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A STUDY OF SPEED BREAKER POWER GENERATION AND CONTACT STRESS ANALYSIS OF GEARS BY FEM

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Abstract*- Harnessing waste energy is an alternative way to generate electricity. Speed breaker power generation unit (SBPGU) is a propitious method to trap waste energy at speed breaker. This unit uses rack and pinion mechanism with an aid of intermediate gear mechanism which converts waste potential energy of a vehicle at speed breaker to useful mechanical energy. Unlike other methods it yields power from both upward and downward motion of the rack. It generates about 43 watts from one push of 65 kg weight. which can convert into electric energy by generator and later stores in batteries. In this particular study gear, rack and pinion were used for fabrication of the experimental setup. The life cycle of gears is mainly depending upon the stressed developed in it. Bending and contact stresses are two major stresses that the gears experience the most. Contact stresses of rack and spur gear were analyzed under static loading conditions using Hertz theory and finite element analysis.*

Keywords: Power generation, Speed breaker, Rack and pinion mechanism, Hertz theory, Finite element analysis.

1. INTRODUCTION

Conventional energy sources like fossil fuel, nuclear reaction generates most of the energy of today's world. These are effective means but responsible for global warming. Particularly in Bangladesh, where demand is high but environment is vulnerable. As of 2015, 92% of the urban population and 67% of the rural population had access to electricity. An average of 77.9% of the population had access to electricity in Bangladesh. sustain its economic growth Bangladesh requires an estimated 34,000 MW of power by 2030. As of 2011, 79 natural gas wells were present in the 23 operational gas fields which produce over 2000 millions of cubic feet of gas per day (MMCFD). Use of natural gas no longer will be possible because natural gas reserves are expected to expire by 2020 [1]. Below Figure 1 showing use of fossil fuel in electricity generation of Bangladesh in January of 2019.

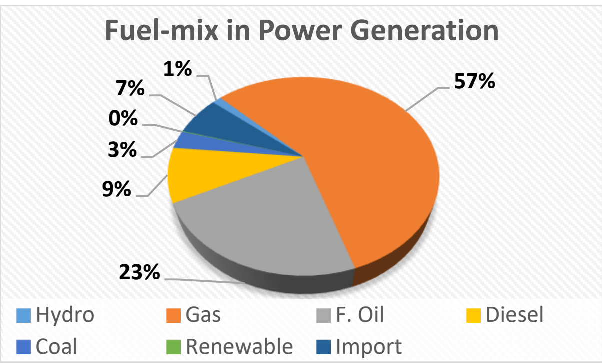

Fig.1: Power generation by sector in Bangladesh [2].

Energy harvesting is the process by which energy is derived from external sources [3]. Mechanical energy associated with motion and vibration is ubiquitous but usually wasted. It has pulled in tremendous attention from scientists around the world to scavenge such mechanical energies. Various process develops to scavenges mechanical energy. Such as photovoltaics and thermoelectric generators. Scientist and engineers also work on fluid flow, pyroelectric effect electrostatic, magnetic induction, ocean energy to harvest energy.

Bangladesh is a developing country. Vehicle and infrastructure is essential for development of a country. Use of car in Bangladesh increase rapidly. Presumably it will be grow higher in coming age. Car speed needs to control by introducing speed breaker. Speed bumps (or speed breakers) are the common name for a family of traffic calming devices that use vertical deflection to slow vehicle traffic in order to improve safety conditions [4]. Speed bumps are effective in keeping vehicle speeds in range. A speed breaker is a bump in a roadway with heights typically ranging between 7.5 to 10 cm. The traverse distance of a speed bump is typically less than or near to 30 cm. Speed bumps vary in length, but it is typical to leave space between the bump and either edge of an enclosed road. Every speed breaker is now a potential source of electricity. As number of vehicle is increasing it is high time to replace typical speed bump to a unit like the "Power Generation Unit from Speed Breakers", much of energy can be trapped. This energy can further use for the lights on the either sides of the roads or other commercial use. Amount of speed breaker also increasing to control traffic flow caused by growing number of vehicle. A chart in Figure 2 below showing increasing of number of vehicle in Bangladesh over the years.

