowledge about assembly sensitivity is important to allocate tolerances with respect to both functionality and cost. Additionally, it is allow in the early stage to predict a dynamic characteristic that effects manufacturing and tolerance to achieve a robust design.

Different assembly rules are discussed in this study, parallel, series and mixing ones. These rules are applied to assembly the tail bearing housing of the aeroplane engine. Twelve different assembly models are introduced using different techniques, such as changing located parts to each other or by using assembly fixtures for positioning of assembly stability, as summarized in Table 2. Models one to ten are built with the same tolerance values for T-Sectors and also for the inner ring (1 mm). The results showed that using a series assembly method is not as good as the parallel assembly one (as in models one and four). Reducing number of assembly parts at same assembly scenarios can improve results (as in models one and five). Using mixing scenarios between parallel and series are usually better than series one only (as in models one and three). However, series scenario is not always inferior than the mixing one but it depends on the mixing scenario itself and the assembled parts. Models six, seven, eight, and nine are all assembled according to mixing between series and parallel strategies; however, results are different due to dissimilar scenarios. The best results (from models one to ten) are shown with model ten but it is not fulfilling the requirements (the requirements are Ms1=1mm and Ms2= 0.4mm, while results of model ten are Ms1=1.53 mm, Ms2 = 1.12 mm). Model ten is built using a parallel scenario and a fixture. To get acceptable results, model eleven is built with tolerance 0.4 mm for inner ring in radial direction, 0.2 mm for outer ring in circumstance direction, and 0.05 mm between fixtures and the T-sectors. The variation in results were about Ms1=0.431 and Ms2= 0.426 mm. Model twelve is built as same as model eleven except for changing the positioning points of the T-Sectors in order to avoid the tolerance between the T-Sectors and fixtures. It is built with tolerance about 0.4 mm for inner ring in radial direction, 0.2 mm for outer ring in circumstance direction, and no tolerance between fixtures and the T-Sectors. The variation in results were about Ms1=0.44 mm and Ms2=0.245 mm in circumstance direction. The variation in circumstance direction (Ms2) is almost half of radial direction (Ms1). Table 3 summarizes the best results models. Finally, one may conclude that RD&T can minimize the developing time and reducing the production cost since there is not adjustments needed during assembly stage. With this methodology, engineers will be able to analyze a wider range of scenarios and, in turn, choosing between them in the early stage of design process. Finally, some hints to use the RD&T properly are summarized in the appendix.

Table 3. Models presented the best results

<table>
<thead>
<tr>
<th>Models</th>
<th>Tolerance (mm)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T-Sector</td>
<td>Inner ring</td>
</tr>
<tr>
<td>Model 10</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Model 11</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Model 12</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

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**Appendix 1**

**Assembly rules**

**1- Rule one**

Generally, a robust design is a design that is insensitive to variation or disturbance. The important performance characteristics of any product are insensitive to manufacturing variation. Figs. 6 and 7 show an example of a non-linear relation between an input parameter, x, and an output characteristic, y. By shifting the nominal value, x₀, the sensitivity Δy/Δx is decreased. The main source of variation considered here is the manufacturing variation. By decreasing the sensitivity of the design, we gain wider tolerances in input parameters, i.e. geometry features may be used. For many cases, these results will be in lower manufacturing costs.

**2- Rule two**

In the theory of axiomatic design, the design activity is described as a mapping between functional requirements (FRs) and design parameters (DPs) and the proper selection of DPs that satisfy FRs. The design equation relates a group of parallel DPs on the same hierarchical level in the assembly structure to their corresponding FRs. Equation 1 describes an arbitrary group of parallel solutions with three DPs and three FRs, as follows.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix} \tag{1}
\]

The coefficients, \(a_{ij}\), represent the partial derivatives, \(\delta FR_i/\delta DP_j\) at any specific design point. The rule two could be divided into two different sub-rules as follows.

**2.1- Rule 2a**

A good, uncoupled design is characterized by the fact that each output is controlled by only one input. This is described by a diagonal design matrix as follows:

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
a_{11} & 0 & 0 \\
0 & a_{22} & 0 \\
0 & 0 & a_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix} \tag{2}
\]

**2.2- Rule 2b**

A decoupled design is an acceptable design that fulfils the independence but must be tuned in a certain order. If per-
formed in the correct order, each FR can be satisfied by its dedicated solution without affecting previously chosen solutions. This is represented by a triangular design matrix, as in equation 3.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

(3)

3. Examples

In order to make previous rules clearer, let us discuss these examples:

3.1. Example One (Rules 1 & 2)

We will use a 2D (2 dimensions) design problem with a beam supported by two supports, $DP_1$ and $DP_2$, as shown in Figure 8. The vertical position of the two end points of the beam is critical for the overall functions. The two functional requirements (position of left end beam and right end beam, i.e. $FR_1$ and $FR_2$) are satisfied by the two supports, $DP_1$ and $DP_2$. Geometrical variation applied to the two supports, $DP_1$ and $DP_2$, is verified by position variations in the two end points, $FR_1$ and $FR_2$.

$$\frac{\Delta FR_{2}}{\Delta DP_1} = \frac{l_3}{l_2}$$

(7)

$$\frac{\Delta FR_{2}}{\Delta DP_2} = \frac{l_2 + l_3}{l_2}$$

(8)

Initially, the position of the supports were chosen such as $l_1 = l_3 = l_2$, resulting the following design equation:

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

(9)

This solution is a coupled solution since the non-diagonal elements are $\neq 0$. It can also be noted that, since the diagonal elements are greater than 1, this solution amplifies the input variation, which is characterized of a sensitive design.

