DFMA analysis of front axle assembly of an excavator

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Abstract. The front axle assembly of a hydraulic excavator consists of front axle, stub axle and thrust bearing. The front axle carries the weight of the front part of the vehicle, as well as to facilitate steering and to absorb shocks due to road surface conditions. In addition, it absorbs torque applied on it due to the braking of vehicle. It is constructed with I-section in center and the ends are made either circular or elliptical. Stub axles are connected to the front axle by king pins. Front wheels are mounted on stub axle’s arrangement for steering. A nominal assembly gap in the front axle assembly has to be maintained for better performance and for easy maneuvering of the vehicle during operation. The gap depends on the model and the assembly dimensions of the front axle, stub axle and thrust bearing. A typical value ranging from 0.1 and 0.5mm is required for one particular model being manufactured by the local industry. It is reported that there are more number of assembly rejections in maintaining the said gap which lead to higher cost and downtime due to rework or interchange of parts. To reduce this, DFMA analysis was carried out using the concept of stack up tolerance to reduce the rejections and improve the performance of front axle assembly, without affecting the manufacturing.

1 Introduction

Excavators are earth movers commonly used for digging, pulling and lifting in construction and agricultural fields. The front axle assembly of an excavator is the most important part in carrying the load. It carries the vertical load of the vehicle including the load it handles. The front axle assembly consists of front axle, stub axle and thrust bearing, which are connected with a king pin and is used for directional control of the vehicle. Similar to any assembly of parts, the front axle assembly components are designed with specific tolerances for manufacturing and clearances are provided based on its functional requirement viz. smooth and ease of steering, up and down movement of the wheels based on earth surface. Due to the cumulative tolerance effect, the gap in the assembly varies widely from a very large clearance to nil clearance or interference. These large bandwidths of the clearance due to the cumulative effect of the tolerance of components vary the performance and life of the assembly. Hence, based on either field study or from the historical data of similar assembly, the tolerance gap width is restricted to certain range. The tolerance gap due to the assembly part plays an important role in avoiding rejections at the assembly stage. The stub axle is assembled with a front axle and a thrust bearing as shown in figure 1. The opening in the stub axle is 177.5 mm (shown as Dim A in fig. 2) with an existing tolerance of +0.5/+0.2mm. It is also further provided with a constraint tolerance from the right and left end of the part as 88.0 ±0.2 and 89.5 ± 0.2 mm respectively.
The part that fits inside the stub axle is the thrust bearing with a width of 23.416 mm (shown as Dim B in fig. 3) with an existing tolerance of ±0.254 mm and front axle with a width of 154 mm. (shown as Dim C in fig. 4) with an existing tolerance of -0.1 / -0.3 mm.

The existing tolerance produced with high percentage of assembled parts with less than 0.1 mm gap and greater than 0.5 mm were high resulting in difficulty in assembly and usage of shim. This research work does a DFMA analysis on the existing tolerances using stack up method to target the assembly tolerance gap between 0.1 mm and 0.5mm to address the above problems identified.
2 Review of Literature

K.W. Chase et al. (1988) discussed about applying worst case and statistical method tolerance analysis and allocation by proportional scaling factor, constant scaling factor and constant precision factor depending on size and using optimization techniques (cost vs tolerance function and lagrange multipliers). They also developed estimated mean shift model and concluded that for advanced analysis and optimization of tolerance allocation methods proper quality control techniques are needed to determine the capability of the process, cost analysis and to model and perform DOE. Fritz Scholz
et al. (1995) discussed various tolerance stack up methods with mathematical analysis. He used inflation factor for various distributions and concluded with risk analysis stating to maintain a risk of 0.27% out of compliance assemblies.

Kenneth W chase (1999) discuss about the tolerance allocation by center of mean, limits for spread and reduction of spread. He also discussed about allocation by scaling, weight factor and least cost optimization. He summarized that the optimization reduced the cost and the modified tolerance after adjusting to conform to process limits, resulted in decrease of cost. Zhinua Zou et al. (2004) researched the gap based approach for mechanical assembly to find out the condition of fits. They developed an algorithm to find out the condition of fit inside the assembly. Each of the fitting condition was provided by a weight factor for linear sum of gap size and geometry parameters. Ragu.K. et al.(2007), analyzed a five stage pump mathematically with monte carlo simulation and probability. They also compared similar results for different number of stages and concluded stating the need to standardize the coupling. Selective assembly was recommended for non standard coupling length.