Sl. No	Type of Vehicles	Upto-2010	2011	2012	2013	2014	2015	2016	2017	2018/March	Grand Total
1	Ambulance	2793	219	181	243	338	480	378	495	172	**5299**
2	Auto Rickshaw	126763	20423	23545	15697	19897	20000	11173	9168	2425	**249091**
3	Auto Tempo	14266	175	626	395	500	1095	1322	1592	451	**20422**
4	Bus	27778	1761	1439	1107	1488	2391	3833	3760	817	**44374**
5	Cargo Van	3522	489	282	687	608	399	1017	1413	413	**8830**
6	Covered Van	5658	2354	1421	2271	2869	2354	3340	5176	1675	**27118**
7	Delivery Van	17063	1004	774	894	1176	1719	2181	2410	715	**27936**
8	Human Hauler	6520	1152	715	385	225	1142	3487	3393	497	**17516**
9	Jeep(Hard/Soft)	32286	2134	1569	1314	1870	3601	4892	5425	1346	**54437**
10	Microbus	66379	4051	3044	2537	4313	5224	5804	5575	1248	**98175**
11	Minibus	25644	276	249	148	256	323	472	492	102	**27962**
12	Motor Cycle	759257	114616	101588	85808	90685	240358	332057	326550	94740	**2145659**
13	Pick Up (Double/Single Cabin)	32240	10460	7625	6553	9554	10257	11371	13512	3587	**105159**
14	Private Passenger Car	219830	12950	9224	10472	14699	21062	20304	21959	5160	**335660**
15	Special Purpose Vehicle	6371	396	226	227	172	296	620	993	305	**9606**
16	Tanker	2706	317	195	226	362	324	394	319	96	**4939**
17	Taxicab	44380	75	172	51	374	88	44	15	32	**45231**
18	Tractor	20600	5200	3494	1885	1522	1699	2576	2777	1114	**40867**
19	Truck	82871	7327	4335	5129	8136	6330	7275	10353	3325	**135081**
20	Others	1317	7	1	1080	1595	2073	3870	5021	1558	**16522**
	TOTAL	**1498244**	**185386**	**160705**	**137109**	**160639**	**321215**	**416410**	**420398**	**119778**	**3419884**

Fig.2: Number of registered vehicle in Bangladesh [5].

2. LITERATURE REVIEW

Several attempts and models have been suggested and tested for harnessing energy of vehicles using a speed bump. Some of the engineers proposed various system for generating power from speed bumper. Many models were introduced according to condition. After each generation the efficiency of model increased and the limitation diminished. Mechanisms which include springs by A.K. Singh, Deepak S., Madhawendra K. and V. Pandit, Rack and Pinion by Aswathaman. V and Priyadharshinim in “Every Speed Breaker Is Now a Source of Power” [6], by Shakun Srivastava, Ankit Asthana in “Produce electricity by the use of speed Breakers” [7] and by Ankit Gupta, Kuldeep Chaudhary & B.N Agrawal in “An Experimental study of Generation of Electricity using Speed Breaker” [8] in above mentioned methods, whenever a vehicle is allowed to pass over the dome it gets compressed with the assistance of spring and rack which is attached to the base of the arch moves downward in reciprocating motion. Since the rack has teeth connected to gears, there exists conversion of reciprocating motion of rack into rotational motion if gears but two gears rotate in opposite direction. By the use of ball bearings, one of the motions is use to generate power [9]. Study also include slider crank by Noor Fatima and Jiyaul Mustafa in “Production of electricity by the method of road power generation” [10] has been suggested for producing electricity where when a vehicle pass over a bumper, the bumper would plunge vertically downward due to the weight place on it. This vertically translation movement is then converted into rotational movement by means of crank shaft system which then utilized to drive a dynamo to generate electricity. Another process called Electrodynamics based models by Ankita and Meenu Bala in” Power generation from speed breaker” [11] have also been suggested, but are not only expensive to fabricate but involve complicated calculations and can’t be used a large scale very easily. Totaram [12] utilizes a platform plate which is kept slanted on a raised base level to let vehicles pass over the raised surface. In roller mechanism, a roller fitted in between a speed breaker and some kind of a grip is provided on the breaker so that when a vehicle passes over speed breaker it rotates the roller. This movement of roller is used to rotate the shaft D.C. generator by the help of chain drive which is there to provide different speed ratios. As the shaft of DC. generator rotates it produce electricity. This method introduced by C.K. Das, S. M. Hossain and M.S. Hossain in “Introducing speed breaker as a power generation unit for minor needs” [13].

