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Design of Continuous Variable Transmission and it's Cooling

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***Abstract*: Continues Variable Transmission (CVT) is an automatic transmission, which gives an infinite variable ratio between driver and driven pulley as per requirement of vehicle. Generally, it is used in moped, All Terrain vehicle (ATV), 4 wheelers etc. In which ratio is changed by varying belt diameter wrapped around the drive and driven pulley. Which will change its diameter with the help of friction between belt and pulley. Due to the friction between them will increase the temperature of both pulley and belt, which results to decrease the performance and life of CVT. We can increase it by decreasing the temperature.**

***Keywords*: Primary pulley, Secondary pulley, Speed ratio, Thermoelectric generator.**

1. Introduction

Continuously variable transmission (CVT) is gearless transmission system, which will give variable speed ratio according to resistance on vehicle by varying it's belt diameter over the pulleys under the action of centrifugal force by weights & friction between belt & sheave of pulleys. Mainly there are three parts- Primary pulleys, Secondary pulley & Belt. Each pulley will consist of one fixed sheave & another one will be movable sheave. In some cases, rubber V-belts are used to connect the two pulley to transfer power. Primary pulley will consist of fixed & movable sheave, a set of flyweight and a compression spring. Primary pulley is mounted on engine shaft. As the engine rpm increases a set of flyweights in the primary pulley will apply the centrifugal force on movable sheave to push the belt upward to change its diameter over the pulley. However, it is not possible until the force applied by a set of flyweights is able to overcome the force opposed by the compression spring. As its overcome, the force by a set of flyweights will start to enlarge the diameter of belt over the primary pulley and reduce over the secondary pulley by opposing the spring forces in both the pulleys. The secondary pulley consists fixed and movable sheave, helix and a helical spring. As the primary pulley apply the force on belt, it will create the tension in belt. The tension in belt will apply the force on sheaves preloaded by a helical compression spring to reduce the diameter of belt over the secondary pulley. This process will vary the speed ratio according to resistance on a vehicle.

A. Various Components of CVT

Mainly the CVT has three part- primary pulley, secondary pulley and belt. Where primary pulley is mounted on the engine shaft and secondary pulley is mounted on input shaft of a drive assembly. Power is transmitted to the drive assembly by connecting primary pulley to secondary pulley with the help of belt. The list of components used in the CVT are as follow:

- Primary Pulley
    - Fixed Sheave
    - Movable Sheave
    - Post
    - Arms
    - flyweights
    - Ram
    - Primary Spring
    - Rollers
- Secondary Pulley
    - Fixed Sheave
    - Moving Sheave
    - Post
    - Secondary Spring
    - Helix
    - Rollers
- Belt

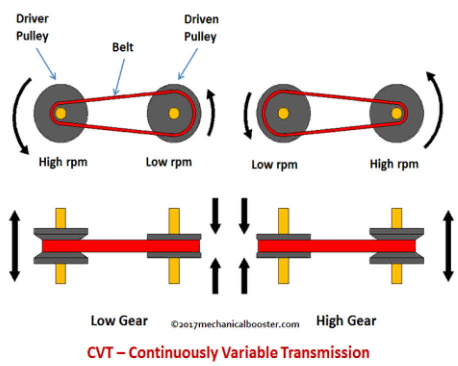

Fig. 1. Working of CVT

2. CVT Geometry

The parameters of the CVT geometry are shown in figure 3. The subscripts a and b are refer to the primary and secondary pulleys respectively. As CVT is V belt transmission, the angle of belt is 26°.

OEM belt (HPX2217)
Top Width = 29.2 mm
Base Width = 22.5 mm
Thickness = 12 mm
Length = 844 mm
Therefore half wedge angle of sheaves are 13° & it is denoted by $\propto$.

Selection of CVT ratio

By comparing various OEM CVT's available in market for selecting the ratio. We analysed some of the CVT's as follows:

1) GAGED GX9: 3.9 -0.9
2) CV Tech: 3-0.43
3) Comet CVT: 3.31-0.5
4) Polaris CVT: 3.8-0.7

The data given by the above mentioned CVT's are not suitable for our vehicle to tackle the obstacles on off road track

By calculations we have got our ratio **3**.9 – 0.5 which is suitable for off road conditions.

