Statistical Optimization of Power Generation From A Piezoelectric Transducer Equipped Automobile Tire

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ABSTRACT:

A 10-inch aluminium forged wheel assembly equipped with piezoelectric transducers is fabricated and analysed using the statistical methods and found the optimum loading parameters. The loading parameters considered were Normal Load, Angular velocity and Internal Tyre Pressure. Whereas the output of current experimental setup is power generated and these factors are evaluated using the Taguchi and ANOVA optimization methods. The findings of this experiment state that the maximum influence is caused by the normal load followed by the internal tyre pressure and then the angular velocity. As per the statistical methods suggested the net power output is found to be maximum when the optimum input parameters are given, thus supports the analysis.

Key words: *Wheel rim, Piezoelectric transducers, Taguchi, ANOVA*

1. Introduction:

To meet the continuous growth in transportation needs of the world the development of new technologies in transportation which can be led the humanity to sustainability became quite necessary in these recent times. Even though there are several new alternative transportation mediums' the major considerable alternative is Electric vehicles as they offer several advantages over other alternatives like Air compressed Engine, etc. The transition from conventional internal combustion engines to electric motors is not quite simple, the limitations of electric vehicle must be eliminated before the transition is done. There are several current developing technologies which are working towards the improvement of efficiency and range of an electric vehicle, the piezoelectric wheel rim is amongst those[1]. The wheel rim is very crucial component of any vehicle as the power is transmitted from the source to the ground via wheels, so the wheel needs to be designed in such a way that the safety and the performance of the vehicle is optimum.

2. Materials and Methods

The piezoelectric wheel rim is designed and fabricated in such a way that the weight of the wheel is between optimum range. In this Work, the 10-inch aluminium forged solid wheel rim is equipped with the composite ceramic high voltage piezoelectric transducers in the inner section of the tyre and the transducers are connected in a series column wise and parallel in the row wise, such that the voltage generated in the circuit is constant. The positive terminal is coupled to battery via a slip ring component designed to extract the power generated in piezoelectric wheel rim and the negative terminal is coupled to the wheel base itself as it acts a ground.

When the vehicle is in motion due to the external forces acting on the wheel such as the normal load of the vehicle which includes the weight of the vehicle and the passenger combined and the internal tyre pressure which is acting on the walls of the tyre and the wheel rim. The piezoelectric transducers placed are subjected to compressive loads. As the principle suggests the piezoelectric effect "the mechanical strain is converted into electrical energy or vice versa" the strain produced due to the loading in the transducers is converted into electrical energy. This energy is stored in the battery. In order to generate electrical energy continuously the loads on the transducers must be applied and removed in a frequency, this is only possible when the vehicle is moving, the frequency of the loading is determined via the angular velocity of the wheel rim, the greater the velocity the greater the frequency of load application the greater the power generated [2-4].

2.1 Factors Influencing the Power Generation:

Even though there are several factors influencing the wheel rim, in this paper the factors which contribute to the power generation are only considered. The ineffective factors which contribute less percentage are eliminated and not considered. The major factors influencing the power generation in piezoelectric wheel are Normal load, Angular velocity and the Internal tyre pressure[5-8].

(a) The Normal load is also a major factor influencing the efficiency as the load acting is equally distributed between the tyres(assumed) the weight of the vehicle and passenger combined is divided by the number of wheels and the mechanical load acting on the piezoelectric transducer is given by the mechanical load in vertical direction by the surface area of the transducer, so as the load increases the mechanical stress applied on the transducer increases and power generation capacity increases and lesser the load the lower the power generation.

(b) Angular velocity is taken as a randomly varying factor as it will be varying continuously under motion due to several reasons like braking or stopping and acceleration of the vehicle, the angular velocity is defined as the angular displacement per second, the units are radians per seconds. The effect of angular velocity on the piezoelectric transducer is such as a way that the wheel rotates the load will act on the portion of the tyre which is known as the eye of the tyre. The transducers placed in that portion will experience the loading and power is generated when the load is removed from the transducers. Hence, the faster the wheel rotates the faster the eye of tyre changes its position on the tyre and the faster the power is produced.

