Design and Analysis of Flywheel based Kinetic Energy Recovery System

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Abstract – *The paper aims to present an alternate system of kinetic energy recovery from the wheels during braking for the most emerging sector in mechanical engineering, electric vehicles. The motors used with the wheels of the electric vehicles today are capable of energy recovery using EMF, but it increases the cost of assembly largely, and thus increases the cost of the car. It also leads to lot of wear-tear and maintenance of the motors, which decreases the life of motor. This paper presents an alternate solution idea to the mechanism using Flywheel engagement and disengagement through clutch system. The power from the wheel is transmitted to the flywheel through belt drive system. The final assembly is designed in CAD software Solidworks, and major component analysis is done in ANSYS.*

Key Words: Braking, analysis, alternator, flywheel, regeneration, inertia, structural, energy.

1. INTRODUCTION

In the present times, when the need to consume minimum energy is utmost important especially in automobile sector which primarily uses conventional sources of energy production like petroleum, coal etc. Many progressions have been made to improve efficiency of a vehicle by reducing input and maximizing output. The idea of Kinetic Energy Recovery Systems (KERS) promotes the same cause. The basic principle of working of KERS is to recover the energy lost during braking in an automobile. The energy wasted is mostly lost to the environment through friction which leads to heat energy along the brakes. The aim of KERS is to help restore this energy lost during braking and give it back to battery to reuse it.

KERS is a system that collects a portion of a vehicle's active energy when it is decelerating, stores it, and then releases it into the vehicle's drivetrain, giving it a boost in power. In this day and age of cutting-edge technology, KERS offers a wide range of applications. It is applicable in bicycles, bicycles, automobiles, and any other moving application that has a change in speed as a result of deceleration, as they are all business and practical applications.

When compared to traditional stopping mechanisms, the KERS framework used in automobiles serves the purpose of saving a portion of the energy lost while braking. It can also be operated at high temperatures and is effective. In order to reduce energy loss, we assume that the topic KERS has a broad basis in the design field. The system can recover around 30% of the energy given, according to the results of a segment of the experiments he oversaw.

The use of more productive frameworks could result in massive reserve funds in any country's economy. We're assuming that the topic KERS has a broad background in the design sector in order to minimize energy loss.

2. LITERATURE REVIEW

P. Veera Raju designed and fabricated Kinetic energy recovery system through mechanical brakes which demonstrate a designed model in 3D Experience software. Any auxiliary energy transfer or energy conversion equipment must be efficient, compact, and reasonably priced, and the energy storage unit must be compact, durable, and capable of handling high power levels efficiently. This chapter discusses the project's background, including the issue statement, objectives, and scope. All of this information is necessary to provide a starting point for the project's progress. The goal of this project is to use CATIA design software to build and fabricate a regenerative braking system employing mechanical brakes [1].

Thomas Matthews implemented the KERS system integrated in vehicles. The project used a flywheel for transfer of energy from moment of braking back to the battery unit. The flywheel KERS system has the potential to be a game-changing technology. It increases the power of all vehicles while also improving their fuel efficiency. A cleaner, greener environment is directly proportional to improved fuel economy. It has a positive influence on the environment since it minimizes dangerous CO_2 emissions. The quantity of CO_2 emitted during the construction of one flywheel KERS has been determined to be recovered during the first 12,000 km of driving. Furthermore, unlike a hybrid electric vehicle, a mechanical hybrid powered by a flywheel does not require the disposal of hazardous chemicals present in batteries [2].

Rohan Rane and Sandeep Mistry designed a light, compact and inexpensive system. In a regenerative braking system, the regenerative brake recovers around half of the wasted energy and uses it to power the engine, whereas traditional brakes squander 80% of the overall energy. A regenerative braking system reduces fuel consumption by 10% to 25%. Regenerative braking has also been demonstrated to enhance fuel economy — by as much as 20% – at greater speeds. Regenerative braking is a minor but critical step toward our eventual fossil-fuel independence. Batteries with these types of brakes can be used for longer periods of time without needing to be charged externally. The driving range of fully electric vehicles is also increased by using these types of braking systems. When compared to a car with merely friction brakes, the regenerative braking system offers a number of major benefits. The regenerative braking system can provide the majority of the overall braking force in low-speed, stop-and-go traffic where less deceleration is required. As a result, we can see that regenerative braking is a very promising topic with many applications in the near future [3].

