Product Design Variables Optimization using Design for Six Sigma (DFSS) Approach

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Abstract: To achieve customer satisfaction and product excellence many quality programs such as quality circles, Kaizen, TQM, Design for Six Sigma have been developed & practiced. Most of quality techniques are focused on production and shop floor related activities. It is now realized that improving a product in design phase is much easier and controllable than attempting to make improvements after it is in production phase. This paper explores the opportunities of optimizing Design for Six Sigma (DFSS) approach in product development particularly to product design at early stage of the design process. A mechanical product (bolted joint) has been selected to carryout analysis and seeking optimum design values. Once the controllable variables are established, then the process of optimum seeking is carried out using Monte Carlo Simulation. It is found that there is no need to tighten the tolerances of inputs as conventional method practiced is worst case which resulted in tighter tolerances causing additional costs with no value addition to the product. The key input means and standard deviations have been optimized to obtain critical to quality (CTQ) characteristic mean, close to target values and its variation within acceptable limits. The decision variables with optimization runs resulted optimize decision variables that improve the proposed design C_P & C_PK.
[Mirza Jahanzaib, Syed Athar Masood, Omer Jamil, Khalid Akhtar. **Product Design Variables Optimization using Design for Six Sigma (DFSS) Approach.** *Life Sci J* 2013;10(1):57-63] (ISSN:1097-8135). http://www.lifesciencesite.com. 9

Keywords: Critical to Quality; Design for Six Sigma; Improved Design Process; Optimum seeking in design.

1. Introduction

The product development process starts from idea generation and is a sequential process that includes steps or stages to realize a product from the stage of idea generation to its production and launch [1]. Design process is an important part of the product development process as decisions made have the greatest impact on product quality and cost. It is observed that if errors not addressed early, more costly changes are required later in the product development process [2]. It is needed to integrate quality concepts at the design stage of product development process to avoid design mistakes and late design changes in the product development process, thus enabling shorter time to market, cheaper & quality products. Deductive approach to research is utilized in this research work. It starts with the extensive study of the existing theories available in the areas of product design and development, quality, six sigma & design for six sigma [3, 4]. An empirical study is conducted by taking a design project from a local mechanical design company; the empirical finding extracted from study is then analyzed. Application of DFSS quality tools at each stage of the design process has been assessed. The proposed model suggested has improved the existing design process which is explored in the following section as a case study [5].

2. Methodology of Research

The case company selected is engaged in the design of mechanical products for process industry. A separate department of quality is dedicated to check the quality of products. Every effort is made to reduce the errors and defects of products during the process. Due to large variety of products manufactured in shorter time, there is a need to control the products quality at the early stage of design. Therefore presented work is a real case study which has been implemented in the company to use quality tools at the design stage named "Design for Six Sigma". The nature of the complaints is different as they are occurring from different sources. For example feedback from manufacturing includes, product designs are too complex to manufacture, unnecessarily tight tolerances, feedback from assembly floor includes, interferences in parts even made to specifications, difficult assembly & disassembly etc. Feedback from end users include, malfunctioning of products. Screening investigations have shown that most of above mentioned problems arise from the inappropriate designs. Non- conforming to quality in the form of rework and scrap at manufacturing and assembly floor resulted costly operations and lost customers.

Organizations around the world have realized huge returns on their investment in Six Sigma by eliminating waste and defects. However Six Sigma methods cannot repair defective requirements or inherently defective designs [6]. DFSS initiatives overcome this limitation by focusing on the development of new products and processes. By incorporating DFSS tools into product development, companies can invent, develop, and launch new products that exceed customer requirements for performance, quality and cost. By selecting Critical to Quality characteristics (CTQs) based on customer requirements, and by focusing development activity on those CTQs, DFSS closes the defect gap. When DFSS works well, product features & characteristics measured and controlled by the developers are the one most important to the customer. IDOV is a known design for six sigma methodology. The IDOV acronym represents DFSS implementation phases as Identify, Design, Optimize and Validate [7]. It has four phases: Phase 1: Identify the product characteristics and feature that satisfy customer needs, Phase 2: Design the product that meets customer requirements and possess key product characteristics, Phase 3: Optimize key product output characteristics, Phase 4: Validate that product key output characteristics conform to customer requirements.

