Teaching Design for Assembly Using Simulation of an Industry Case

by

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Abstract

Industry has consistently identified lack of experience in Design for Assembly (DFA) as one of the key competency gaps among new engineering and engineering technology graduates. This paper describes the development of a teaching aid that introduces DFA in the engineering technology curriculum. The simulation-based teaching aid applies Monte Carlo simulation to model and analyze the assembly process of an industry-based case of automobile torque converter. The analysis uses 2500 virtual torque converter assemblies with random selection of part dimensions. A probability distribution for each dimension of the torque converter is used to represent the variant values. The developed model is capable of evaluating the acceptability of the dimensions and tolerances in the assembly process as well as identifying the critical dimensions which impact the assembly. The purpose of the teaching aid is to assist the students in understanding the relationship between part design and the ease or difficulty of assembling parts. Using a real industry case to teach DFA is important because the case gives the students an appreciation for powerful the DFA can be in performing manufacturing assembly analysis.

Keywords: Design for assembly; Design for manufacturing; Monte Carlo simulation; Tolerance analysis; Tolerance stack; Torque converter.

Notation

S designed gap at the pitch diameter
R_c radius of the spline corner
R_{cp} radius of contact point
R_p radius of pitch circle
R_{min} minor radius of the inner race
W_c spline width at contact point
W_g width of the gap to the adjacent spline
W_{rst} resultant spline width
W_s width of stator spline

h spline surface waviness
α assembly angle
δ difference in angle between components
θ_g gap angle at the contact radius
θ_s spline width angle at the contact radius

1. Introduction

Design for assembly (DFA) is an integrated technique and used widely throughout many large industries. Experience shows that DFA is the key to very significant reductions in overall manufacturing costs. The design for assembly technique involves two important steps: minimization of the number of separate components; and improvement in the assemblability of the components [1]. Nevertheless, DFA was identified as one of the major competency gaps in the supply and demand for engineering and engineering technology education according to the research conducted in 2005 [2]. The survey data suggested that industry would like more emphasis on the DFA competencies: a) identifying part features or characteristics that affect part assembly, b) identifying part features or characteristics that affect part handling and c) using solid modeling software to verify that mating parts will assemble.

Responding to the needs of industry, universities have, over the years, developed undergraduate manufacturing curricula to include DFA topic in the courses of manufacturing processes, process engineering, or CAD/CAM. Despite the importance of hands-on experience on the DFA, most typically manufacturing courses are of a 'show and tell' format where the concept and the benefits of the DFA are described. Some engineering drawings and the DFA guidelines applied to those particular products might be discussed as examples in the lectures. Although much can be learned from the lectures, it is difficult for students to fully understand the relationship between part geometry and the ease or difficulty of assembling a part.

In order to assist the students in thoroughly understanding the DFA and gain hands-on experience, a simulation-based teaching aid is developed. This interactive teaching aid applies Monte Carlo simulation to model and analyze the assembly process of an industry-based case of automobile torque converter. The analysis uses 2500 virtual torque converter assemblies with random selection of part dimensions. A probability distribution for each dimension of the torque converter is used to represent the variant values. The developed model is capable of evaluating the acceptability of the dimensions and tolerances in the assembly process as well as identifying the critical dimensions which impact the assembly. Using a real industry case to teach DFA is important because the case gives the students an appreciation for powerful the DFA can be in performing manufacturing assembly analysis.

2. Tolerance Stack Analysis in Assembly Process

The tolerances are the amount of manufacturing error that a designed part can tolerate and remain reliable and functional. The functional quality of a product assembly is heavily dependent upon one or more critical dimensions of the assembly. These critical dimensions result from the cumulative effect of two or more functional dimensions on individual components. In order to identify the functional dimensions that are affecting a critical dimension, a tolerance analysis has to be conducted. Tolerance analysis is the process of determining the effect that the tolerances on individual manufactured components will have on an assembly of these components. As such, tolerance analysis forms an important link between the design and manufacturing processes to evaluate the acceptability of the dimensions and tolerances in the assembly process as well as identify the critical dimensions which impact the assembly. Therefore one important subset of the DFA is tolerance analysis. Tolerance analysis is a continued focus of the manufacturing industry as it seeks to both improve the quality of its products and produce them with lower cost. Many literatures exist in this field. Hu and Xiong [3] proposed a computer-aided approach of assigning geometric tolerance type and value in assembly. Nogi and Min [4] presented a numbered tree model to optimize the allocated tolerances of all components in an assembly such that all interaction requirements are met. Nogi and Teck [5] developed a mathematical model which allocates the required assembly tolerances to the components. A method for evaluating tolerance stack in using Monte Carlo simulation driven by feature discretization, tooling error analysis, and virtual inspection was proposed by Musa [6].

In practice, the tolerance zones that are applied to assembled component dimensions are usually determined through a tolerance stack analysis. The tolerance stack analysis is a common method for evaluating the conformity of an actual assembled part to a tolerance zone. The tolerance stack is the sum of tolerances of two or more dimensional tolerances. It is often used to determine the minimum and maximum distance between two features of an assembly. Three types of tolerance stack analysis are worst limits analysis, probability stacks or Root Sum Square (RSS), and Monte Carlo simulations [7, 8].

