Parametric Design and Finite Element Analysis of a Dog Clutch

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Abstract - *Parametric designing is a generalized and sophisticated approach towards CAD modelling which comprises of modelling by altering the predefined geometrical parameters of the given CAD model. It enables to design in a systematic method. Additionally, it aids in studying the effect of changing the predefined parameters of the CAD model on the geometry and strength of the component being designed. This paper aims to present the parametric design and modelling of a dog clutch as well as the FEA simulation for the same. Both of the following processes were executed on Solidworks 2019.*

Key Words: **Dog Clutch, Parametric Design, CAD, FEA, Solidworks**

1.INTRODUCTION

Positive clutches are utilized in applications where a positive drive is required. Positive drive is a type of mechanical drive system which does not allow slippage during power transmission. This clutch engages not by friction but by interference. It has the benefit of allowing both shafts to turn at the same speed without slipping and with minimal clutch wear. The simplest type of positive clutch is a dog clutch which is also called as a jaw clutch. The dog clutch permits one shaft to drive another through a direct contact of interlocking teeth. It consists of two halves, one of which is fastened to the driver shaft and possesses axial movement along the shaft in order to function properly. This axial movement can be facilitated by providing straight splines for pure axial engagement or by providing helical splines for converting rotary movement of the shaft to axial movement of the dog clutch and hence engagement. The other half of dog clutch is fastened to the driven shaft and remains stationary with respect to the shaft. This half aids in positive driving of the driven shaft.

Depending on the function, the tooth profile of dog clutch is selected. The tooth profiles are majorly classified as unidirectional and bidirectional. The names, unidirectional means a dog clutch which will provide torque transmission in one direction only while bidirectional means a dog clutch which provides torque transmission in both directions.

Dog clutch has various applications across mechanical field. They are used inside manual automotive transmissions to lock different gears to the rotating input and output shafts. Another application of a dog clutch can be seen in marine propeller drives involving reversible outboard propulsion units. A distinctive application of dog clutch is in freewheel units. A freewheel or overrunning clutch is a device in a transmission that disengages the driveshaft from the driven shaft when the driven shaft rotates faster than the driveshaft. The unidirectional dog clutch performs better than an one way sprag clutch as freewheel since it works on interference rather than friction.

The main objective is to design and model an unidirectional dog clutch for a freewheel unit application with predetermined design parameters such that it is able to operate at the design torque and has considerable amount of factor of safety.

2. Design Calculations

2.1. Initial Design Parameters

Before initiating the design process, the initial design parameters considered were as follows:

Maximum torque to be transmitted= 40 Nm

Outer Radius of clutch surface (R_o)= 34 mm

Inside Radius of clutch surface (R_i)= 26 mm

Number of teeth on dog clutch (N_t)= 12

Maximum tooth height (h)= 3 mm

The following three dimensional geometric tooth profile was modelled. It involved all design consideration and multiple trials until the final and accurate profile for the clutch was determined.

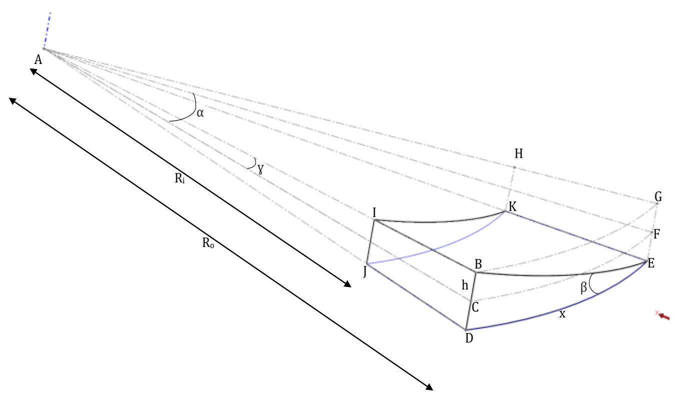

Fig -1: Dog clutch geometric tooth profile

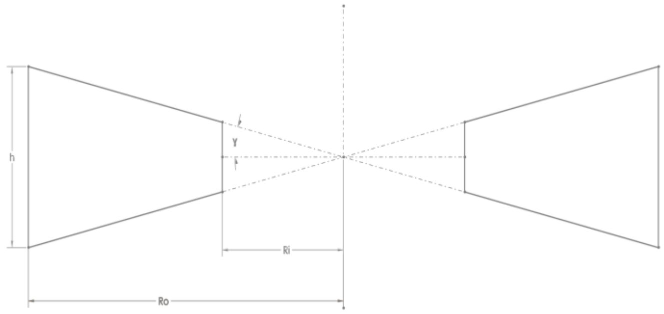

Fig -2: Dog clutch geometric sectional view

2.2. Geometric Relations

As per the three dimensional tooth profile, the geometric relations and equations obtained are as follows:

Pitch angle =∠CAF= α degrees

Tooth engagement angle=∠DEB= β degrees

Flank angle=∠BAC= γ degrees

Arc CF=DE=BG=x mm

Length AE=AD=R_o

Length AJ=AK=R_i

$\alpha=360/Nt$

$\tan \gamma= h/(2\times Ro)$

$\tan \beta= h/x$

$x= \alpha \times R_o$

By rearranging and substitution we get:

$\tan \gamma= (\tan \beta) \times \alpha/2$

where β and γ are in degree and α is in radians.