3. METHODOLOGY

For the proposed system, each and every process of design procedure for a project is followed. Starting with the schematic for finalization of idea and design is done. The design calculations referring to standard books and research are done in the next part. As the calculations provided with different design parameters of each component, an assembly of CAD design is done in Solidworks 20.

3.1 WORKING OF THE SYSTEM

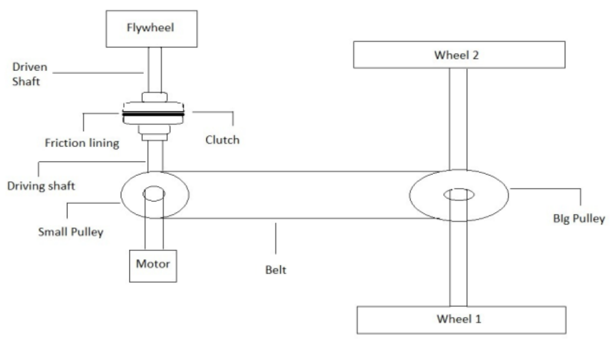

Fig -1: Schematic Diagram

In electric vehicles, motor is the prime mover. Motor transfers the energy to the wheels which keep the vehicle moving. Under normal circumstances, the KERS is disengaged from the main system comprising of motor, transmission, and wheels. The Flywheel which will be used to regenerate is mounted on a separate shaft. The motor shaft and flywheel shaft are not connected when the vehicle is running. Now, after applying brakes, transmission of pressure from the main master cylinder to slave cylinder pushes the clutch plate axially. This clutch plate comes in contact with the friction plate mounted on flywheel shaft and it starts rotating. The kinetic energy of the wheels through the same transmission system is now been transferred to flywheel via the engagement of clutch. The rotation of flywheel leads to an increase in the moment of inertia of the vehicle, which helps to decelerate the vehicle. This rotational kinetic energy stored in the Flywheel can then be converted into electrical energy with the help of an Alternator. The spring which retracted due to application of brake comes back to its mean position once the brake pedal is released, thus clutch plate and friction plate disengages and the vehicle can be accelerated again using motor.

3.2 THEORETICAL CALCULATIONS

Gross weight of vehicle (m) =800 kg
For the calculation for the energy stored in the flywheel,
Let us assume that the flywheel stores enough energy to take the whole system from rest (u) to final velocity (v) 10 km/hr in 5 sec.

$a= [(v-u)/t] =0.556\ m/sec^2$

Energy of the system when it reaches 10 km/ hr = E

$E= (0.5\times m\times v^2) = 0.5 \times 800 \times 2.78^2 =3091.36\ J$

We also need to calculate the speed of the wheel for which diameter of wheel (D_W) = 228.6 mm.
Number of revolutions (N_W) made by the wheel at 10 kmph per sec

$N_W = v/ (2\times \pi\times R_w \times w) = 2.78/ (2\times\pi\times114.3\times7) = 232.25\ rpm$

The force (F) required taking the vehicle from rest to 10 kmph in 5 sec is calculated as follows:

$F= m \times a = 800 \times0.556 = 444.8\ N$

Also, we know that there is friction between the road and the tire of the vehicle considering the rolling resistance

$F_r = \mu \times F = 0.02 \times 448.8 = 8.9\ N$, where μ=0.02 for rolling resistance between vehicle tires and road.

