UNCERTAINTY ANALYSIS IN LASER DEPOSITION FINISH MACHINING OPERATIONS

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ABSTRACT

The Laser Aided Manufacturing Process (LAMP) from Missouri S&T is a laser based metals rapid manufacturing process that uses machining to improve the final part's surface finish. When free-form machining, the absence of enough deposited material results in inconsistent scallop heights which result in poor surface finish or incorrect geometry in the final part. This paper investigates a probabilistic approach to various uncertainties involved in the deposition and subsequent machining of an arbitrary part. Furthermore, this paper analyses the machine errors which makes the response of Scallop Height to exceed the predefined maximum scallop height when traveling along the tool path interval distance. Tackling these problems allows us to achieve the final part shape with higher accuracy.

NOMENCLATURE

IPM = Inches per minute
ANOVA = Analysis of Variance
DOE = Design of Experiments
r.v. = Random variable
L = Tool path interval
h = Scallop height
R = Radius of curvature
r = Radius of the tool
μ = Mean of the random variable
σ = Standard deviation of the random variable
P_f = Probability of failure

1. INTRODUCTION

Machining harder materials such as titanium takes a lot of time. Moreover the tool life in machining such materials ends up being very less. Thus the concept of Scallops has been introduced to reduce the overall machining time under the constraints of achieving certain surface finish defined by the user. Scallops are defined as the amount of material that is intentionally left behind on the surface of the final machined part as shown in Figure 1.

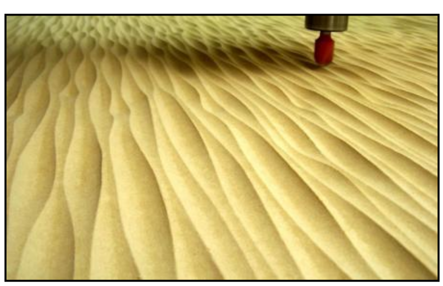


Fig. 1: Example of Scallops

Scallop Height can be defined as the perpendicular distance from the actual part surface to the tip of each scallop. This has been shown in Figure 2 [3]. Basically, it is the height of the scallop when the tool moves in a direction perpendicular to the feed direction that is the side step direction.

Semi-Cylindrical shapes as shown in Figure 3 have been machined out and the reliability of the machined parts has been calculated. If the scallop height exceeds a certain predefined height (in our case it has been set to 0.5mm).

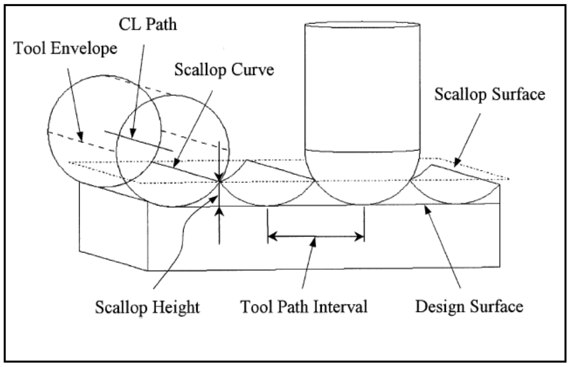


Fig. 2: Scallop Height and Tool Movement

Fig. 3: Machined Semi-Cylindrical Geometry

2. EXPERIMENTAL SETUP

Experiments have been conducted on wax blocks and a predefined contour of semi-cylindrical shape has been chosen as shown in Figure 3.

We have performed all the machining on a Fadal 5Axis Vertical Machining Center CNC (VMC) machine. The material used for machining out the scallops was wax blocks. The Spindle Speed was kept at a constant of 2000 rpm. Three major components pointed out in the Figure 4 are:

1. Tool – Ball end Mill = 0.375 inches in diameter
2. X-Y Table – this shows the movement of the job block during the machining
3. Rotating Head – Even though the FADAL machine has a capability of 5-Axis machining, we have only focused on 3-Axis machining as the geometry to be machined is not complicated.