The worst limits analysis is the most popular tolerance stack analysis where the assembly tolerance is determined by summing the component tolerances linearly. Each component dimension is assumed to be at its extreme limits (maximum or minimum limit) simultaneously, resulting in the worst possible assembly limits. It is assumed that the component dimensions can have any value within the tolerance range and the arithmetically stacked tolerances describe the range of all possible variations for the assembly criterion of interest. The pro for a worse limits analysis is that defined component tolerances will always be assembled as long as the manufacturing process controls the dimensions to be within the tolerance limits. The con of the worse limit analysis is that the component tolerances are more restrictive to the manufacturing processes [9]. The manufacturing processes are driven to more expensive solutions to obtain these tighter tolerance limits. The cost to implement these processes and maintain the tooling is more expensive than is needed.

The root sum squared (RSS) is the basic statistical tolerancing scheme. It is assumed that component dimensions vary randomly according to a normal distribution, centered at the midpoint of the tolerance range and with its $\pm 3\sigma$ spread covering the tolerance interval. The tolerance range of the assembly dimension is calculated by the root sum square, i.e. taking the square root of the summation of the square of each component tolerance [10, 11]. For given component dimensions, this kind of statistical analysis typically leads to much tighter assembly tolerances. On the other hand, for a given assembly tolerance, it requires considerably less stringent tolerances for component dimensions, resulting in significant savings in production cost. While the normal distribution is closer to the tolerance distribution for most processes, it does not allow for other types of statistical distributions or variations in the mean value of the distribution. Hence, the variation in the mean value of the distribution is the major concern with RSS [12]. The RSS is mostly used to justify the results of the worst limit analysis [13].

The Monte Carlo method is a stochastic technique based on the use of random numbers and probability statistics to investigate problems. Given a function $F = G(x_1, x_2, \ldots, x_n)$, where $x_1, x_2, \ldots,$ and x_n are random variables with known statistics described by probability density functions (pdfs), Monte Carlo simulation can proceed by sampling from these pdfs. The outcome of these random samplings, F, must be accumulated or tallied in an appropriate manner (usually a histogram) to represent a discrete approximation of F's probabilistic behavior. Note that Monte Carlo simulation is a general tool that can be applied to many engineering or non engineering problems. The Monte Carlo simulation has been applied to tolerance analysis because it permits non-normal distributions as models of component variation [14]. This method can give much better estimates of the number of rejects than simple statistical analysis, when the component distributions are well-known non-normal functions [15]. A complete distribution for each component must be inputted into the assembly equation before the models can predict the resulting assembly distribution and fraction of rejected assemblies. This type of analysis is based on the random selection of dimensions for each component. That is, each proposed dimension and its tolerance distribution are used to define the actual dimension of each component. Components that are outside of the limits cannot be assembled. The advantage of the Monte Carlo simulation is that different tolerance variation distributions can be applied to each dimension. The result is an assembly analysis that imitates the intended manufacturing process and is a more representative assembly variation than either of the other two types of analyses [5].

3. Overview of Torque Converter Assembly

Torque converter is placed between the engine and the automatic transmission and delivers the power from the engine to the transmission unit, as shown in Figure 1 [16]. The torque converter is a hydraulic coupling of rotating speed difference sensitive type that gives and receives the angular momentum of a fluid to transmit torque, where the torque to transmit is automatically determined according to the difference in rotating speed between input and output shafts. The torque converter also replaces the clutch that is required in a manual transmission; this is how an automatic transmission vehicle can come to a stop while still being in gear without stalling the engine. The torque converter also acts as a torque multiplier, or extra gear ratio, to help the car get moving from a stop. In modern day converters this theoretical ratio is anywhere between 2:1 and 3:1. The torque converter absorbs and damps the variation of engine torque or the vibration input from the reduction gear and has a smooth torque transmission characteristic.

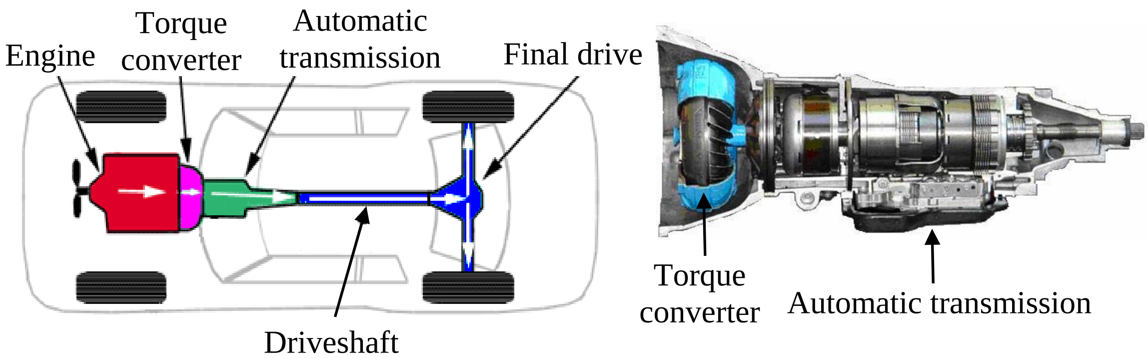

Figure 1: Typical automotive driveline layout [16]

The torque converter consists of three main components - turbine, stator and pump, as shown in Figure 2. The pump is the input element and is driven directly by the engine. The turbine is the output element and is hydraulically driven by the pump. The stator is the reaction (torque multiplying) element. When the pump rotates faster than the turbine, the torque converter is multiplying torque. When the turbine approaches the speed of the pump, the stator starts to rotate with the pump and turbine. When this occurs, torque multiplication stops and the torque converter functions as a fluid coupling. A lock-up clutch is located inside the torque converter assembly as a mechanical engagement between the engine and transmission to provide quicker vehicle shift response and greater fuel economy. The lock-up clutch consists of two elements - the piston/clutch material and the damper. The piston/clutch/damper assembly is splined to the converter element which drives the transmission gear box. The torque converter has many other components such as the one-way clutch, bearings, o-ring seals and a stator side-plate. These components are essential to ensure the proper function of the torque converter but act in a supporting role to the more important pump, stator and turbine.