The aerodynamic drag (F_A) also affects the performance of the system and it is necessary to consider it.
$F_A = C_d \times \rho \times A \times v^2$, where C_d = coefficient of drag =0.5, ρ = density of air = 1.25 kg/ m³ at 25°C, A= projected area = 2.09 m²

But the grad is proportional to the square of the velocity, so the average of FA can be calculated using integral function.

$$FA = \frac{C_d \times \rho \times A \int_0^{2.78} v^2\, dv}{\int_0^{2.78} dv} = 3.36\ N$$

Considering other frictional resistances (F_f) according to standard assumptions, F_f = 5 N.

Total requirement of force (F) = 444.8+8.9+3.36+5 = 479.704 N.

To get the required force, the center of wheel needs to provide Torque (T_w), which can be calculated by

$T_w = F \times R_w = 54.83$ N-m.

Calculations of flywheel:

The flywheel rotates at high speeds and it is necessary to calculate the energy it releases (E_{fl}) and it is formulated as $E_{fl} = 0.5 \times I \times (\omega_1^2 - \omega_2^2)$, where ω_2 = 24.31 radians/sec
And ω_1 is constrained by the top speed of the vehicle, therefore ω_1 = 146.22 radians/sec and I is moment of inertia of flywheel.

$E_{fl} = 0.5 \times I \times (\omega_1^2 - \omega_2^2) = 10394.65 \times I$

Also the energy of the flywheel (E_{fl}) will be consumed in bringing in bringing the vehicle into motion 10 kmph and overcome the resistances. Using energy as a product of Force and displacement and replacing displacement from Newton's third law.

$E_{fl} = F \times ((v^2 - u^2))/ (2 \times a) = 3333.9428$ J

Comparing these two values
I = 0.32
But, $I = m \times r^2/2$ (for circular disc) and
$m = \rho \times \pi \times d^2 \times t$

Constraining the diameter of flywheel to the size of motor diameter, we get d= 22.07 cm
$\rho = 7500$ kg/m³ (Stainless steel material) and thickness = 4 cm= 0.04 m
Mass of flywheel = 11.5 kg

Now, after getting the dimensions from various calculations, calculating various parameters of the clutch is also important. Also, considering design limitations, Outer diameter (D_o) of clutch is restricted by Flywheel outer diameter.

D_o =220.7 mm

We have used **Uniform wear theory** for analysis. (Assuming that the wear is uniformly distributed over the entire surface area of the friction disk plate.)

$M_t = (\pi \times \mu \times P_a \times d) /8 \times (D_d^2 - d_d^2)$, where
D_d = outer diameter of friction disk = 0.2207 m
Dd = inner diameter of friction disk = 0.112 m
p = intensity of pressure at radius, r = 0.1 N/mm
P = total operating force (N)
M_t = torque transmitted by the clutch = 54.83 N-m

Required spring force to keep the clutch in an engaged position

$P = (\pi \times P_a \times d) \times (D-d) / 2$

By substituting the values, we get, **P= 1633.62 N**

Calculations of shaft:

Stresses acting on the shaft are torsional Shear stress and bending moment. We can get the value of torsional stress as:
Torsional Shear stress ($\boldsymbol{\tau}$) = ($16T / \pi d^3$), where, d= shaft diameter, T = Torque= 54.83 N-m.
Therefore $\tau = 279.24/d^3$ (d is diameter of shaft)

Bending moment ($\boldsymbol{\sigma}$) = $M \times y/I = 114.91/d^3$, where
M = F × d= 11.2815, y=d/2 and $I = (\pi/64) \times d^4$

It is combined loading; therefore we make use of theory of failure. In this case, Maximum Shear stress theory of failure (Tresca's theory) is applied.

$$\boldsymbol{\tau}_{max} = \boldsymbol{\tau}_{permissible}/FOS$$

The material used for shaft is stainless steel which has yield strength of 215 MPa.

Substituting all the values, d=18 mm.

Calculations of spring:
Spring will be used to actuate the system when the brake pedal will be placed. Stresses acting on the spring are direct shear stress and torsional shear stress.

It is given by, $T = Ks * (8 \times P \times D)/ (\pi \times d^3)$, where Ks= Wahl's correction factor.