According to B&S engine shaft diameter the minimum diameter of post is 40mm

$R_a(min) = 40/2$
$= 20$ mm

Reduction Ratio=R_b/R_a (1)

Where,

R_a & R_b are radius of belt over the primary & secondary pulley respectively

Lower Ratio

$3.9 = \frac{Rb(max)}{Ra(min)}$
$= \frac{Rb(max)}{20}$

R_b (max) = 78 mm
D_b (max) = 156 mm
Half wedge angle of sheave ($\propto$) = 13°

Maximum axial (X_a) movement of movable sheave of primary pulley

X_a = 22.5 mm

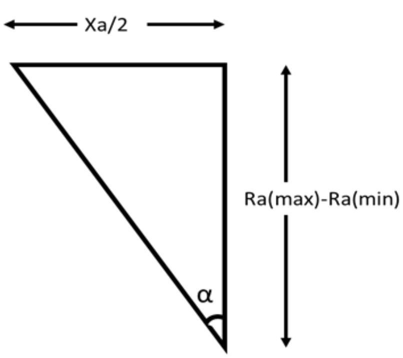

Fig. 2. Sheave geometry

$\frac{Xa}{2} = (R_a \max - R_a \min) * \tan \propto$ (2)

$\frac{22.5}{2} = (R_a \max - 20) * \tan 13$

$R_a \max = \frac{22.5}{2 * \tan 13} + 20$

R_a max = 68.73 mm
D_a max = 137.45 mm

Higher Ratio

$0.5 = \frac{Rb(min)}{Ra(max)}$
$= \frac{Rb(min)}{68.73}$

R_b (min) = 34.36 mm
D_b (min) = 68.73 mm

Maximum axial (X_b) movement of movable sheave of secondary pulley

$\frac{Xb}{2} = (R_b \max - R_b \min) * \tan \propto$ (3)

$X_b = 2 * (R_b \max - R_b \min) * \tan \propto$
$X_b = 2 * (78 - 34.36) * \tan 13$
X_b = 20.15 mm

Diameter of pulleys

D = Maximum diameter of belt over the pulley + (2 * Thickness of belt) (4)

Primary pulley
D = 137.45 + (2 * 12)
= 161.45 mm

Secondary pulley
D = 156 + (2 * 12)
= 180 mm

Centre to centre distance of two pulleys (l_h)

Belt Length = $2l_h + \frac{\pi(D-d)}{2} + \frac{(D-d)^2}{4l\_h}$ (5)

$844 = 2l_h + \frac{\pi(180-54)}{2} + \frac{(180-54)^2}{4l\_h}$

l_h = 216 mm

Wrap Angle The wrap angles are determined by relations:

$th_a = 180 + (2 \times \beta)$
$th_b = 180 - (2 \times \beta)$ (6)

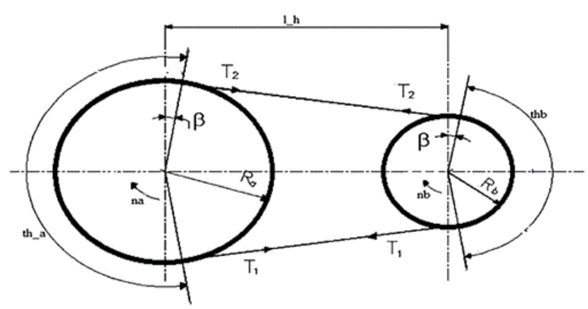

Fig. 3. CVT geometric parameter at higher ratio of CVT

where,

$\beta = \tan^{-1}\frac{(Rb-Ra)}{l\_h}$

$\beta = \tan^{-1}\frac{(78-20)}{232}$ (7)

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β = 12.16°
At Lower ratio wrap angle be
th_a = 180 - (2 × β)
th_a = 180 - (2 × 12.16)
th_a = 155.68°
th_a = 2.272 rad

th_b = 180 + (2 × β)
th_b = 180 + (2 × 12.16)
th_b = 204.32°
th_b = 3.57 rad

3. Material Selection

The material to be used for component must be rigid enough to sustain all the forces that would occur on it. The materials commonly used for CVT are aluminium, cast iron and steel. As the objective of the design weight of the CVT has to be kept minimum. Aluminium serves this condition to be lightest among other materials.

A. Factors considered for material selection and cooling for CVT

- Heat convection.
- Cooling.
- Damping of vibrations produced.
- High strength to weight ratio.
- Cost effectiveness.
- Material availability.

