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DESIGN AND ANALYSIS OF HYDRAULIC CONTINUOUSLY VARIABLE TRANSMISSION

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Abstract - New regulations enacted by Indian Government for emission and fuel economy has encouraged the development of Continuously variable transmission as a key technology for improving fuel efficiency with infinite gear ratio within specified range to attain optimum performance.CTV provides better gas mileage and acceleration, as it runs at the most efficient number revolutions per minute for given vehicle speed.

As a continuously variable transmission development continues, the cost will reduce and performance will increase which will make the application of CVT technology more desirable.

This project deals with the design of a Continuously Variable Transmission with hydraulic means of actuation. The complete design and analysis of mechanical and hydraulic system is carried out using standard design procedures and software.

Key Words: CVT, Gear Ratio, Vehicle transmission, hydraulic system

1. INTRODUCTION

The Continuously Variable Transmission (CVT) permits engines to work potentially by freely moving through infinite number of gear ratios to maximize performance and fuel economy. Solid gears are a thing of the past. The CVT uses the readings through multiple sensors to keep engine rotating at a constant RPM with two variable pulleys and a steel belt[2].

CVT is a compact system and as will be described, it does not require the use of bulky gear sets or as many components as in the conventional transmission. A CVT system consists of two conical pulleys and a belt. As the sheaves of each pulley move closer or farther away from one another, their conical shape causes the belt to rise and fall b/w the sheaves of each pulley.[5] Depending upon the state of the belt, the active gear ratio is changed. Instead of switching between bulky fixed gears which only supply a limited number of gear ratios, the CVT pulleys create a continuous exchange of gear ratios by constantly altering the state of the belt b/w the pulleys[3].

Few mechanisms that allow the control of the pulley diameter include engine speed, flyweights, 3 springs and a torque ramp. When all of these mechanisms work simultaneously, they act to increase vehicle speed smoothly while maintaining engine speed at a particular value. This feature of engine speed maintenance is possible due to the continuity of gear ratios.

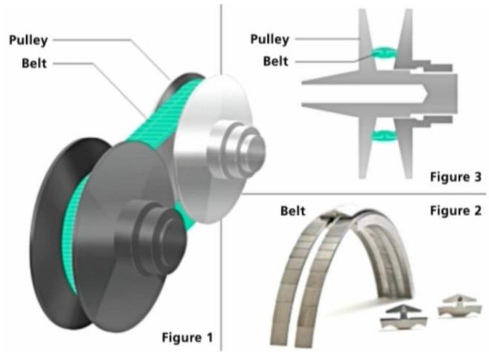


Fig.1 Continuously Variable Transmission (CVT)[1]

2. METHODOLOGY

The project work starts with definition of problem. This is to be followed by exhaustive literature review. The various concepts of automobile transmission should be studied. This includes manual and automatic transmission. Further, the study of CVT should be prioritized. This includes the types of CVTs, its working principles and various concepts related to design and analysis of CVT. The vehicle required for CVT design is to be selected. The various engine parameters of the vehicle need to be selected and studied for further application in the design[4]. The design and selection of mechanical components like pulley, belt, etc. is to be carried out. 3D CAD model of the components and system should be created. The finite element analysis of various components is to be carried out to ensure the safety against failure and optimization. The 2D drawings of components need to be prepared. Finally, the scaled prototype needs to be made using 3D printing for demonstration of design and development. The methodology is outlined with the help of flow chart.

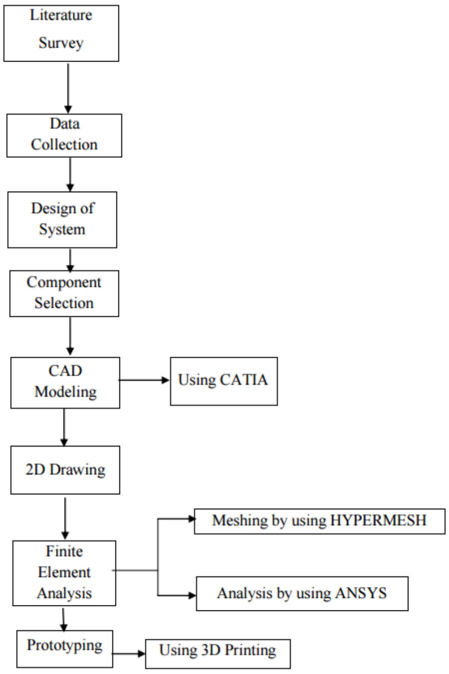


Fig. 2: Project Methodology

3. ANALYTICAL DESIGN

Design of CVT:-

Design procedure is divided into following steps:-

1. Vehicle engine parameters.
2. Vehicle transmission specification.
3. CVT ratio selection.
4. Pulley design.
5. Belt selection.