An important task in product design is tolerance allocation that tolerances must be distributed or allocated among the individual component dimensions in some rational way such that the product can be produced economically and functions properly. The allocation of tolerances among the components of a mechanical assembly can significantly affect the resulting manufacturing cycle time and costs [17]. Assembly cycle time of the torque converter is a major concern in the high volume production line. A tight fit between the components results in more variation in assembly time and vice versa a lose fit reduces the variation in assembly time. The torque converter assembly is especially difficult because the mating of the splines is a blind assembly. Therefore the assembly process might need manual aid in an additional step which increases assembly time.

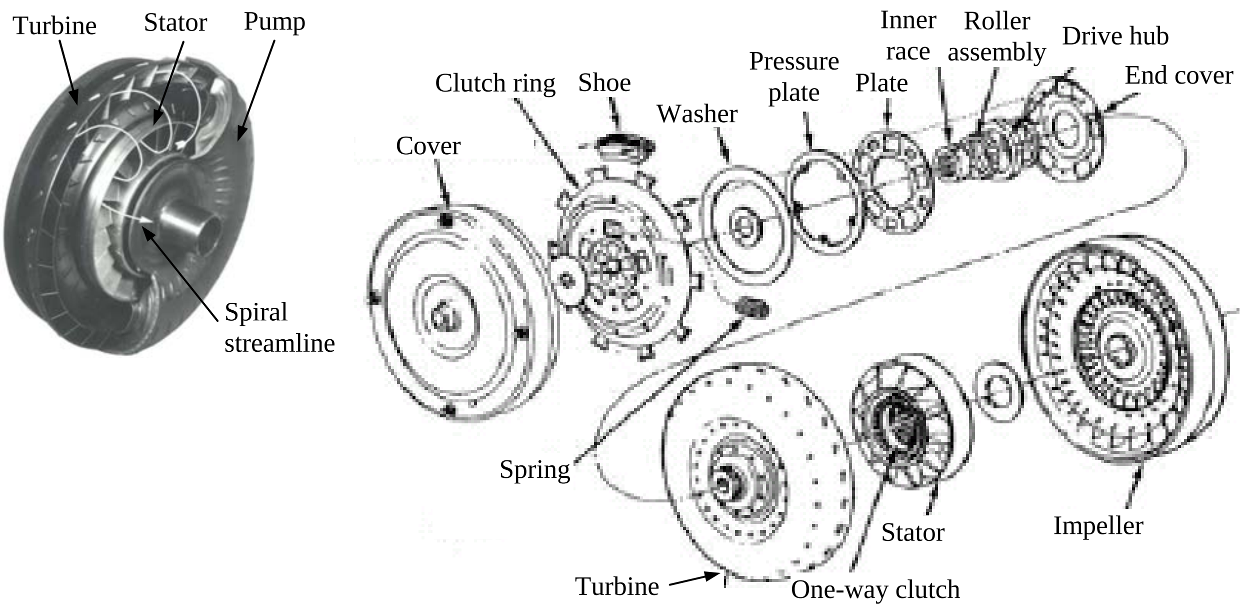

Figure 2: Typical assembly of automotive torque converter

4. Application of Monte Carlo Simulation in Torque Converter Assembly

Monte Carlo simulation is a random number based method for performing assembly tolerance analysis. The manufacture of an assembly is simulated, for example, by creating a set of component dimensions with small random changes to simulate natural process variations. Next, the resulting assembly dimensions are calculated from the simulated set of component dimensions. The numbers of rejects that fall outside the specification limits are then counted. These three steps are illustrated in Figure 3. The Monte Carlo analysis is used to understand tolerance allocations and sensitivity.

The computations used in this project were accomplished with a spreadsheet in Microsoft Excel add-in program [18]. Although asymmetrical tolerance intervals occur in practice, they are usually not discussed much in the literatures. This developed teaching aid thus focused on the symmetric case. The analysis uses 2500 virtual torque converter assemblies with random selection of part dimensions. As shown in Figure 3, a probability distribution for each dimension on the torque converter is used to represent the variant values.

As previously mentioned, the functional quality of a product assembly is heavily dependent upon one or more critical dimensions of the assembly. In the torque converter assembly process, the interference between the stator shaft and the roller clutch inner race has been identified by the assembly plant as the critical area where assembly problems frequently occur. Therefore the evaluation of assembly capability is based on whether assembly will occur by the direct insertion of the roller clutch inner race into the stator shaft without an additional step. The acceptable dimensions and tolerance allocations are based on those assemblies that require no additional operations. All of the dimensions that dominate the interface between the roller clutch inner race and the stator shaft are taken into account in the assembly simulation. Most of the linear dimensions are assumed to have standard normal distribution with 99.73 % of the components within the specification limits. The angular dimensions of the stator shaft spline and inner race spline are considered to have a uniform distribution. Alignment of the splines during initial assembly is the major consideration and several assumptions are made to simplify the analysis: homogeneous of spline geometry, concentricity of all rotating parts, and frictionless between all parts.

