Computational Finite Element Analysis of Magneto-rheological Clutch

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Abstract - Magneto-rheological fluid is a smart fluid that is a stimulus to an externally applied magnetic field. magneto-rheological fluid has a high response time and better controllability. These properties are used for designing the MR clutch. To understand the working of the magneto-rheological clutch, the study on the magneto-rheological fluid has been performed for better interpretation of its working principle. The different types of magneto-rheological clutches are studied, their limitations and design challenges are understood. The clutch is designed for lightweight automobile applications. The theoretical torque transfer model of the magneto-rheological clutch is developed. The magnetostatic analysis is carried out to optimize the magnetic circuit and clutch design. The finite element analysis of different parts of the magneto-rheological clutch is performed. The simulation of the clutch is carried out.

Key Words: *Magneto-rheological clutch, multi-disk clutch, FEA, magnetostatic analysis*

1. INTRODUCTION

Magnetorheological (MR) fluid is a type of solid-liquid two-phase smart material. MR fluid is a controllable fluid that changes its properties under the influence of a remote external magnetic field. It contains solid magnetic particles suspended in carrier liquid which is standard hydraulic oil. The carrier liquid used is hydraulic oil, synthetic oil, mineral oil, or water. MR fluid under normal conditions, when there is not any external magnetic field, acts as a Newtonian fluid. When the external magnetic field is applied, acts as a non-Newtonian fluid capable of developing yield stress within it. MR fluid is operated in three modes i.e. flow mode, shear mode, and squeeze mode. MR clutch is operated in shear mode [2].

To understand the previous work on the MR clutch, a literature survey is conducted. The book was written by Brian Cantor et al. [1] on Automotive Engineering Lightweight, Functional, and Novel Materials has discussed the historical development of ER and MR fluids, the structure of MR fluid by application of the external magnetic field. The behavior of MR fluid under the magnetic field was also stated. Applications of MR fluid in various sectors are described. The effects of temperature on MR fluid are discussed. M. Zeinali et al. [2] in their paper have proposed the different applications of MRF. The modes of operations of MRF are also discussed. It contains the different applications of MRF with their modes of operation such as dampers, different configurations of MR valves, mount, brakes, and clutch. Yanjuan Zhang et al. [3] have presented the rheological properties of the MR fluid under external magnetic fields. The microstructure of MRF is shown which contains a chain structure of iron particles. D. Lampe et al. [4] have designed the high transmittable torque MR clutch with low idle. The experimentation is also carried out to validate the results. Different design types of MR clutch i.e. disc-type and bell-type clutches are discussed. The problem of particle centrifuging action is addressed for a disc-type clutch. The new wear less permanent magnet seal for MRF is described. F Bucchi et al. [5] have designed different MR clutches using permanent magnets to check the torque capabilities. Multi-gap MR clutch designs are provided in both disc-type and bell-type clutches and demonstrated the feasibility. K. Hema Latha et al. [6] discussed the structural behavior of MR fluid and its benefits. The experimental validation and their calculations for the MR clutch are derived. B. Kavlicoglu et al. [7] have designed the MR clutch for automotive limited-slip differential application. They have performed the three-dimensional electromagnetic finite element analysis (FEA) for optimization of magnetic circuit and clutch design. The theoretical torque transfer model is also provided for the Bingham-plastic model. Experimentation is done for different velocities and current inputs. The clutch characteristics are examined. K. Nagaya et al. [8] have presented the torque controllable viscous coupling model using the MR fluid which is filled in housing. The torque transfer model is proposed for the coupling consisting of discs and slits combinations. The effect of slits is discussed and tested experimentally by using reference plates. Shangqiu Dai et al. [9] designed the novel composite MR clutch. The experimentation is conducted to obtain the transmissible torque. The finite element analysis of the magnetic structure of clutch is also carried out which resembles the results with experimental results.

Most of the literatures demonstrated shows the work for robotic systems. The replacement of conventional clutch with MR clutch due to its merits over conventional clutches in Automobile applications is not explored yet. Hence, the design is to be made for the replacement of conventional clutch and is to be analyzed for different input parameters like current, speed. The finite element analysis of different parts is carried out. The conclusion is to be made based on the results.