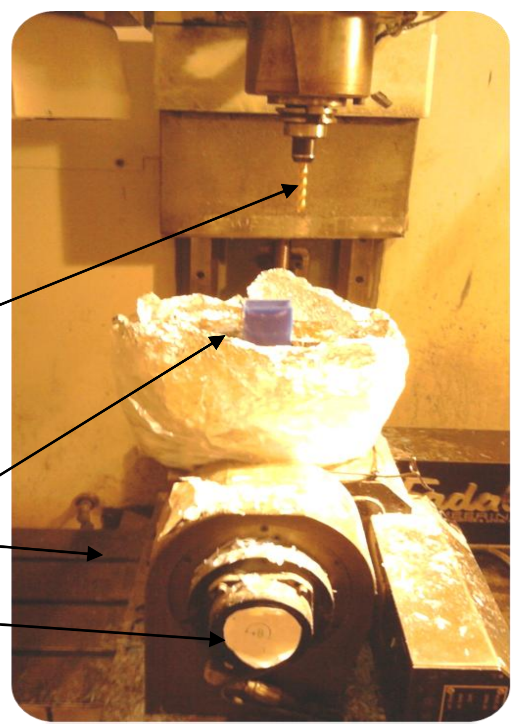


Figure 4: FADAL VMC Machine Setup

3. PROCEDURE

Design of Experiments concept has been applied to carry out the machining. The data thereafter is used to get the standard deviation and the mean value of the random variables.

The conducted experiment is a Factorial experiment. There are 3 factors and each factor has 2 levels. The different factors utilized and their levels have been listed below.

1) Feed Rate
   a) 5 IPM
   b) 100 IPM
2) Tool Path Strategy (Tool path movement Direction)
   a) Parallel to the Axis of the Semi Circular surface
   b) Perpendicular to the Axis of the Semi Circular surface
3) Radius of Curvature of the Part Geometry
   a) Convex side Radii
   b) Concave Side Radii

Response Variable: This would be the Absolute difference between the Average Scallop Height achieved from each run on a 2 x 2 x 2 (l x b x h) wax blocks. We will have 2^3 factorial experiments, that is 8 treatment combinations.

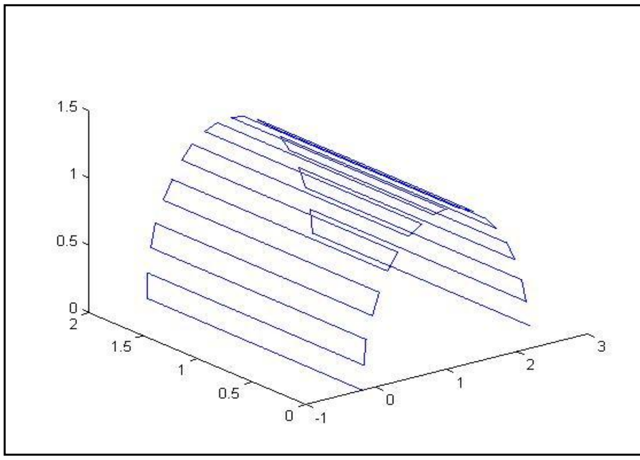
Number of Replications: Each Treatment Combination will be replicated only Twice. This is in consideration to the fact that we would be performing and setting up the experiments of machining the wax blocks from the scratch and thus keeping in mind the practicality we have decided to go ahead with only two replications which we can achieve by machining 16 wax blocks = 8 x2.

Randomization Scheme: Microsoft Excel and the function therein which is "=rand ( )" has been used. Furthermore, we rearrange the random number column in increasing order to get the randomized treatment combinations approach (that is randomized treatment combination rows). The randomization has been applied to both the replicates. Table 1 shows the results.

Completely Randomized Treatment Combinations				
Sr. No	**Feed Rate**	**Tool Path Strategy**	**Radius of Curvature**	**RESPONSE = Scallop Height (in mm)**
3	5 IPM	Perpendicular to Axis	Concave	0.64008
4	5 IPM	Perpendicular to Axis	Convex	0.69342
7	100 IPM	Perpendicular to Axis	Concave	0.51562
1	5 IPM	Parallel to Axis	Concave	0.4445
8	100 IPM	Perpendicular to Axis	Convex	0.68072
5	100 IPM	Parallel to Axis	Concave	0.42418
2	5 IPM	Parallel to Axis	Convex	0.8636
6	100 IPM	Parallel to Axis	Convex	0.79756
9	5 IPM	Parallel to Axis	Concave	0.42672
10	5 IPM	Parallel to Axis	Convex	0.84582
15	100 IPM	Perpendicular to Axis	Concave	0.6604
16	100 IPM	Perpendicular to Axis	Convex	0.87376
11	5 IPM	Perpendicular to Axis	Concave	0.69342
13	100 IPM	Parallel to Axis	Concave	0.46482
14	100 IPM	Parallel to Axis	Convex	0.66548
12	5 IPM	Perpendicular to Axis	Convex	0.84582

Table 1: Design of Experiments Result

Tool path generation: Tool Path is generated using MATLAB and the program generates the required G & M codes. The two different tool path strategies of moving parallel to the axis and perpendicular to the axis have been shown in Figure 5(a) and Figure 5(b).



