Optimization of Continuously Variable Transmission

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Abstract— The Automotive industries has undergone a massive change in last few decades. Producer of the cars are now looking for more sophisticated designs to reduce the cost and Consumers are now focusing on reduction in work and improvement in comfort. There are various innovative ideas implemented by Automotive industries to ensure the desired comfort with minimizing the cost, weight, work and time. Gear transmission system in one of the major parts of an automobile. The aim of this paper is to see how transmission system of an automobile can be sophisticated and automated. Through this study, the working of automatic gear transmission system, it's advantages and limitations along with different ways of Optimization are discussed. Finally, optimized transmission systems are presented.

Key words: (CVTs) Continuouslt Variable Transmission System; Belt; Conical Roller; HyperWorks-OptiStruct; production

I. Introduction

Few decades ago, Continuously Variable Transmission system was not considered as the primary transmission system in an automobile. But in today's era, many automobile manufacturers are preferring CVT over conventional manual gearboxes and epicyclic geartrains due to its better fuel economy and stepless gear ratio change. CVTs work on the same principle as the conventional manual transmission system. Different pitch circle diameters of the input and output gear results in different gear ratios, whereas, different diameters of the input and output pulleys results in different gear ratios in CVT. CVT has been popular transmission systems among many automobile industries such as, Nissan, Audi, Chevrolet, Honda, Ford, etc. The most familiar and mostly used CVT is pulley based CVT. Cone based CVT uses two pulley and power is transmitted through the belt. This is the highly optimized CVT. It the lightest CVT with the performance. The other types of CVTs are eliminated due to their disadvantages. This paper focuses on one of the outdated CVT and elimination of its limitations.

Conical roller and belt based CVT used two conical rollers instead of pulleys and power is transmitted through the belt. Different diameter of conical roller results in different gear ratios. This type of CVT provides stepless gear ratios and with the appropriate electronics support, the economic conditions can be achieved. Use of conical roller instead of movable pulleys, makes this CVT easy to manufacture and with less manufacturing cost. Even though pulley based CVT has certain advantages over Automatic Transmission System, weight of CVT is remarkably large than that of other CVTs and Automatic Transmission. Large volume of conical roller makes it bulky. Purpose of this paper is to optimize the weight of conical roller.

HyperWorks-OptiStruct is an optimization software developed by Altair. It has been widely used for topology optimization due to its precise and simple functioning.

II. Litterature Review

The most important function of the transmission system is to convert the torque. Stationary vehicle needs high torque in order to move with the compromisation of RPM (Speed). Whereas, moving vehicle needs higher speed with lower torque. Different torque variation methods are using, Geartrains, Harmonic Drive, Micro-controllers, Hydraulic/Pneumatic Actuators, Continuously Variable Transmission. Geartrains have the issues regarding limited range of gear ratios and rough transmission. Harmonic drives are highly efficient in torque conversion but are costly. Micro-controllers have high risk of errors, failures and they are costly. Fluid lines are required for Hydraulic/Pneumatic actuator along with compressor/pump which makes it costly and bulky. On the other hand, CVTs are not as costly as others, they have a smooth transmission, infinite gear ratios. While in CVT, there is Belt CVT which has limited range of gear ratios and it is difficult to manufacture making it comparatively costly. Spherical CVT is not suitable for high torque applications since it has a slippage problem. Toroidal CVT has a complex design and so it has a higher manufacturing cost. Cone CVT is easy to manufacture, it has wide range of gear ratios. (Ashish Singlaa, 2016)[9]

Cone type CVT does not only offer stepless smooth transmission but also better performance in terms of efficiency. 'Srinath N' of 'RMK College of Engineering & Technology' states advantages of cone CVT with its design in his publication. According to that design weight of the CVT seems to be one of the major issue when that weight is compared with other types of CVT. (N, 2015) [10]

To obtain maximum performance with the minimum weight objective, "Design optimization of a two-stage compound gear train", by 'Nikhil Kotasthane, Priyank Gajiwala, and Pratik Baldota' was referred. Authors suggested either to select material with low weight density or to reduce the volume with appropriate constraints. (Nikhil Kotasthane) [11]

This paper focuses on reducing the weight of Cone of CVT and increasing its performance.