3. METHODOLOGY

When a car reaches on speed breaker, rack moves downward to generate linear motion [14]. Pinions attached to a rack which converts the linear motion of rack into rotary motion to the shaft. Which flow through intermediate gear mechanism. At the end of shaft, a flywheel is attached which used to provide uniform motion. A chain is used to transfer mechanical motion to DC generator. DC generator generates electricity which is stored in batteries. The generated power can be used from there.

3.1 Rack and Pinion Mechanism:

In this mechanism when load applies on the rack it rotates pinion. Let, only left side pinion rotate and transmit power. Other pinion will rotate but not transmitting any power. This acts on ratchet mechanism. Intermediate gear mechanism work as a mechanical motion rectifier. When rack move upward due to force exerted by the spring, this time only right pinion will transmit power, other pinion will rotate but not transmit any power like the previous time. Below Figure 3 demonstrates how load will apply and rotation of pinion with it. Note that vehicle load caused downward motion and spring reaction provides upward motion of the rack.

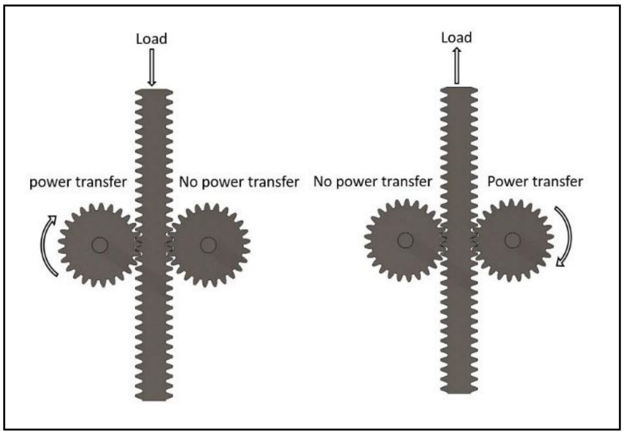

Fig.3: Rack and Pinion Mechanism.

3.2 Experimental Setup:

In this experiment load from the speed breaker fed into rack or by spring. This force generated by the load applied on rack and energy stored by the spring simultaneously. Linear motion converted into Rotary motion by the help of pinion gear. This rotary motion traveled to flywheel through shaft and intermediate gear set. Flywheel stored energy and turned DC generator by the help of a chain attach to it. DC generator generated electricity which later stored in battery. In intermediate gear use of ratchet mechanism allowed rotational direction of shaft to vary. For instance, when load applied on the rack it rotated both pinion but ratchet mechanism allowed only left pinion to transmitted power. This power rotated the intermediate gear set which has three spur gear. Left spur gear which connected to the left shaft with left pinion rotated when left pinion transmitted power. This left spur gear caused to rotate middle gear in opposite direction and right gear in same direction. But meanwhile right shaft rotated in opposite direction. This contradictory motion separated by introducing another ratchet mechanism in right spur gear. So it could freely rotate. This whole mechanism repeated in case of upward motion caused by spring but vice versa. Figure 4 represents a prototype model used in this experiment.