Mathieu Mansuy et al. (2011) in their research work proposed a new algorithm to express the relationship in linear form between the connecting tolerance and functional conditions with modification coefficient. He concluded that the relationship between a functional condition and the geometric tolerances on different surfaces was linear in worst case tolerance allocation. Jhy-Cherng Tsai et al. (2013) researched by redistribution of tolerance by negative tolerancing. They concluded that by providing negative tolerancing the accumulated tolerance can be constraint for assemblies with more number of parts instead of providing precision tolerance which result in high cost. Mathieu Mansuy et al. (2013) in their paper defined a generic algorithm for analyzing the tolerance of tri-dimensional mechanism. They developed an algorithm to satisfy the analysis of all kinds of tri-dimensional mechanism. Dinesh Shringi et al. (2013) discussed non traditional tolerance stack up conditions for worst case, RSS, spots model and mean shift model for a bearing and shaft assembly. They concluded that the cost for RSS model is less as compared to other models. Yang et al. (2013) analyzed straight built mechanical assemblies using probabilistic approach to analyse the variation on eccentricity of the assembly. They developed linear expressions and analyzed with direct, best and worst built assemblies. These expressions shall be used to rotate and select the orientation that minimize and maximize the eccentricity of the final assembly. Jhy-Cherng Tsai et al. (2015) investigated the effect of grouped random assembly. They concluded that the assembly tolerance are reduced with suitable grouping when the tolerance of set of components are close. They claimed 96% reduction is achieved when the tolerance of two component sets are equal.

Benjamin Schlesih et al. (2016) compared tolerance analysis approach for rigid mechanical models. They concluded that the skin model shapes predicted real assembly characteristics. This model is based on generation and sealing of the work parts which have been deviated from the tolerances and processed by computational geometry algorithm. Gaurav Ameta et al. (2018) analysed by tolerance map (T-Map) which uses the number of points from the size, position, orientation and form of the tolerance. They analyzed tolerance with size, form variation, parallelism and with manufacturing bias to produce probability density function (PDF) on T-maps to classify the possibilities of a feature in its tolerance zone. They concluded that the PDF can be used for tolerance allocation to reduce costs and loosen tolerance.

Satchit Ramnath et al. (2018) in their research compared various tolerance analysis methods applied to complex assembly. They concluded that the T-map model was precisely modeled as compared to Monte-Carlo and VisVSA Model for 3D variations and their interactions.

3 Objective

The existing tolerance resulted in high percentage of parts not falling within the required tolerance gap of 0.1 mm to 0.5 mm. Therefore the objective of this research is aimed to allocate tolerance by tolerance stack up analysis in DFMA to establish the tolerance gap and to increase the probability to
fall between 0.1 mm to 0.5 mm such that 1) interference or difficulty in assembly is avoided due to less gap (less than 0.1 mm) and 2) also to avoid use of shim due to too much gap (greater than 0.5 mm).

4 Methodology

Based on the literature survey and research objectives, the methodology to be adopted for the present research work is shown in Figure 5

1) The existing design and tolerances provided are detailed along with the need/objective of the research. The need raised as the tolerance gap was too low or too high in most of the parts.
2) DFMA analysis carried out on the existing parts to find out the distribution of tolerance with mean and standard deviation
3) With the results of DFMA, Z score and subsequently probability analysis carried out to find the percentage of parts at various values of gaps.
4) The target mean and range of tolerance is determined to fit within a probability of 5% variation
5) From the target mean and range and with probability requirements, reverse calculation was done to find the modified tolerance
6) DFMA analysis carried out on the modified parts to find out the distribution of tolerance with mean and standard deviation
7) With the results of DFMA, Z score and subsequently probability analysis carried out to find the percentage of parts at various values of gaps
8) Above results were compared with the results obtained from existing tolerance analysis (Pt. 3) to confirm the target tolerance gap is met

![Figure 5 DFMA analysis on tolerance stack up of front axle assembly](image)
5 DFMA analysis of the existing tolerance:

The original dimensions are:

Stub axle opening

| Nominal       | 177.5+0.5/-0.2 |
|---------------|----------------|
| From Centerline|                |
| Right Side    | - 88±0.2       |
| Left Side     | - 89.5±0.2     |
| Total         | 177.5±0.4      |

Range of Tolerance

| Nominal       | 177.7 to 178.0 |
|---------------|----------------|
| From Centerline| 177.1 to 177.9 |
| Overall       | 177.1 to 178.0 (min. to max.) |

Mean (Existing Tolerance) (MET): \( (177.1+178.0)/2 = 177.55 \)