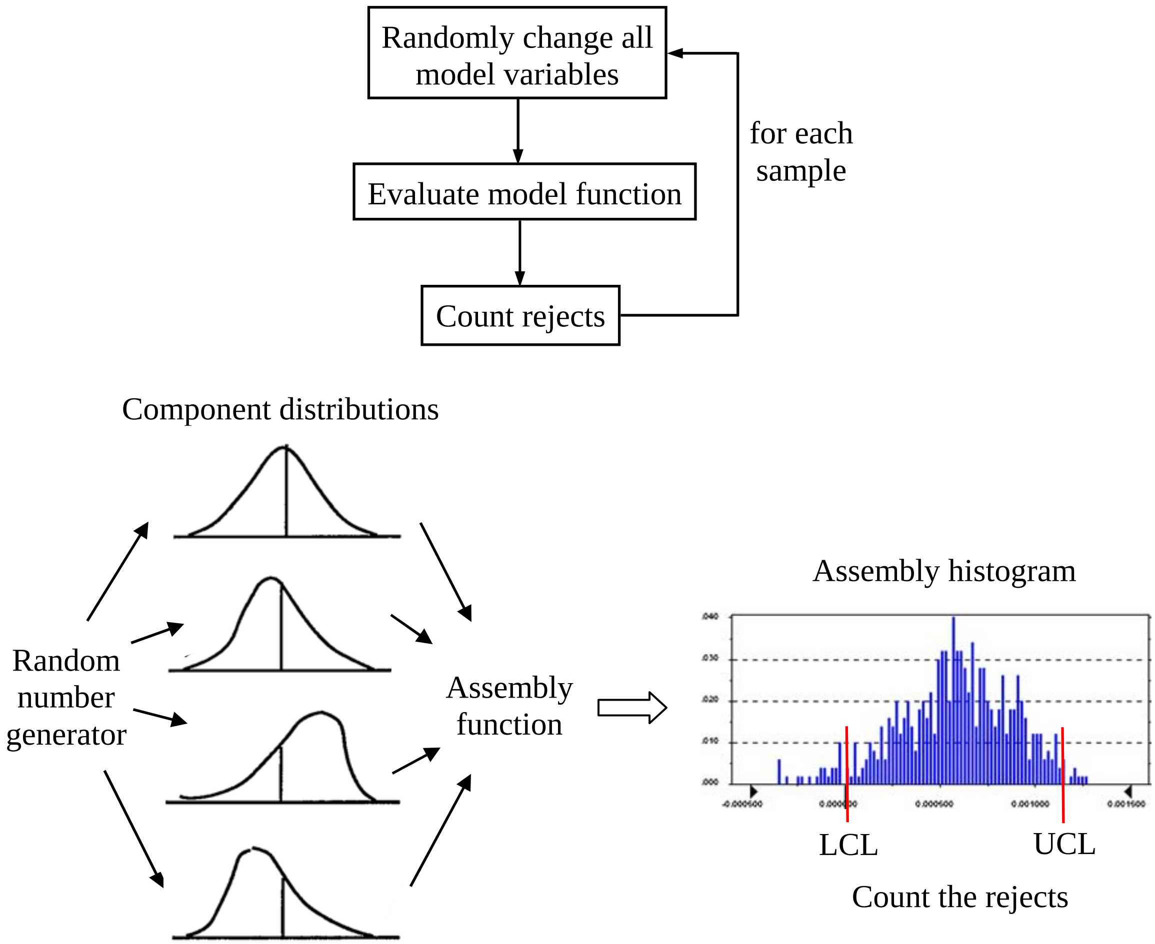

Figure 3: Steps of Monte Carlo simulation

The purpose of lead chamfer angles on the splines is to adjust insertion of two non-concentric parts in assembly process. The lead chamfer angles on the splines are respectively 53 and 32 degrees on the roller clutch inner race and stator shaft. The difference of theses two chamfer angles results in an initial contact near the inner race (minor diameter) of the splines, as shown in Figure 4. The actual contact point also depends on several dimensions: the minor diameter of the inner race (internal splines), the corner radius of the splines, and the angle of the spline face. As shown in Figure 5, the radius at the contact point of two splines is defined as:

$$R_{cp} = R_{min} + R_c\,(1\text{- } sin\ 32°) \tag{1}$$

where R_{cp} is the radius at the contact point, R_{min} is the minor radius of the inner race, and R_c is a radius of the spline corner.

The gap width of the adjacent splines in the roller inner race, W_g, depends on the location of contact point on the corresponded splines of the roller and stator shaft. This width must be converted to the location of the contact point. Since each spline face is treated separately, the resultant space is twice of the calculated value as:

$$W_g = S + 2\,(R_p – R_{cp})(tan\ 32°) \tag{2}$$

where S is a designed gap at the pitch diameter of the roller inner race and R_p is the radius of pitch circle. The spline width at the contact point on the stator shaft, W_c, is determined in the similar manner as:

$$W_c = W_s + 2\,(R_p – R_{cp})\,(tan\ 32°) \tag{3}$$

where W_s is the width of the stator splines.