(c) The internal tyre pressure affects the tyre contact area and the effectiveness of load acting on the piezoelectric transducers. The correct inflation leads to perfect contact between the tyre and road which in turns increases the load acting on the piezoelectric transducers. Where as in case of under inflation or over inflation the contact area between tyre and road decreases which decreases the efficiency of the power generation.

2.1. Piezoelectric Transducers:

Piezoelectric transducers are the devices which work on the principle of piezoelectric effect and convert the mechanical strain into electrical energy or vice versa. Even though there are several types of piezoelectric transducers present in the market like PZT, PVDF, etc. The optimum material choice would be the ceramic based PZT element. PZT element possess characteristics like high mechanical resilience, can be stacked on one other to increase the efficiency, high voltage generation, etc.[9].

2.1.1. Piezoelectric Strain Coefficient

The piezoelectric strain coefficient quantifies the change in volume of the material when ever a mechanical load is applied on the material or whenever an electrical energy is applied to the material.

2.1.2. Piezoelectric Voltage Coefficient

The piezoelectric voltage coefficient quantifies the electric field generated due to application of mechanical load or electrical energy in the piezoelectric material. In other words, it is the mechanical strain experienced by the piezoelectric material per unit electric displacement applied. The dimensions and other piezoelectric constants of the piezoelectric material is listed in the table 1.

Table 1. Dimensions and Piezoelectric Constants.

SL.NO	PARAMETER	VALUE
1	Diameter of PZT module (d)	28 mm
2	Thickness	2 mm
3	d33	$350*10^{-12}$ C/m^2

4	g33	$16.6*10^{-3}$ Vm/N
5	Electromechanical coupling	0.69

3. Loads Calculations:

Even though there are several static and dynamic loads acting on the wheel rim, in this work, the loads are considered which are acting towards the power generation. The loads acting on the wheel rim are reduced to the following two loads[10, 11].

A. load due to the weight of the vehicle and passenger.

B. Load due to internal tyre pressure.

3.1. Loads due to the weight of the vehicle and passenger: The weight of the vehicle is supported by the wheels so the intensity of the load is equal the total weight of the vehicle divided by the number of wheels of the vehicle. The load intensity (PW) is given by the equation.

PW = N/M……………………….. Eq (1)

PW = load due to weight of the vehicle on each wheel

N = total weight of the vehicle

M = number of the wheels.

3.2.Load due to internal tyre pressure: Wheel is equipped with the tyre for performance and comfort parameters, the tyres are needed to be maintained at a constant pressure for maximum performance and comfort, the internal pressure between the tyre and the wheel rim applies an equal pressure on both the areas and this is given by the below equation. The standard tyre pressure (PI) is taken as 0.241 Mpa.

PI = 0.241 Mpa…………………. Eq (2)

3.3.Loads Acting on Piezoelectric Elements:

The loads acting on the piezoelectric transducers are mechanical load applied due to the combination of weight of the vehicle and internal tyre pressure, the load calculations are done by using the formulae Eq(3) to Eq(10).

Table 2. Loading conditions

Sl no.	Parameter	Value
1	Weight of the vehicle	150kg
2	Weight distribution 50:50	50:50
3	Wheel Radius	254 mm (10-inch)
4	Tire Air Pressure	0.30 Mpa

3.4.Number of modules mounted on each wheel (N)

The maximum number of modules that can be mounted or installed in the wheel is known as the N where it is evaluated by the circumference of the wheel divided by the sum of the diameter of the piezoelectric element and the suitable clearance gap between the two consecutive modules or elements.

N = (Circumference of the wheel) / (Diameter of element +gap between two modules) Eq (3)

N = π * 254/(28mm+2mm) = 56

Therefore, the total number of modules in each wheel is 56.