Standard deviation (Existing Tolerance) (SDET): 0.150

Assembly

| Front Axle (Nominal) | 153.8 ± 0.1 (154\(^0\).1/-0.3) |
| Thrust Bearing       | 23.416 ± 0.254 |

Nominal assembly dimension (MA): 153.8+23.416 = 177.216

Calculation of Assembly tolerance:

Arithmetic Tolerance:

Tolerance, \( u = \sum u_i = 0.1+0.254 = 0.354 \)

Normal distribution

Tolerance, \( u = \sqrt{\sum u_i^2} = \sqrt{(0.1^2+0.254^2)} = 0.273 \)

Stack up tolerance was evaluated using arithmetic tolerance and normal distribution methods for comparison. The tolerance stack up analysis resulted in a tolerance of 0.354 (sum of tolerances) using arithmetic tolerance method (worst case) and 0.273 using normal distribution method. The overall range of tolerance was from 171.1 to 178.0 mm with a mean of 177.55 mm. The standard deviation of the assembly (SDA) is 0.091, calculated from the stack up tolerance of 0.273 mm from normal distribution.

The normal distribution on the existing stub axle and the assembly of front axle and thrust bearing is shown in figure 6. It is observed from the graph that the mean of assembly (front axle and thrust bearing) is offset to the left of the stub axle by 0.334 mm but the distribution is widely spread gap (standard deviation is high) and therefore it is obvious that the assembly rejections would be more as reported by the industry.
Figure 6 Normal distribution of Assembly – Existing

5.1 Analysis of the Existing Tolerance

Analysis was done to find out the probability at (1) No gap, (2) with 0.1 mm gap and (3) with 0.5 mm gap.

Mean of Existing tolerance (MET) : 177.550
Standard deviation (SD ET) : 0.150

Difference in mean (MD-ET):

1) For No gap : MD-ET (gap=0) = MET-MA(gap=0) = 177.550-177.216 = 0.334
2) For Gap at 0.1 mm : MD-ET (gap=0.1) = MET-MA(gap=0.1) = 177.550-177.316 = 0.234
3) For Gap at 0.5 mm : MD-ET (gap=0.5) = MET-MA(gap=0.5) = 177.550-177.716 = -0.166

Difference in standard deviation (SD-ET):

For no gap, gap at 0.1 mm and gap at 0.5 mm (Same for all 3 values)

\[ S_{D-ET} (gap=x) = \sqrt{(SD_{ET})^2 + (SD_{MA(gap=x)})^2} \]
\[ = \sqrt{(0.091^2 + 0.150^2)} = 0.175 \]
The difference in mean was found to be 0.334, 0.234, -0.166 respectively for above gap levels. The standard deviation is same for all three gap levels which is 0.175.

### 5.2 Calculation of Probability for existing tolerance

The probabilities that the parts not meeting the above three levels of gap (g=0 mm, g=0.1mm and g=0.5mm) were calculated. The Z score \( Z_{ET(g=x)} = \frac{(0-MD_{ET(gap=x)})}{SD_{ET(gap=x)}} \) calculated resulted in values of -1.904, -1.334 and -0.946 for the above gaps respectively. The probability for the corresponding Z score from normal table was 0.028, 0.091 and 0.172 respectively.

The probability of tolerance at Z score from the standard normal distribution table for not maintaining a minimum 0.1 mm gap is 9.1% and for the tolerance exceeding 0.5 mm the probability is 17.2 % which requires usage of shim in the assembly. Also, it was observed that the probability of parts with no gap is 2.8 % (Interference) and therefore those parts are difficult to assemble.

The figure 7 shows the probability in y axis for the specified level of gap in mm in the x axis. We target to bring the probability below 5% for both at less than 0.1 mm and greater than 0.5 mm ie. 95% of the assembly parts shall maintain a minimum gap of 0.1 mm and also with a maximum gap of 0.5 mm.