A further consideration is to take machined surface-quality geometrical parameter into account. The external splines on the stator shaft are normally produced by the hobbing process which generates the waviness on the splines surfaces. The surface waviness occupies an intermediates position between surface roughness and deviations of shape. The waviness on the spline face can affect the ability of assembling the stator shaft. To take this effect into account, the waviness is subtracted from the spline width at contact (W_c) on each side of the spline. Therefore, the resultant spline width in the stator shaft is defined as:

$$W_{rst} = W_c – 2*h \tag{4}$$

where W_{rst} is the resultant spline width and h is the surface waviness in the stator shaft. The waviness occurs like a spiral along the axis of the shaft as shown in Figure 5. Any position from the peak to the valley can be contacted during assembly process. The contact area occurred on the valley is more likely than the peak, meaning that possibility of getting a valley verses a peak is not a normal distribution. However, the value of the waviness is assumed to be a normal distribution to simplify the analysis.

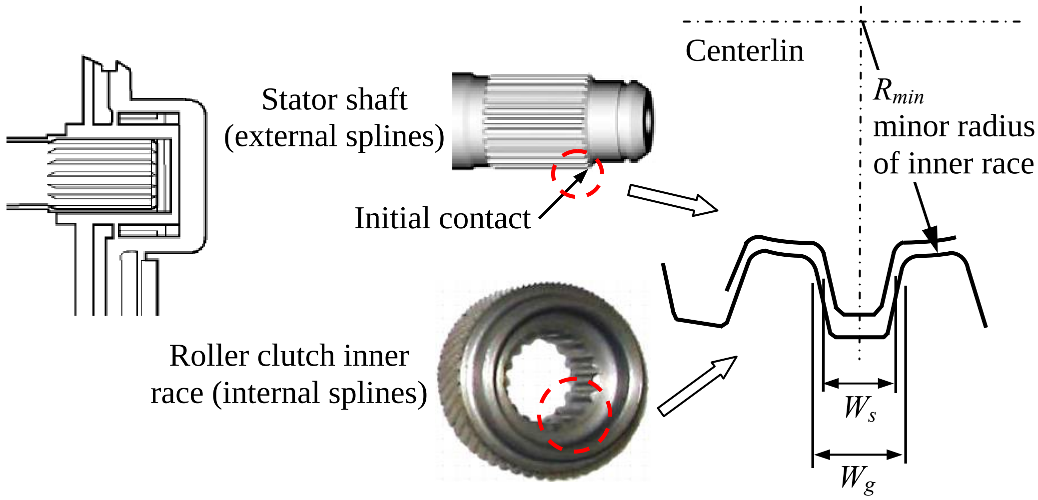

Figure 4: Relationship of stator shaft splines and the roller clutch inner race splines

The angular position of the stator shaft relative to the inner race can be referred to an angle formed by the centerlines of two adjacent splines. For a stator shaft has 25 splines, the angle is represented in Equation (5).

$$\alpha = 360^\circ / 25 \text{ splines} = 14.4^\circ / \text{spline} \tag{5}$$

where α is an assembly angle. A uniform distribution is used in the analysis because there is an equal probability of selecting any of the angles. This is the major difference comparing to other variable distributions. The ability to assemble the torque converters depends upon placing the stator spline in the space of the inner race. To determine whether the assembling has occurred, the angle formed by the thickness of the spline at the contact point is taken into calculation as:

$$\delta = \theta_g - \theta_s + \alpha \tag{6}$$

where δ is the difference in angle between the components, θ_g is the gap angle at the contact radius, and θ_s is the spline width angle at the contact radius. The inner race gap and stator shaft spline angles are calculated from the spline variables. The value of angle δ is used to determine whether the components will be assembled. If the angle δ is equal to or greater than zero, the components can be assembled. In contrast, the components will have interference and cannot be assembled if the angle δ is negative.