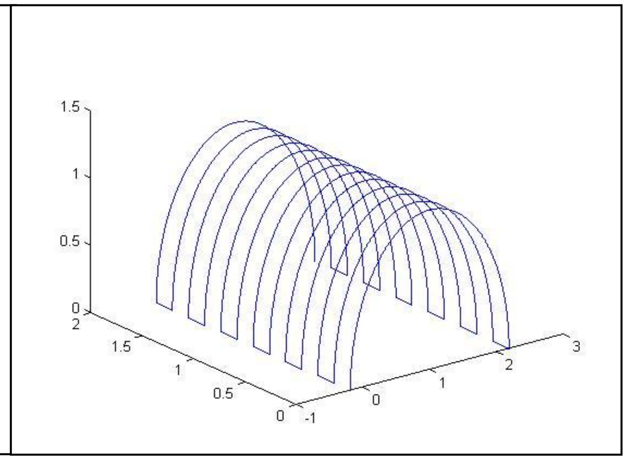


Fig. 5(a): Parallel to the Axis of Semi Circular surface

Fig. 5(b): Perpendicular to Axis of Semi Circular surface

Determination of Scallop Heights: After 16 runs over 16 wax blocks we get the results as shown in Figure 6. The acute protrusions on the surface of each work piece are the scallops. We are trying to find out the absolute difference between the height of these scallops from the semi-cylindrical contour and 0.5

We then scanned these blocks using a 3D Scanner. The orientation of the blocks in front of the Scanner was kept in a way so that
X Axis: Along the length of the scallops or rather along the feed direction
Y Axis: Along the Side-Step direction of the tool or rather along the width of the scallops
Z Axis: Pointing towards the 3D Scanner

The scanned data points were then synthesized and sliced as zero thickness scallops. These were then plotted on a Y-Z Axis so as to find the Scallop Height. An example of this plot from one of the treatment combination results have been shown in Figure 7. The calculation of scallops from the 3D scanner is done using MATLAB.

Figure 6: Machined wax blocks from conducted Factorial Experiments

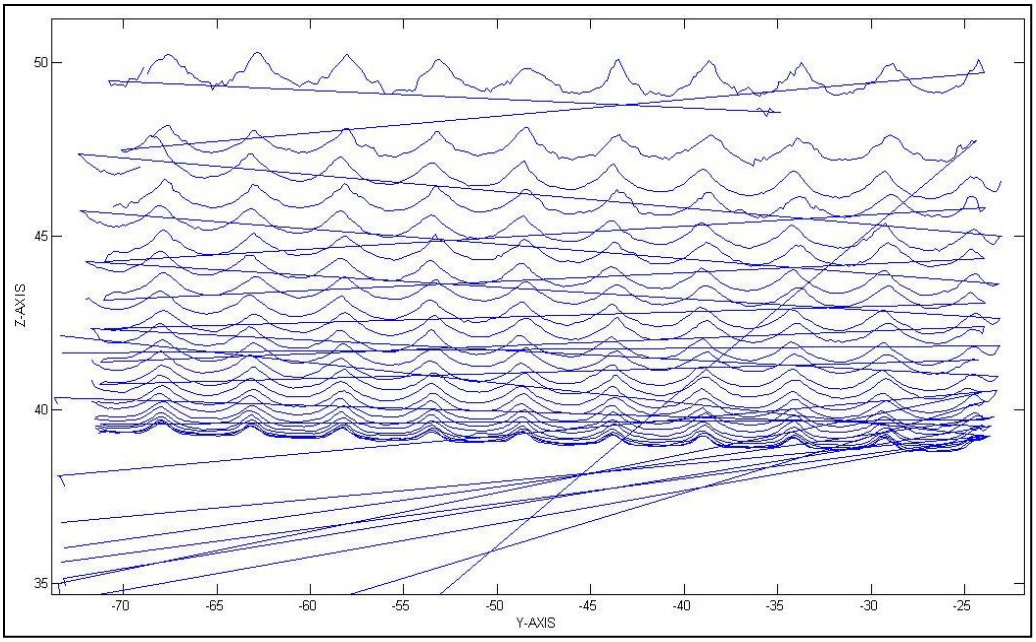


Figure 7: Zero Thickness Scallops plotted to calculate the Scallop Heights

4. STATISTICAL ANALYSIS OF EXPERIMENTAL DATA

This analysis is carried out to find out the Standard deviations of the random variables and to validate their normality. However, the r.v. of radius of the tool has a standard deviation of 0.01875 which has been defined by me based on the mean of 0.1875".Different design of experiments methods are used to check for the accuracy and normality of the various variables. The plots shown in Figure 8 further validate the assumptions of environmental errors being normally distributed throughout the experimental data. 2^3 factorial design experiments were analyzed in Minitab and here are the results.

