

Design of Experimentation for Formulation of Experimental Data Based Model for Stirrup Making Operation Using HPFM

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Abstract

In this present work of research is the design of experimental work to be executed for formulation of experimental data based model for stirrup making operation by using human powered flywheel motor. This paper presents an experimental investigations and Sequential classical experimentation technique has been used to perform experiments to establishment of stirrup making operation by using HPFM. An Attempt of minimum and maximum principle has been made to optimize the range bound process parameters for minimize the processing time, maximise the number of bends and maximize the processing torque. The influence of bending operation was studied experimentally by performing 144 experimental tests. By using experimental data various model is formed and comparison of these model with help of reliability, coefficient of determinate and analysis is done.

Keywords: Bar bending process, Stirrup, Buckingham's π theorem, HPFM, bar bending

1. Introduction

Formulation of experimental data based model for stirrup making operation by using human powered flywheel motor is formed by using Design of Experimentation (DOE), DOE is the planning process in a research study to meet specific objectives. The proper planning of an experiment is very much important consideration in order to achieve the research objectives clearly and efficiently with the right type of data and appropriate sample size.

The evolution of stirrup making operation using human power is a complex phenomenon. There are many factors affecting the performance of stirrup making operation. In this chapter the attempt is made to present the adopted design of experimentation in detail and to generate design data in the form of evolving experimental data based models for various dependant/ response variables of human powered stirrup making operation by carrying out experimentation.

1.1 Overview of stirrup making process

In this research work, since the process unit is stirrup making unit which is energized by human

powered flywheel motor (HPFM) i. e. Input energy unit, it becomes necessity to make the overview of the literature regarding bar bending processing or stirrup making machines.



Fig.1 Manually stirrup making process

Stirrups are rectangular shaped bars used in civil construction. Stirrups are the integral part of columns and beams construction. Stirrups provide strength to the cement column. Material used for making the stirrups is mild steel which is ductile in nature. So the bending of the bar carried out easily. Diameter of mild steel bar used for this purpose from 6,8,10 mm as per size of the construction. In Turn this process is time consuming and at the time more manpower is required. These results in increasing the overall cost & the time required to complete the work. The stirrup making unit offers employment opportunities for unskilled, semi-skilled and technically trained personnel for its operation.

1.2 Experimental Procedures for stirrup making by HPFM:

Stirrup making machine shown in fig.1 is utilized for stirrup bending operation and stirrup making operation by HPFM is performed as follows.

The operator drives the bicycle by pedalling the mechanism while clutch is in disengage position. The human power operated flywheel motor is energy source. This energy source energizes the process unit i.e. stirrup making unit through clutch and transmission. The flywheel is accelerated and energized which stores some energy inside it. When the pedalling is stopped, clutch is engaged and stored energy in the flywheel is transferred to the process unit input shaft by means of clutch. For

experimentation purpose MS plain and TMT rod samples of three different sizes were used.

During experimentation, the stirrup rod of three varying lengths i.e. 968.4mm, 1068.4 mm, and 1220.4 mm with two type of material i.e. 6 mm plain, 6 mm TMT having 6 mm diameter are processed in the stirrup bending machine by HPFM at four different speeds i.e. 300 rpm, 400 rpm, 500 rpm and 600 rpm at three different gear ratios 1/2, 1/3, and 1/4. Thus the two different types material are used during experimentation for monitoring the actual feasibility of the machine. During experimentation processing time, resistive torque, number of bends, time of flywheel to speed up etc. are measured using specially designed electronic kit i.e. instrumentation system as described below.

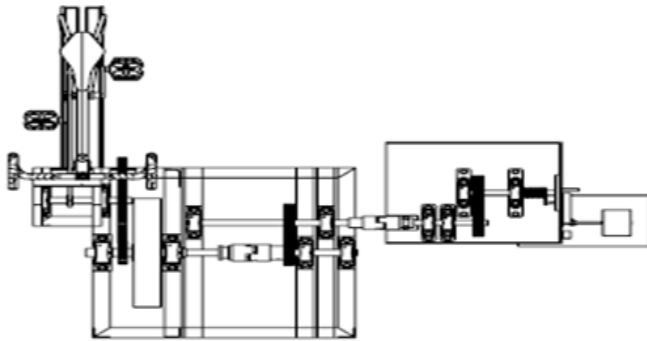


Fig.2 Schematic arrangement of stirrup making by HPFM.