2. MR CLUTCH

The main function of a clutch is to disengage the transmission system from the engine. In the MR clutch, it is obtained by using the MR fluid characteristics. The MR clutch consists of an input disk connected to the input shaft, an output disk that is connected to the output shaft and MR fluid is filled in between the two disks. The clutch operates in an engaged position when the MR fluid is magnetized. The torque is transmitted from engine to transmission system. In that condition, both input and output shaft run at the same speed. When MR fluid is demagnetized, the clutch disengages from the engine, and two shafts run at different speeds. Mainly the MR clutch operates in the shear mode of operation. The MR clutches can be designed as per the requirement of the amount of torque, applications, and the availability of the space. The various designs and the governing equations are proposed for the MR clutches [1,5].

There are two main types of MR clutch designs and are called as disk-type and bell-type. In the disk-type MR clutch, the shear gaps filled with the MR fluid are oriented perpendicular to the rotational axis of the clutch. It is suited for the requirement in compact space. Many parallel plates are arranged perpendicular to the shaft to maintain the shear gap. So, it transmits large torque. At higher rotational speed, centrifugal force acts on the heavy iron particles so, particle separation takes place, which is undesirable to torque transmission. In the bell-type MR clutch, the MR fluid gaps are oriented parallel to the rotational axis of the clutch. In this, particles move vertically over a small distance of the MR fluid gap. It has less torque transfer capacity as compared to the disk-type MR clutch. When the combination of both i.e. disk-type and bell-type is used, then it is known as the composite MR clutch. For the application of a magnetic field, an electromagnetic coil circuit or a hybrid magnetic circuit is used. [5]

The single fluid gap sometimes cannot provide the required transmittable torque. Because of that, slippage can happen. This can be overcome by using multiple fluid gaps. Usage of multi-gaps increases the output torque at expense of the same magnetic field as an input. Multi-gaps can be used with both types of clutch designs. In disk-type, if multiple gaps are provided, is stated as multi-disk MR clutch. In this, multiple disks are used which make contact of both sides with MR fluid gaps. In cylinder-type, if multiple gaps are provided, is stated as a multi-cylinder MR clutch. In this, multiple cylinders are used which make contact of both sides with MR fluid gaps. The design is done with the help of permanent magnets or electromagnetic coils or a combination of both. The total torque transmitted is calculated simply by multiplying the torque transmitted by a single fluid gap clutch with the number of disks or cylinders used in it. The advantage of using a multi-gap clutch is that the requirement of large initial torque to overcome the static friction can be fulfilled by it. [5,7]

3. DESIGN OF MR CLUTCH

MR clutch is designed for transferring the torque for lightweight motorcycle application. The survey is carried out for deciding the rated torque of lightweight automobile. The rated torque decided as 12 Nm. The service factor for lightweight applications is taken as 1.5. Therefore, the design torque becomes 18 Nm. The clutch is designed as the multi-disk MR clutch as it has advantages over the multi-cylinder type MR clutch.

3.1 Theoretical torque transfer model

Let us consider, two discs with r_i and r_o as inner and outer radii respectively as driving disc and driven disc. MR fluid is comprised in between them from radial distance R_1 to R_2.

The theoretical torque transferred by the disc, depends upon the shear stress developed in the Bingham plastic fluid and viscous forces when magnetic field is applied. The shear stress developed is assumed as constant throughout the MRF gap.

The shear stress developed in the MR fluid is given by equation (1).

$$\tau = \tau_y(H) + \mu_P \frac{\partial u}{\partial y} \tag{1}$$

The shear force generated is given as, $dF = \tau.dA$. The torque developed is given as, $dT = dF.r$. Here, dA is given as, $dA = 2\pi r.dr$. Hence, the torque developed at radius ‘r’ from centre is given by equation (2),

$$dT = \tau \cdot 2\pi r \cdot r\, dr \tag{2}$$

and total torque is obtained by integrating the above equation and is given by equation (3).

$$T_{OUT} = \int_{R_1}^{R_2} \left[\tau_y(H) + \mu_P \frac{\partial u}{\partial y}\right] 2\pi r \cdot r\, dr \tag{3}$$

By using above governing equations, the MR clutch is designed. It contains 2 mm thick plates mounted on the input and output shaft alternately and 1 mm gap is maintained between them to generate fluid gap. The shaft size is maintained 25 mm. The key is used for mounting the output plates and extended input hub. The electromagnetic coil is mounted on plates in circular windings which is placed inside the outer casing. The Fig. 1 shows the schematic diagram of the MR clutch. Table 1 enlists the components of the MR clutch.