III. Problem Statement

In many countries such as India, other developing countries or even the European countries prefer Manual transmission over automatic transmission. Automatic transmission hasn't been popular in India due to various reason. Firstly, high cost of Automatic transmission system and low fuel efficiency. Fuel economy has always been the deciding factor for an average Indian customer while purchasing the car. This is the reason why only few international automobile manufacturers offer Automatic transmission in India. CVT hasn't been popular in India due to its high cost. One of the most important reason for Automatic transmission being widely used in developed countries is the good road condition, well organized traffic which moves at constant pace and mostly breakdowns are avoided and so the gearbox running at high gear ratio resulting in better fuel economy. But in a developing countries like India where roads are not that good, traffic moves at a very slow pace and regular downshifts are required and hence resulting in poor fuel economy. Hence most of the domestic automobile manufacturers in India prefer highly economic transmission system. Even though CVT provides good fuel efficiency, its high cost has been one of the constraint for the Manufacturer in India. India manufactures almost 5% of the total automobiles built in the whole world. This makes a need of New Automatic Transmission System with higher fuel economy and relatively lower cost. With the weight optimization, cost optimization and maximization of the range of Gear ratios, required objective can be achieved.

IV. DESIGN

A. *Conical Rollers:*

In this type of Gearbox, two conical rollers are used instead of movable pulleys. The shape of those Rollers would be as shown in figure. This part of the CVT is to be optimized. In order to obtain its dimensions, following design is required.

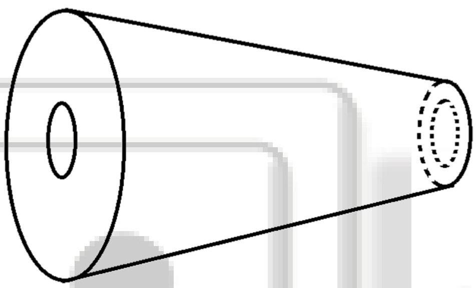

Fig. 1: Conical Roller

I have used 2013 Nissan Altima specifications for the design, which includes following data.

P = 82 KW

n = 6000 rpm

D = Diameter of the Driven roller = 300 mm

d = Diameter of the Driver roller = 100 mm

Center Distance between the Pulleys = C = 250 mm

F_1 = Tension on tight side of the belt

F_2 = Tension on the slack side of the belt

Tension on belt:

$$P = \frac{(F_1 - F_2)v}{1000}$$

Where,

$$v = \frac{\pi dn}{60000} = 31.4159\ \frac{m}{s}$$

$$82 = \frac{(F_1 - F_2) \times 31.4159}{1000}$$

$$(F_1 - F_2) = 2610.14\ N$$

Length of the belt:

$$L = 2C + \frac{\pi(D+d)}{2} + \frac{(D-d)^2}{4C}$$

$$L = 1168.31mm \cong 1169$$

Wrap angle for the smaller pulley:

$$\propto_s = 180 - 2\sin^{-1}\left[\frac{D-d}{2C}\right]$$

Wrap angle for the bigger sized pulley:

$$\propto_b = 180 + 2\sin^{-1}\left[\frac{D-d}{2C}\right]$$

Both pulleys are identical. At the initial stage, belt would be in contact with the smaller end of the driving pulley. As the operation starts, belt will slide along the both pulley. In case of driving pulley, belt would be sliding from smaller end diameter to bigger end diameter of the roller. Since the driving pulley starts with the smaller diameter end, we would have to use smaller pulley wrap angle till it reaches to midpoint of the roller. Length of the roller is 500 mm, hence 250 mm would be the midpoint of the roller. At 250mm length from either of the side, wrap angle would be 180^0 on the both pulleys. From midpoint to end driving pulley would be having greater diameter than driven pulley. Hence, in that case, larger wrap angle is required for the pulley. At initial stage, when the belt is at the start of driving pulley (d = 100 mm), it is on end of the driven pulley (D = 300 mm).