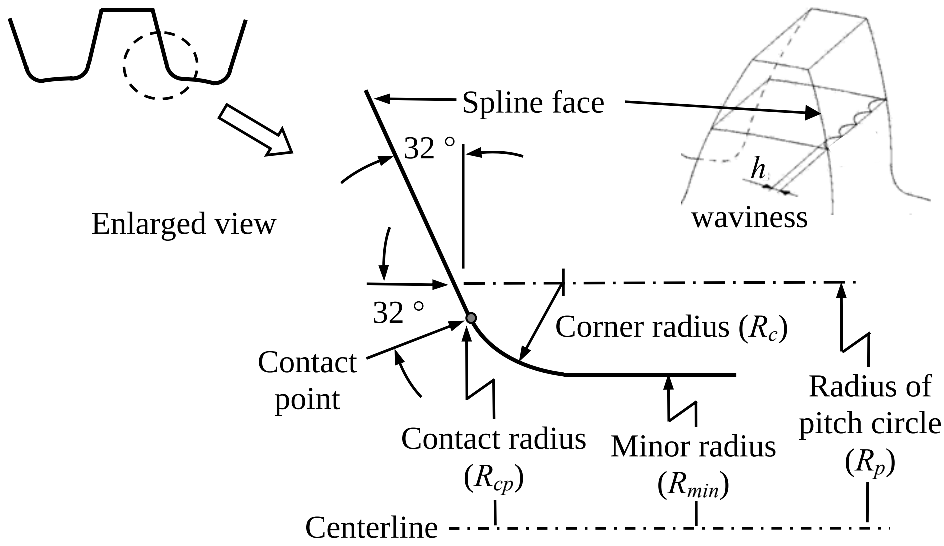

Figure 5: Relationship of contact point to dimensions on the inner race

5. Simulation Results

The application of Monte Carlo simulation is to randomly select a specific dimension from the range of possible dimensions for each variable. The simulation results listed in Table 1 to 4 are examples of 10 assemblers out of the 2500. In each table, each column represents a variable or the calculated result. The second column is the gap width to the adjacent spline in the roller inner race (W_g). Column seven is the resultant spline width (W_{rst}) of mating stator shafts. The last column shows the fraction of accepted assemblies that represents the proportion of production without additional manual aid operation. The first analysis is a baseline that includes all of the component dimensions except waviness. The effect of the waviness is added for the other analyses.

The simulation result of assembling 2500 of the inner races and stator shafts is shown in Table 1 where the acceptance rate is 81.4%. This baseline analysis treats the assembly angle (α) as a constant zero. The 3σ normal distribution on seven dimensions will ideally make 98.125 % acceptance ($.9973^7$=.98125). The 81.4% of the paired components that assembled is used as the upper limit for the other analyses. Any modification to the components should not result in the percent of assemblies that exceed 81.4%. Table 2 shows the results including the assembly angle α as a variable. The number of component pairs that can be assembled decreases to 30.6%. The drop from 81.4% is specifically due to the potential of the overlap on splines. The ideal assembled percent dropped slightly to 97.86% (from 98.125%) because the number of variables that are being analyzed increased by one (from seven to eight). Table 3 shows the results considering the surface waviness of the splines on the stator shaft. The effect of waviness increases the probability of assembly by 0.8% (30.6% to 31.4%) and the ideal assembled percent dropped to 97.60% (from 97.86%) because one more variable is added (from eight to nine).

The designed gap width at the pitch diameter (*S*) is 2.05 mm. Table 4 shows the simulation results with an increase in the *S* to its maximum allowable value (2.81 mm). With the increase in *S*, the percent of assembled component pairs increases to 48.5%. Based on the assembly validation (81.4% assembly rate) and the analysis of a larger gap width on the inner race (48.5% assembly rate), approximately 60% of the production assemblies do not require any type of assembly aid. Forty percent require additional aids such as removal and re-installation of the torque converter, rotation of the converter during assembly, or rocking of the torque converter while it is sitting on the stator shaft.

Table 1. Sample simulation results of baseline assembly

R_p	W_g	W_s	h	W_{rst}	θ_g	θ_s	α	δ	accept	% assembled
18.2961	2.7926	2.3330	0	2.7117	7.87	7.78	0	0.09	yes	81.4% (98.125% ideal value)
18.2965	2.9202	2.3704	0	2.8865	8.45	8.44	0	0.01	yes	
18.4634	2.9649	2.3282	0	2.9264	8.47	8.52	0	-0.05	no	
18.2251	2.9280	2.3844	0	2.7982	8.38	8.12	0	0.26	yes	
18.2613	2.7689	2.2708	0	2.6804	7.81	7.70	0	0.11	yes	
18.2990	2.9925	2.3121	0	2.7315	8.57	7.86	0	0.71	yes	
18.3614	2.8824	2.3555	0	2.8246	8.18	8.17	0	0.01	yes	
18.3764	2.9371	2.3372	0	2.8545	8.38	8.29	0	0.09	yes	
18.2821	2.8843	2.3615	0	2.7737	8.20	8.01	0	0.19	yes	
18.2729	2.8377	2.3358	0	2.7863	8.06	8.08	0	-0.02	no	

Table 2. Sample simulation results including the assembly angle

R_p	W_g	W_s	h	W_{rst}	θ_g	θ_s	α	δ	accept	% assembled
18.2961	2.7926	2.3330	0	2.7117	7.87	7.78	-6.9323	-6.8423	no	30.6% (97.86% ideal value)
18.2965	2.9202	2.3704	0	2.8865	8.45	8.44	0.7213	0.7313	yes	
18.4634	2.9649	2.3282	0	2.9264	8.47	8.52	-5.9675	-6.0175	no	
18.2251	2.9280	2.3844	0	2.7982	8.38	8.12	-1.0056	-0.7456	no	
18.2613	2.7689	2.2708	0	2.6804	7.81	7.70	-0.2990	-0.1890	no	
18.2990	2.9925	2.3121	0	2.7315	8.57	7.86	1.8350	2.5450	yes	
18.3614	2.8824	2.3555	0	2.8246	8.18	8.17	-1.2180	-1.2080	no	
18.3764	2.9371	2.3372	0	2.8545	8.38	8.29	-3.7727	-3.6827	no	
18.2821	2.8843	2.3615	0	2.7737	8.20	8.01	-0.4755	-0.2855	no	
18.2729	2.8377	2.3358	0	2.7863	8.06	8.08	2.3274	2.3074	yes	

Table 3. Sample simulation results including waviness of the splines on the stator shaft