$Ks = ((4C-1)/ (4C-4)) + (0.615/C)$, where C = spring index
Considering C=6 for best manufacturing conditions
Therefore Ks=1.2525.
Also, Pressure (p) = P/A where $A = (\pi/4) \times (0.3^2 - 0.26^2)$ and p=0.1 N/mm², we get the value of spring force as:
P =1760 N

Springs are made of oil tempered steel with Yield strength= 1320 MPa

Calculations of Alternator:

The energy that flywheel gets from braking needs to transferred back to the battery with minimal losses of the system. Alternator is the device which can be used for this operation. It is necessary to calculate the amount of energy and efficiency of system to understand validity of the project.

Maximum Kinetic energy (KE) of vehicle= $0.5 \times m \times v^2$
$KE = 0.5 \times 800 \times 16.67^2 = 111.2$ KJ

Considering friction, 80% of KE is required for braking.
$KE_b = 0.8 \times 111.2 = 89$ KJ

We need to recover this KE_b which be lost in braking. Assuming efficiency of transmission of energy to be 0.25, we need to check if the flywheel is safe for this amount of energy.

$KE_f = 0.25 \times 89 = 22.25$ KJ.
Time period of transmission considered is 5 seconds.
Power = 22.5/5 =4.45 KW.

Now, alternator is used to convert the mechanical energy to electrical energy.
Output voltage of alternator = 14.2 V
Rated current = 300 Amp
Rated rpm = 3500 rpm
Output power = 300 × 14.2 = 4.26 KW

Therefore, due to various losses in alternator such as eddy current losses and transmission losses, some amount of energy is lost.
Alternator losses = 4.45 – 4.26 = 0.283 KW

Efficiency of system $= \frac{\textit{Alternator Output}}{\textit{Braking Power}} = \frac{4.167}{17.8} = \mathbf{23.41\%}$

3.3 WORKING OF CLUTCH-BRAKE SYSTEM

Instead of a mechanical connection, a hydraulic clutch mechanism employs a hydraulic line to convey pedal movement. At the clutch operation, a piston on the master cylinder at the pedal transmits pressure to the slave cylinder piston via a fluid. A pressure value directs the flow of pressure to clutch (13-35 bar) and then to brake and clutch both (35 -80+ bar).

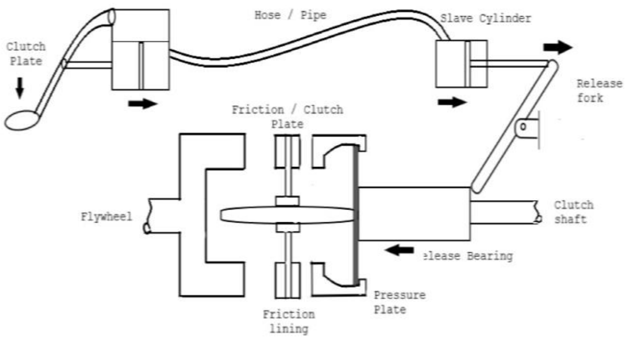

Fig -2: Clutch-brake system working

The specifications of Hydraulic clutch are actuation pressure for clutch ranges from 13-35 bars. The master cylinder bore diameter is 22.5 mm whereas slave cylinder bore diameter is 27 mm. The pressure range in hydraulic lines during panic braking is 80-90 bars. The pressure in hydraulic line during normal braking (in order to make vehicle stop) is between 70-80 bars. Pedal ratio in vehicle for easier braking is 6. Pedal force required for pressure of 80 bars is 500N. Pedal force required for 35 bar is 230 N. Mechanical advantage from linkage system between slave cylinder and clutch spring after calculations comes out to be 2.5. A hydraulic diagram for the same mechanism is added to show clarity in working of the clutch brake system that is proposed.