Fig.4: Fabricated model of the experimental unit.

Structural steel was considered for simulation of gear pair and rack and pinion gear. Table 1 shows the dimensions of gear pair and Table 2 shows the material properties of gears.

Table 1: Dimensions of gear (ISO)

Dimensions	Values
No. of teeth	57
Module	2
Pressure angle	20
Nominal shaft dia.	50
Face width	10
Hub style	Type A

Table 2: Material properties

Material Property	Unit	Structural Steel
Density	kg/m3	7850
Young's Modulus	Pa	2.00E+11
Poisson's Ratio	-	0.3
Bulk Modulus	Pa	1.67E+11
Shear Modulus	Pa	7.69E+10

For simulation purpose, CAD models were created in CAD software which was exported to simulation software later. Here, Figure 5 and Figure 6 show the CAD models used in simulation.

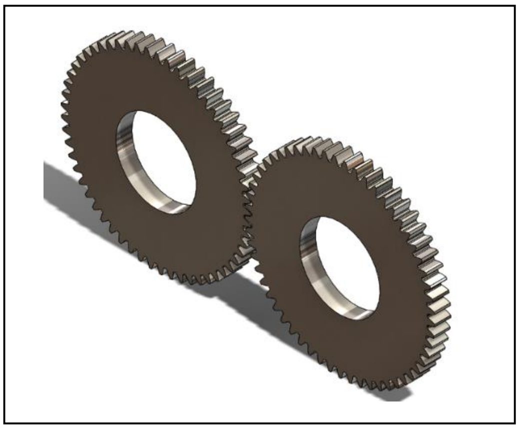

Fig.5: Pinion and gear assembly

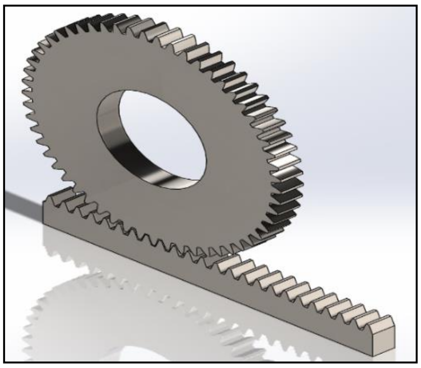

Fig.6: Rack and Pinion assembly

4. EQUATIONS AND CALCULATION

This portion of study consists of two parts. First one is generation of power in forward and reverse stroke. The second one is analysis of contact stresses of gears according to Hertz theory and finite element analysis.

4.1 Generation of Power in Forward and Reversed Stroke

Vehicle load converts into mechanical energy through the motion of rack and pinion. For taking output at the end of the flywheel it has to measure torque and angular velocity. In rotational system, power is the product of the torque and angular velocity.

$$P = \tau \cdot \omega \text{ ...... (1)}$$

For torque which is "turning effect" of the rotational equivalent of linear force [15] that is the product of the magnitude of the force and perpendicular distance of the line of action of force from the axis of rotation, in this case radius of the gear is the distance of line of action from force.

$$\tau = F \cdot r \text{ ...... (2)}$$

and,

$$F = M \cdot g \text{ ...... (3)}$$

Angular velocity refers to how fast an object rotates or revolves relative to another point, that is how fast the angular position or orientation of an object changes with time. It can be obtained from the equation,

$$\omega = \frac{2\pi N}{60} \ldots\ldots(4)$$

Consider a vehicle of mass 95 kg pass over a speed breaker. Gear ratio is 1 so no change in torque and number of rotation from pinion to final pulley. The radius of the final pulley is 3.2 cm and having revolution speed (N) is equal to 17 RPM.

F = 932 N

τ = 29.82 Nm

P = 53 W

Downward motion of rack is due to the weight of the vehicle at speed breaker and upward motion of rack is take place due to the utilization of energy from spring force. Total generated power in forward and reversed stroke.