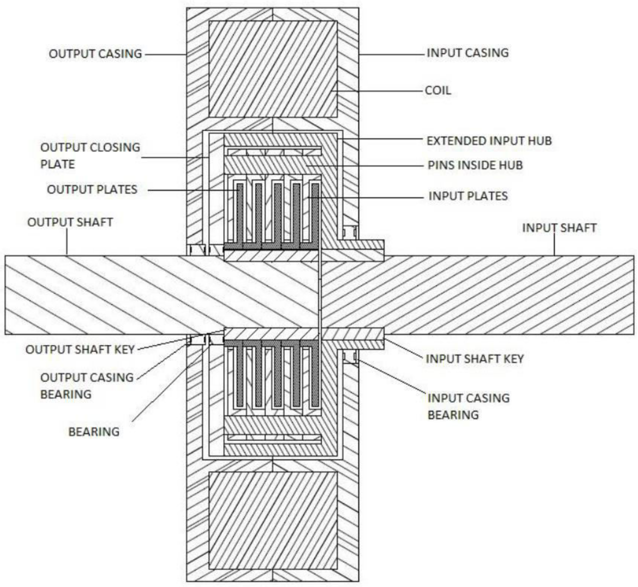

Fig -1: schematic diagram of the MR clutch

3.1 Design of electromagnetic coil

The solenoidal coil is designed by using Ampere’s Law. It depends upon the length of coil, maximum current carrying capacity of conductor and resistance of conductor. It gives the magnetic field intensity at the centre of the coil. Ampere’s law for solenoid is given by equation (4).

$$H = \frac{NI}{L} \tag{4}$$

Table -1: Lists of the MR clutch components

Sr. No.	**Name of parts**	**Inner Diameter** (mm)	**Outer Diameter** (mm)	**Material**
1	Input plate	35	93	Mild Steel
2	Output plate	25	71	Mild Steel
3	Extended input hub	25	103	Mild Steel
4	Inner casing	105	113	Mild Steel
5	Outer casing	175	183	Mild Steel
6	Coil	114	174	Copper
7	Bearing	25	32	Stainless steel

The coil length L is the horizontal distance on which coil wire is wound. The maximum current I passed through wire is 3 A. Hence, number of turns N is obtained by,

$$N = \frac{HL}{I} = \frac{(55.53).(41)}{3} = 759$$

3.2 Magnetostatic analysis

The magnetostatic analysis is carried out to perform FE analysis of electromagnetic coil, in ANSYS Workbench 16.0. The element type used for magnetostatic analysis is SOLID 97. The non-uniform air enclosure is provided with 30 mm cushioning. The meshing is done with 87133 as number of nodes and 40933 as number of elements. New cylindrical coordinate system is created for defining current in circular form and is assigned to coil geometry.