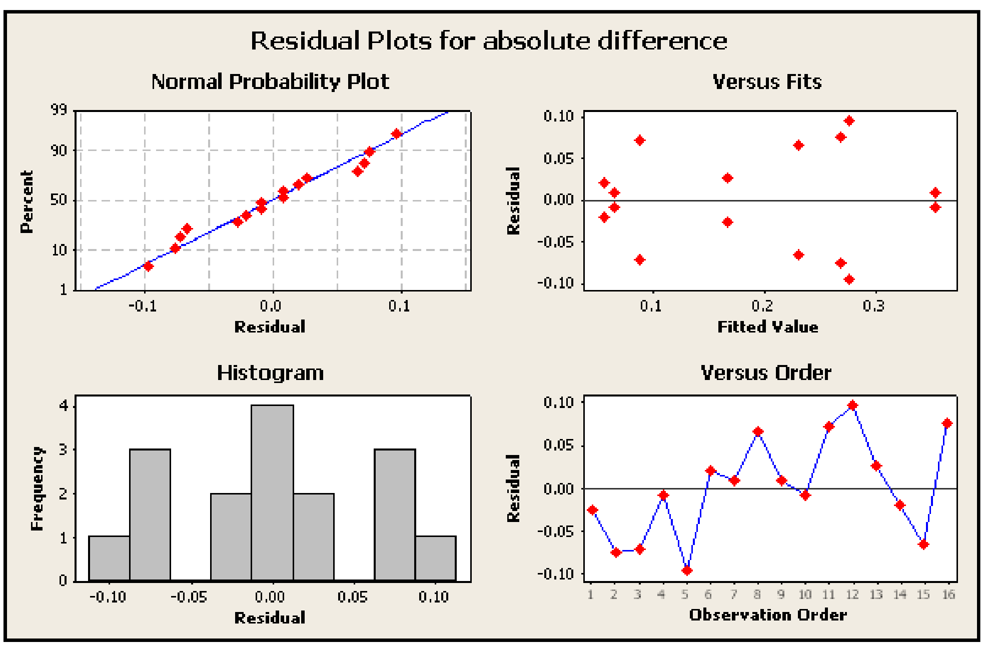


Figure 8: Four plots validating the Model Assumptions of Normal Distribution

Model Assumptions:
This collection of the four plots shown in Figure 8 shows the validity of the model assumptions.

I. **Normal Probability Plot:** From the first plot, we are looking to see if the assumption that our errors are identically and independently normally distributed (iid) with mean 0 and variance σ^2 is violated. Since the points in our plot do not deviate significantly from the line, we can say that the assumption is not violated, that is, the errors are iid $N(0,\sigma^2)$.

II. **Second plot** is checking the assumption that all variances are equal. We want the variance of all the treatments to be roughly the same. In our plot they don't look exactly the same, which could be a problem. However, since we are employing a balanced fixed effects model, the F-test is only slightly affected. It could be possible to try a variance stabilizing transformation on the data, but we did not try this. Upon investigation it seems that the treatments with the largest variances are the four treatments that are ran at 100 Inches per minute (IPM). We believe the large difference between 5 IPM and 100 IPM is the cause for this variance, and although it doesn't help the constant variance assumption, it at least explains the differing variances. Also note that the reason we used such a large difference in IPM is because of our material choice (wax). If we were using steel, or any other harder material, even a small difference in IPM could lead to significant differences in accuracy. However, since we used wax, we wanted to use widely different levels of our factors, since we believed the machine would have an easy time cutting through wax at lower IPM's.

III. **Third plot** is again looking at the normality of our error term. And it looks okay here. It's oddly symmetrical, but that's good. We see no striking deviations from normality.

IV. **Last plot** is used to make sure there is no pattern in the residuals (i.e.: Not getting larger/smaller over time). You can see they look quite random, which does not violate our assumption.

