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Experimental Investigation of Gyroscopic Couple by Response Surface Methodology

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***Abstract*: The investigation about the influence of input parameters over the output parameters through designed experiments has become a growing trend in understanding the relationship between them. It is highly essential to ascertain the effect of one over the another to avoid undesired results. The major objective of this experimental investigation is to conduct designed experiment to evaluate gyroscopic couple through Response Surface Methodology (RSM). It has been adopted for creating the full factorial experimental design using Design Expert 11.0 software to study the effect of Speed and Load which are varied with three levels. The output values of gyroscopic couple are further analyzed to identify the significant parameter influencing the gyroscopic couple using ANOVA technique. Load is found to be more significant than speed over both the measured responses angle turned, time taken and the calculated response gyroscopic couple The predicted equation for gyroscopic couple may be used for further processing.**

***Keywords*: ANOVA, Central composite design, Gyroscopic couple, Response surface methodology.**

1. Introduction

The field of optimization has been considered by most of the authors and researchers in order to achieve their desired outputs. Optimization is actually adopted to identify the best parameter combination and also the significant parameter which influences the output parameter. Response Surface Methodology is a type of experimental design used for creating the experimental plan or layout by using different parameters associated with a process. It finds application in many areas of mechanical engineering in optimization of process parameters such as traditional machining, welding, engine performance improvement, tool wear reduction, enhancement of material removal rate and so on. Avinash A. Thakre et. al [1] has described that Response surface methodology is a powerful statistical tool for mathematical modeling of engineering systems and for optimization of the process parameters. The steps of this process start with the identification of the control parameters and their domain under consideration. The next step is to select the orthogonal design and to conduct the experiments based on this design. Then the empirical models are developed between the response and the process variables. Ashvin J et. al. [2] has investigated the influence of turning process parameters such as Cutting speed (v), Feed rate (f), Depth of cut (d) and Nose radius (r) over the output parameter surface roughness for AISI 410 Steel through RSM technique by conducting 81 experiments in total and reported parameter feed rate has the highest influence over surface roughness Pardeep Sharma [3] has reported about the dry sliding wear of aluminium metal matrix composites through by applying RSM technique for Parameter optimization and found that Sliding distance is the most influential factor on wear rate of composites than load, speed and percentage reinforcement. E.O. Ajala et. al [4] has adopted response surface methodology for optimizing the two stage process of biodiesel production from shea butter. The authors had selected four different operating conditions to conduct investigation and to reduce the free fatty acid content present in shea butter and to increase the percentage yield of shea biodiesel. Sarehati Umar [5] has utilized response surface methodology for the damage detection using frequency and mode shape.Sourab Sinha [6] has investigated the effect of input parameters such as current, voltage and pulse on-time which influences the two major response characteristics namely material removal rate (MRR) and tool wear rate (TWR) and found that current is the most significant factor for the material Incoloy 800HT machined using EDM technique. Ajitanshu Vedrtnam [7] has done optimization of submerged arc welding process parameters through response surface methodology, regression analysis and genetic algorithm. The authors have considered the input parameters such as arc voltage, welding current, nozzle to plate distance and welding speed for understanding their effect over the weld quality of stainless steel material.

2. Gyroscope

A gyroscope is a device used for measuring or maintaining orientation and angular velocity. It consists a spinning wheel or disc in which the axis of rotation (spin axis) is free to assume any orientation by itself. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the momentum. Gyroscopes based on other

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operating principles also exist, such as the microchip-packaged MEMS gyroscopes found in electronic devices, solid-state ring lasers, fibre optic gyroscopes and the extremely sensitive quantum gyroscope Applications of gyroscopes include inertial navigation systems, such as in the Hubble Telescope, or inside the steel hull of a submerged submarine. Gyroscopes can be used to construct gyrocompasses, which complement or replace magnetic compasses (in ships, aircraft and spacecraft, vehicles in general), to assist in stability (bicycles, motorcycles, and ships) or be used as part of an inertial guidance system.