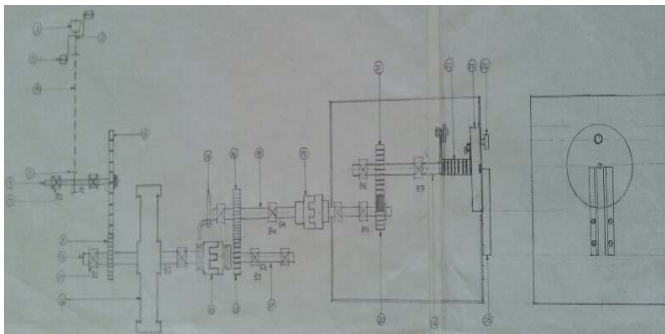


Fig.3 line diagram for stirrup making operation by HPFM

Following is the parts detail of stirrup making unit and human powered flywheel motor unit

1-Seating arrangement	9-Pinion	17-Shaft B3
2- Small Chain Sprocket	10-Shaft B2	18- Shaft B4
3 - Pedal	11-Bearing	19-Clutch for Process Unit
4 - Chain	12- Flywheel	20-3/4 th Teeth spur gear
5 -Large Sprocket	13 -Clutch	21-1/4 th Teeth spur gear
6- Shaft B1	14- Lever	22-helical spring
7-Bearing for bicycle	15- Gear II	23- Rotating Disk
8 - Gear I	16- Gear III	24- Rotating Pin

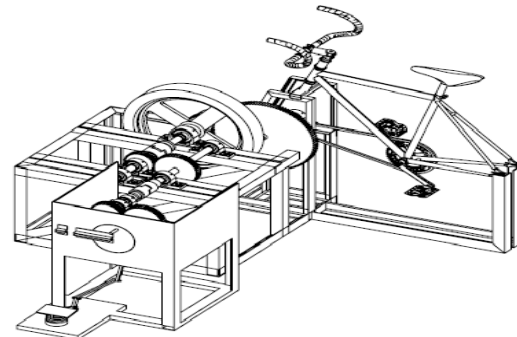


Fig.4 CAD Model of Experimental Set up



Fig.5 Fabricated view of actual experimental setup

2. Design of Experiment

A theoretical approach could be adopted in a case; if a known logic can be applied correlating the various dependent and independent parameters of the system. Though qualitatively, the relationships between the dependent and independent parameters are known based on the available literature references, the generalized quantitative relationships are not known some times. Whatever quantitative relationships are known pertains to a specific machining data and specific task.

Design of experiment involves following steps:

i) Based on the known qualitative physical characteristics of the phenomenon, identifying the independent and dependant variables which affect the phenomenon and establishing the dimensional equations for human powered stirrup making operatio is of prime importance. The experimentation becomes time consuming, tedious and costly if system involves large number of independent variables. So with the help of dimensional analysis one can reduce the number of variables and hence these reduced number of dimensional equations are the targeted form of mathematical models.

ii) Test planning consists of deciding test envelope, test sequence and plan of experimentation for the set of deduced dimensional equations.

It is necessary to evolve the physical design of experimental set up in setting up the test points, adjusting

the test sequence, execution of proposed experimental plan, noting down the responses and provision for necessary instrumentation for deducing the relation of dependent pi terms of the dimensional equation in terms of independent pi terms. Experimental set up is designed in such a way that it can accommodate the ranges of independent and dependant variables within the proposed test envelope of experimental plan. After noting down the responses and obtained dimensional relations of dependant pi terms of dimensional equations.

3. Dimensional Analysis

Dimensional analysis is a useful mathematical technique used in reduction of variables by forming non-dimensional groups of the variables which are called as pi (π) terms. Deducing the dimensional equation for a phenomenon reduces number of independent variables pi terms in the experiment. The exact mathematical form of this dimensional equation is the targeted model. Thus this method of dimensional analysis provides a systematic experimental planning and permits the presentation of results in more useful and concise format.