P = 106.1 W

4.2 Contact Stress Calculation (Hertz Theory)

The power transfer between gears usually takes place right at the contact point between the acting teeth. The contact stresses are computed by means of Hertz theory. This theory shows a mathematical expression of stresses and deformations of curved bodies which are in contact. Here, Figure 7 shows a model applied to the gear-two parallel cylinders in contact.

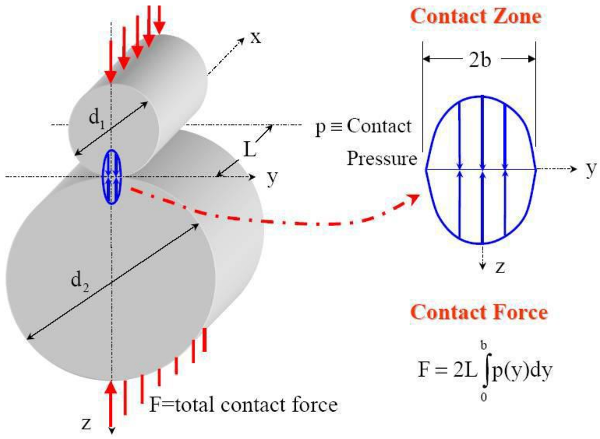

Fig.7: Contact stress in Hertz theory [16].

Hertz equation for contact stresses in the gear teeth is given below:

$$\sigma_c = \sqrt{\frac{F * \left(\frac{1}{R_1} + \frac{1}{R_1}\right)}{L * \pi * \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]}}$$

Where,

F = Contact Force, R1 = Radius of Pinion

R2 = Radius of Gear, L = Face width

E1 & E2 = Young's Modulus of pinion & Gear

υ1 & υ2 = Poisson's Ratios of Pinion & Gear

For the boundary condition of simulation, force applied on rack and pinion contact was considered 932 N. On the contrary, moment applied on the gear was considered 70 Nm which yielded the force as 1227.57 N.

5. SUMMARY OF RESULTS

This section demonstrates the power generation for different types of loads. It also shows the comparison of contact stresses calculated in Hertz equation and finite element analysis.

5.1 Power Generation on Different Loadings

Different output was obtained by this setup for different loads. Take four trails with varying weight. Instead of vehicle, human used as a load carrier. Table 3 shows the obtained data.

Table 3: Summary of data and result

Trial no	Mass (kg)	Output for speed breaker (P)	Output with spring (P)
01	65	21.4	42.8
02	73	28.75	57.5
03	82	37.7	75.4
04	95	53	106.1

In Figure 8, a graph illustrates amount of power generates due to weight. Here bottom line (Blue line) shows power generate by only downward motion which caused by vehicle passes over spped breaker. On the other hand top line (Orange line) shows total power generates using both speed breaker and spring reaction force. Both of them rise linearly with different slope.

Fig.8: Power variation due to weight

5.2 Comparison Between Simulation and Theoretical Results

Contact stresses of rack and pinion and gear pair were calculated theoretically by Hertz equation in MATLAB. Simulation was conducted to find out the results approached by finite element analysis. Then results from both methods were compared. Here, In Figure 9 and Figure 12 show the supports for assembly in simulation interface. Figure 10 and Figure 13 show the mesh. It is clearly seen that fine mesh was used in the contact region of teeth. Figure 11 and Figure 14 shows the equivalent von-mises stresses in contact regions.

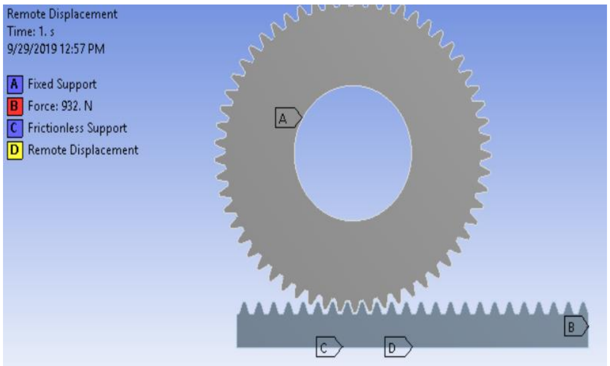

Fig.9: Support for rack and pinion assembly.