1. Vehicle engine parameters:-

Maruti Suzuki swift is selected.

Engine	
Type	K-Series Petrol Engine with VVT
Capacity	1197cc
Number of cylinders	4
Number of valves	16
Bore x Stroke	73 mm x 71.5 mm
Compression ratio	11.0:1
Maximum power	84.3 ps @ 6000 rpm
Maximum torque	115 Nm @ 4000 rpm

Table1: Vehicle Engine Specifications

2. Vehicle transmission specification:

Transmission	
Drive	5 MT
Clutch Type	DSD (Dry Single Disc)
Gear Ratio - 1st Gear	3.545
Gear Ratio - 2nd Gear	1.904
Gear Ratio - 3rd Gear	1.280
Gear Ratio - 4th Gear	0.914
Gear Ratio - 5th Gear	0.757
Reverse Gear Ratio	3.272
Final Drive Ratio	4.388

Table 2: Vehicle Transmission Specifications

3. CVT ratio selection:

For maintaining the same output performance at the wheels, the 1st and 5th gear ratio of the manual version mentioned above are taken as CVT ratio limits. Therefore the CVT speed reduction varies from low gear ratio – 3.545 to high gear ratio- 0.757. This performance is obtained by changing the contact diameter of belt on driving and driven pulleys.

4. Pulley design:

From the above CVT ratio calculation and constant belt length of 925mm.The dimension of driving pulley and driven pulley is calculated. As the groove angle of the belt is 20 degree, groove angle for driving pulley is taken as 12 degree and for driven pulley is taken as 10 degree to have a firm grip of the pulley on the belt. The minimum and maximum pitch circle of the pulley is mentioned below:

	Driving pulley	Driven pulley
Max. PCD	D1=142.1 mm	D2=222.7 mm
Min. PCD	d1=60 mm	d2=100 mm

Centre distance between pulley, C = 225 mm
Belt length, L = 925 mm
Groove angle, α = 20 degree

5. Belt selection:-

Variable speed steel belt is the special type of belt for CVT to withstand high tension. Specification of the belt is obtained from the catalogue of BOSCH CVT Pushbelt.

PART NUMBER: 901086
DESCRIPTION: 30/12/-/930.0/Hitachi
ELEMENT WIDTH: 30
NUMBER OF RINGS: 12
BELT LENGTH: 930 mm
RING MATERIAL: Hitachi

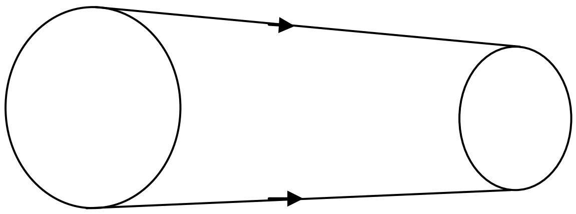
Table 3: Belt Specification

Belt groove angle	30 degree
Belt length	925 mm
Belt width	30 mm
Belt thickness	10 mm

4. ACTUATING FORCES ON PULLEYS

The actuating forces on driving and driven pulleys are calculated below:

4.1 CALCULATION OF FORCES ON DRIVING PULLEY



	Driving Pulley	Driven Pulley
Max PCD	**D_i =** 142.1 mm	**D_o =** 222.7 mm
Min PCD	**d_i** = 60 mm	**d_o** = 100 mm

1. Design torque on driving pulley (T_{maxi}):

T_{maxi} = 138 N-m

2. Belt tensions on driving pulley(F_{1i} and F_{2i}):

$T_{maxi} = (F_{1i}-F_{2i})\times R_{maxi}$

$138 = (F_{1i}-F_{2i})\times \frac{14}{2X1}$

$(F_{1i}-F_{2i})$ = 1942.29 N

Di = maximum pitch circle diameter of driving pulley
=142.1 mm
do = minimum pitch circle diameter of driven pulley
= 100mm
C = Centre distance between two pulleys
= 225mm