Furthermore, $\tan \gamma= (\tan \beta) \times(\alpha\times\pi/360)$
where α, β and γ are in degrees

The above equation helps to establish a relationship between geometrical angles α, β and γ. Additionally it helps to calculate the tooth engagement angle. For a self-engaging dog clutch with minimal axial force, angle β should be maximum 45 degrees. As β increases, the axial force to hold the cultch in engaging position increases.

Now substituting all the predetermined data, we receive:

$\alpha=360/Nt$

$\alpha=360/12$

$\alpha= 30^o$

$x= \alpha\times R_o = 17.8024$ mm

$\tan \gamma= h/(2\times Ro)$

$\tan \gamma= 3/ (2\times34)$

$\gamma=3.5763^o$

$\tan \gamma= (\tan \beta) \times(\alpha\times\pi/360)$

$0.0441176= (\tan \beta) \times(30\times\pi/360)$

$\tan \beta=0.0441176/(30\times\pi/360)$

$\beta=9.5654^o$

$\beta <45^o$ hence self-engaging clutch

3. Parametric CAD model

Using the above obtained data, the final CAD model was accurately designed in Solidworks 2019. The fastener locations were also added in order to fix the dog clutch on to the shaft. Six number of metric six diameter bolts were considered as a fastening method. The assembly model of the dog clutch reveals the perfect meshing of both halves of the unidirectional dog clutch. Since there were no visible geometric gaps observed during the mating of the components including both the halves of dog clutches, it proved that the meshing was highly accurate. The model designed is as follows:

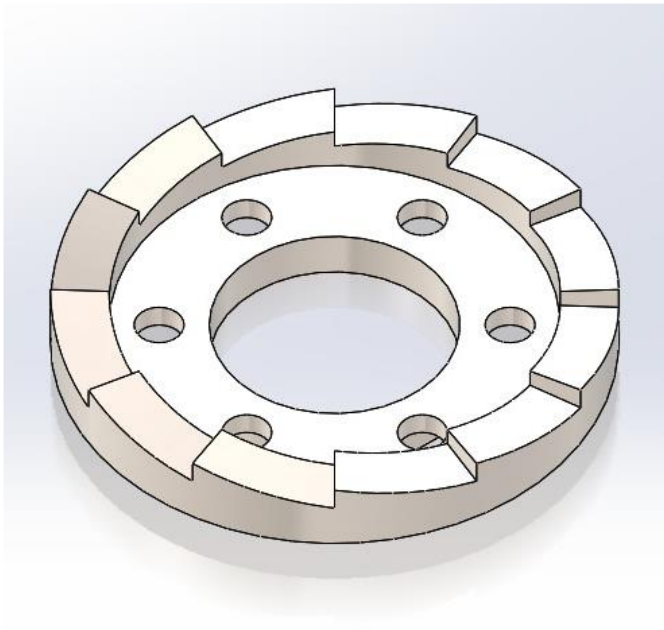

Fig -3: Dog clutch parametric CAD model

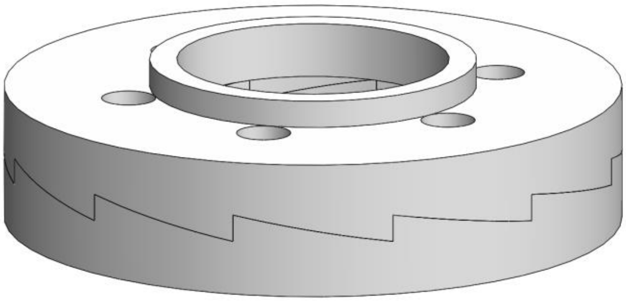

Fig -4: Dog clutches assembly model

4. Finite Element Analysis

Post the parametric design, the dog clutch is analyzed using finite element method. The finite element analysis (FEA) is executed using Solidworks simulation. Material selection is one of the important criteria since material properties decide the factor of safety and service life of the component being designed.

The dog clutch works on interference hence it is subjected to a large amount of shock loading just before engagement. The prime criteria for material selection thus will be high shock resistance and toughness.