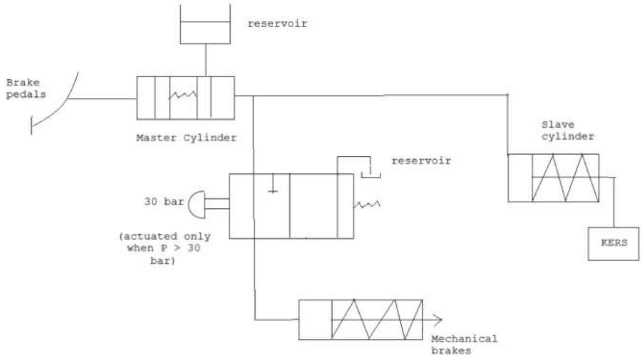

Fig -3: Hydraulic circuit diagram

4. ASSEMBLY OF THE COMPONENTS:

All the above components of the assembly have been designed in Solidworks software. The results of the calculations above have been used to create a Computer-Aided Design of each major individual component.

Then, all the components have been combined into a Solidworks assembly, and colorful features have been added to each component to make the model easily to understand and analyze.

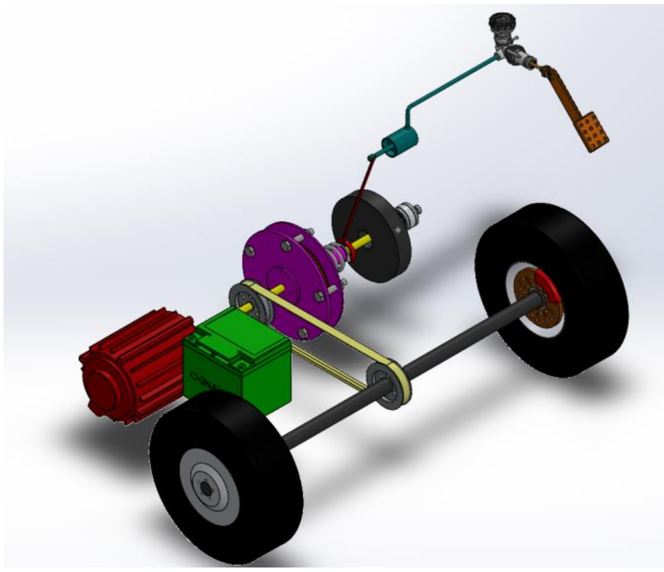

Fig -4: Assembly (Isometric view)

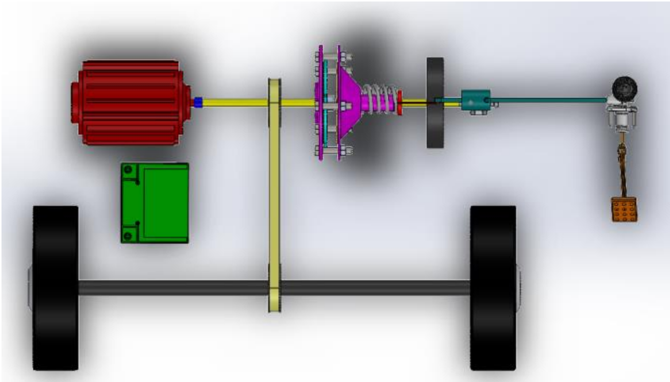

Fig -5: Assembly (Top view)

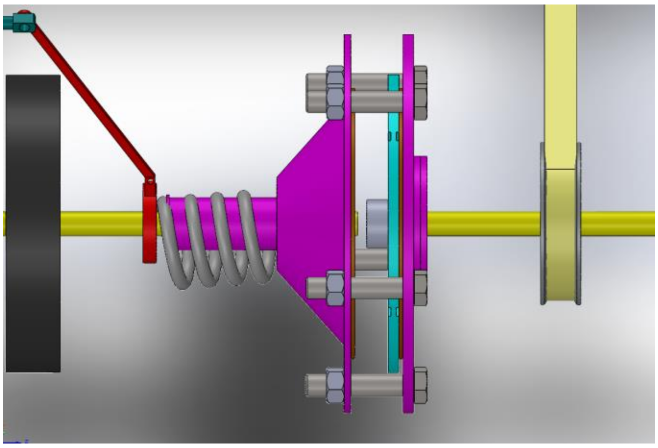

Fig -6: Clutch assembly

5. ANALYSIS OF THE COMPONENTS:

Some of the components in the assembly will be subjected to lots of thermal and structural stresses. Hence, proper analysis is required with all the given conditions to simulate under various cases of failure. This will assure that the system is free from failure. The Analysis of the components of the system is done in ANSYS Workbench software.