Wrap angle:

$$\propto_s = 180 - 2\sin^{-1}\left[\frac{D-d}{2C}\right]$$

$$\propto_s = 180 - 2\sin^{-1}\left[\frac{300-100}{2 \times 250}\right]$$

$$\propto_s = 132.8436^0 = 2.3185^c$$

Tension on the tight side of the belt and tension on the slack side of the belt:

$$\frac{F_1}{F_2} = e^{\mu\alpha_s}$$

Where, μ is the coefficient of friction = 0.35

$$\frac{F_1}{F_2} = 2.2512$$

From above,

$$(F_1 - F_2) = 2610.14\ N$$

$$F_1 = 4696.24\ N$$

$$F_2 = 2086.10\ N$$

Arc of contact factor (Assuming Linear interpolation):

$$F_d = 1 + \frac{(1.04-1)(180-132.84)}{(180-132.84)} = 1.04$$

1) *Corrected Power:*

$$\text{Corrected Power} = 1.04(82) = 85.28KW$$

At belt speed of 31.41 m/s:

$$\text{Corrected belt rating} = \frac{0.0118(31.41)}{5.08} = 0.07296\ \text{KW}$$

2) *Belt width:*

$$b = \frac{\text{Corrected Power}}{\text{Corrected belt rating}} \times \frac{1}{12}$$

$$b = 96.82mm \approx 100mm$$

Thickness of the belt = 30mm.

The whole design would vary with respect to the diameter of driving and driven roller belt is in contact with. At the midpoint, where center of width of belt is at 250mm distance from either end, wrap angle would be 180^0 and hence the belt tension would vary.

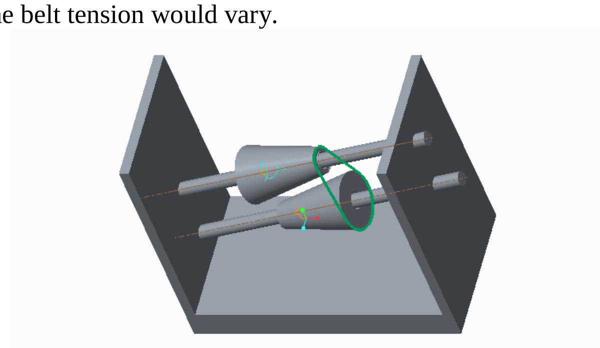

Fig. 2: Creo Modeling of CVT

In order to calculate belt tensions at different belt positions, the length of conical roller is divided in to 100 nodes and distance between each node is 5mm. To calculate belt tensions at each corresponding node, following MATLAB code has been developed:

```
P = 82;
D = 300;
n = 6000;
d = 100;
theta = atan(100/500);
i = 10;
C = 250;
v = (pi * d * n)/60000;
Force_Difference = (P * 10^3 / v);
alpha = pi - (2 * asin((D - d)/(2 * C)));
%alpha = (alpha_degree) * pi/180;
F2 = Force_Difference/(alpha - 1);
F1 = Force_Difference + F2;
fprintf('Initial_F1 = %d, Initial_F2 = %d', F1, F2);
while (i < 501)
   d = 2*(50 + (tan(theta) * i));
   D = 2* (50 + (tan(theta) * (500 - i)));
   v = (pi * d * n)/60000;
   Force_Difference = (P * 10^3 / v);
   if (D > d)
      alpha = pi - (2 * asin((D - d)/(2 * C)));
   else
        alpha = pi + (2 * asin((d - D)/(2 * C)));
   end
   F2 = Force_Difference/(alpha - 1);
   F1 = Force_Difference + F2;
   fprintf(' \n \t F1 = %d, \t F2 = %d, \t Alpha = %d', F1, F2,
alpha);
   i = i + 10;
end
```

Following results shows the belt tension on tight side and on the slack side at legths 5mm, 250mm and 500mm respectively. Forces are calculated with the mesh size of 5.