ANOVA Analysis:

We continue on with our analysis, knowing that our assumptions are satisfied, or at the very least, mostly satisfied. I mentioned the possibility of doing a transformation on the data to achieve equal variances, but we just kept our data as is, and ran the analysis of variance. The results are shown in Table 2.

Our first step is to check for a three way interaction between our three factors. With a p-value of 0.249, we conclude that there is not a significant interaction, and can move down to the two-way interactions. The next three p-values are 0.310, 0.865, and 0.714, none of which are even close to our level of significance of 0.05. Again we conclude that there is no significant two way interaction and move on to test the main effects. The only significant main effect is RoC, which is the Radius of Curvature. Its p-value 0.002 is underlined in Table 2. The existence of interaction between TPS and RoC can be seen in the plots shown in Figure 9; however these interactions are not significant enough to affect the response.

We conclude that the only factor that has a significant effect on scallop height accuracy (absolute difference), is the radius of curvature. That is, whether you cut the wax in a convex, or concave manner, has a significant effect on the accuracy of our wax blocks. Now, it's probably best to find out which Radius of Curvature is more accurate, and which is less accurate. We could perform Tukey's test, but it's unnecessary. Since we know that ROC has a significant effect on scallop height, and there are only two levels of ROC, we can just look at a main effects plot as shown in Figure 10 and it will show us which one is more accurate or rather as to which one gives an absolute difference closer to zero.

Here you can see that we observed a smaller absolute difference for the Concave blocks, than we did for the convex blocks. We know that there is a significant difference between our levels from the F-test above, so we can conclude that cutting the blocks in a Concave manner is more accurate than in a convex manner. As for why this is, we are not quite sure. Perhaps the machine has an easier time carving down into the blocks, than it does carving upwards at first. But this is pure speculation, we don't know why exactly, but the CNC machine is more accurate when the radius of curvature is run at the concave level of the RoC factor.

Analysis of Variance for absolute difference

Source	DF	SS	MS	F	P
Feed Rate	1	0.010284	0.010284	1.59	0.244
TPS	1	0.002298	0.002298	0.35	0.568
RoC	1	0.143663	0.143663	22.14	**0.002**
Feed Rate*TPS	1	0.000941	0.000941	0.14	0.713
Feed Rate*RoC	1	0.000201	0.000201	0.03	0.865
TPS*RoC	1	0.007623	0.007623	1.17	0.310
Feed Rate*TPS*RoC	1	0.010028	0.010028	1.55	0.249
Error	8	0.051903	0.006488		
Total	15	0.226941			