3.1 Identification of variables

The term variables are used in a very general sense to apply any physical quantity that undergoes change. If physical quantity can be changed independently of the other quantities, then it is an independent variable. If the physical quantity changes in response to the variation of one or more number of variables, then it is termed as dependent or response variable. If the physical quantity that affects our test is changing in random and uncontrolled manner, then it is called an extraneous variable. Depending upon the working operation of the stirrup making phenomenon by HPFM, the various dependent or response variables, independent variables and extraneous variables affecting the phenomenon are identified and the data purification is carried out to remove the extraneous variables to avoid their unwanted effect on the phenomenon. Table 1 shows

Table 1: Various dependant and independent variables for stirrup making operation by HPFM

Sr.	Variables	Unit	MLT
1	Tr = Resistive Torque-Dependent	N-m	ML ² T ⁻²
2	tp = Processing Time-D	Sec	T
3	nb = No.of actual bend per cycle-D	--	M ⁰ L ⁰ T ⁰
4	Ef = Flywheel Energy - Independent	N-m	ML ² T ⁻²
5	ωf = Angular speed of flywheel	rad /s	T ⁻¹
6	tf = Time to speed up the flywheel	Sec	T
7	ds = Diameter of stirrup	m	L

8	s = Size of stirrup	m ²	L ²
9	θ = Angle of bend	Degree	-
10	Hs = Hardness of stirrup	N/m ²	ML ⁻¹ T ⁻²
11	r = Distance between pin & center	m	L
12	G = Gear Ratio	--	M ⁰ L ⁰ T ⁰
13	k = Stiffness of spring	N/m	MT ⁻²
14	dr = Diameter of Rotating Disc	m	L
15	tr = Thickness of Rotating Disc	m	L
16	g = Acceleration due to Gravity	m/s ²	LT ⁻²
17	Ls = Length of stirrup	m	L
18	Es= Modulus of Elasticity of stirrup	N/m ²	ML ⁻¹ T ⁻²

D-for dependent variable and remaining term is Independent

It is seen from table 1 that there are total eighteen variables which affects the phenomenon of stirrup making operation by human powered flywheel motor. The fundamental physical dimensions to express all these eighteen variables are only three i.e. Mass (M), Length (L) and Time (T). Out of these total eighteen variables the first three variables are the dependant/ response variables and the later fifteen variables are independent variables.

3.2 Reduction of Pi terms by using Buckingham's II- Theorem

The Buckingham's II- Theorem method is used to form the pi (π) terms for all dependant/response and independent variables affecting the phenomenon of human powered stirrup making operation

3.3 Formation of pi (π) terms for independent variables:

Tr = Resistive Torque, tp = Processing Time, nb = No. of actual bend per cycle, Ef = Flywheel Energy, ωf = Angular speed of flywheel, tf = Time to speed up the flywheel, ds = Diameter of stirrup, s = Size of stirrup, θ = Angle of bend, Hs = Hardness of stirrup, G = Gear Ratio, k = Stiffness of spring, dr = Diameter of Rotating Disc, tr = Thickness of Rotating Disc, g = Acceleration due to Gravity, Ls = Length of stirrup, Es= Modulus of Elasticity of stirrup

Total Variable = 18

No of dependent variable = 03

No of Π terms = 15

Repeating Variable = g ,Ls , Es ,

Tr = f (Ef, ωf, tf, ds, s, θ, Hs, r, G, k, dr, tr, g ,Ls, Es)

OR f1 = f (Tr, Ef, ωf, tf, ds, s, θ, Hs, r, G, k, dr, tr, g ,Ls, Es) = 0

g, L_s, E_s are considered as the repeating variables (i.e. m = 3)

Total no. of independent variables = n = 15 and No. of Π terms = n – m = 15 – 3 = 12

f₁ (Π₁, Π₂, Π₃, Π₄, Π₅, Π₆, Π₇, Π₈, Π₉, Π₁₀, Π₁₁, Π₁₂,) = 0

First Π term:

$$\Pi_1 = (g)^{a_1} (L_s)^{b_1} (E_s)^{c_1} E_f$$

$$(M)^0 (L)^0 (T)^0 = (LT^{-2})^{a_1} (L)^{b_1} (ML^{-1}T^{-2})^{c_1} (ML^2T^{-2})$$

The values of a₁, b₁ and c₁ are computed by equating the powers of M, L & T on both sides as given below :