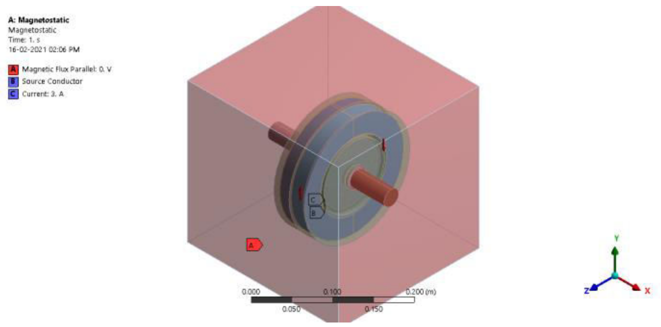

Fig -2: Boundary conditions for magnetostatic analysis

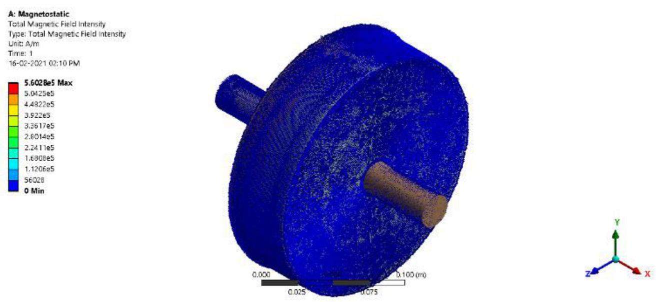

Fig -3: Contour of magnetic field intensity

The boundary conditions are applied as magnetic flux parallel, conductor type and current. All six surfaces of air enclosure are assigned as magnetic flux parallel surfaces as shown in Fig 2. The conductor type is selected as stranded with 759 number of turns. The current 3 A is applied in circular pattern. The solution time is set for 10 s. The results are evaluated, and the magnetic field intensity result obtained by FEM at middle of fluid gap is 56.028 $^{kA}/_{m}$, whereas the analytical result is 55.52 $^{kA}/_{m}$.. The error between them is about 8.17%. The Fig 3 shows the distribution of the magnetic field intensity.

3.3 Analysis of components of clutch

The different components of clutch which are designed are to be analyzed. The finite element analysis is performed of each individual component. The FE analysis is performed by using ANSYS Workbench software. It is performed to verify the maximum stress generated in the component and the safety against the maximum allowable stress in the material. The FE analysis performed on the different components are as follows.

3.3.1 Input shaft

The input shaft is being rotated at very high angular speed which transfers the motion from engine to the output shaft via plates and MR fluid assembly. It is supported by bearing at one end. The extended input hub with input plates mounted on it, input bearing and half of outer casing are mounted on another end of shaft. The half of total weight is directly carried by input shaft. Therefore, it acts as cantilever.

The meshing of shaft is done with medium element size. The shaft contains total 9591 nodes and 5414 elements with tetrahedral in shape. Mapped meshing is applied to create more uniform meshing pattern. The boundary conditions imposed on the input shaft are the dead weight, support at one end and rotational speed. The dead weight contains weight of extended input hub, input plates, casing, and coil weight. The rotational speed given to it is 5000 rpm. The earth gravitational acceleration is provided along Z axis. The Fig 4 shows the boundary conditions applied on the input shaft.

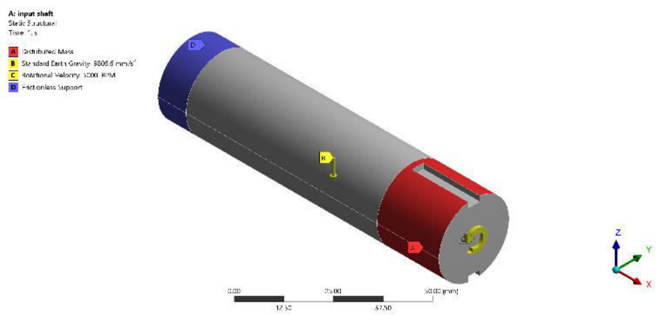

Fig -4: Boundary conditions applied on the input shaft

The total deformation obtained of the shaft is 6.28 μm which is very small. The total Von-mises stress generated in it is 19.32 MPa which is quite smaller than the allowable shear stress. The Fig 5 shows the total deformation contour of input shaft.

The analytical value of equivalent stress comes 17.73MPa. The difference in the both results i.e. analytical and FEA is due the keyway present on the shaft. The Table shows the comparison of results of both analytical and FEA. The Fig 6 shows the contour of stress distribution on the input shaft. The Table 2 compares the FEA and analytical results of the input shaft.