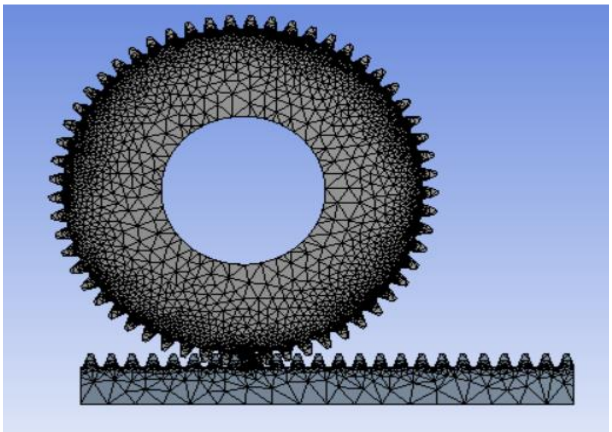

Fig.10: Meshing of rack and pinion assembly.

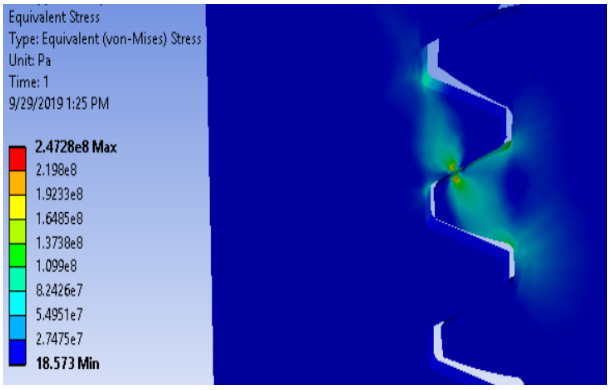

Fig.11: Equivalent von-mises stress of rack and pinion.

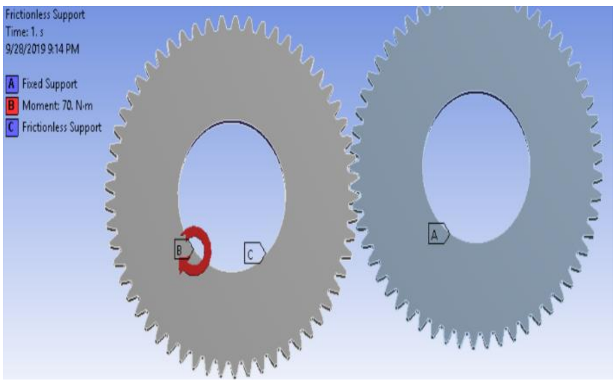

Fig.12: Support for gear and pinion assembly.

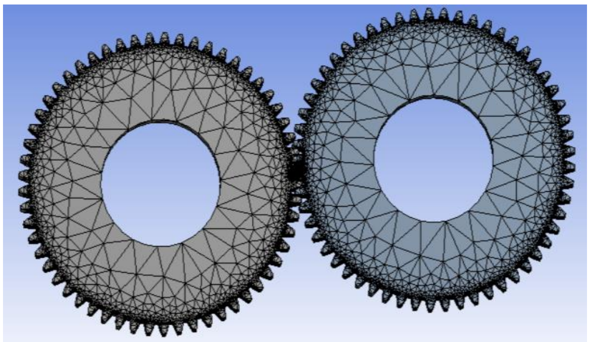

Fig.13: Meshing of gear and pinion assembly.