S = 0.0805472   R-Sq = 77.13%   R-Sq(adj) = 57.12%

Table 2: ANOVA Table

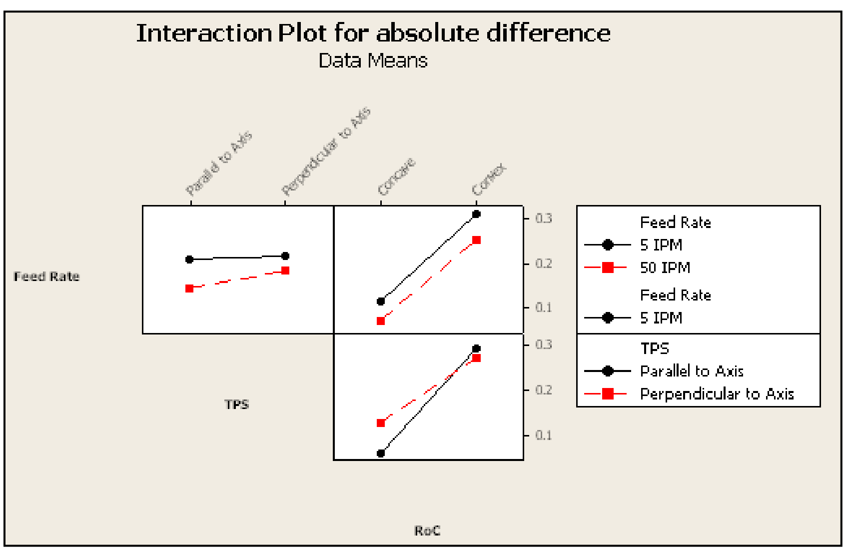


Figure 9: Interaction Plot for Scallop height absolute difference

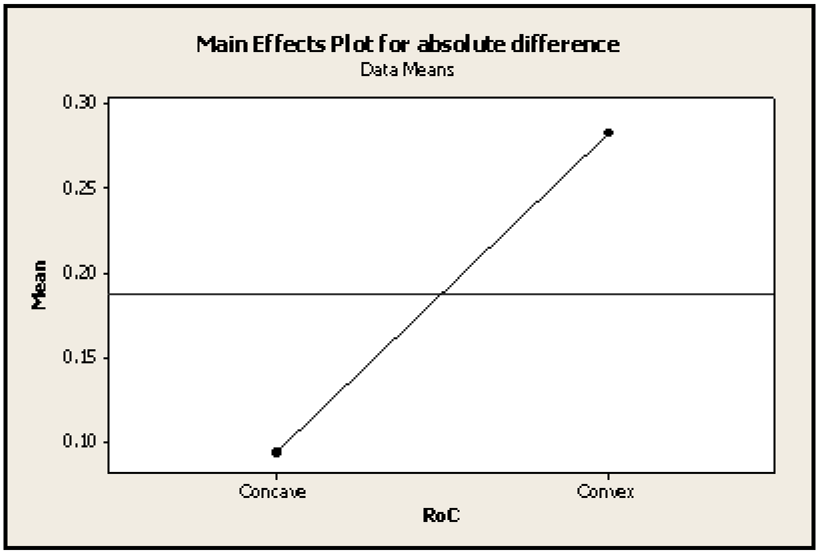


Figure 10: Main effects plot for Scallop Height (absolute difference)

Conclusion from DOE:

Our final conclusion is that tool path strategy, and feed rate have no significant effect on the scallop height, while the radius of curvature has a significant effect on it. Also, we found that the concave radius of curvature results in the most accurate scallop heights, and the convex radius of curvature results in the least accurate. By least accurate I mean that the absolute difference from 0.5mm in scallop height is the largest, which you can see in the plot above.

It is also interesting to note, that although the higher feed rate of 100 IPM resulted in a larger variance of scallop heights, it did not have a significant effect on scallop height.

We would also like note that these conclusions should probably only be applied to wax, as we didn't test any other materials. We used wax because of time/monetary constraints, but think it would be interesting to test other harder materials separately, or perhaps test multiple materials at one time, while blocking by material.

5. RELIABILITY ANALYSIS

5.1. Mathematical Equation

The equation [1] for calculating the scallop height on the convex surface can be given as:

$$L \simeq \sqrt{\frac{8h r \rho}{\rho + r}} \qquad (1)$$

5.2. One of the notations of 'ρ' has been replaced by 'R'. The above equation and the condition of minimizing the scallop heights, together give us the final equation of 'g'[3].

$$g = h - \frac{L^2(R + r)}{8R \times r} \qquad (2)$$

5.3. Types of Variables

5.3.1. Constant Variable

In my experiments the only constant variable is the Radius of curvature 'R' = 1 inch

5.3.2. Random Variables

There are three random variables which are the Scallop Height, The tool path interval and the radius of the tool. The variables are represented below in the form –

$$r.v. \approx N(\mu, \sigma)$$

Scallop Height : $h \approx N(0.41148, 0.39624)$

Tool path Interval : $L \approx N(3.99796, 0.70866)$

Radius of Tool : $r \approx N(4.7625, 0.47625)$ All dimensions are in mm.

5.4. Uncertainty Analysis

5.4.1. Monte-Carlo Simulation

Monte Carlo simulation has been performed using a million random sampling of the three random variables. Failure region is defined as the region whenever *'g'* becomes less than zero. That is to say that whenever the calculated value exceeds the predefined Scallop Height value of 0.5mm, failure occurs.

5.4.2. First Order Second Moment Method

If the first two moments (mean and standard deviation) of a random variable are known, the moment matching method can be used to estimate the mean and standard deviation of a performance function. Then the mean and standard deviation of the performance function may be used to estimate the probability of failure.

5.4.3. First order Reliability Method (FORM)

The name of First Order Reliability Method (FORM) comes from the fact that the performance function g(X) is approximated by the first order Taylor expansion (linearization).