B. By considering following factors the material selected for various components are as follows

1. Fixed and Movable sheave.
   Since fixed and movable sheave are continuously in friction which will generate more heat.
   Material selected- Aluminium 6061-T6.
2. Post, Arms and Helix
   Material Selected- Aluminium 6061-T6.
3. Ram
   Since it is continuously in contact with rollers (which is an OEM component). so to avoid wear the material was selected.
   Material selected- EN 24

Table 1
Properties of Aluminium 6061- T6

S. No.	Parameter	Value
1	Density	2870 kg/m^3
2	Modulus of Elasticity	68.9 GPa
3	Tensile Strength	310 Mpa
4	Yield Strength	276 MPa
5	Thermal Conductivity	167 W/mK
6	Cost to Weight Ratio	360 Rs/kg

Table 2
Properties of Aluminium 6061- T6

S. No.	Parameter	Value
1	Density	kg/m^3
2	Modulus of Elasticity	GPa
3	Tensile Strength	Mpa
4	Yield Strength	MPa
5	Thermal Conductivity	W/mK
6	Cost to Weight Ratio	95 Rs/kg

4. Force Balance Equations

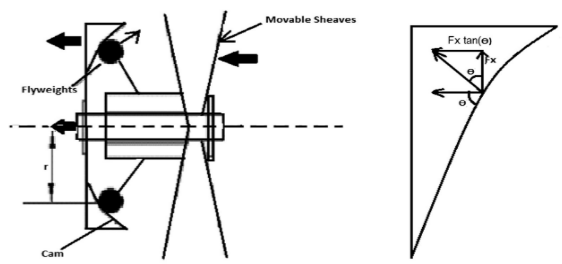

Fig. 4. Flyweight system and primary ram free body diagram

$$Fx=m\times(\omega^2)\times r\times\tan(\theta)-\int_0^{xa} ka(xa)\times dxa \qquad (8)$$

A. Axial force applied by flyweights on sheave

At max torque condition
Consider
Mass of weights (m) = 150 gm/arm
Radius of arm (r) = mounting radius of ram – apex of arm from base of ram
r = 65 – 17.244
= 47.75 mm
N = 2800 rpm
Angular Velocity of pulley (ω) = $\frac{2\pi N}{60}$
= $\frac{2\pi * 2800}{60}$
= 293.22 rad/s
Angle of ram (θ) = 11°

Forced by one arm
$m r \omega^2 \tan(\theta)$=0.15*0.0478*293.22^2*tan(11) (9)
= 119.83 N
Forced by all three arm
= 3 * 119.83
= 359.48 N

B. Tension in belt at max torque of engine

$$\frac{F1}{F2}=e^{\frac{\mu * tha}{\cos\alpha}} \qquad (10)$$

Where,
μ = coefficient of friction between sheave & belt
= 0.3
th_a = wrap angle at lower ratio
= 2.27 rad
α = half wedge angle of sheave

$$\frac{F1}{F2} = e^{\frac{0.35 * 2.27}{\cos 13}}$$

$\frac{F1}{F2}$=2.26

P=(F$_1$–F$_2$)*V (11)

Where,

P = power supplied by engine

= 6.7 Kw

V = velocity at max torque in m/s

$= \frac{\pi * D * N}{60000}$

$= \frac{\pi * 40 * 2800}{60000}$

= 5.86 m/s

$F_1 - F_2 = \frac{6.7*1000}{5.86}$

F$_1$–F$_2$=1142.50 (12)

From equation 11 & 12

F$_1$ = 2049.24 N

F$_2$ = 906.7 N

C. Axial force applied by belt on secondary sheave

Now,

Force applied on movable sheave & fixed sheave of secondary pulley,

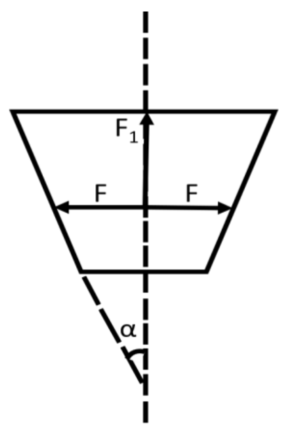

Fig. 5. Secondary pulley and belt free diagram

$F_1 = \frac{2 * F_{x\prime}}{tan\alpha}$ (13)

$2049.24 = \frac{2 * F_{x\prime}}{tan13}$

$F_{x'} = \frac{2049.24 * tan13}{2}$

= 236.55 N

Fx'=[kb×Δb]×tan($\delta \pm \phi$b) (14)

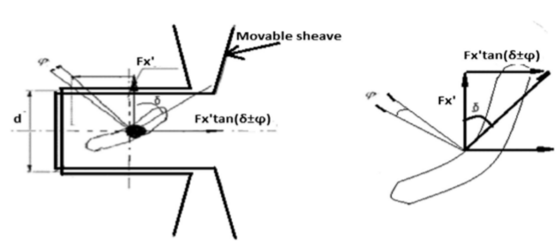

Fig. 6. Secondary Helix free body diagram

Figure shows the free body diagram of the torque feedback secondary helix. It exerts the axial force on the sheaves directly proportional to the twist (angle turned by the helix) in the secondary helical spring and tends to oppose the upshift. The axial force on the secondary sheaves exerted by the cam is given by Equation (14). Where kb is the torsional stiffness of the spring and delb is the twist angle of the secondary spring.