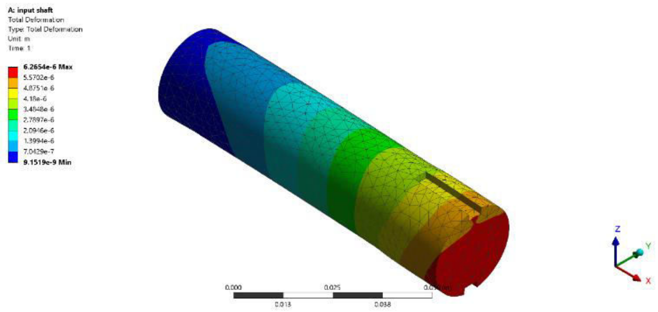

Fig -5: Total deformation of input shaft

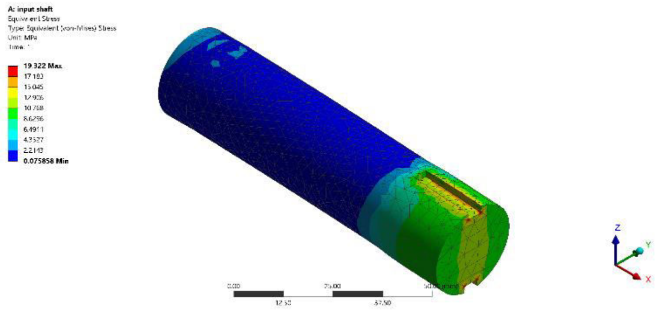

Fig -6: Contour of stress distribution on the input shaft

Table -2: Comparison of FEA and analytical results

	FEA Result (MPa)	Analytical Result (MPa)	Error
Equivalent stress	19.32	17.73	8.2%

3.3.2 Input plate

The input plate is being rotated at very high angular speed by the input shaft. It is supported on the extended input hub. The shearing stress is imparted by the MR fluid on the walls of the plate. The meshing of plate is done with fine relevance and element size with 2 mm. The plate contains total 40778 nodes and 21582 elements with tetrahedral in shape. Mapped meshing is applied to create more uniform meshing pattern. The boundary conditions imposed on the input plate are the torsional moment and rotational speed. The torsional moment generated in each fluid gap is applied on the plate which is 3987 Nmm. The rotational speed given to it is 5000 rpm. Fig 7 shows the boundary conditions applied on the input plate.

The total Von-mises stress generated in plate is 106.99 MPa, which is smaller than the allowable shear stress. The Fig 8 shows the equivalent stress in input plate.

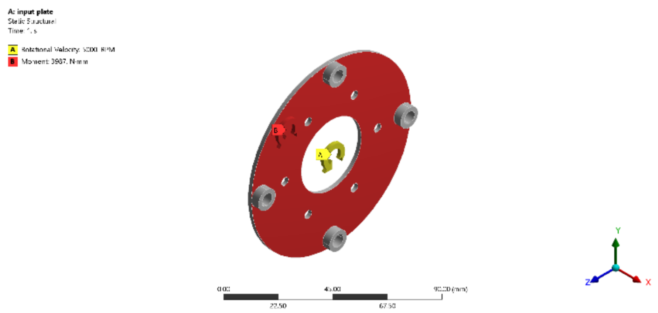

Fig -7: Boundary conditions applied on the input plate

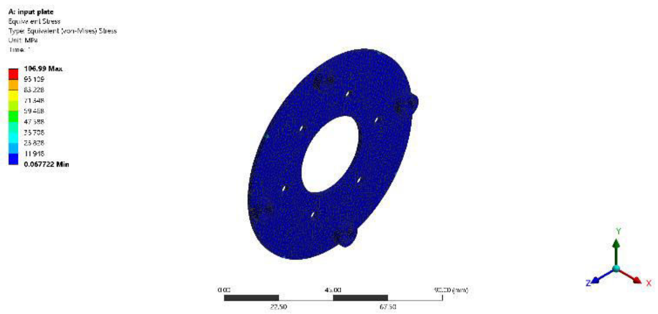

Fig -8: Equivalent stress in input plate

The analytical value of equivalent stress comes 105 MPa. The difference in the both results i.e. analytical and FEA is due the keyway present on the shaft. The Table shows the comparison of results of both analytical and FEA. The Table 3 compares the FEA and analytical results of input plate.

Table -3: Comparison of FEA and analytical results

	FEA Result (MPa)	Analytical Result (MPa)	Error
Equivalent stress	106.99	105	1.89%

3.3.3 Output shaft

The output shaft is being rotated at very high angular speed by the output plates. It is supported by bearing at one end. The output plates and outer casing with the bearing are mounted on it. The half of total weight is directly carried by output shaft. Therefore, it acts as cantilever. The meshing of shaft is done with medium element size. The shaft contains total 15898 nodes and 9020 elements with tetrahedral in shape. Mapped meshing is applied to create more uniform meshing pattern. The boundary conditions imposed on the input shaft are the dead weight, support at one end and rotational speed. The dead weight contains weight of extended input hub, input plates, casing, and coil weight. The rotational speed given to it is 5000 rpm. The earth's gravitational acceleration is provided along the Z axis. The Fig 9 shows the boundary conditions applied on the output shaft.