3. Design of Experiments

Design of Experiments is a method to determine the relationship between the input and output parameters. The present work considers two input factors such as speed and load to experimentally determine the value of gyroscopic couple. A 2 Factor Full Factorial Central Composite Design has been used for preparing the experimental layout and a total of 13 experiments need to be conducted. The experimental layout is prepared using the Design Expert V 11.0 Software. The software has capability to conduct comparative tests screening, characterization, optimization, robust parameter design, mixture designs and combined designs. The software determines the main effects of each factor as well as the interactions between factors by varying the values of all factors in parallel. The factors levels are coded as 1 for high values, 0 for middle values and -1 for lower level values. The Table 1 represents the input factors considered for conducting the experimental work in both coded and uncoded form.

4. Experimental Setup

A very simple setup for conducting the gyroscope experiment used with the undergraduate curriculum in engineering has been utilized for the present study. The setup consists a circular disc made up of mild steel weighing 2.5 kg with a diameter of 300mm and thickness 8mm. The circular metal disc is fitted to a frame and the base of the setup consists graduated scale in circular form for measuring the angle turned by the body when the load is applied. A DC motor is coupled with a voltage regulator through which the rotational speed of the disc can be varied by altering the voltage. Hollow cylindrical bars weighing 1 Kg and 0.5 Kg are used for applying the load to find the gyroscopic effect at a particular speed. A stopwatch is included to count the time for the maximum turning of the body. The Fig 1 shows the gyroscopic experimental setup and Fig. 2 (a) (b) (c) shows the weights used for loading, voltage regulator for varying speed and stopwatch for time calculation.

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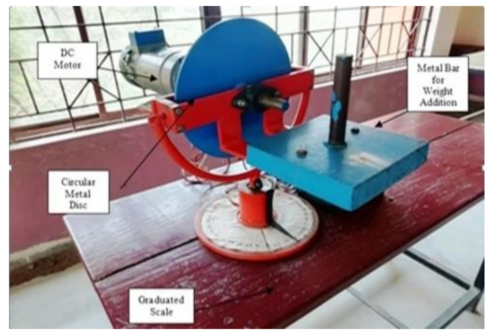

Fig. 1. Gyroscope experimental setup

Fig. 2. (a) Weights for loading (b) Voltage regulator (c) Stopwatch

Table 1
Input Factors in Coded and Uncoded form

S.No	Input Parameter	Symbol	Coded Factors			Uncoded Factors		
			Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
1	Speed	A	-1	0	1	600	750	900
2	Load	B	-1	0	1	0.5	1	1.5

6. Experimental Procedure

The experiments are conducted as per the experimental design matrix prepared through Face centered central composite design. The circular disc of the setup is made to rotate by varying the voltage of the DC motor and later to that load is added to the metal bar to know the gyroscopic effect caused with the combined effect of load and speed. The load applied causes the rotating disc to undergo gyroscopic effect and the body undergoes gyroscopic motion. The angle displaced by the body can be observed from the graduated scale and the time taken for the angular displacement is observed through the stopwatch. The Table 2 shows the experimental design Matrix prepared by Response Surface Methodology values are represented. Table 3 shows the measured values of angle turned and time taken and the calculated response gyroscopic couple.

Table 2
Experimental Design Matrix

Std	Run	Coded Values		Uncoded Values	
		A	B	A	B
		RPM	Kg	RPM	Kg
2	1	1	-1	900	0.5
9	2	0	0	750	1
6	3	1	0	900	1
3	4	-1	1	600	1.5
10	5	0	0	750	1
13	6	0	0	750	1
4	7	1	1	900	1.5
11	8	0	0	750	1
7	9	0	-1	750	0.5
5	10	-1	0	600	1
8	11	0	1	750	1.5
12	12	0	0	750	1
1	13	-1	-1	600	0.5

7. Measured and Calculated Outputs

The measured response such as angle turned, time taken are tabulated from experimental work and gyroscopic couple is calculated .The formulas used for calculating the gyroscopic couple is represented below. Table 3 represents the measured and calculated outputs.

$$C = I*\omega*\omega_P \quad (1)$$

$$I = \frac{mr^2}{2} \quad (2)$$

C- Gyroscopic Couple, Kg-m
m- Mass of the disc in Kg
r – Radius of the disc in mm
N – Speed of disc rotation in RPM
$d\theta$ – Angle turned by the disc in radians
dt – Time taken for the disc turning in secs

$$\omega = \frac{2\pi N}{60} \quad (3)$$

$$\omega_P = \frac{d\theta}{dt} \quad (4)$$

Mass of the Disc = Kg
Diameter of the Disc = 300 mm
Thickness of the disc = 8mm
I – Moment of Inertia, N-m^2
ω – Angular Velocity in m/s
ω_P = Angle of Precession