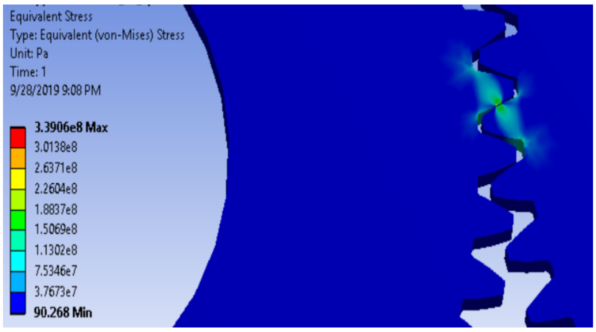

Fig.14: Equivalent von-mises stress of gear and pinion.

Here, Table 4 shows the comparison of results between theoretical method and finite element method.

Table 4: Comparison of Hertzian Contact Stress with FEM

Assembly type	Forced applied (N)	Contact stress by FEM (Mpa)	Hertz contact stress (Mpa)	Error (%)
Pinion and Gear	1227.6	339.06	389.9	13.04
Rack and Pinion	932	247.28	240.24	2.93

5. ANALYSIS

Different output is obtained from different loads in this setup. Generally, only downward motion is applied to generate power. In this particular design we can now get nearly twice energy than previous methods. Primary goal was to utilize the lost energy in spring which obtain by implication of this model and. As it is clearly seen that contact stress found from Hertzian equation and finite element method for rack and pinion assembly was quite similar with 2.93% of error which was in limit. But in case of gear and pinion assembly error was bit higher 13.04%. Therefore, overall prediction of contact stresses by FEM was quite justifiable.

6. CONCLUSION

This setup can generate a considerable amount of power. However, for generate electric energy the process followed here is not suitable. Gear ratio was too low for a substantial output of electricity. Also It is necessary to take action against rain. A protective rubber tunnel can be introduced below speed breaker. In general, where we use only one force from a source, we can now utilize this again by storing it in spring. Which is effective if it is an intermittent or a periodic force. A suitable example is ocean wave. It also can be implemented on the toll plazas, highways or drive-thru restaurants. Prediction of contact stresses by FEM showed a validity of computational techniques on engineering field. This computational technique can really decrease the expenditure of practical testing. Hertzian theory of contact stress and FEM method showed almost same results with mere percentage difference.

7. ACKOWLEDGEMENT

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9. NOMENCLATURE

Symbol	Meaning	Unit
F	Force	(N)
N	Revolutions per minute	(rad/s)
M	Mass	(Kg)
r	Radius	(m)
g	Gravity	(m/s^2)
T	Torque	(N.m)
ω	Angular velocity	(rad/s)
P	Power	(watt)

APPENDIX

MATLAB Code for Hertzian Stress Analysis

```
%% Description
% Hertzian contact stress = sigma = S
% Applied force = F
% R1, R2 = Pitch radii of gear and rack.
% Face width of gear = L
% v1, v2 = Poisson Ratio of gear 1 and gear 2 or rack.
% E1, E2 = Modulus of elasticity of gear1 and gear2 or rack
%% Input Command
F= input ('Applied force F \n');
R1=input ('Pitch radii of gear R1 \n');
R2=input ('Pitch radii of gear R2 \n');
L=input ('Face width of gear L \n');
v1=input ('Poisson ratio of gear1 v1 \n');
v2=input ('Poisson ratio of gear2 or rack v2 \n');
E1=input ('Modulus of elasticity of gear1 E1 \n');
E2=input ('Modulus of elasticity of gear2 or rack E2 \n');
inverse_of_R2 = 0; % For rack radius of curvature is infinity
%% Hertzian contact stress calculation
A1=(1-(v1).^2)./E1;
A2=(1-(v2).^2)./E2;
B1=(1/R1)+(1/R2);
B2=(1/R1)+(inverse_of_R2);
if R2==0
   S= sqrt((F*B2)/(L*pi*(A1+A2)))/1000000;
else
   S= sqrt((F*B1)/(L*pi*(A1+A2)))/1000000;
end
%% Display of Result
fprintf('Contact stress');
disp(S);
```