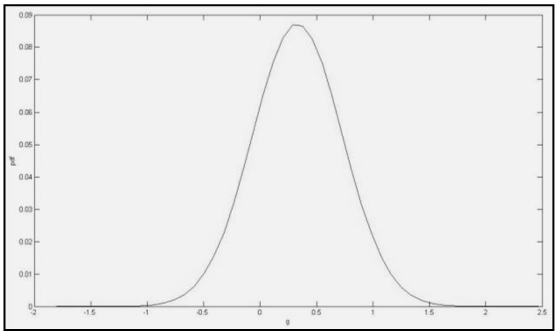
5.4.4. Error analysis on Monte-Carlo simulation

As the number of samples increases the solution becomes more and more accurate. We have used 95% confidence level and the equation below to find the error. Knowing the error [2] is important in Reliability Analysis accuracy is the main goal to be achieved.

$$\varepsilon\% \approx 200\sqrt{\frac{1-p_f}{Np_f}} \qquad (3)$$

6. RESULTS

METHOD	RELIABILITY	PROBABILITY OF FAILURE
Monte – Carlo Simulation *Fig. 11(a), Fig. 11(b)*	0.7973; 79.73%	0.2027; 20.27%
First Order Second Moment Method *Fig. 12(a), Fig. 12(b)*	0.4212; 42.12%	0.5788; 57.88%
First Order Reliability Method *(Table 3)*	0.4210494; 42.10494 %	0.5789506; 57.89506 %



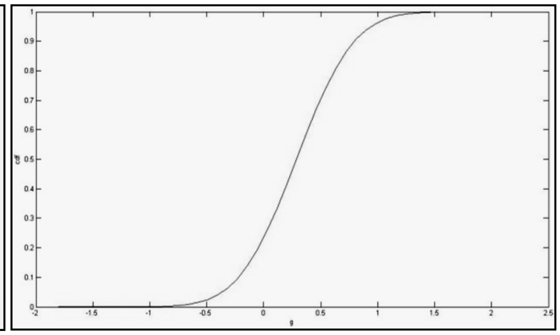


Figure 11(a): CDF Curve **Figure 11(b): PDF Curve**

7. CONCLUSIONS

From the Monte- Carlo Simulation method we could come to know the ideal suppose to be reliability of the machined part under the given standard deviations and mean of the random variable. These results were simulated in a computer specific ideal space.

On the other hand, the P_f using and FORM and SORM seems to be really high. However, the reason could most probably be, the FADAL VMC machine being really old or the wax blocks for the initial machining to be erroneous.

Also as the method of FOSM makes the non-linear function into linear, there might be inherent errors in the approximation.

The Objective was to achieve the maximum tool path interval, while maintaining the scallop height at 0.5mm.

Figure 12(a) shows on the x, y and z axes the tool path interval, radius of tool and scallop height. As can be seen from Figure 12 (a) and especially figure 12(b), the scallop height lies in the region of 0.5mm when the tool path interval is in the region of 4mm (4mm ≈ 0.1875inches). This is a desirable result.

Since we can see that there is a lot of scope of improving the reliability of the system, methods such as reliability based design and robust design can be used to improve the reliability of the system.

Iteration	U1	U2	U3	g(u)	Beta
1	0.0000000000	0.0000000000	0.0000000000	-0.0034134000	0.0000000000
2	0.1808500000	-0.0806070000	0.0191470000	-0.0000049600	-0.1989200000
3	0.1816400000	-0.0796730000	0.0186140000	0.0000000718	-0.1992100000
4	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
5	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
6	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
7	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
8	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
9	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
10	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000
11	0.1816300000	-0.0796850000	0.0186210000	0.0000000000	-0.1992100000