Table 3
Measured and Calculated Outputs

Std	Run	Response 1	Response 2	Response 3
		Angle	Time	Gyroscopic Couple
		Radians	Secs	Kg-m
2	1	0.35	5.28	0.175
9	2	0.79	7.5	0.231
6	3	0.96	7.5	0.339
3	4	1.40	7.5	0.329
10	5	0.79	7.5	0.231
13	6	0.87	7.36	0.262
4	7	1.57	8	0.520
11	8	0.79	7.4	0.234
7	9	0.26	5.54	0.104
5	10	0.70	5.4	0.228
8	11	1.48	7.84	0.418
12	12	0.79	7.4	0.234
1	13	1.00	5	0.353

8. Results and Discussion

The experimental results obtained through experimental work are tabulated in the prepared design matrix for further evaluation of results. The measured responses such as Angle turned and time taken are used for calculating the third response gyroscopic couple which is of the research interest in the current study. The detailed analysis of the output responses has shown the significant parameter over the measured responses and calculated responses in detail.

1) Angle Turned (R1)

In case of the angle turned the suggested model for analysis is found to be quadratic which includes the input parameters A, B and in combination AB and A2 for analysis. The Model F-value of 13.99 implies the model is significant. There is only a 0.16% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case B, AB are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The Lack of Fit F-value of 42.51 implies the Lack of Fit is significant. There is only a 0.17% chance that a Lack of Fit F-value this large could occur due to noise. Significant lack of fit is bad and the model needs to be made fit. Table 4 represents the ANOVA results for Angle turned and Fig. 3 represents the 3D contour for angle turned with input parameters.

Table 4
ANOVA table for angle turned

	Source	Sum of Squares	DF	Mean Square	F-value	P-value
Model	1.6817617	5	0.3363523	13.985879	0.00158	Significant
A-Speed	0.0080667	1	0.0080667	0.3354204	0.5806353	
B-Load	1.3442667	1	1.3442667	55.896	0.0001401	
AB	0.1681	1	0.1681	6.989772	0.0332387	
$\hat{A}^2$	0.0357635	1	0.0357635	1.4870853	0.2621597	
B^2	0.0653255	1	0.0653255	2.7162999	0.1433186	
Residual	0.168346	7	0.0240494			
Lack of Fit	0.163226	3	0.0544087	42.506765	0.0017167	Significant
Pure Error	0.00512	4	0.00128			
Cor Total	1.8501077	12				

Table 5
ANOVA table for time taken

	Source	Sum of Squares	DF	Mean Square	F-value	P-value
Model	13.163664	5	2.6327329	13.184263	0.0018935	Significant
A-Speed	1.3824	1	1.3824	6.9228162	0.0338572	
B-Load	9.4250667	1	9.4250667	47.199077	0.0002376	
AB	0.0121	1	0.0121	0.0605947	0.8126207	
$\hat{A}^2$	1.0830397	1	1.0830397	5.4236726	0.0527009	
B^2	0.411954	1	0.411954	2.0629933	0.1940591	
Residual	1.3978126	7	0.1996875			
Lack of Fit	1.3813326	3	0.4604442	111.7583	0.0002596	Significant
Pure Error	0.01648	4	0.00412			
Cor Total	14.561477	12				

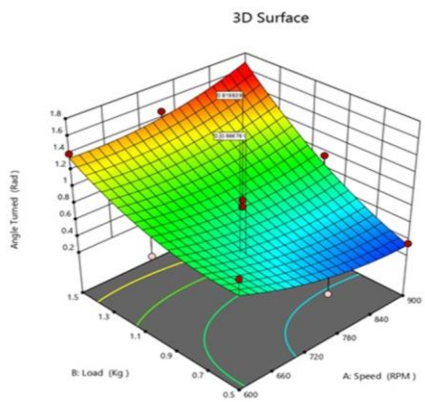

Fig. 3. 3D Contour representing the variation of Angle turned with Input Parameters

2) Time Taken (R2)

In case of the time taken the suggested model for analysis is found to be quadratic which includes the input parameters A, B and in combination AB and A^2 for analysis. The Model F-value of 13.18 implies the model is significant. There is only a 0.19% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The Lack of Fit F-value of 111.76 implies the Lack of Fit is significant. There is only a 0.03% chance that a Lack of Fit F-value this large could occur due to noise. Significant lack of fit is bad and the model needs to be made fit. Table 5 represents the ANOVA results for time taken and Fig 4 represents the 3D contour for time taken with input parameters.