For 'M'	For 'L'	For 'T'
M → 0 = c ₁ +1	L → 0 = a ₁ + b ₁ -c ₁ +2	T → 0 = - 2a ₁ - 2c ₁
c ₁ = -1	(From eq. of T, subst. a ₁ = 0)	-0 = - 2a ₁ - 2(-1)-2, Hence a ₁ = 0
	0=0+ b ₁ - (-1)+2	Subst. in eq of L to get value of b ₁
	Hence b ₁ = -3	

Substituting the values of a₁, b₁ and c₁ in the eq. of Π₁ term, we have:

$$\Pi_1 = (g)^0 (L_s)^{-3} (E_s)^{-1} E_f$$

$$\Pi_1 = \frac{E_f}{L_s^3 E_s}$$

In the similar way the all remaining pi (π) terms for independent variables are calculated by dimensional analysis and are listed in the following table 2. The table 2 shows total eleven pi terms for independent variables

Table 2: Pi terms for independent variables

Independent Π terms			
Π ₁ = $\frac{E_f}{L_s^3 E_s}$	Π ₂ = $\omega_f \frac{\sqrt{L_s}}{\sqrt{g}}$	Π ₃ = $t_f \frac{\sqrt{g}}{\sqrt{L_s}}$	Π ₄ = $\frac{d_s}{L_s}$
Π ₅ = $\frac{s}{L_s^2}$	Π ₆ = 0	Π ₇ = $\frac{H_s}{E_s}$	Π ₈ = $\frac{r}{L_s}$
Π ₉ = G	Π ₁₀ = $\frac{k}{L_s E_s}$	Π ₁₁ = $\frac{dr}{L_s}$	Π ₁₂ = $\frac{tr}{L_s}$

3.4 Formation of pi (π) terms for dependent variables:

Now dimensional analysis for dependant variables Tr, t_p, n_b are performed as follows:

In the similar way, the dimensional analysis for dependent variables is performed by applying again Buckingham's Π- Theorem.

$$\Pi_{01} = (g)^{a_{01}} (L_s)^{b_{01}} (E_s)^{c_{01}} Tr$$

$$(M)^0 (L)^0 (T)^0 = (LT^{-2})^{a_{01}} (L)^{b_{01}} (ML^{-1}T^{-2})^{c_{01}} (ML^2T^{-2})$$

The values of a₀₁, b₀₁ and c₀₁ are computed by equating the power of M, L & T on both sides as given below :

For 'M'	For 'L'	For 'T'
M → 0 = c ₀₁ +1	L → 0 = a ₀₁ + b ₀₁ -c ₀₁ +2	T → 0 = - 2a ₀₁ - 2c ₀₁ -2
c ₀₁ = -1	0 = 0+ b ₀₁ +1+2	0 = -2a ₀₁ +2 - 2, Hence a ₀₁ = 0
	(From eq. of T, subst. a ₀₁ = 0) Hence b ₀₁ = -3	Subst. in eq of L to get value of b ₀₁

$$\Pi_{01} = (g)^{a_{01}} (L_s)^{b_{01}} (E_s)^{c_{01}} Tr$$

$$\Pi_{01} = (g)^0 (L_s)^{-3} (E_s)^{-1} Tr$$

$$\Pi_{01} = \frac{Tr}{(L_s^3)(E_s)}$$

In the similar way the all remaining pi (π) terms for dependent variables are calculated by dimensional analysis and are listed in the following table 3. The table 3 shows total three pi terms for dependent variables:

Table 3. Dependant variables Π terms

Π ₀₁ = $t_p \frac{\sqrt{g}}{\sqrt{L_s}}$	Π ₀₂ = nb	Π ₀₃ = $\frac{Tr}{(L_s^3)(E_s)}$
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3.5 Reduction of Variables

To reduce the complexity and to obtain the simplicity in the behavior of the phenomenon, the pi terms of independent variables are reduced by reduction of variables method as suggested by Schenk Jr. The following table 4 shows the new pi terms of independent variables in reduced form. Thus the total twelve pi terms of independent variables are reduced to seven new pi terms as shown table 4.