1) i = 5, F1 = 4.474376e+003, F2 = 1.915414e+003, Alpha = 1.338420e+002, d= 102, D = 298
2) i = 250, F1 = 1.914463e+003, F2 = 6.093925e+002, Alpha = 180, d= 200, D = 200
3) i = 500, F1 = 1.163523e+003, F2 = 2.934761e+002, Alpha = 2.271564e+002, d= 300, D = 100

Where, i = Distance of belt from the smaller diameter end of the conical roller
F1 = Tension due to tight side of the belt
F2 = Tension due to slack side of the belt
Alpha = Wrap angle of belt on conical roller corresponding to length
d = Small end diameter of conical roller
D = Big end diameter of the conical roller

Once all the forces are calculated, we have calculated the stresses developed on the conical roller at each node with corresponding forces and the wrap angles. In order to use Hypermesh for mass optimization, force analysis is done on the conical roller using Hypermesh. To validate those results, using same loading conditions and constraints analysis is done using Ansys Workbench. We are using Hypermesh and Ansys for the analysis on one Conical roller each and we would be comparing both the results.

In reality, belt tension acts tangentially with respect to the surface of conical roller. In order to apply tangential force, the tension is divided into two components with respect to global co-ordinates. The magnitude of components of tension is given by:

$$F_x = F_1 \cos\frac{\propto}{2}$$

$$F_y = F_1 \sin\frac{\propto}{2}$$

For calculating the components at every node on the roller, the following modification can be incorporated into the initial Matlab Code:

```
F1 = Force_Difference + F2;
Fx = F1 * cos(alpha/2);
Fy = F1 * sin(alpha/2);
fprintf('\n \t i = %d, \t Fx = %d, \t Fy = %d', i, Fx, Fy);
```

3) Matlab Results:

i = 5,	Fx = 1.753955e+003,	Fy = 4.116270e+003
i = 10,	Fx = 1.675865e+003,	Fy = 4.029641e+003
i = 15,	Fx = 1.601356e+003,	Fy = 3.946405e+003
i = 20,	Fx = 1.530202e+003,	Fy = 3.866363e+003

4) Hypermesh Optistruct:

Structural Analysis**:**

Since, we have calculated 200 Forces on 100 points at a distance of 5 mm each, mesh size was selected as 5. Meshing used was tetrahedral.