ANALYSIS OF FLYWHEEL

The Flywheel is tested for structural analysis and modal analysis in two modes. Flywheel is one the most structurally strong component of the system and has the least amount of chance to undergo failure. Material here considered in structural steel.

For static structural analysis in ANSYS, forces on flywheel are gravitational force and rotation due to inertia (150-370 rad/s). The support of the flywheel is fixed support at the axis of rotation.

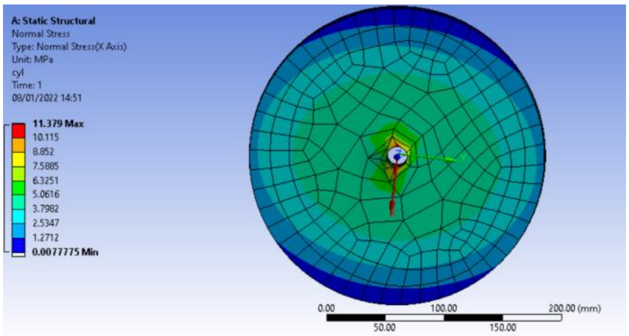

Fig -7: Normal Stress on Flywheel

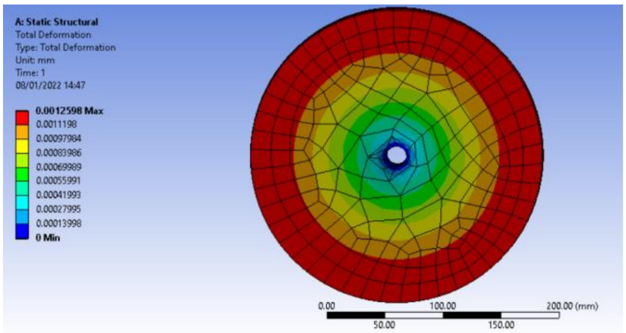

Fig -8: Total Deformation of Flywheel

Modal analysis shows the movement of different parts of the structure under dynamic loading conditions, and helps to determine the vibration characteristics (natural frequencies and mode shapes) of a mechanical structure or component. In structural dynamics, the mode shape and natural vibration shape are employed. When a component vibrates at its native frequency, its mode shape characterizes the deformation it will exhibit. The vibration and deformation, on the other hand, do not occur unless there is an excitation. The entire vibration of a structural component, which is primarily made up of separate vibration forms, is determined by this excitation. So the data from static structural is then imported to modal analysis tool in ANSYS and the results are obtained for different modes of vibration.

Table -1: Frequency of modes of vibration

No.	Mode	Frequency (Hz)
1	**1**	1069.8
2	**2**	1762.1
3	**3**	1765.8
4	**4**	2664.7
5	**5**	3858.3
6	**6**	3860.2

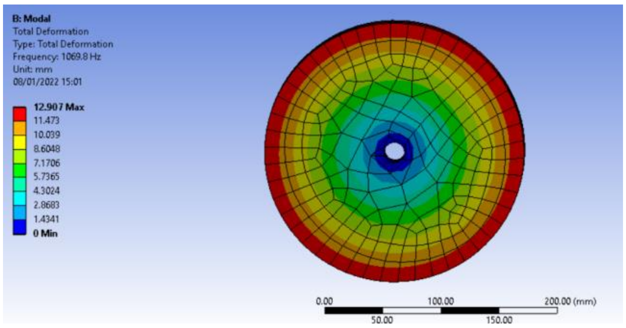

Fig -9: Total Deformation (Mode 1)