3.5.Contact patch area(c)

Contact patch area(c) is defined as the area of contact of the wheel when it is rest or in motion, this is evaluated by the load acting on each wheel divided by the internal tyre pressure.

C = Load on the wheel/internal tyre pressure ………. Eq (4)

C = ((150 * 9.81) /0.28) =5928.40947 mm^2

3.6.Mechanical stress induced

It is defined as the stress induced in one piezoelectric element due to the load applied on the tyre, this is evaluated by the ratio of total load to the contact patch area.

σ = (load on the wheel/ contact patch area) …. …. Eq (5)

σ = (150 * 9.81) / 5928.40947 = 9022134.375 N/mm^2

3.7.Open Circuit Voltage (OCV)

Open Circuit Voltage is the maximum voltage produced due to the load applied and it is the product of the constant piezoelectric voltage coefficient(g33), mechanical stress induced and the thickness of the module.

OCV = g33 * σ * t…. ….. Eq (6)

σ = induced mechanical stress in the module

t = thickness of the module

Therefore,

O.C.V = 16.6 * 10^{-3}* (9022134.375) * 0.002 = 16.52 V

3.8. **Power Generated in One Element:**

Power generated in one element is evaluated for one revolution. In one revolution the load is applied and removed from the element in such a way that it acts as a cyclic load which produces the continuous power as the wheel rotates the location of the load application changes which enables the pulsating action required to generate the power through piezoelectric transducers.

3.8.1. Charge density(D)

It is the capacity of the charge that can be produced by the mechanical strain in the element and it is the product of the piezoelectric strain coefficient(d33) to the mechanical stress induced in the module.

Charge Density (D) = d33 * σ……………….……Eq (7)

D = 350 * 10-12 * 9022134.375 = 3.16* 10^{-3} C/MM^2

3.8.2. Charge on each module(Q)

It is the product of charge density to the area of the piezoelectric module and it is defined as the charge produced in one element due to application of the load.

Charge on each module(Q) = D * π * 0.014^2…...Eq (8)

Charge on each module(Q) = 1.94* 10^{-6} Amps.

3.8.3 Power generated in each module (P):

It is the product of open circuit voltage and the charge on each module

Power Output by each module =OCV * Q……………. Eq (9)

P =16.52 * 1.94 = 3.21*10^{-5} W

3.9. Total Power Generated (pt):

It is the total power generated in the wheel for one revolution due to application of the mechanical load.

Total power output(pt) = Power Output by each module * Number of modules in the wheel. …. Eq (10)

pt = 3.21* 10^{-5} * 56 = 1.80* 10^{-3} Watts.

The power generated is about 1.80 * 10^{-3} Watts per sec.

Table 3. Load calculation results

Sl.No	Parameter	Value
1	Mechanical stress induced (σ)	9022134.375 N/mm^2
2	Number of modules(N)	56
3	Contact patch area(c)	5928.40947 mm^2
4	Open Circuit Voltage (OCV)	16.52 V
5	Charge density(D)	3.16E-03 W/mm^3
6	Charge on each module(Q)	1.94E-06 Amps.
7	Power generated in each module (P)	3.21E-05 W
8	TOTAL POWER GENERATED (p_t)	1.80E-03 Watts.

4. Taguchi Optimization Method

Taguchi optimization method is widely used in the research and development to reduce the occurrence of the defective characteristics in the product, thus improving the quality of the product. In this work the Taguchi method is employed to improve the quality and quantity of the output, which means to optimise the power generated from the product by selecting the best input parameters[12].

In this method the key deciding parameters have a great influence on the output of the product, to determine the best level of the factor which produces the maximum output is known as “STATIC PROBLEM”.

(a)**Signal to Noise Ratio**

The robustness metric used to discover control elements that minimize the effects of random variables to reduce variability in a product or process (noise factors). There are three main signals to noise ratios by which we can determine the optimised levels.