$\alpha_i = \sin^{-1}(\frac{142.1-100}{2\times 225})$ = 0.0936 radians

$\Theta_i = \pi-2(0.0936)$

Θ_i = 2.954 radians

$\frac{F1i}{F2i} = e^{\frac{0.2\times 2.954}{\sin 15}}$ radians

$F_{1i} = 9.8\, F_{2i}$

$(F_{1i}-F_{2i})$=1942.29 N

F_{1i} = 2163.004 N

3. Total tension on driving pulley (F_{Ti}):

F_{Ti} =2383.71 N

4. Normal reaction between belt and driving pulley (F_{Ni}):

F_{Ni} = 9209.94 N

5. Frictional force between belt and driving pulley (F_{fi}):

F_{fi} =1841.98 N

6. Component of normal reaction in axial direction on driving pulley (F_{a1i}):

F_{a1i}=8896.12 N

7. Component of frictional force in axial direction on driving pulley (F_{a2i}):

F_{a2i} = 476.74 N

8. Frictional force between shaft and driving pulley (F_{a3i}):

$F_{a3i} = \mu\ F_{Ti}$
=0.3×2383.71
= 715.113 N

9. Total axial force on driving pulley(F_{ai}):

$F_{ai} = F_{a1i}+F_{a2i}+F_{a3i}$
F_{ai} = 8896.12+476.74+715.113
F_{ai} =10087.97 N ………………………. (14)

4.2 CALCULATION OF FORCES ON DRIVEN PULLEY

1. Design torque on driven pulley (T_{maxo}):

T_{maxo} = 5122 N-m

2. Belt tensions on driven pulley (F_{1o} and F_{2o}):

F_{1o} = 5453.3 N
F_{2o}= 853.4 N

3. Total tension on driven pulley (F_{To}):

F_{To} =6306.7 N

4. Normal reaction between belt and driven pulley (F_{No}):

F_{No} = 24367.27 N

5. Frictional force between belt and driven pulley (F_{fi}):

F_{fo} =4873.4 N

6. Component of normal reaction in axial direction on driven pulley (F_{a1o}):

F_{a1o}=23536.98 N

7. Component of frictional force in axial direction on driven pulley (F_{a2o}):

F_{a2o} = 1261.3 N

8. Frictional force between shaft and driven pulley (F_{a3o}):

F_{a3o} =1892.01 N

9. Total axial force on driven pulley (F_{ao}):
F_{ao} =26690.29 N

4.3 HYDRAULIC SYSTEM CALCULATIONS

4.3.1 Forward Stroke of Driving (Primary) Pulley:

1. Axial displacement of pulley (x_i):
x_i = 11 mm = 11 x 10^{-3} m

2. Selection of dimensions of hydraulic cylinder:
Selecting model A5 for which,
Bore/ Piston diameter = 100mm
Rod diameter = 50 mm