Table 3: FORM Convergence history Table

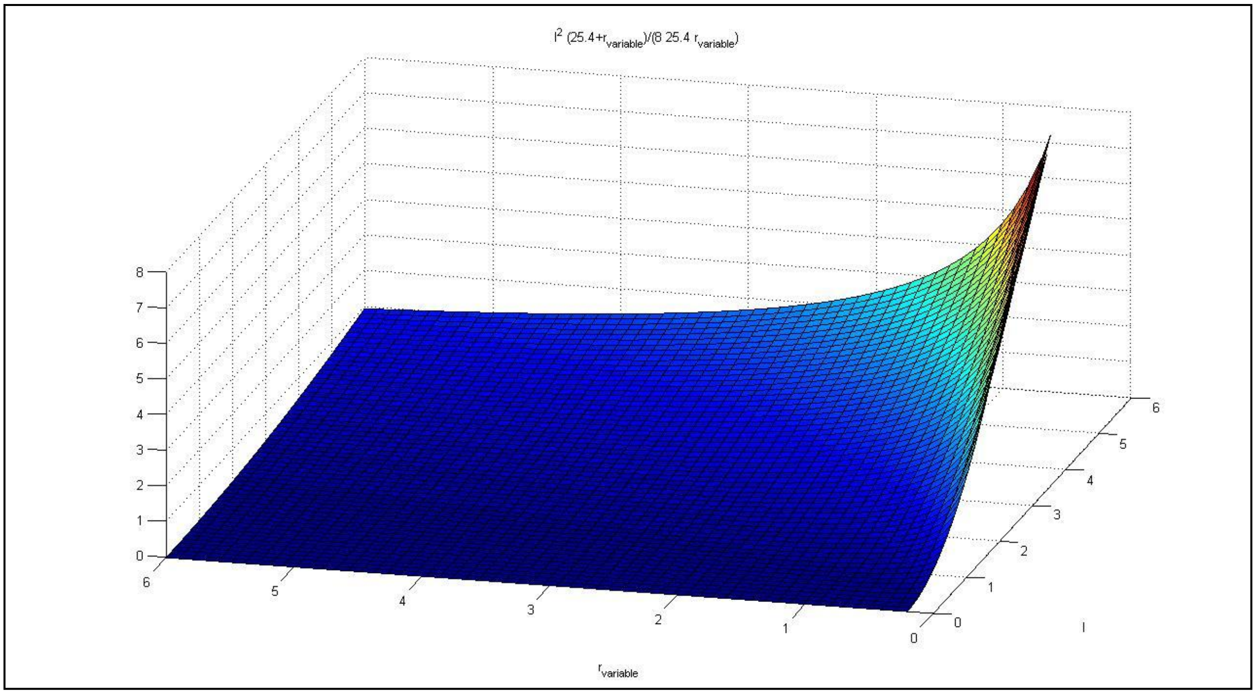


Figure 12(a): Plot of Surface Function (Isometric View)

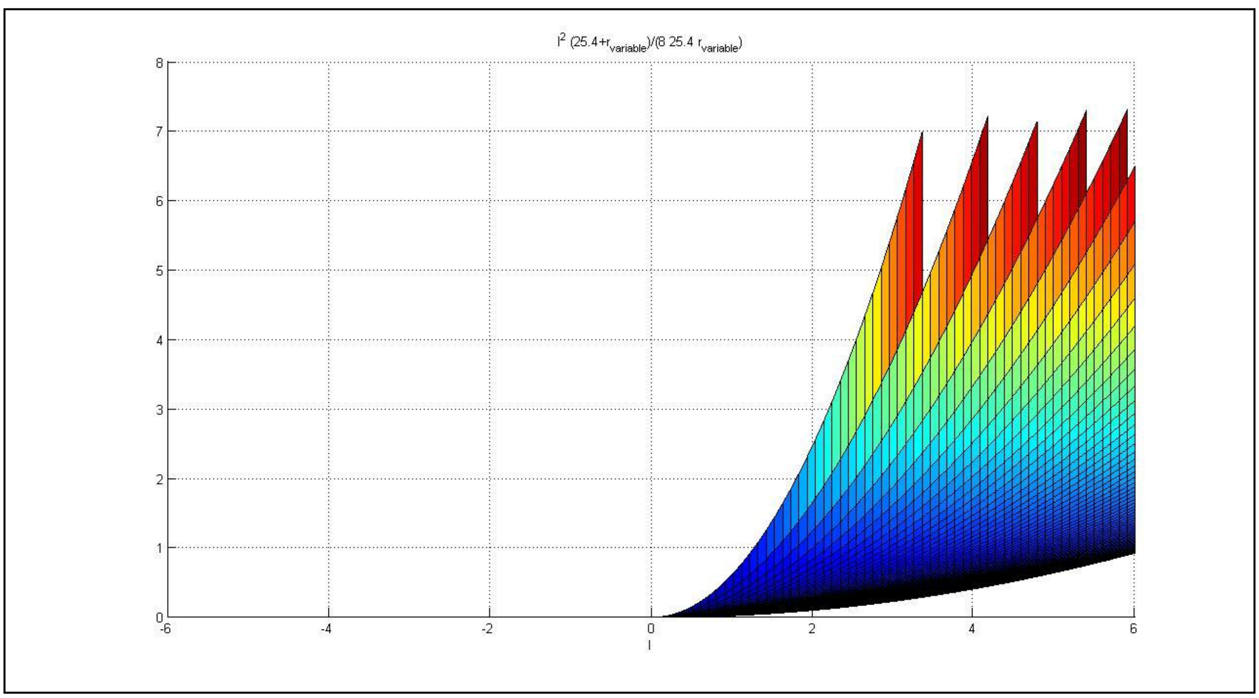


Figure 12(b): Plot of Surface Function (Side View)

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9. References

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