Design for Six Sigma process start with the identify phase to identify customer and product functional requirements. This is started with the voice of customer which is the first step in proposed DFSS process. Product requirements have been obtained in the form of functional requirements, some of them as technical parameters are summarized. Outer Diameter of Pipes to be joined = 610 mm; inner diameter of pipes to be joined = 590 mm; nominal pressure = 11 bars with expected fluctuations; maximum temperature = 230 °C; explosive fluid to be handled; no leakage at interface; easy assembly and disassembly; and proper alignment of two mated pipes. Once product or functional requirements are established, the next step is to identify the requirements that are Critical to Quality (CTQs) and must be given more attention and efforts. For that purpose from the quality toolkit Quality Function Deployment (QFD) tool is found to be the most suitable and useful [8].

Quality Function Deployment

In our case functional requirements collected through VOC are what's of the House of Quality and are given importance rating (0 for 'not important' and 5 to 'most important') on the basis of customer interests given in figure 1.

Two important customer's functional requirements are 'explosive fluids to handle' and 'no leakage'. These are interrelated since explosive fluid is being handled in pipes because leakage is extremely dangerous and to avoid that proper sealing is needed. Next is design phase which includes concept development and preliminary design together with applicable quality tools to design the product able to fulfill functional requirements and specifically include features to satisfy CTQs.

Most Important = 5 Important = 3 Less Important = 1 Not Important = 0	Strong relationship = 5 Medium relationship = 3 Weak relationship = 1 No relationship = 0										
Customer requirements (Functional Requirements) \ **Design Characteristics / Parameters**		**Importance**	Type of flange	Material of flange	Joint Type of Flange with pipe	Thickness of flange	Type of gasket (material)	Width for gasket	PCD of bolts used	No. of Bolts	Diameter of Bolts
Large Dia (∅610 mm) Pipes to be joined		1	1	-	1	1	-	1	1	1	1
Pressure (11 bars) with fluctuations		3	3	3	1	1	3	5	3	3	3
Maximum Temperature (230 °C)		3	1	3	-	-	5	-	-	-	-
Explosive fluid to handle		5	1	3	1	-	5	5	1	1	1
No leakage		5	1	-	5	1	5	5	3	3	3
Easy Assembly & Disassembly		1	-	-	-	-	-	-	1	1	1
Alignment of mated pipes		3	-	-	1	-	-	-	1	1	1
Importance Rating			23	33	34	9	74	66	34	34	34

Fig. 1 Functional requirements in House of Quality

Concept Development

Concept development includes the formalization of basic configuration and selection of main components, subassemblies & assemblies to meet functional requirements especially CTQs. A pair of flanges is used for Bolted Flange Joint. The three components of a bolted flange sealing system are; flange (related to sealing is flange facing); gasket and bolts (related to sealing is bolt force). The three components of the Bolted Flange Joint are shown in following figure 2.

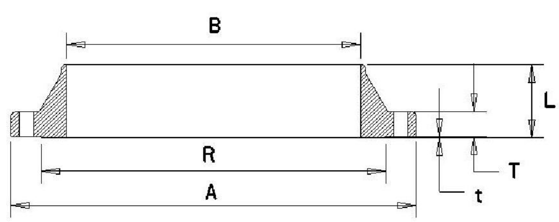


Fig. 2 Bolted Flange Joint

Nominal sizes of components, material specifications are finalized. Flange nominal dimensions to satisfy pipe size & operating conditions in millimeters are: outer diameter of pipe=∅610; outer diameter of flange (A) = ∅813; Inner diameter of flange (B) = ∅590; Thickness of flange (T) =54; Length of the flange (L) = 152; outer raised face (R) = ∅692; thickness of the raised face (t) = 1.6. Once preliminary design is complete, Design Failure Modes and Effects Analysis is the most appropriate tool applicable in the process for analyzing problems.

Design Failure Modes and Defects Analysis (DFMEA)

DFMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures [9]. Design failure mode and effects analysis for the three components is performed in order to find out the potential failures that can be encountered by these components. This allows for deep insight into design parameters of these components especially related to CTQ and provide aid in selection and calculation of design parameters.