3. Pressure for forward stroke (P_{fori}):
P_{fori} = 12.84 bar.

4. Piston velocity during forward stroke (V_{fori}):
V_{fori} = 2.75 x 10^{-3} m/s

5. Flow rate of oil during forward stroke (Q_{fori}) :
Q_{fori} = 1.296 lpm

6. Power requirement during forward stroke (W_{fori}):
W_{fori} = 32.63 W

4.3.2 Return Stroke of Driving (Primary) Pulley:

1. Axial displacement of pulley (x_i):
x_i = 11 mm = 11 x 10^{-3} m

3. Axial force during return stroke:
F_{air} = 1191.85 N

4. Pressure for return stroke (P_{reti}):
P_{reti} = 2.023 bar.

5. Piston velocity during return stroke (V_{reti}):
V_{reti} = 2.75 x 10^{-3} m/s

6. Flow rate of oil during return stroke (Q_{reti}) :
Q_{reti} = 0.97 lpm

7. Power requirement during return stroke (W_{reti}):
W_{fori} = 3.87 W

4.3.3 Forward Stroke of Driven (Secondary) Pulley:

1. Axial displacement of pulley (x_o):
X_o = 16.44 mm = 16.44 x 10^{-3} m

2. Pressure for forward stroke (P_{foro}):
P_{foro} = 33.98 bar.

3. Piston velocity during forward stroke (V_{foro}):
V_{fori} = 4.11 x 10^{-3} m/s

4. Flow rate of oil during forward stroke (Q_{foro}) :
Q_{foro} = 1.94 lpm

5. Power requirement during forward stroke (W_{foro}):
W_{foro} = 129.12 W

4.3.4 Return Stroke of Driven (Secondary) Pulley:

1. Axial displacement of pulley (x_o):
x_i = 16.44 mm = 16.44 x 10^{-3} m

2. Axial force during return stroke:
F_{aor} = 3153.3N

3. Pressure for return stroke (P_{reto}):
P_{reto} = 5.35 bar.

4. Piston velocity during return stroke (V_{reto}):
V_{reto} = 4.11 x 10^{-3} m/s

5. Flow rate of oil during return stroke (Q_{reto}) :
Q_{reto} = 1.45 lpm

6. Power requirement during return stroke (W_{reto}):
W_{foro} = 12.38 W

4.3.5 System Parameters:

(i) Maximum working pressure:
P_{foro} = 34 bar = 34 × 10^5 N/m²
(ii) Maximum flow rate:
Q = Q_{foro} = 3.23×10^{-5} m³/s
(iii) Power:
kW_{foro} = 129.12 W

4.4 DESIGN OF SHAFTS:

4.4.1: Design of Driving (Primary) Shaft:

(i) Maximum bending moment:
M_i = 169.24 x 10^3 N-mm
(ii) Maximum torque:
T_i = 115 x 10^3 N-mm

(iii) Equivalent torque:

T_{ei} =288.9 x 10^3 N-mm

Material for shaft : Alloy Steel 35Ni5Cr2 with
S_{ut} = 800 N/mm² & S_{yt} = 500 N/mm²
τ_{max} = 144 N/mm²

$$\tau_{max} = \frac{16Tei}{\pi di^3}$$

$$144 = \frac{16 \times 288.9 \times 10^3}{\pi \times di^3}$$

di = 21.69 mm or 25 mm
∴ di = 25 mm

4.4.2 Design of Driven (Secondary) Shaft:

(i) Maximum bending moment:

M_o = 532.91 x 10^3 N-mm

(ii) Maximum torque:

$$T_o = 512.2 / 1.2 = 426.8 \times 10^3 \text{ N-mm}$$

(iii) Equivalent torque:

$$T_{eo} = 949.37 \times 10^3 \text{ N-mm}$$

$$\tau_{max} = 144 \text{ N/mm}^2$$

$$\tau_{max} = \frac{16 T_{eo}}{\pi d_o^3}$$

$$144 = \frac{16 \times 949.37 \times 10^3}{\pi \times d_o^3}$$

$$d_o = 32.26 \text{ mm or } 35 \text{ mm}$$

$$d_o = 35 \text{ mm}$$

Analysis using ANSYS R19.1

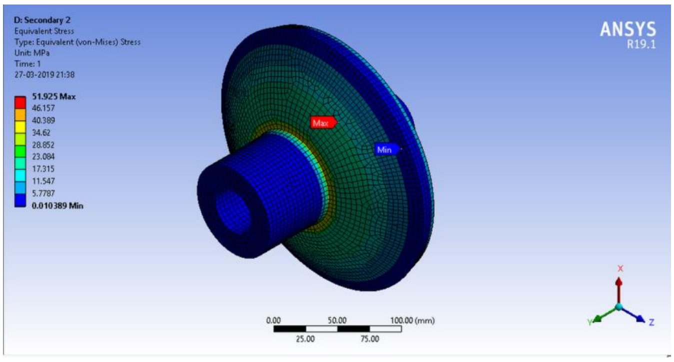


Fig 3: Equivalent Stress of Primary sheave 2

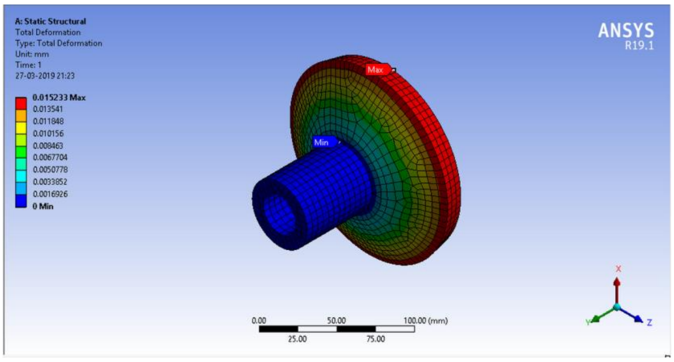


Fig. 4 :Total Deformation of Primary Sheave 2

5. CONCLUSIONS

Today, only a handful of cars worldwide make use of CVTs, but the applications and benefits of continuously variable transmissions can only increase based on today's research and development. Considering the specification of the vehicle the ratio for CVT are selected. Further pulley dimensions were calculated along with other parameters. 3D CAD model of the pulley has been designed.

Further hydraulic system for the actuation of CVT is to be designed. Complete analysis of the CVT assembly will be carried out using suitable software

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