Generally, in order to increase the robustness of the design and to make it uncoupled regarding to rule one, a diagonal matrix with the diagonal elements is preferable to be less than 1. In this case, the design is improved by choosing $l_1 = l_2 = 0$, i.e. moving the supports to the ends of the beam. This results in a fully diagonal matrix with the diagonal elements equal to 1, which is the best possible solution in this case. To improve the design even further, the supports, $DP_1$ and $DP_2$, must be placed outside $FR_1$ and $FR_2$. This may be accomplished either by extending the beam or by moving $FR_1$ and $FR_2$ inside $DP_1$ and $DP_2$.

3.2. Example Two (Rules 2a & 2b)

The locating scheme of the stability matrix describes the influence of each part of the locating scheme on the position of each part in the assembly when a small disturbance is applied to each locating point in its locating direction. Figures 9 and 10 show two types of assemblies and the related stability matrices. In a parallel assembly, the position of each part is controlled by its own locating scheme (P-frame) only, which represents an uncoupled design that is easy to adjust and tune. However, the series assembly represents a coupled design, which is more difficult and time-consuming to adjust and tune. A triangular stability matrix may however be adjusted if done in the correct order, starting with A, then B and so on. Real assemblies are often a mix of the parallel and series cases with involving assembly fixtures as well.

By studying the stability matrix, two positioning aspects may be judged: the degree of coupling and the robustness. Here, a fully uncoupled design is represented by a diagonal matrix. The robustness is judged by studying the values of the matrix elements. A value higher than one means that variation is amplified by the P-frame, whereas a value below one means that the input variation (variation in the contact points) is suppressed by the P-frame. A value equal to zero
indicates that there is no coupling between input and output at all.

\[
\begin{bmatrix}
\text{Position PartA} \\
\text{Position PartB} \\
\text{Position PartC} \\
\text{Position PartD}
\end{bmatrix} = \begin{bmatrix}
X & 0 & 0 & 0 \\
0 & X & 0 & 0 \\
0 & 0 & X & 0 \\
0 & 0 & 0 & X
\end{bmatrix} \uparrow P - \text{frame A}
\]

Figure 9: Parallel uncoupled assembly solution.

\[
\begin{bmatrix}
\text{Position PartA} \\
\text{Position PartB} \\
\text{Position PartC} \\
\text{Position PartD}
\end{bmatrix} = \begin{bmatrix}
X & 0 & 0 & 0 \\
X & X & 0 & 0 \\
X & X & X & 0 \\
X & X & X & X
\end{bmatrix} \uparrow P - \text{frame A}
\]

Figure 10: Serial decoupled assembly solution.

Appendix 2

Hints to use the RD&T properly.

As any new software, it is probable to face some obstacles of using RD&T software for a first time. In the following lines, some hints may be helpful for a new user. These hints we collected while we are using RD&T software for assembling our models of the tail bearing housing of the jet engine.

- Colour is extremely important to see the differences between the variations along the models; the work will be less confusing especially when the model is large.

- It is not possible to create parts by that software in case of complicated drawing. The only available way is to get the drawing as IGES files from CAD system.

- It is not possible to delete any part of the drawing like line or points directly from the screen but you must choose it from the corresponding list. That is not an easy task, especially with a big file and complicated drawing.

- You can’t evaluate the results of the software manually since manual calculation way is totally different from the software. There are considerable reasons for variety of results between manual and the software. These varieties are related to the way of doing the calculations. In particular, the manual way applied only the linear tolerance, i.e. one direction (1D) but the software applied the linear and angular tolerances, i.e. three direction (3D), so that the results are totally different.

- If you want to improve your results, you should change the contact points. If you tried to do so by the way of moving positioning point icon (icon number 23 in the toolbar), the new points may be go inside the part and not in the contact surfaces.

- To use the RD&T efficiently, you should standardize the names of the points, parts, subassemblies, tolerance, measure and positioning schemes. Then it is easier for anyone to use the created model properly.

- In order to obtain a good positioning system, you should widespread it within all the parts.

- When it comes with a large model, a powerful computer is needed to be able to handle the drawings.

- It is possible to start working on a model without knowing the tolerance at the beginning.

- Using many measures increase the calculating time.

- The results are affected by the sequence of assembling, i.e. each order of assembly may give a different result.

- It is suggested to develop this software more. There are some other software can do almost as same function as RD&T like, for example, VSA-3D, while the best software in the market will be the most developed one.

- Finally, it is important to highlight that the RD&T is required for at least two reasons. Firstly, it helps for the direct calculation of tolerance values, which can be plotted as a graph at different colours to clarify the variation of each measure. Secondly, it can perform an analysis to improve the tolerance values. In general, the RD&T can make the job of any designer engineer easi-
er and more efficient. In particular, engineers can design any part and check if your design is robust or not and how much level of its robustness. Accordingly, one obtains a feedback on structural properties early in the design cycle, which enable engineers to optimise their designs.