1. Gasket Material Selection: Choice of gasket material is wide and to avoid failure mode 1, solid flat soft aluminum gasket is selected. The reason for such selection is because it can withstand high temperature conditions whereas rubber, paper and cloth gaskets cannot be used; it can be used with our flange facing type i.e. raised face (dimensions gasket factor M = 4 and Min design seating stress Y = 8800 Psi); it is easily available (easy to fabricate and can be cut from a sheet); and relatively cheap. Dimensions i.e. ID (Inner Diameter) and OD (Outer Diameter) of gasket will be same as that of raised face dimensions.

2. Gasket blown out: High gasket factor is required. Gasket factor is in the ratio of gasket stress to internal pressure and it depends upon material and construction. Our selected gasket has gasket factor of 4 as discussed above. It means that the contact pressure that would be applied on gasket to seat it properly will be 4 times the internal pressure and there is no chance of blowing out.

3. Gasket deformation into pipe: same *as above*.

4. Leakage due to roughness of flange face: Surface finish value for flange face is set to 1.6 microns

5. Leakage due to uneven flange face: Flatness value of flange face is set to 0.1 mm

6. Ineffective Sealing: Minimum seating force is to be calculated so that gasket material may yield and fill the irregularities

7. Gasket Crushing: Maximum limit of seating force is to be calculated to avoid crushing of gasket.

3. Research Design and Analysis

Figure 3 show the different forces acting on the gasket. Upon the application of internal pressure, hydrostatic end force tends to separate and decrease the seating force of gasket. Leakage will occur under pressure if the hydrostatic end force is sufficiently greater than the difference between it and the bolt seating load reduces the gasket load below a critical value. It may be possible with too low a contact pressure on the gasket for the gasket to be blown out by the internal pressure. The ratio of gasket stress when the vessel is under pressure to the internal pressure is known as gasket factor.

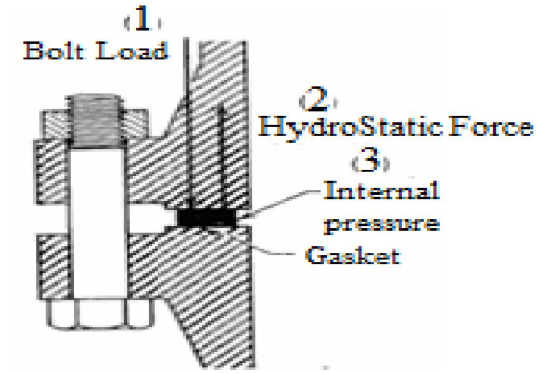


Fig. 3 Forces on Flange Joint

In selecting proper gasket for an existing closure one of the first steps is the determination of the total amount of force required to make the gasket yield and to maintain a tight seal under operating conditions. Mathematically;

$$F_b = F_{\min} + F_h \qquad (1)$$

$$F_b = \frac{\pi}{4}\left(d_0^2 - d_i^2\right)Y_{\min} + \frac{\pi}{4}\left(d_0^2\right)P \qquad (2)$$

F_b = Total force required for tightening bolts
F_{min} = Minimum force required to yield gasket
F_h = Hydrostatic end force
d_o = Outer diameter of gasket = 692mm
d_i = Inner diameter of gasket = 510 mm
Y_{min} = Min Yield Stress required to seat gasket = 8800 psi = 60 MPa
P = Internal Pressure = 11 bar = 1.1 MPa

Putting values in equation

$$F_b = \frac{\pi}{4}\left(0.692^2 - 0.590^2\right)60 + \frac{\pi}{4}\left(0.692^2\right)1.1 = 64644$$

The total force is applied through the bolts to properly seat the gasket to avoid leakage. DFMEA show (seven points), 'Y' is a critical parameter to be controlled; if 'Y' is less than minimum value leakage is expected and if it is greater than required the gasket could be crushed. Gasket Yield Stress is observed to be dependent upon four input factors; force applied by bolts or seating force, internal pressure, gasket inner diameter, and gasket outer diameter.

Transfer Function

Transfer function relates the output variable (Y) to input variables (X). Transfer functions can be mathematically derived, empirically obtained from a DOE, or regressed using historical data. The transfer function is an engineering equation derived from above equation as:

$$Y = \frac{\left[F_b - \frac{\pi}{4}\left(d_o^2\right)P \right]}{\left[\frac{\pi}{4}\left(d_o^2 - d_i^2\right) \right]} \quad (3)$$

It is used to analyze the effect of variation in input factors on the output i.e. gasket yield stress mean value and its variation in order to estimate the design C_{PK} which is a measure of estimation of design performance in use after its manufacturing and installation.