3) Gyroscopic Couple (R3)

In case of the calculated output response gyroscopic couple the suggested model for analysis is found to be quadratic which includes the input parameters A, B and in combination AB and A^2 for analysis. The Model F-value of 13.65 implies the model is significant. There is only a 0.17% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case B, AB, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The Lack of Fit F-value of 23.63 implies the Lack of Fit is significant. There is only a 0.53% chance that a Lack of Fit F-value this large could occur due to noise. Significant lack of fit is bad and the model needs to be made fit. Table 6 represents the ANOVA results for gyroscopic couple and Fig. 5 represents the 3D contour for angle turned with input parameters.

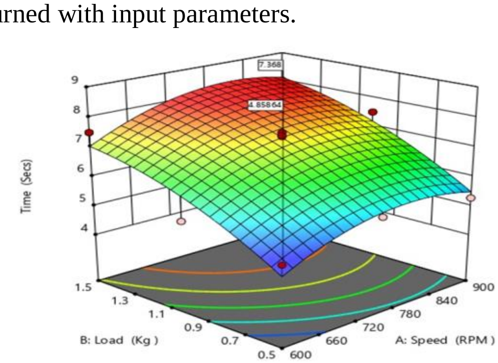

Fig. 4. 3D Contour representing the variation of Time taken with Input Parameters

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Table 6
ANOVA Table for Gyroscopic Couple

Source	Sum of	df	Mean	F-value	p-value	
Model	0.12869	5	0.02574	13.6457	0.0017	Significant
A-Speed	0.00256	1	0.00256	1.35867	0.28194	
B-Load	0.0672	1	0.0672	35.6302	0.00056	
AB	0.03404	1	0.03404	18.0474	0.0038	
$\hat{A}^2$	0.01114	1	0.01114	5.90764	0.04538	
B^2	0.00465	1	0.00465	2.46356	0.1605	
Residual	0.0132	7	0.00189			
Lack of Fit	0.0125	3	0.00417	23.63	0.00525	Significant
Pure Error	0.00071	4	0.00018			
Cor Total	0.14189	12				

$$\text{Angle} = +0.7803 - 0.0367*A+0.4733*B +0.2050*AB+0.1138*A^2+0.1538*B^2 \quad (5)$$

$$\text{Time Taken} = 7.33+ 0.4800*A+1.25*B +0.0550*AB-0.6262*A^2-0.3862*B^2 \quad (6)$$

$$\text{Gyroscopic Couple} = 0.2331 + 0.0207*A+0.1058*B+0.0923*AB+0.0635*A^2+0.0410* B^2 \quad (7)$$

The predicted equation for angle turned, time taken and gyroscopic couple in coded factors are represented in equations 5, 6, 7.

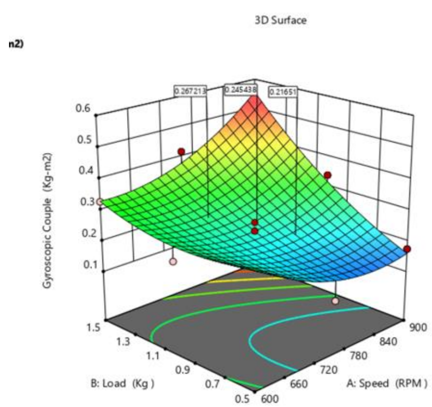

Fig. 5. 3D Contour representing the variation of gyroscopic couple with input parameter

9. Conclusion

The following conclusion may be drawn from the experimental results and ANOVA analysis.

- For both the measured and calculated output responses the model suggested for analysis is found to be quadratic.
- For all the three output responses lack of fit is found to be significant which is generally considered as bad and model need to be made fit.
- In case of the measured output response Angle turned the input parameter load and its product with speed is found to be significant. The input parameter speed is not found to be significant as per the p-test value as an individual.
- In case of the measured output response time taken both the input parameters load and speed are found to be significant as per p-test value. Load is highly significant than speed.
- In case of the calculated output response Gyroscopic couple the input parameter load is significant and the squared value of speed and the product of speed with load are found to be significant.

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