Table 4: New Pi terms in reduced form for independent variables

pi terms	pi terms equations	Description
π ₁	π ₁ = $\left(\frac{E_f}{L_s^3 E_s}\right)$	Geometric Term related to energy of Flywheel
π ₂	π ₂ = $(\omega_f \cdot t_f)$	Geometric Term related to angular speed and time required to speed up of flywheel
π ₃	π ₃ = $\left(\frac{K}{L_s E_s}\right)$	Geometric Term related to Stiffness of spring
π ₄	π ₄ = $\left(\frac{H_s}{E_s}\right)$	Geometric Term related to material properties ie. Hardness and elasticity
π ₅	π ₅ = $\left(\frac{d_s \cdot r \cdot d_r \cdot t_p}{L_s^4}\right)$	Geometric Term related to stirrup machine parameters

π_6	$\pi_6 = \left(\frac{S}{L_s^2}\right)$	Geometric Term related to Area of Stirrup
π_7	$\pi_7 = (\theta, G)$	Geometric Term related to angle of bent and Gear ratio

3.6 Dimensional Equation for Dependent Response Variables

For Processing Time (tp): The dependent variable /response variable, processing time (tp) can be expressed in terms of all the fifteen independent variables as shown below:

$$t_p = f(E_f, \omega_f, t_f, ds, s, \theta, H_s, r, G, k, dr, tr, g, L_s, E_s)$$

$$\text{OR } f_1 = f(Tr, E_f, \omega_f, t_f, ds, s, \theta, H_s, r, G, k, dr, tr, g, L_s, E_s) = 0$$

$$\Pi_{01} = f_1(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7, \Pi_8, \Pi_9, \Pi_{10}, \Pi_{11}, \Pi_{12}) = 0$$

$$\pi_{01} = \left\{ \left(\frac{E_f}{L_s^3 E_s}\right) \left(\omega_f \sqrt{\frac{L_s}{g}}\right) \left(t_f \sqrt{\frac{g}{L_s}}\right) \left(\frac{ds}{L_s}\right) \left(\frac{H_s}{E_s}\right) \left(\frac{r}{L_s}\right) \left(\frac{K}{L_s E_s}\right) \left(\frac{dr}{L_s}\right) \left(\frac{tr}{L_s}\right) \left(\frac{S}{L_s^2}\right) (\theta, G) \right\}$$

$$\left(t_p \sqrt{\frac{g}{L_s}}\right) = \left\{ \left(\frac{E_f}{L_s^3 E_s}\right) (\omega_f, t_f) \left(\frac{K}{L_s E_s}\right) \left(\frac{H_s}{E_s}\right) \left(\frac{ds, r, dr, tr}{L_s^3}\right) \left(\frac{S}{L_s^2}\right) (\theta, G) \right\}$$

$$(t_p) = \sqrt{\frac{L_s}{g}} \left\{ \left(\frac{E_f}{L_s^3 E_s}\right) (\omega_f, t_f) \left(\frac{K}{L_s E_s}\right) \left(\frac{H_s}{E_s}\right) \left(\frac{ds, r, dr, tr}{L_s^3}\right) \left(\frac{S}{L_s^2}\right) (\theta, G) \right\} \quad (1)$$

Similarly for number of bends (nb) and resistive torque (Tr), the dimensional equations are found as follows:

$$(n_b) = \left\{ \left(\frac{E_f}{L_s^3 E_s}\right) (\omega_f, t_f) \left(\frac{K}{L_s E_s}\right) \left(\frac{H_s}{E_s}\right) \left(\frac{ds, r, dr, tr}{L_s^3}\right) \left(\frac{S}{L_s^2}\right) (\theta, G) \right\} \quad (2)$$

$$(T_r) = L_s^3 E_s \left\{ \left(\frac{E_f}{L_s^3 E_s}\right) (\omega_f, t_f) \left(\frac{K}{L_s E_s}\right) \left(\frac{H_s}{E_s}\right) \left(\frac{ds, r, dr, tr}{L_s^3}\right) \left(\frac{S}{L_s^2}\right) (\theta, G) \right\} \quad (3)$$

The equations (1), (2) and (3) are the mathematical equations for three response variables (viz. processing time tp, number of bends nb and resistive torque Tr) of stirrup making phenomenon operated by human powered flywheel motor (HPFM) which are used for formation of mathematical models of these variables for stirrup bending phenomenon.

4. Test Planning

This comprises of deciding test envelop, test points, test sequence and experimental plan Hilbert Schenck Jr (1961) [4] for the deduced set of dimensional equations. Range of pi from the data of the values of various variables can be substituted in the equation to get the values of pi term. If these values are arranged in the descending or ascending order, the maximum and minimum values of pi term can be calculated to get range for pi. These ranges for pi term are given in Table

Test Envelope: Deciding the end points or limits comprises the test envelope and it is obvious and best way

to select or fix the test points. All such test points are covered in the test envelope.