![Figure 7 Probability of the part not maintaining the specified gap](image-url)

### 6 Determination of Modified Tolerance

Mean Gap Suggested \( (\text{mean of the target gap}): (0.1+0.5)/2 = 0.3 \text{ mm nominal (to maintain a gap of 0.1 mm to 0.5mm)} \)

Nominal Gap to be maintained shall be

\[= 177.216 + 0.3 \text{ (Mean gap)} \]

\[= 177.516 \]

New Nominal Dimension (rounded off for manufacturing) : 177.50
Tolerance to be worked out such that the probability should be \( \leq 0.5 \) or 5% (ie. for gap < 0.1 mm and should be \( \geq 0.95 \) or 95% for gap > 0.5 mm)

Therefore \( Z \) score = -1.645 and 1.645 (from standard normal table) for above conditions

For less than 0.1 mm gap, the difference in mean is 0.184 (177.5-177.316) and the difference in standard deviation = \( \frac{0}{Z \text{ score}} \) = 0.112. Similarly for greater than 0.5 mm gap, the difference in mean is -0.216 (177.5-177.716) and the difference in standard deviation is 0.131. Therefore limiting to the minimum spread, the lower value of 0.112 mm is taken for further calculation, which shall provide even better results for gap greater than 5 mm.

\[
\text{Standard deviation} = \sqrt{((0.112)^2-(0.091)^2)} = 0.065
\]

Modified tolerance taken as 3*SD = 3*0.065 = 0.195 mm (rounded off to 0.2 mm)

Modified tolerance : ± 0.2 mm

Range : 177.300 to 177.700

Reworking new tolerance for Stub axle:

Existing : 177.4 +0.5/+0.2 ie Nominal at 177.85
Modified : 177.3 +0.3/+0.1 ie Nominal at 177.50
Range : 177.4 to 177.6

Both Nominal and Range falling within required calculation limits

From centerline – Nominal : to be maintained the same nominal as 177.5

Therefore centerline to nominal to be reworked for right and left side with a difference of 1.5 mm approximately

\[
\begin{align*}
\text{Right side} &= (177.5-1.5)/2 = 88.0 \\
\text{Left side} &= (177.5+1.5)/2 = 89.5
\end{align*}
\]

Figure 8 shows the existing nominal and right and left side dimensions from centerline. These centerline dimensions were reworked for right and left side with a difference of 1.5 mm between the two.

Right side = (177.5-1.5)/2 = 88.0

Left side = (177.5+1.5)/2 = 89.5
Total = 177.5

Tolerance for Centerline deviations to be fixed such that the deviation should be between 177.3 to 177.7. Since the tolerance range shall be given to individual side, a minimum of 0.1 mm tolerance shall be provided for each half. ie ± 0.2 mm in total

Tolerance range for dimension from centerline is 177.3 to 177.7

7 The DFMA analysis with the modified dimensions are shown below

The modified dimensions are:
- Stub axle opening
  - Nominal: 177.3 ± 0.3
  - From Centerline: Left side - 88 ± 0.1, Right Side - 89.5 ± 0.1
  - Total: 177.5 ± 0.2

Range of Tolerance
- Nominal: 177.4 to 177.6
- From Centerline: 177.3 to 177.7
- Overall: 177.3 to 177.7 (min. to max.)

Mean (Modified Tolerance) (MMT): \((177.3 + 177.7)/2 = 177.50\)

Standard deviation (Modified Tolerance) (SDMT): 0.067

Assembly
- Front Axle (Nominal): 153.8 ± 0.1 (154 ± 0.1/0.3)
- Thrust Bearing: 23.416 ± 0.254
- Nominal assembly dimension. (MA): 153.8 + 23.416 = 177.216

Calculation of Assembly tolerance:
- Arithmetic Tolerance:
  - Tolerance, \(u\) = \(\sum u_i = 0.1 + 0.254 = 0.354\)
  - Normal distribution
    - Tolerance, \(u\) = \(\sqrt{\sum u_i^2} = \sqrt{(0.1^2 + 0.254^2)} = 0.273\)

Stack up tolerance was evaluated using arithmetic tolerance and normal distribution methods for comparison. The tolerance stack up analysis resulted in with a tolerance of 0.354 (sum of tolerances) using arithmetic tolerance method (worst case) and 0.273 using normal distribution method. The overall range of tolerance was from 177.3 to 177.7 mm with a mean of 177.50 mm. The standard deviation of the assembly (SDA) is 0.091, calculated from the stack up tolerance of 0.273 mm from normal distribution.
Figure 9 shows the normal distribution of assembly parts at 0.1 and 0.5 mm gap. Also, it shows the normal distribution of stub axle parts with existing tolerance and modified tolerance. It can be seen that the mean is close to the midway of the 0.1mm and 0.5mm curve as compared to the mean of the existing tolerance and also the standard deviation is much less than the existing tolerance which may lead to better performance of the assembly.

The above graph shows the normal distribution of assembly parts at 0.1 and 0.5 mm gap. Also it shows the normal distribution of stub axle parts with existing tolerance and modified tolerance. It can be seen that the mean is close to the midway of the 0.1mm and 0.5mm curve as compared to the mean of the existing tolerance and also the standard deviation is much less than the modified tolerance.