(b)**Larger the Better**

In this criterion the reciprocal of the measured value and taking the S/N ratio as the largest case to be better.

n = -10 Log10 [mean of sum squares of reciprocal of measured data] ……Eq (11)

(c)**Nominal the Better**

In this criterion the reciprocal of the measured value and taking the S/N ratio as the nominal case is the better.

$n = 10 \text{ Log10 } (\text{Square of mean} / \text{ Variance})$……… Eq (12)

(d)**Smaller the Better**

In this criterion the reciprocal of the measured value and taking the S/N ratio as the nominal case is the better/

n = -10 Log_{10} [mean of sum of squares of measured data] ………Eq (13)

By considering the factors effecting the performance of the piezo electric power generation, three levels of loading conditions are used to calculate and evaluate the power produced in these three levels by varying the three input parameters.

To obtain the number of experiments to get optimized results, the Taguchi Orthogonal arrays are used, in this case L9 design of 2-3 levels design is used to generate the experimental input loading conditions.

The below table consists of three input parameters with three different levels of loads used to generate the Taguchi L9 design which is later used to for Analysis of variance (ANOVA) and standard deviation.

Table 4: Initial Loading Conditions

Level	Tyre pressure (psi)	Angular velocity (rad/sec)	Normal load (kilogram)
1	20	417.72	150
2	25	522.16	200
3	30	574.37	250

The Taguchi L9 design is given by the table 5, the above Table 4 is compared with the three levels and three columns to generate the required design to conduct experimental calculations using Minitab Statistical software Version 2021.[13]

Table 5. Taguchi orthogonal array L9 design for three input parameters.

A	B	C
1	1	1
1	2	2
1	3	3

2	1	2
2	2	3
2	3	1
3	1	3
3	2	1
3	3	2

The table 6 is obtained by the replacing the values in the Table 5 by the input parameters mentioned in the table 4 and the response is obtained by the calculations and the responses are stored in the Table 7.

Table 6: Orthogonal array merged with the input parameters

Tyre Pressure	Velocity	Load
0.2	417.7	100
0.2	522.16	150
0.2	574.37	200
0.25	417.7	150
0.25	522.16	200
0.25	574.37	100
0.3	417.7	200
0.3	522.16	100
0.3	574.37	150

5. ANOVA

ANOVA is used to determine if survey or experiment results are valid or not. In other words, they assist in determining whether the result should accept the alternative hypothesis or reject the null hypothesis. The t-test is generalised beyond two means by ANOVA, which offers a statistical test for the equality of two or more population means. In other words, the ANOVA is employed to determine if two or more means differ from one another[14, 15].

6. RESULTS AND DISCUSSIONS:

Table 7: Solution values of Loading conditions.

Tyre Pressure	Velocity	Load	Power Generated
0.2	417.7	100	0.993939716
0.2	522.16	150	1.656566194
0.2	574.37	200	2.277778516
0.25	417.7	150	1.060202364
0.25	522.16	200	1.656566194
0.25	574.37	100	1.093333688
0.3	417.7	200	1.104377463
0.3	522.16	100	0.828283097
0.3	574.37	150	1.214815209

The Table 7 consists of the experimental initial conditions along with the power generated in the piezoelectric transducers per sec in the wheel, by evaluating the results (power generated) the graphs and standardized data of standard deviation and analysis of variance are generated using Minitab software by providing the response as power generated and the factors are taken as Tyre pressure, Angular Velocity and Normal load. To analyze the Taguchi Model, it is mandatory to have a response which will be Power generated in this case as the aim of this project is to produce power, so the response is taken as the power generated. In this analysis the response is considered as the larger the better, cause the power generated must be maximum to increase the efficiency.