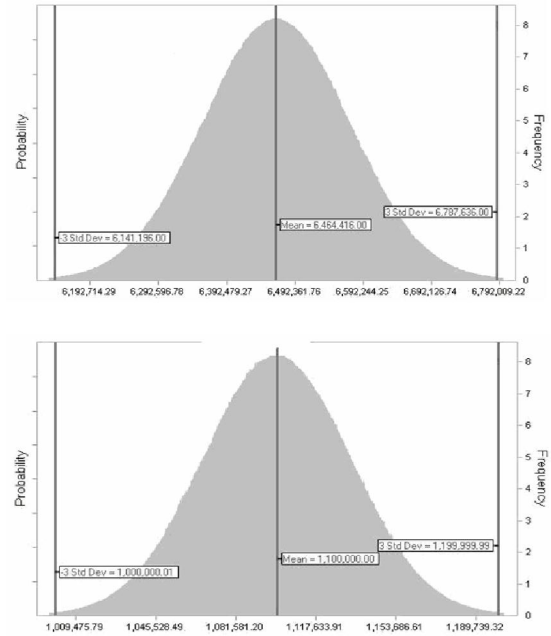
Design C_{PK} Analysis

The design C_{PK} is a measure of the design quality: how the design meets its intended specifications, regardless of the manufacturing steps necessary to produce the product or system. It is determined by the variability of the components specified in the design versus the overall system design performance to its specifications. Depending on the target C_{PK} for the design, the components distribution could be evaluated from the center to one side of the specification to measure either three sigma for $C_{PK} = 1$ or four sigma for $C_{PK}= 1.33$ or six sigma. Minimum yield stress for soft aluminum is 60 MPa and it gets crushed at 90 MPa. Keeping a factor of safety of 1.25 the allowable range of gasket stress value is 60 MPa to 72 MPa. From equation we can see the input factors on which Y depends are; force exerted by bolts, F_b, internal pressure P, gasket inner diameter d_i, gasket outer diameter, d_o. In the previous section nominal values of above variables are used. In real world these factors possess variation. In this section design / process capability of gasket is found and current sigma level i.e. baseline Design C_{PK} is determined.

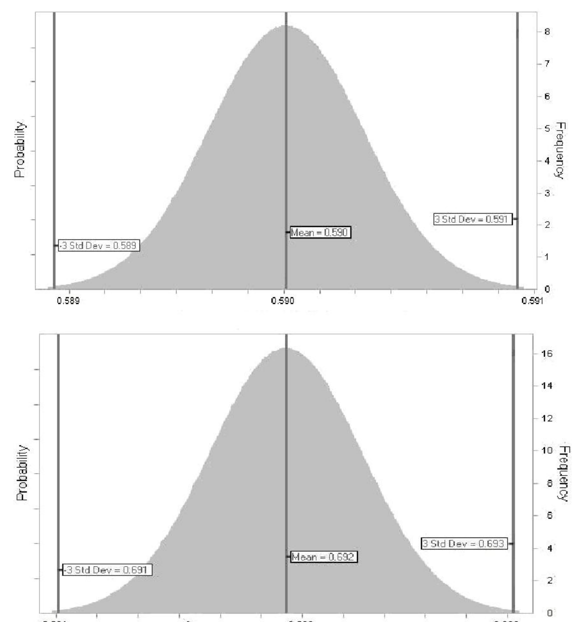
Probability Distribution of Input Factors

Force is applied on gasket through bolts by tightening them with the help of a torque wrench. Accuracy of available torque wrench is found to be ±5%. Upper and Lower Specification Limits are therefore +5% & -5% of the force (nominal value) to be applied. It is assumed that tightening of bolts process works at ±3σ.

Expected fluctuation in internal pressure is ±0.1 MPa. The upper specification limit is 1.2 MPa and lower specification limit is 1.0 MPa, (assumed sigma level is ±3σ). Probability distribution of internal pressure is given permissible variation in gasket inner and outer diameters is ±0.1mm because of manufacturing constraints, it is assumed that gasket's manufacturing process is working at ±3σ, respective probability distributions are shown in figure 4 (a ~ d).