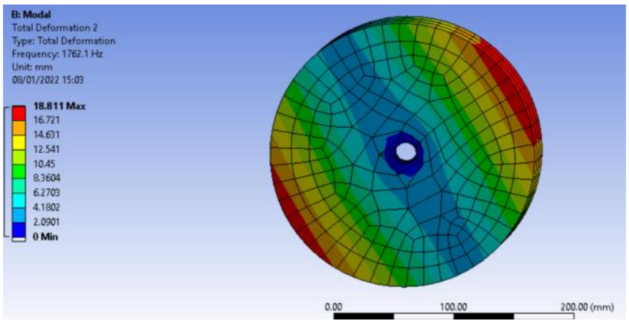

Fig -10: Total Deformation (Mode 2)

From the ANSYS static structural and modal analysis data we can see:

- Total deformation for max rotation = 0.00125mm
- Normal stress = 12.081 MPa
- Safety factor= 14.38
- Deformation at 1st mode of vibration =12.08mm
- Deformation at 2nd mode of vibration =18.81mm

The above data show that the design of the flywheel is completely safe.

ANALYSIS OF SPRING

Spring is required to actuate the mechanism so that the pressure plate of clutch is in contact with the friction plate through which energy is transferred to the flywheel. The material of the spring is oil tempered steel.

Spring Force required: 1760 N

Mean diameter D=60 mm

Coil diameter= 10 mm

Boundary conditions: One end is fixed, Load of 1760 N applied on the other end.

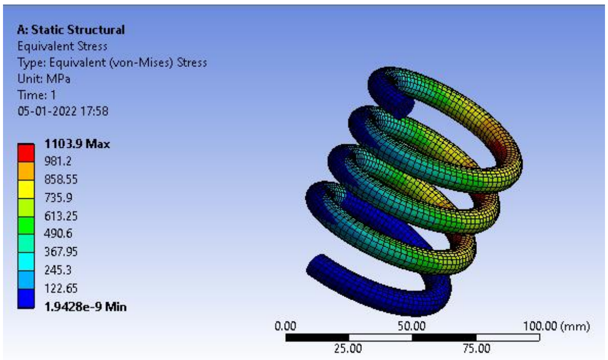

Fig -11: Equivalent Stress on spring

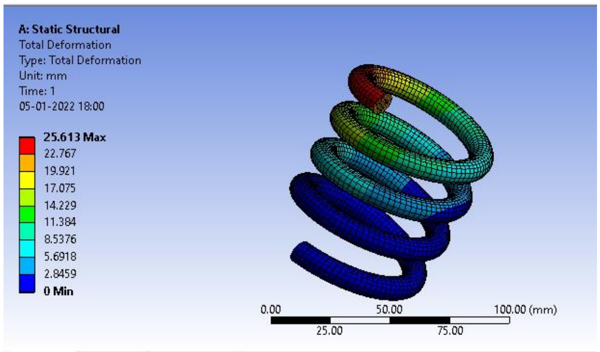

Fig -12: Total Deformation of spring.

From the ANSYS analysis results, we get the value of maximum stress=1104 MPa and maximum deformation= 25.613 mm.

ANALYSIS OF CLUTCH

Clutch is used to engage the drive shaft with the flywheel to transfer the kinetic energy of the wheels to Flywheel. The outer diameter of clutch is 0.2207 m while inner Diameter is 0.1314 m and the thickness is 8 mm. The material for the clutch is Asbestos (Density= 2000 kg/m3, Coefficient of friction =0.25). The boundary conditions are: 1. Fixed support at Inner Diameter. 2. Uniform pressure of 0.1 MPa over the friction surface.