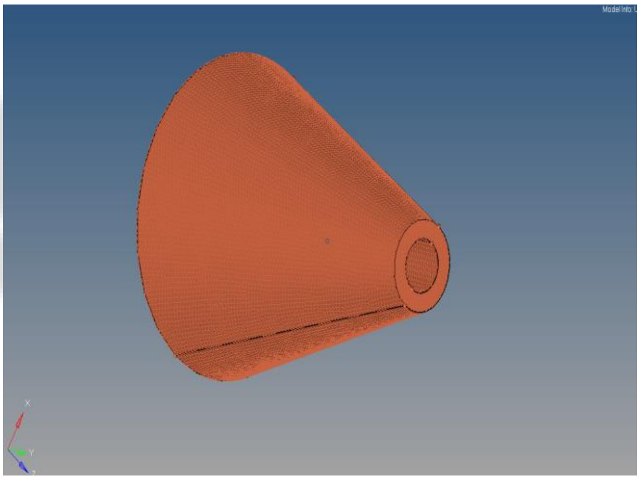

Fig. 3: Meshed Conical Roller

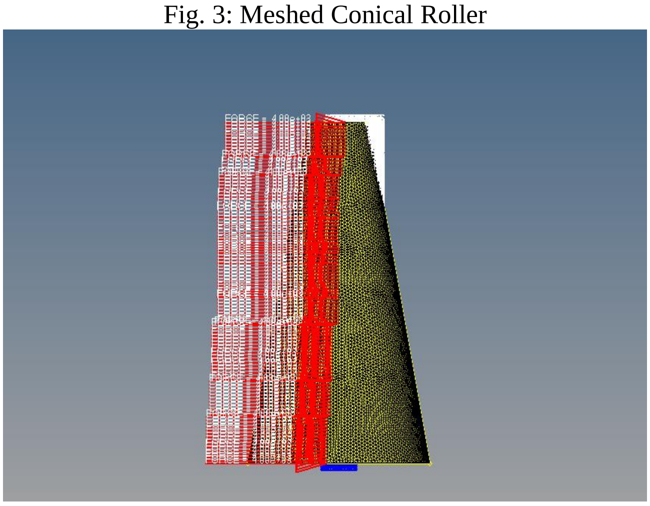

Fig. 4: Forces applied on nodes of driving conical roller

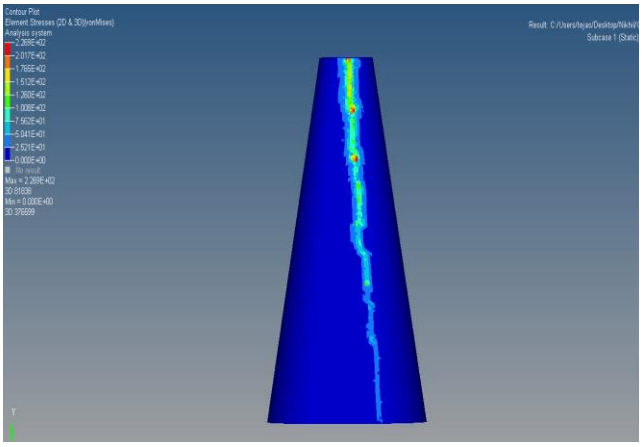

Fig. 5: Von Mises Stress analysis

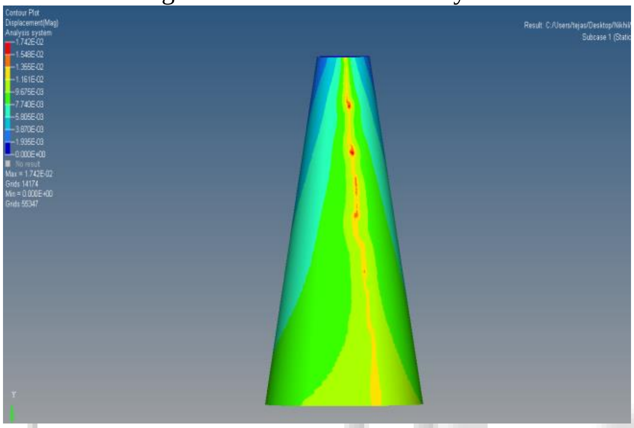

Fig. 6: Deformation/Displacement on Driving Conical Roller

Above figures shows the forces applied on the one location of the conical roller. When forces are applied on 8 different locations on the driving conical roller, we get the following results.

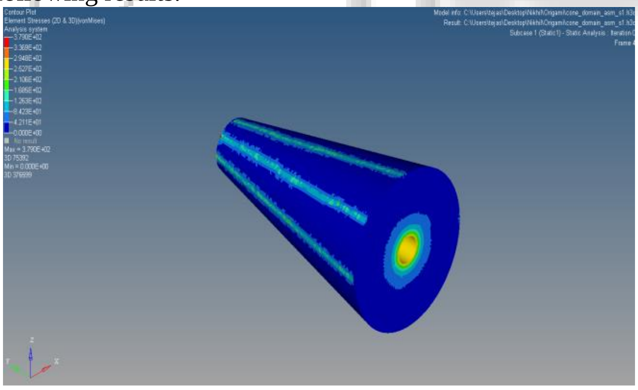

Fig. 7: Von Mises Stress analysis

5) Mass Optimization:

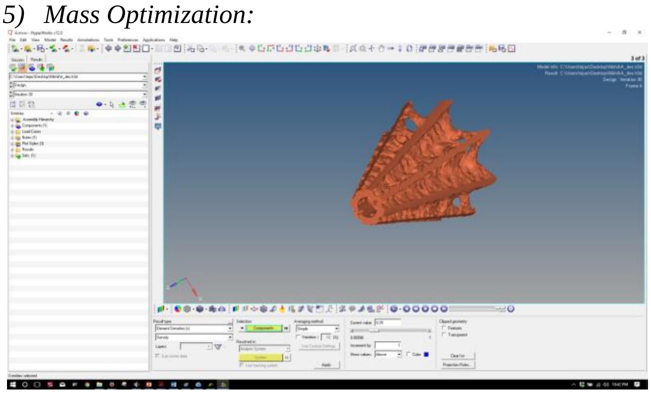

Fig. 8: Optimized driving Conical Roller

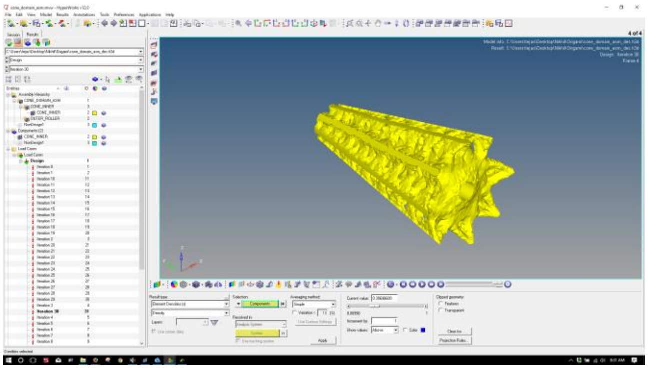

Fig. 9: Optimized driven conical roller

Keeping the outer body as non-design domain and the inner part as the design domain, we have got the Optimized conical roller. Since, 70% of the Material has been removed using SIMP Method, Volume becomes 30% of the Original Volume.

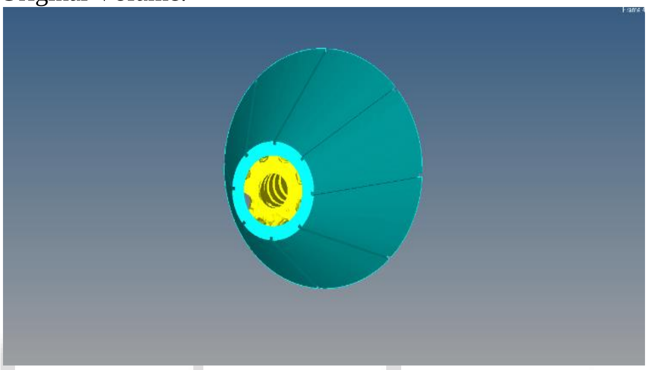

Fig. 10: Non-Design domain and design domain

Material used for the Conical roller - Steel, high strength alloy ASTM A514

Yield Strength of the material - 690 MPa

V. RESULTS

SR. No.	Volume	V-M Stress (MPa)	Density (Kg/mm^3)	S_{yt}	Mass (Kg)
1	16 x 10^6	231	7.85 x 10^{-6}	690	127
2	7.2 x 10^6	268	7.85 x 10^{-6}	690	57

VI. CONCLUSION

We started from the initial values taken from the original design. The multi objective project was needed to be evaluated. Need of the optimization was necessary. So, after the whole paper, we can conclude, the mass of the conical roller was optimized effectively. Initially the mass of the Conical roller was greater due to its large volume, but Optistruct eliminated the unnecessary material in order to reduce the volume of conical roller. The mass was reduced by 55%. Even though the mass has been reduced by huge amount, the manufacturing cost of the optimized design would be greater.

VII. RECOMMENDATIONS

1) Even though the mass has been reduced by huge amount, the manufacturing cost of the optimized design would be greater.

2) Elimination of other disadvantages of the roller based CVT.
3) Force analysis on the belt would be crucial along with its fatigue life analysis.

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