Force applied by bolts; b) Internal pressure



c) Gasket ID; d) Gasket OD

Fig. 4 Probability Distribution

Monte Carlo Simulation

Real systems can be represented by mathematical models or transfer functions. These mathematical models can be simulated, equivalent to virtual experiments, in order to predict the behavior of real systems instead of conducting physical experiments on them. A mathematical model constructed in Excel that relates output i.e. Gasket yield to inputs. The output in the language of Monte Carlo simulation is called "Forecast" and inputs are called "Assumptions". The initial model with nominal values, there upper and lower specification limits and standard deviations are shown in the table 1.

Table 1. Model for Monte Carlo Simulation for Gasket Yield Stress

Inputs / Factors	Nominal Values	Lower Spec	Upper Spec	Std. Deviation
Force app by bolts	6464416	6141195	6787637	107740
Internal Pressure	1100000	1000000	1200000	33333.33
Gasket ID	0.59	0.589	0.591	0.00033
Gasket OD	0.692	0.691	0.693	0.00033
Output Response				
Gasket Yield Stress	58947221.26	60000000	72000000	
Target	66000000			

A simulation is run for 1000 trials following results are shown in figure 5.

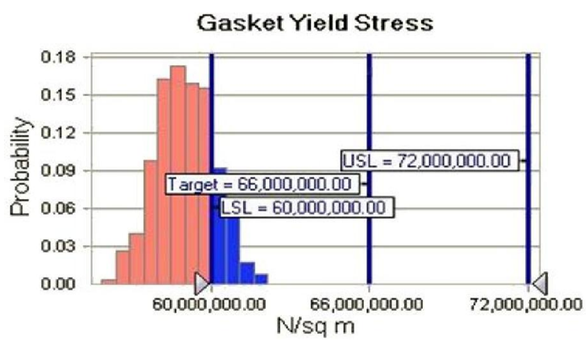


Fig. 5 Simulation for Gasket Yield Stress (baseline)

The result show design nominal values and the standard variation are giving unacceptable results. Most of the data is following outside the lower specification limit shown by red bars in above histogram. Thus representing the situation, the most of the gaskets would fail to seal the joints because of less yield stress in it. This simulation is equivalent to 1000 bolted flanges testing. Above histogram shows that C_{PK} value is -0.3116 which should be 1.5 or more for a six sigma product is very away from its target value i.e. 66 MPa. Spread of Gasket yield strength is nearly acceptable i.e. C_p = 1.8, while Cp = 2 is needed for a six sigma product. For further analysis scatter plots and sensitivity analysis is performed. Simulation carried out for the gasket yield stress baseline is: Mean (58,962,433.60); Standard Deviation (1,109,962.66); C_p (1.80); C_{pk}-lower (-0.3116); C_{pk}-upper (3.92); C_{pk} (-0.3116); C_{pm} (0.2807); Z-LSL (-0.9348); Z-USL (11.75).

Sensitivity Analysis

C_P and specially C_{PK} values for gasket yield stress are much lower and need to be improved. This is done by investigating the root cause/s that is responsible for lower C_{PK} value. For that purpose scatter plots are drawn and figure 6 show the combined sensitivity result. The gasket yield stresses mean value can be brought close to target value by manipulating the force applied by bolts. Sensitivity analysis shown in figure 6 demonstrates the contribution to variance by force applied by bolts is highest, therefore by tightening the upper and lower specification values or tolerance C_P for Gasket yield stress can be increased.

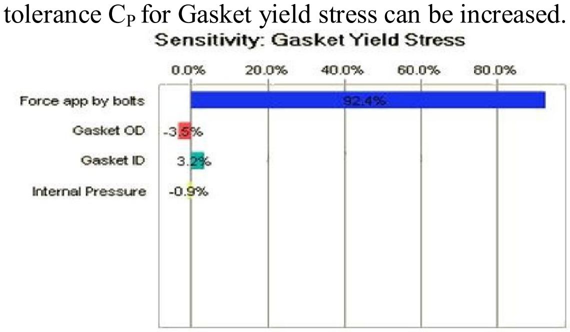


Fig. 6 Sensitivity Analysis

With the knowledge of behavior of key product preliminary design feature's inputs and outputs, optimization phase can be commenced to optimize input variables to get target output.