The material for analysis thus selected is EN-36 alloy Steel also known as AISI 3415. A nickel/chrome case hardening steel. When carburized and hardened attainable core values of 850-1230N/mm^2 can be achieved. Chromium increases the hardenability while the nickel content will increase the toughness and resistance to shock. Applications include heavy duty gears, sprockets, cams, crankshaft, transmission components and track rod pins. Characterized by high core strength, excellent toughness and fatigue resistance in relatively large sections with case hardness up to Rc 62 when carburized, hardened and tempered. Machinability of this steel in softened condition is 65% of mild steel. It has a yield strength of minimum 730 N/mm^2 and tensile strength of 800-1000 N/mm^2. For the FEA simulation, average tensile strength of 900 N/mm^2 is considered.

Table -1: Mechanical properties of EN-36 alloy Steel

Condition	Yield strength (MPA)	Average tensile strength (MPA)
Case Hardened	730	900

Thus, initially the material was first defined in Solidworks material library and then applied to the designed clutch during FEA simulation. As discussed earlier the six fastener holes were used in FEA simulation as fixtures. Further a torque of 40 Nm corresponding to maximum value was applied on the contact surface of each of the 12 teeth in the direction normal and into the plane of the contact surface.

The solver used for the simulation was the standard FFEPlus available in Solidworks. The FFEPlus solver uses advanced matrix reordering techniques that makes it more efficient for large problems. In general, FFEPlus is faster in solving large problems and it becomes more efficient as the problem gets larger (up to the maximum memory available).

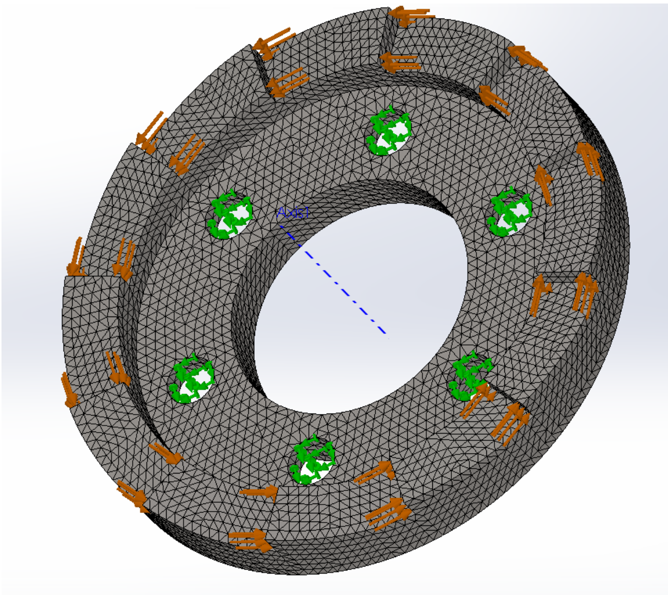

Fig -5: Dog clutch meshed model

Fig-5 shows the meshed model of the dog clutch. The six holes are made into fixtures. The torque totaling to 40Nm is added on each of the 12 teeth normal to the contact surface with the reference axis as the center of the cylindrical face of the dog clutch.

The mesh details are as follows:
Element type: 3D tetrahedral solid element
Element size: 1.23997mm
Element tolerance: 0.0619987mm
Jacobian points: 4
Mesh quality: High
Total number of nodes:92596
Total number of elements: 59905

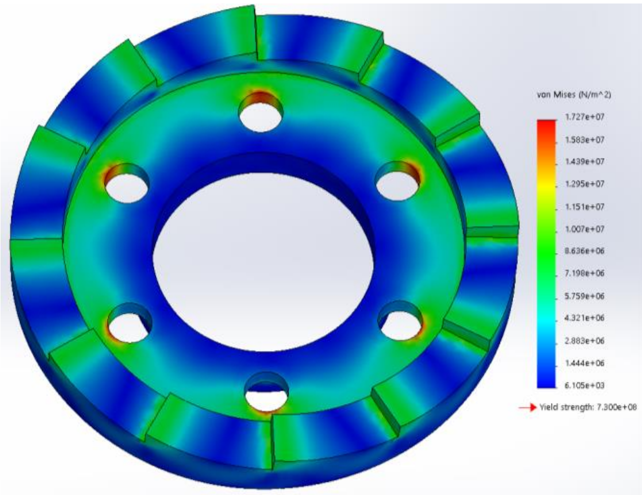

Fig -6: Dog clutch Von Mises Stress plot

Fig-6 shows the Von Mises Stress plot result. The Von Mises criteria was considered since material is ductile in nature. The minimum value of Von Mises stress at a given point is $6.105\times10^3 N/m^2$ while the maximum value of Von Mises stress is $1.727\times10^7 N/m^2$. The results show that the maximum value of Von Mises stress is well below the maximum limit governed by yield strength of $7.3\times10^8 N/m^2$. Thus, leading to an appreciable value of factor of safety.