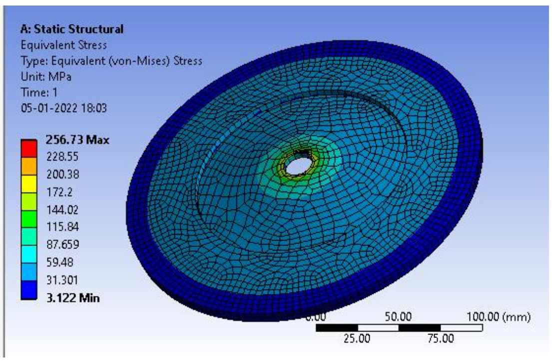

Fig -13: Equivalent Stress on clutch

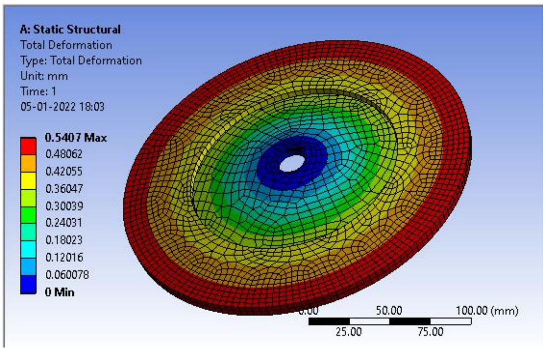

Fig -14: Total deformation of clutch.

From the ANSYS analysis results, we get the value of maximum stress=256.73 MPa and maximum deformation= 0.54 mm.

ANALYSIS OF SHAFT

Diameter of the shaft on which the flywheel is supported is 18 mm made of structural steel with yield strength of 215 MPa. The boundary condition for the analysis is that the one end of the shaft is fixed. A load of 138 Newton is applied on the other end.

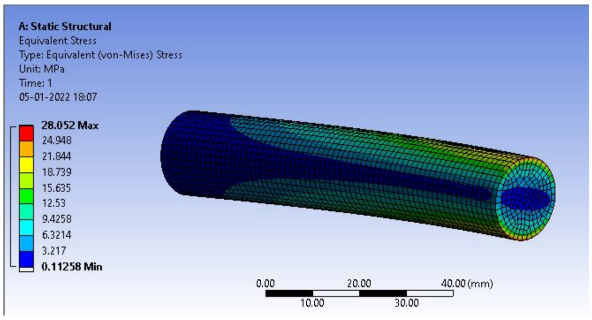

Fig -15: Equivalent stress on shaft

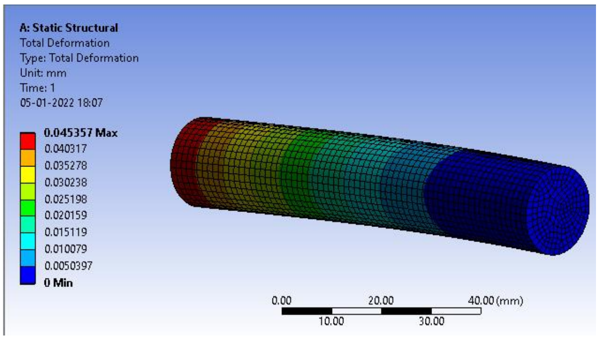

Fig -16: Total deformation of shaft

From the ANSYS analysis results, we get the value of maximum stress=28.05 MPa and maximum deformation= 0.045 mm.

All the important components which are continuously under various types of stresses are modelled and analysed in ANSYS for the types of stresses and total deformation the component will go, if subjected to maximum loads. From various ANSYS results, we can conclude that every component design is safe and is in the safe range of factor of safety.

6. CONCLUSION

An introductory design of the kinetic energy recovery system (KERS) is carried out. The design contains every aspect of transmission and regeneration from otherwise wasted brake energy. A schematic explaining concept of the project has been added. All the design calculations are carried out according to standard reference books. Each component is modeled in Solidworks and then assembled. Every major component is analyzed in ANSYS to check if it fails in any condition. The efficiency of the system comes out around 23.4%, which is in good range compared to how Tesla proposes its experimented system at 30%. With better experimentations, use of better materials and more analysis, this project surely aims towards higher regeneration of wasted energy. The proposed idea and design presented in this paper will hopefully trigger cheaper and affordable electric vehicles in the industry.

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