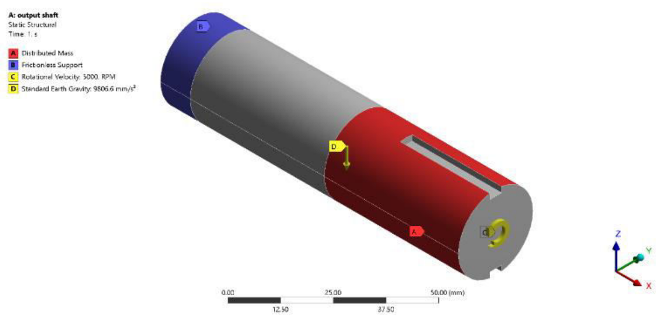

Fig -9: Boundary conditions applied on the output shaft

The total deformation obtained of the shaft is 5.43 μm which is very small. The total Von-mises stress generated in it is 9.26 MPa, which is quite smaller than the allowable shear stress. The Fig 10 shows the total deformation of the output shaft.

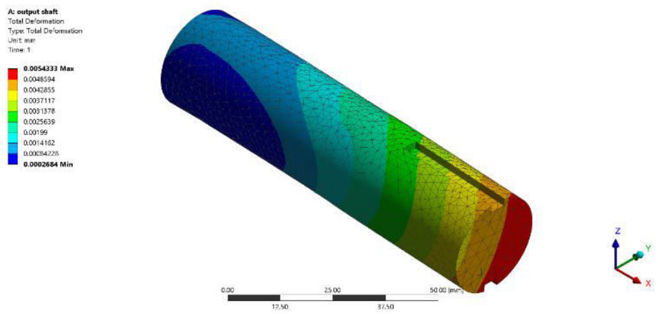

Fig -10: Total deformation of the output shaft

The analytical value of equivalent stress comes 11.32 MPa. The difference in the both results i.e. analytical and FEA is due the keyway present on the shaft. The Fig 11 shows the contour of equivalent stresses in the output shaft. The Table 4 shows the comparison of results of both analytical and FEA results of the output shaft.

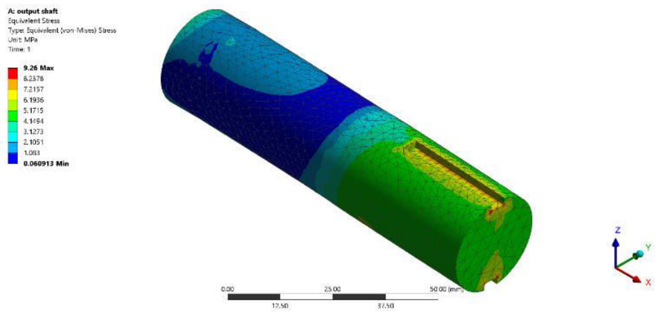

Fig -11: Equivalent stresses in the output shaft

Table -4: Comparison of FEA and analytical results

	FEA Result (MPa)	Analytical Result (MPa)	Error
Equivalent stress	9.26	11.32	17.6%

3.3.4 Output plate

The output plate is being rotated at very high angular speed by the input plate and MR fluid assembly. It is supported on the output shaft. The shearing stress is imparted by the MR fluid on the walls of the plate. The meshing of plate is done with fine relevance and element size with 2 mm. The plate contains total 27486 nodes and 14694 elements with tetrahedral in shape. The mapped meshing is applied to create more uniform meshing pattern along the surfaces of the plate that gives closer results.

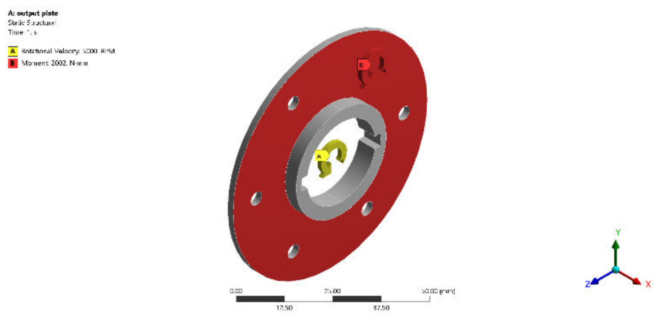

Fig -12: Boundary conditions applied on the output plate.