In figure 1 the maximum value of the power generated is observed and recorded for the input parameters, tyre pressure (0.25 Mpa), Angular velocity (522.1610835 Rad/Sec) and Load (2452.5 Newtons), the minimum value of the power generated is observed and recorded for the input parameters, tyre pressure (0.3 Mpa), Angular Velocity (522.1610835 Rad/Sec) and Load (1471.5 Newtons). The maximum and Minimum values of power generated are supporting the graph in figure 2 and table 8 data in terms of the type of effect produced by the three factors on the power generated.

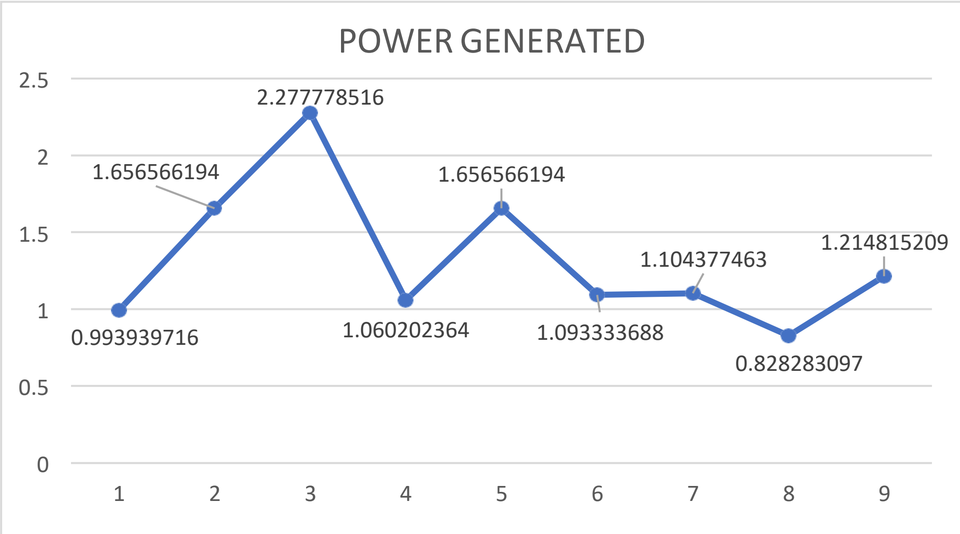

Figure 1: Graph Representing Power Produced in Respective Experiments.

6.1 MEANS:

The Taguchi model defined is analyzed using the response as the power generated and the means obtained from the table 8, the delta is Delta is the difference between the maximum and minimum average response (signal-to-noise ratio or standard deviation) for the factor. The Rank is the rank of each Delta, where Rank 1 is the largest Delta and followed by the rest.

Table 8: Response Table for Means

Level	Tyre Pressure	Velocity	Load
1	1.6428	1.0528	0.9719
2	1.2700	1.3805	1.3105
3	1.0492	1.5286	1.6796
Delta	0.5936	0.4758	0.7077
Rank	2	3	1

In the above Table 8 as per the obtained table the load is ranked as the 1st, highest delta, followed by the tyre pressure and then the angular velocity of the wheel rim. The main effects plot for means are plotted versus the mean of means in the figure 2 indicates that the value of power generated when tyre pressure is level 1, the velocity is level 3 and the load is level 3 is maximum and optimum value whereas the power generated when the tyre pressure is level 3, the velocity is level 2 and the load is level 1 is minimum value the mean value is obtained when the tyre pressure is level 2, the load is level 2 and the velocity is level 1.

By observation the internal tyre pressure of the tyre must be minimum to generate maximum power as the standard rated tyre pressure is 0.25 Mpa for 10 inch – 19- inch alloy wheels the power generated will be optimum and if the tyre pressure is maintained higher than the rated pressure the efficiency of the power generation will be reduced by a greater value.