R_p	W_g	W_s	h	W_{rst}	θ_g	θ_s	α	δ	accept	% assembled
18.2961	2.7926	2.3330	2.102e-04	2.7113	7.87	7.78	-6.9323	-6.8333	no	31.4% (97.60% ideal value)
18.2965	2.9202	2.3704	2.993e-03	2.8805	8.45	8.44	0.7213	0.7663	yes	
18.4634	2.9649	2.3282	5.964e-03	2.9145	8.47	8.52	-5.9675	-5.9825	no	
18.2251	2.928	2.3844	4.033e-03	2.7901	8.38	8.12	-1.0056	-0.7106	no	
18.2613	2.7689	2.2708	2.766e-03	2.6749	7.81	7.70	-0.2990	-0.1540	no	
18.2990	2.9925	2.3121	2.216e-03	2.7271	8.57	7.86	1.8350	2.5800	yes	
18.3614	2.8824	2.3555	5.345e-03	2.8139	8.18	8.17	-1.2180	-1.1730	no	
18.3764	2.9371	2.3372	3.928e-03	2.8466	8.38	8.29	-3.7727	-3.6477	no	
18.2821	2.8843	2.3615	3.557e-03	2.7666	8.20	8.01	-0.4755	-0.2505	no	
18.2729	2.8377	2.3358	5.261e-03	2.7758	8.06	8.08	2.3274	2.3424	yes	

Table 4. Sample simulation results with a larger designed gap width

R_p	W_g	W_s	h	W_{rst}	θ_g	θ_s	α	δ	accept	% assembled
18.2961	2.7926	2.3330	2.102e-04	2.7113	7.87	7.78	-6.9323	-4.2733	no	48.5% (97.60% ideal value)
18.2965	2.9202	2.3704	2.993e-03	2.8805	8.45	8.44	0.7213	1.6933	yes	
18.4634	2.9649	2.3282	5.964e-03	2.9145	8.47	8.52	-5.9675	-5.0555	no	
18.2251	2.9280	2.3844	4.033e-03	2.7901	8.38	8.12	-1.0056	0.2164	yes	
18.2613	2.7689	2.2708	2.766e-03	2.6749	7.81	7.70	-0.2990	0.7730	yes	
18.2990	2.9925	2.3121	2.216e-03	2.7271	8.57	7.86	1.8350	3.5070	yes	
18.3614	2.8824	2.3555	5.345e-03	2.8139	8.18	8.17	-1.2180	-0.2460	no	
18.3764	2.9371	2.3372	3.928e-03	2.8466	8.38	8.29	-3.7727	-2.7207	no	
18.2821	2.8843	2.3615	3.557e-03	2.7666	8.20	8.01	-0.4755	0.6765	yes	
18.2729	2.8377	2.3358	5.261e-03	2.7758	8.06	8.08	2.3274	3.2694	yes	

The simulation results indicate that the ability to assemble a torque converter is dominated by the width of the spline root on the stator shaft and the design gap width at the tip of the inner race spline. The critical areas are near the minor diameter of the splines on each component. The surface waviness of the stator shaft does not affect the ability of assembling. However, a large surface waviness might increase the reject rate on the assembly line. It might conclude that approximately 60% of the production assemblies of the torque converters do not require any type of additionally manual aid when a maximum allowable gap width on the inner race is designed. The remaining 40% require an additional manual aid step in the assembly process. The proposed method is basic a two-dimensional model because symmetric tolerances are assumed for all the components that also have the same centerline. Misalignments of these components may occur in the assembly as asymmetrical tolerances present. The misalignments induce other dimensional errors which becomes a three-dimensional problem.

6. Course Outcomes Assessment

The Engineering Technology Division within the College of Engineering at the Wayne State University offers six distinct upper-division programs, all leading to BS degrees, namely: Computer Technology, Electrical/Electronic Engineering Technology, Electromechanical Engineering Technology, Mechanical Engineering Technology, and Manufacturing/Industrial Engineering Technology (MIT). The MIT3600 course, Process Engineering, is one of the elective courses in the program. This course focuses on the processing functions, methods of manufacturing analysis, manufacturing sequence, mechanization, selection of tooling and equipment, and planning the process of manufacture. The topics of DFA and DFM are discussed in the MIT3600.

The developed DFA teaching aid was implemented in the MIT3600 course in the Winter term 2008. Evaluation was carried out in the form of end-of-semester student surveys in which students were asked to rate if they agreed that they had achieved the specified course outcomes. The results of the surveys are shown in Table 5 below. There were 10 course outcomes (listed in the sixth column) and students indicated their response by selecting from five options: Strongly Agree (SA), Agree (A), No Opinion (NO), Disagree (DA), or Strongly Disagree (SD). On the right hand side of the Table, results for SA and A are aggregated under YES and the results for DA or SD are aggregated under NOT; giving a quick indication of whether the learning outcomes had been met or not. A threshold score of 75% was set to indicate an acceptable level of performance.