The boundary conditions imposed on the input plate are the torsional moment and rotational speed. The torsional moment generated in each fluid gap is applied on the plate which is 2002 Nmm. The rotational speed given to it is 5000 rpm. The Fig 12 shows the boundary conditions applied on the output plate.

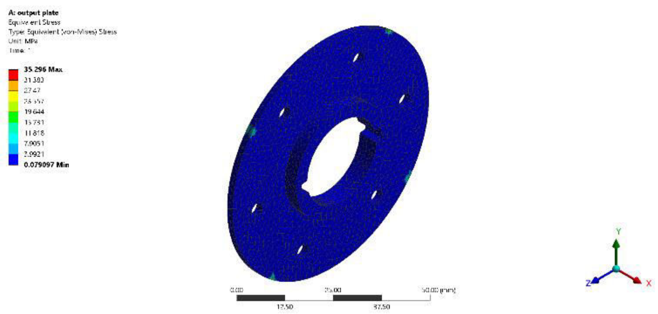

Fig -13: Equivalent stresses in output plate

The total Von-mises stress generated in output plate is 35.296 MPa, which is smaller than the allowable shear stress. The Fig 13 show the equivalent stress in output plate.

The analytical value of equivalent stress comes 31.56 MPa. The difference in the both results i.e. analytical and FEA is due the keyway present on the shaft. The Table 5 shows the comparison of results of both analytical and FEA.

Table -5: Comparison of FEA and analytical results

	FEA Result (MPa)	Analytical Result (MPa)	Error
Equivalent stress	35.296	31.56	10.58%

3.3.5 Extended input hub

The output plate is being mounted on the input shaft using the key. The motion is transferred from input shaft to the hub and from hub to the input plates. The meshing of plate is done with fine relevance and element size with 2 mm. The plate contains total 57049 nodes and 31774 elements with tetrahedral in shape. Mapped meshing is applied to create more uniform meshing pattern. The boundary conditions imposed on the hub is rotational speed. The rotational speed given to it is 5000 mm. The Fig 14 shows the boundary conditions applied on the extended input hub.

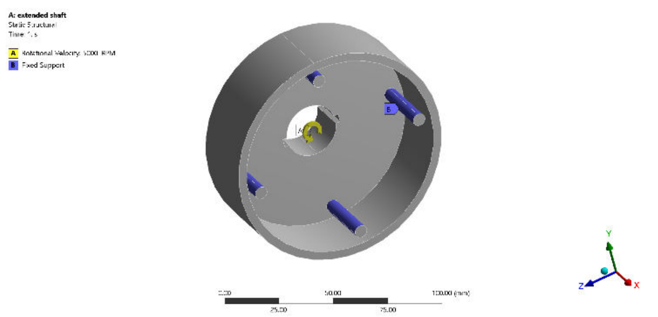

Fig -14: boundary conditions applied on the extended input hub

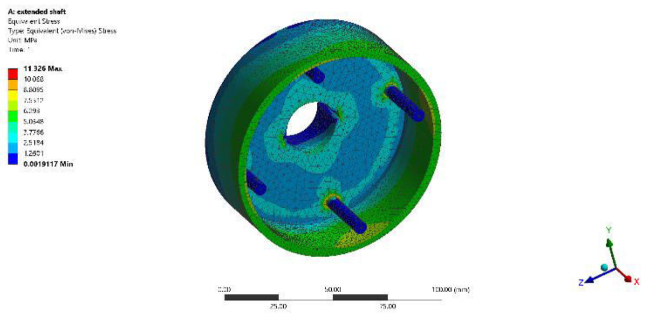

Fig -15: Equivalent stresses in extended input hub

The total Von-mises stress generated in hub is 11.326 MPa which is smaller than the allowable stress. The Fig 15 shows the equivalent stress in extended input hub. The critical stress points are located at the bases of the rods mounted on the vertical plate of the extended input hub, which is used as housing of the input plates.

4. CONCLUSION

The Following conclusions are drawn from the study made during the work:

i. The study of the MR clutch and its different types helped in the comparative study of different designs and applications aspects.
ii. FE analysis is carried out to verify the magnetic field intensity generated by coil, which is used to redesign the coil and design optimization of the MR clutch.
iii. The FE analysis of each individual components is performed, and the results resemble with the analytical results.

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