4. Results and Optimization

Given a system transfer function Y = f (X), optimization is the process of finding a setting for 'X' that best meets a specified criterion for 'Y'. Stochastic optimization finds characteristics of 'X' that best optimize characteristics of 'Y' [2]. To achieve improvement in C_P and C_{PK} values for gasket yield stress using 'Opt Quest' which is part of Crystal ball Professional edition 7.3 to find values of 'X' i.e. inputs/assumptions which optimize statistical properties of 'Y' i.e. gasket yield stress. Decision variable are that inputs that can be controlled and defined as: Internal pressure can not changed neither its variation can be controlled; Bolt force is controllable and is taken as decision variable. Its variation is observed due to the variation in torque wrench which is uncontrollable unless better torque wrenches are purchased that need investment; Gasket OD can be changed and is taken as decision variable, its variation is manufacturing constraint and can be taken as decision variable; Gasket ID is same as the ID of flange and pipe and cannot be changed, its variation i.e. tolerance in size is a manufacturing constraint and cannot be changed. Model is setup for optimization objective is to minimize the offset of Mean value of Gasket Yield Stress from its target value.

Table 2: Model for Stochastic Optimization for Gasket Yield Stress

Inputs / Factors	Nominal Values	Lower Spec	Upper Spec	Std. Deviation
Force app by bolts	0			107740
Internal Pressure	1100000			33333.33
Gasket ID	0.59			0.00033
Gasket OD	0			0.00033
Decision variables	**Initial Values**	**Upper bound**		
Force app by bolts	6464416	8000000		
Gasket OD	0.692	0.85		
Output / Response				
Gasket Yield Stress	0	60000000	72000000	
Target	66000000			
Offset from Target	0			

Optimization is run for 1000 simulations. Optimization results are as shown in table 3 showing the best result is 337th simulation which gives optimal mean values for bolt force and gasket OD.

Table 3. Optimization Results

Simulation	Minimize Objective Offset from Target Mean	Force app by bolts	Gasket OD
1	9.8609E+11	7.9187E+06	0.702000
106	9.7112E+11	7.8998E+06	0.702000
122	9.4122E+11	7.9025E+06	0.702000
152	9.3429E+11	7.9738E+06	0.703000
208	9.2312E+11	7.8956E+06	0.702000
222	9.2044E+11	7.9983E+06	0.703000
314	9.1951E+11	7.9849E+06	0.703000
330	9.1326E+11	7.9849E+06	0.703000
Best: 337	8.6862E+11	7.9851E+06	0.703000

The following figure 7 gasket yield stress results in the form of histogram. It is clear that with optimal mean values of force applied by bolts & gasket OD, the mean of gasket yield stress comes very close to the target value and the process spread or variation of gasket yield stress is well within the limits of 60 MPa & 72 MPa.

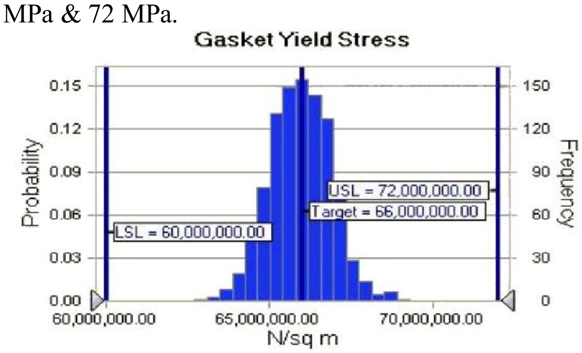


Fig. 7 Gasket Yield Stress Results with optimal input values

Table 2 gives the mean value of 65962684.91N for gasket yield stress which is much closer to the target value i.e. 66 MPa. This is also clear from high C_{PK} value i.e. 2.13 which should be 1.5 or more for six sigma quality. This implies that the mean values of input factors are now adjusted and their variation is accommodated in order to get output. C_P value is 2.15 which should be 2 for six sigma, this means that variation in the output is in acceptable limits. In terms of the physical system, changes that Opt Quest recommended are to increase the force exerted by bolts and to increase the gasket OD in order to get close to target value of gasket yield stress. The improved statistical values for optimal gasket yield stress are: Mean (65,962,684.91); Standard Deviation (931,718.76); C_p (2.15); C_{pk}-lower (2.13); C_{pk}-upper (2.16); C_{pk} (2.13); C_{pm} (2.14); Z-LSL (6.40); Z-USL (6.48). In the phase of validation, prototypes are made and tested to make sure that the product, as designed, meets the requirements. To predict the impact of changes recommended in previous section, optimal values for bolt force and gasket OD are copied back into the simulation model and another run for 1000 trials of Monte Carlo simulation with Crystal Ball is done. Following figure is the histogram of the gasket yield stress using the new optimized values, which shows the dramatic increase in C_{PK}. Monte Carlo Simulation gives following gasket yield stress results in the form of histogram.