Table 5. MIT 3600 course outcomes assessment in Winter term 2008

SA	A	NO	DA	SD	MIT 3600 Course Outcomes	YES	NOT
8	7	0	0	0	1. Apply logical design of a manufacturing process plan	100%	0%
8	6	1	0	0	2. Examine methods of manufacturing analysis and manufacturing sequence	93%	0%
8	5	2	0	0	3. Plan and analyze part design for productivity	87%	0%
9	4	2	0	0	4. Analyze tolerance charting in part design	87%	0%
7	7	1	0	0	5. Recognize and apply Design for Assembly (DFA) and Design For Manufacturing (DFM)	93%	0%
7	5	2	1	0	6. Perform manufacturing process planning of a given part	80%	7%
9	4	1	1	0	7. Analyze and improve manufacturing processes	87%	7%
8	6	0	1	0	8. Select the optimal manufacturing equipment	93%	0%
8	7	0	0	0	9. Perform analysis and selection of cutting tools, coolants, jigs & fixtures, and support systems.	100%	0%
12	3	0	0	0	10. Communicate effectively in oral and written formats.	100%	0%

The results of outcomes 4 and 5 are related to the tolerance analysis and DFA. In the earlier evaluation (Winter term 2007), there was concern about outcomes 4 and 5 that fell below the threshold and especially for outcome 5 with a 25% negative rating. After the implementation of the developed DFA teaching aid in the Winter term 2008, a 93% level of student satisfaction with their course experiences in the DFA was obtained, as indicated in Table 5. The results also indicate that the students met the desired level of performance in all the course outcomes.

7. Conclusions

DFA is an integrated technique and used widely throughout many industries. Experience shows that DFA is the key to very significant reductions in overall manufacturing costs. However, industry has consistently identified lack of experience in DFA as one of the key competency gaps among new engineering and engineering technology graduates. Although undergraduate manufacturing curricula has included DFA topic, it is difficult for students to fully understand the relationship between part geometry and the ease or difficulty of assembling a part. This paper describes the development of a teaching aid that introduces DFA in the engineering technology curriculum. The simulation-based teaching aid assists the students in thoroughly understanding the DFA and gain hands-on experience on the assembly process of an industry-based case of automobile torque converter.

This interactive teaching aid applies Monte Carlo simulation to model and analyze the assembly process of an industry-based case of automobile torque converter. The analysis uses 2500 virtual torque converter assemblies with random selection of part dimensions. A probability distribution for each dimension of the torque converter is used to represent the variant values. The developed model is capable of evaluating the acceptability of the dimensions and tolerances in the assembly process as well as identifying the critical dimensions which impact the assembly. Using a real industry case to teach DFA is important because the case gives the students an appreciation for powerful the DFA can be in performing manufacturing assembly analysis. The result of the course outcomes assessment indicates a high level of student satisfaction with their course experiences in the DFA.

8. References

1. Boothroyd, G. (1987). "Design for assembly- the key to design for manufacture," *International Journal of Advanced Manufacturing Technology*, 2(3), 3-11.
2. Eggert, R. (2006). "Design for manufacture and assembly: a survey of desired competencies," *Proceedings of 2006 ASEE Annual Conference*, 2006-653.
3. Hu, J. and Xiong, G. (2005). "Dimensional and geometric tolerance design based on constraints," *Int. J. Advanced Manufacturing Technology*, 26, 1099-1108.
4. Nogi, B. and Min, O. (1999). "Optimum tolerance allocation in assembly," *Int. J. Advanced Manufacturing Technology*, 15, 660-665.
5. Nogi, B. and Teck, O. (1997) 'A tolerancing optimization method for product design', *Int. J. Advanced Manufacturing Technology*, Vol. 13, pp.290-299.
6. Musa, R.A., Huang, S.H. and Rong, Y.K. (2004). "Simulation-based tolerance stackup analysis in machining," *Transactions of NAMRI/SME*, 32, 533-540.
7. Scholz, F. (1995). "Tolerance stack analysis methods," *Boeing Information & Services*, Seattle, WA, USA.

8. ASME Y14.5.1M (1994). "Mathematical definition of dimensioning and tolerancing principles," *ASME*, New York, USA.
9. Chase, K.W. (1988). "Design issues in mechanical tolerance analysis," ASME, *Manufacturing Review*, 1(1), 50-59.
10. Mansoor, E.M. (1963). "The application of probability to tolerances used in engineering design," Institution of Mechanical Engineers, *J. Engineering Manufacture*, 178(1), 29-51.
11. Parkinson, D.B. (1984) "Tolerancing of component dimensions in CAD," *Computer-Aided Design*, 16(1), 25-32.
12. Greenwood, W.H. and Chase, K.W. (1987). "A new tolerance analysis method for designers and manufacturers," ASME transactions, *J. Engineering for Industry*, 109, 112-116.
13. Spotts, M.F. (1978). "Dimensioning stacked assemblies," *Machine Design*, 50(9), 60-63.
14. Chase, K.W. and Parkinson, A.R. (1991), "A survey of research in the application of tolerance analysis to the design of mechanical assemblies," *Research in Engineering Design*, 3, 23-37.
15. Rubinstein, R. (1981). *Simulation and the Monte Carlo method*, John Wiley, New York, USA.
16. http://www.familycar.com/transmission.htm/. Accessed April 6, 2009.
17. Muthu, P., Dhanalakshmi, V. and Sankaranarayanasamy, K. (2009). "Optimal tolerance design of assembly for minimum quality loss and manufacturing cost using metaheuristic algorithms," *Int. J. Advanced Manufacturing Technology*, DOI 10.1007/s00170-009-1930-1.
18. Barreto, H. and Howland, F.M. (2008). *Installing and using the Monte Carlo simulation Excel Add-in*, Wabash College, Crawfordsville, Indiana.