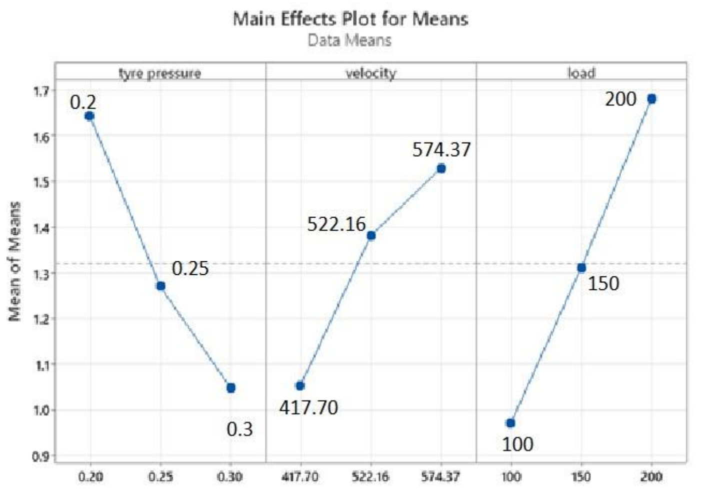

Figure 2: Mean of Means versus Main Effect plot for Means

The angular velocity is affecting the power generated in a positive way as the angular velocity of the tyre increases the frequency of the load applied on the piezoelectric transducers placed in the eye of the tyre (a sectional portion of the tyre where the load is acted maximum) will be increased and the power generated per min will be increased. The normal load is directly acting upon the wheel rim so the greater the load the greater the power generation efficiency as the graph states the value is power generated value is incremented linearly so the load is affecting the power generation linearly.

6.2 Signal to Noise Ratio:

Table 9 consists of the response table for signal to noise ratios of the power generated versus load, velocity and the load, this response table is very similar to that of the response table for mean of means in Table 8 as the data in table 9 is also ranked by the value of the delta, in this table the highest value of delta is occupied by the Load then followed by the tyre pressure and then the lastly the velocity.

Table 9: Response Table for Signal to Noise Ratios

Level	TYRE PRESSURE	VELOCITY	LOAD
1	3.8272	0.4391	-0.3047
2	1.8890	2.3773	2.1941
3	0.3054	3.2052	4.1323
Delta	3.5218	2.7661	4.4370
Rank	2	3	1

In this figure 3 the values of main effects of the SN ratios are plotted against the Mean of SN ratios, after observation this plotted graph is almost identical to the graph in figure 2 but there is slight difference in the mean.

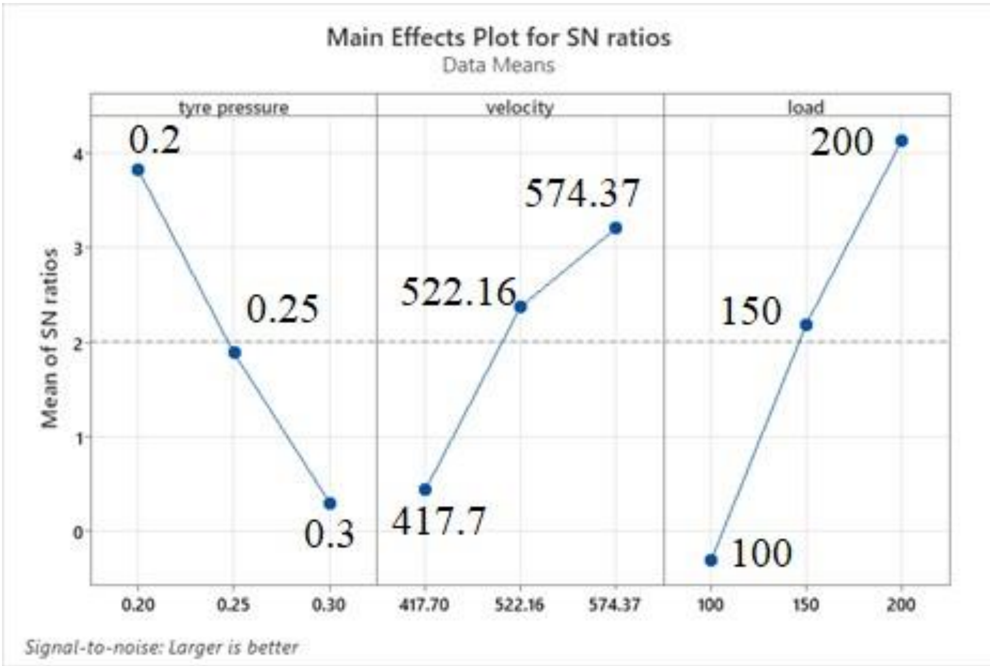

Figure 3: Main effects plot for SN ratios versus Mean of SN ratios.