7.1 Analysis of the modified tolerance

Analysis was done to find out the probability at (1) No gap, (2) with 0.1 mm gap and (3) with 0.5 mm gap.

Mean of Modified tolerance ($M_{MT}$) : 177.500
Standard deviation ($SD_{MT}$) : 0.067

Difference in mean ($MD_{MT}$) :
1) For No gap : $MD_{MT}(gap=0) = M_{MT} - M_{A(gap=0)}$
   $= 177.500 - 177.216$
   $= 0.284$
2) For Gap at 0.1 mm : $MD_{MT}(gap=0.1) = M_{MT} - M_{A(gap=0.1)}$
   $= 177.500 - 177.316$
   $= 0.184$
3) For Gap at 0.5 mm : $MD_{MT}(gap=0.5) = M_{MT} - M_{A(gap=0.5)}$
   $= 177.500 - 177.716$
   $= -0.216$

Difference in standard deviation ($SD_{MT}$):
For no gap, gap at 0.1 mm and gap at 0.5 mm (Same for all 3 values)

$$SD_{MT}(gap=x) = \sqrt{\left(SD_{MT}\right)^2 - \left(\bar{SD}_{A(gap=x)}\right)^2}; (x=0,0.1,0.5)$$
\[ r = \sqrt{(0.0912^2 + 0.0672^2)} = 0.113 \]

The difference in mean is 0.284, 0.184, -0.216 respectively for above gap levels. The standard deviation is same for all three gap levels which is 0.113.

7.2 Calculation of Probability for existing tolerance

The probabilities that the parts not meeting the above three levels of gap (g=0 mm, g=0.1mm and g=0.5mm) were calculated. The Z score \( Z_{MT(g=x)} = \frac{(0- M_{D,MT(gap=x)})}{SD_{MT(gap=x)}} \) calculated resulted in the values of -2.518, -1.631 and -1.915 for the above gaps respectively. The probability for the corresponding Z score from normal table were 0.006, 0.051 and 0.028 respectively.

8 Results and Discussion

The probability for the modified tolerance at Z, from the standard normal distribution table, for not maintaining a minimum of 0.1 mm gap is 5.1% and for the tolerance exceeding 0.5 mm the probability is 2.8 % which requires less usage of shim at present, also the probability of parts with less than 0 gap is almost zero which means none of the assembly parts will result in interference. The probability for the existing tolerance for not maintaining a minimum 0.1 mm gap is 9.1% and for the tolerance exceeding 0.5 mm gap, the probability is 17.2 % which requires usage of shim in the assembly. Also, it was observed that the probability of parts with no gap is 2.8 % (Interference) and therefore those parts are difficult to assemble.

Comparing the results of the existing and modified tolerance it can be clearly noted that due to the modified tolerance the parts not falling within the required tolerance gap of 0.1mm to 0.5mm has reduced by 18.4%, which is a substantial reduction in rejection of parts.

![Figure 10](image-url)

**Figure 10** Probability of the part not maintaining the specified gap

Figure 10 shows the probability along the y-axis for the parts not maintaining the minimum gap specified along the x-axis. It clearly shows that the probability for the modified tolerance is much less than the existing tolerance.
9 Conclusion

By stack up tolerance on existing tolerance and by probability analysis if was deduced that the assembly rejection percentage was higher as reported by the industry. By applying the DFMA analysis to control within 5 percent probability and with reverse calculation the modified tolerance is calculated and with further analysis the following improvements are achieved.

1. The gap variation (maximum to minimum) in the assembly is reduced by 0.100 mm for the nominal dimension and by 0.400 mm for the dimension measured from the center line.
2. The probability for the existing parts that could not be assembled in the first attempt is 2.8%, whereas for the modified tolerance obtained in this research study it is almost reduced to zero percent which reduces improper assembly.
3. The probability of maintaining within the gap range of 0.1 mm to 0.5 mm is reduced by 18.4% which contributed to increased assembly efficiency.
4. The modified design has better interchangeability for parts, easy for assembly and does less usage of shim and in addition none of the randomly selected parts resulted in interference.
5. Based on the analyses, new modified tolerances were derived and it is found that the assembly of the parts is having 5.1 % probability to maintain a minimum gap of 0.1 mm and 2.8% probability exceeding the 0.5mm tolerance. The total probability of not maintaining within the range is 7.9% which is very less compared to the exiting tolerance specifications wherein the total probability is 26.3%. Also, it has a zero percent probability of parts with interference.

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