Test Points: The spacing of the test points within the test envelop is selected not for getting a 'symmetrical' or a 'pleasing' curve but to have every part of our experimental curve map the same precision as every other part.

Test Sequence: In classical or sequential plan, the variables are varied from one extremity to the other in a sequential manner, in the random plan those are varied in random fashion. The classical plan or sequential plan is essentially opted for irreversible experiments or where there is no scope for randomization.

Table5 : Test envelope, test points for Sliver cutting operation by HPFM

Pi Term Equation	Test Envelope	Test Points	Independent Variable in Its own range
π_1 =Geometric Term related to energy of Flywheel $\pi_1 = \left(\frac{E_f}{L_s^3 E_s}\right)$	5.49E-09 to 4.53E-08	5.49E-09, 5.65E-09, 8.18E-09, 8.43E-09, 9.76E-09, 1.01E-08, 1.1E-08, 1.13E-08, 1.45E-08, 1.5E-08, 1.52E-08, 1.57E-08, 1.95E-08, 2.01E-08, 2.2E-08, 2.26E-08, 2.27E-08, 2.34E-08, 3.05E-08, 3.14E-08, 3.27E-08, 3.37E-08, 4.39E-08, 4.53E-08	If=3.44 kg-m ² $\omega_f=31.4, 41.86, 52.33, 62.8$ $E_f=0.51 \omega_f^2=1695.85, 3014.84, 4710.69, 6783.40$ $L_s=968.4, 1068.4, 1220.4$ (mm) $E_s=165000$ N/mm ²
π_2 =Geometric Term related to angular speed and time required to speed up of flywheel $\pi_2 = (\omega_f, t_f)$	659.4 to 3516.8	659.4, 785, 879.2, 942, 1099, 1172.267, 1256, 1318.8, 1465.333, 1570, 1674.667, 1758.4, 1831.667, 1884, 2051.4672093.333, 2198, 2564.333, 2637.6, 2826, 2930.667, 3077.2, 3297, 3454, 3516.8	tf=21, 25, 28, 30, 35, 40, 42, 45, 49, 55, 56, 63 $\omega_f=31.4, 41.86, 52.33, 62.8$
π_3 =Geometric Term related to Stiffness of spring $\pi_3 = \left(\frac{K}{L_s E_s}\right)$	1.47E-08 to 1.91E-08	1.47E-08, 1.52E-08, 1.68E-08, 1.73E-08, 1.86E-08, 1.91E-08	K=3.0545N/mm $L_s=968.4, 1068.4, 1220.4$ (mm) $E_s=165000$ N/mm ²
π_4 =Geometric Term related to material properties ie. Hardness and elasticity $\pi_4 = \left(\frac{H_s}{E_s}\right)$	1.264706 to 1.272727	1.264706, 1.272727	Hs=21000Mpa $E_s= 165000$ N/mm ²
π_5 =Geometric Term related to stirrup machine parameters $\pi_5 = \left(\frac{ds, r, dr, tr}{L_s^3}\right)$	3.94E-07 to 1.49E-06	3.94E-07, 5.92E-07, 6.71E-07, 9.95E-07, 1.01E-06, 1.49E-06	ds = 6 mm Plain , 6 mm Twist r = 45, 67.5 (mm) dr = 180 mm tr = 18 mm $L_s=968.4, 1068.4, 1220.4$ (mm)
π_6 =Geometric Term related to Area of Stirrup $\pi_6 = \left(\frac{S}{L_s^2}\right)$	0.04371 to 0.046895	0.04371 to 0.045941 to 0.046895	S = 179x229= (40991), 229x229= (52441), 229x305 (69845) (mm ²) $L_s=968.4, 1068.4, 1220.4$ (mm)



International Journal and Conferences. He is recipient of U.P. Government Award-2015 from ISTE, New Delhi (India) for outstanding work done in Engineering. He received young delegate award of \$500 in 13th World Congress of IFToMM at Guanajuato, Mexico. He also received three Governments funding of Rs. 30 Lacs under RPS scheme from AICTE, New Delhi. He also published books on “Analysis of Automotive Driveline System using Finite Element Approach”, LAP Lambert Academic Publishing, Germany.