values of the means and the means values of the SN ratios, after these graphs are obtained the Taguchi model is analyzed completely.

6.3 Analysis of Variance (ANOVA):

Analysis of variance is performed using Minitab Statistical where the data set from the Taguchi model mentioned in Table 10 are fitted into the ANOVA model where the Power generated is taken as the response and the factors are taken to be tyre pressure, velocity and the load. The results obtained from the analysis are discussed below

The factor coding is taken to be (-1, 0, +1) while solving the general linear model Power generated versus tyre pressure, velocity, load. The factors are considered to be random as the environment, driving conditions, road texture play an exclusive role in deviating the values from fixed value. It is not possible to maintain the fixed values of the factors at all conditions, so the values are taken to be random.

By taking the factors and the responses from the power generated the Analysis of variance is performed and the obtained results are stored in the Table 10 which consists the percentage of contribution of each factor towards obtaining the maximum value of the power generated.

The percentage of contribution is obtained by the taking the value of the Adjusted Sum of Squares of each factor to the total value of Adjusted Sum of Squares. The sum of the percentage contribution must be cent which is fulfilled in this analysis.

The maximum contribution to achieve maximum power generated is load as the load is directly acted upon the piezoelectric transducers in terms of mechanical stress induced, the greater the load the greater the value of the mechanical stress induced which in turn gives a greater value of the power generated, so 45.06 % of contribution is done by the load.

Table 10: Analysis of Variance (ANOVA).

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Of contribution
Tire Pressure	2	0.5400	0.27004	25.85	0.037	32.37%
Velocity	2	0.3556	0.17784	17.03	0.055	21.32%
Load	2	0.7517	0.37588	35.98	0.027	45.06%
Error	2	0.0208	0.01045			1.25%
Total	8	1.6684				100%

The tyre pressure contributes 32.37% to maximize the response because the tyre pressure maintains the contact between the tyre and the road which is essential to achieve the load application on the wheel rim, so the correct tyre pressure not only increases the tyre efficiency, durability, and road grip. So, the tyre pressure is placed second in the percentage of contribution to the power generated.

Even though the velocity is contributing 21.32% of the total factor effecting the performance of the power generation, it is considered to be the important as it is mandatory to create a pulsed condition to generate power the load needs to be applied and removed the application of the load is caused due to the load the removal of the load is caused by the velocity. The greater the velocity the greater the application of the load and the frequency of the power generated.

The remaining 1.25% is Error while performing the analysis as the value of the error is less than 5% it is considered to be accepted as the confidence level of the test is taken to be 95.

The above data supports that the major factors effecting the efficiency of the power generated using the piezoelectric transducer equipped wheel rim under various loading conditions and the optimum Input loading conditions are found where the power generated per sec in the wheel rim is maximum.

7. CONCLUSION

1) The power generation using the piezoelectric wheel rim is quite effective, this statement is supported by the Engineered prototype and the analysis data from the statistical methods.

2) The optimum Input parameters are obtained and verified using the ANOVA and the Taguchi optimisation method.

3) Load, Angular velocity, and the Internal tyre pressure are found to be the major factors effecting the power generated in a piezoelectric wheel rim.

4) The load is the most contributing factor followed by the Internal Tyre pressure and the angular velocity which effect the rate of power generation.

5) The maximum value of power generated is obtained when the load and the angular velocity are at maximum and the tyre pressure is at minimum.

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