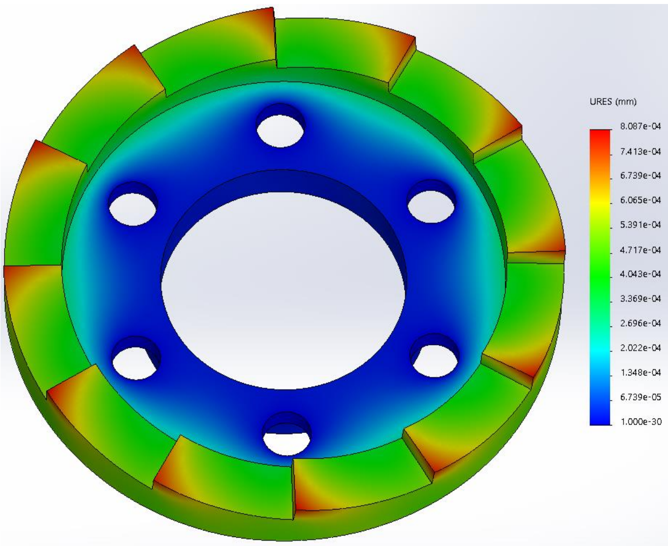

Fig -7: Dog clutch Resultant displacement plot

Fig-7 shows the resultant displacement plot for the dog clutch. A maximum resultant displacement of about 8.087×10^{-4} mm is obtained. This value is well below the working limits of the dog clutch and hence will not cause any issues in the meshing of the dog clutch during operation.

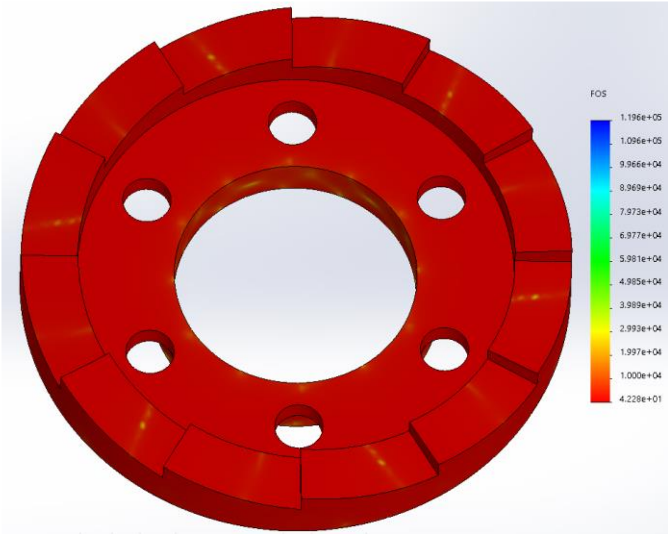

Fig -8: Dog clutch Factor of Safety plot

As discussed earlier, an appreciable factor of safety was obtained. Fig-8 hence shows the factor of safety plot.
Mathematically,

$$FOS = \sigma_y / \sigma_{max}$$

Where σ_y is yield stress of material and σ_{max} is maximum induced stress.
The minimum factor of safety attained is of 42.28 which is well over the design limits and will be able to accommodate for the shock loading easily. This high factor of safety also concludes that the component has an appreciable high amount of service life.

The final results obtained are tabulated below as follows:

Table -1: FEA simulation Results

Loading Torque (Nm)	Maximum Von Mises stress (MPa)	Maximum Resultant Displacement (mm)	Factor of safety (FOS)
40	17.27	8.087×10^{-4}	42.28

5. Conclusion

This paper powerfully presents the parametric designing of a unidirectional dog clutch for a freewheel unit. The objective of the paper has been met. The FEA simulation also demonstrate that the design is regarded as safe in terms of factor of safety and that it is capable of taking the given load in addition to the shock load occurring during engagement. The dog clutch as mentioned before is efficient as a freewheel unit since it works on interference rather than friction. This can be also understood by the fact that the one way sprag clutch freewheel units have considerable amount of drag torque. This can be regarded due to the sprag shaped elements which have higher drag torque as compared to roller or spherical ball rolling elements. On the other hand, the dog clutch being fastened to the shaft hence relies on the momentum of the rotating shaft and the type of support provided on the shaft. The shaft can be supported on ball bearings in order to provide minimum drag torque hence reducing mechanical losses and increasing overall efficiency of the system. The parametric designing process can also be regarded as to help with the generalized approach of designing mechanical transmission components. By varying some of the initial predefined dimensions, the effect on overall geometry as well as on the strength of the component being designed can be observed. Furthermore, algorithms can be developed in order to speed up this generalized CAD modelling process using the parametric approach. Several design combinations can be created and their effects can be studied simultaneously. Hence it can be seen that parametric design has great potential with regards to CAD modelling.

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