There is an increase in C_{PK} from -0.3116 to 1.57 by changing only nominal values of two decision variables without tightening any tolerances. Tightening any tolerances means more cost. C_{PK} 1.5 or more is required for a DFSS product. It means that in real world bolted flange joint assembly will approach to six sigma quality i.e. only 3.4 bolted flanges would fail to meet customer requirements out of 1 million. This simulation represents virtual prototyping and is equivalent to the testing of 1000 physical Prototypes. The validated statistical values for gasket performance are: Mean (67,303,983.93); Standard Deviation (999,552.55); C_p (2.00); C_{pk}-lower (2.44); C_{pk}-upper (1.57); C_{pk} (1.57); C_{pm} (1.22); Z-LSL (7.31); Z-USL (4.70).

5. Conclusion

It is clear that all the design process activities can easily be grouped into four IDOV phases i.e. Identify, Design, and Optimize & Validate. This is helpful in laying the foundation of a structured and systematic design process. In Identify phase 'Voice of Customer' (VOC) is helpful in collecting the customer wants and expectations from the product. In this design project seven customer requirements for Bolted Flange joints are collected. Quality Function Deployment (QFD) is also applicable in Identify phase which aid designers in translating customer wants to Product technical characteristics/requirements/features and prioritizing them according to their importance to customer, naming them as CTQs i.e. Critical to Quality, House of Quality for this case shows that only one out of seven requirements is vital to customer i.e. 'No Leakage' through flange joint. No Leakage means proper sealing is major requirement and hence it is CTQ i.e. Critical to Quality. Design Failure Modes & Effects Analysis (DFMEA) is applicable after preliminary design in design phase. It identifies causes by which product can fail in satisfying critical to quality characteristics. In more descriptive way DFMEA helps design team in identifying the inputs that can cause the problem to outputs of the designed product. Out of seven failure modes only two (ineffective sealing due to less seating force & gasket crushing due to excessive seating force) are found to be given due attention i.e to optimize the values of the input factors so that gasket yield stress remains with upper & lower specification limits for proper sealing.

Transfer function applicable in design phase are used to relate problematic CTQs to their inputs through mathematical model, these mathematical models are then simulated by Monte Carlo Simulation to obtain the baseline Design C_{PK} of that particular CTQ with the help of histogram. Gasket yield stress is related to four input factors through a mathematical model which is simulated with Monte Carlo Simulation to provide baseline Design C_{PK}. Baseline Design C_{PK} depicts the behavior of CTQ characteristic under uncertainty i.e. variation in input values. C_{PK} value should be 2 for six sigma quality. In our case baseline C_{PK} is very low i.e. -0.3116. If Baseline C_{PK} value is less than 1.5; it means that product is not able to deliver six sigma quality i.e. there will be more than 3.4 DPMO, To increase C_{PK} value we use tools like scatter plots and sensitivity analysis to know which inputs (& their variation) is responsible for less C_{PK} value of CTQ. Scatter plots are also drawn which reveals that force applied by bolts has a close positive relationship with gasket yield stress, sensitivity analysis shows that much of variation in gasket yield stress is contributed by variation in force applied by bolts. In Optimize phase we optimize the problematic input's means and standard deviations to obtain CTQ characteristic mean, close to target value and its variation with acceptable limits. For bolted flange joint design project, two decision variables are used (Force applied by bolts & Gasket OD). Stochastic Optimization is run which optimize decision variables. Result of optimization shows that Design C_P & C_{PK} are improved. With CTQs of the product having C_{PK} value of 1.5 or more, six sigma quality is achieved for the product in design & development phase of product life cycle. In our case, the optimum values of the two decision variables are copied to mathematical model and simulation is run for 1000 trial. Results show that Deign C_P & C_{PK} are 2.00 & 1.57 exhibiting six sigma design quality**.**

Acknowledgment

We are very thankful to the National design organization for supporting this research work. The facilities and support of MED, UET Taxila is also acknowledged.

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10/5/2012