D. Secondary Spring

We have to find torsional stiffness of spring (kb)

Helix angle (∅) = 45°

Pitch angle of spring (δ) = 2.06°

Twist angle (Δb) = π

Fx' = [kb × Δb]×tan($\delta \pm \phi$b)

236.55 = (kb × Δb) × tan(45 ± 2.06)

Kb = 70.06 N-mm/rad

5. Cooling of CVT

In an automobile CVT is the most efficient to transmit the power, but there is major problem of heat generation which will reduce the performance of it. While transmitting the power there is friction between the belt and pulley. This results to increase the temperature of both the pulleys and belt.

Where the material properties are dependent on the temperature. Due to increase in temperature there may be slippage of the belt results to reduce the performance of CVT and the life if its component. To solve the problem research works includes the design modification of CVT and using of different material for its component. Similarly, we had work on it and modified are design. To overcome the problem, we have increased the area of heat transfer for convection. We have used aluminum 6061-T6 for the component. Which has thermal conductivity of 97 W/mk and coefficient of the convective heat transfer is 59-64 w/m^{2}k. Many researchers worked on a design modification of the CVT cover and providing fins on the centrifugal fan. Which results to increase the convective area on one side of the sheave and increase the air flow rate into the casing. We had increased the convective area by making assembly such a that both the fixed and movable sheave will have area of convection to dissipate the heat to the surroundings. In addition to that we had provided cooling fans on the CVT cover. Which are working on electric power generated by thermoelectric generator using a heat of CVT.

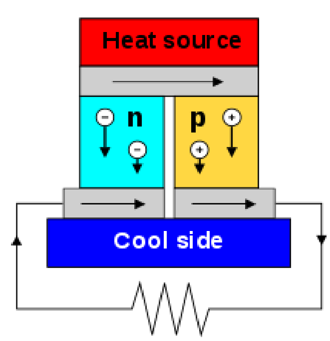

Fig. 7. Thermoelectric module working

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Table 3
Setting while tuning

S. No.	Weights On each arm(gm)	Primary Cam	Helix (Degree)	Primary spring stiffness (N/mm)	Secondary Spring (Red) hole
1	150	R-11-15	45	8.85	6th
2	160	R-11-15	45	8.85	7th
3	150	R-16-12	45	8.85	7th
4	160	R-16-12	45	8.85	7th
5	150	R-12-11	45	8.85	7th
6	160	R-12-11	45	8.85	6th
7	150	R-10-16	45	8.85	6th
8	160	R-10-16	45	8.85	6th

Thermoelectric generator is a circuit which will generate electricity, when there is a change in temperature ΔT on the opposite side of the module as shown in figure 7.

As the temperature rise to particular level this thermoelectric module start working and provide electricity to fan mounted CVT cover. Fan will increase the air flow rate and down the temperature and cycle is going on.

6. Tuning of CVT

After the designing and manufacturing of the CVT. The main aim is to tune the CVT properly to achieve the desired output from the CVT. While tuning tuner has to collect the data of engagement of belt and sheaves at peak of engine torque curve, start of shifting at peak of engine power curve and keeping constant engine RPM (peak of power curve) during shifting in dynamic condition of the vehicle. These can be gathered by DAQ. The variable parameters for tuning are primary compression spring stiffness, secondary helical spring preloading, mass of flyweight, curve of Ram, angle of Helix.

A. Procedure

1. Firstly, magnets were mounted on both the pulleys
2. The hall sensor was mounted on CVT cover such that it is capable of taking readings of both the pulleys
3. The pulleys consisting of the magnets actuates the sensor when the magnetic field falls normally on the sensor surface.
4. The pulse produced by both the primary and secondary pulleys sensors is stored in SD card module as a text file. Which are interface with the Arduino board.
5. These readings can be viewed later for further analysis of performance and to tune the CVT.

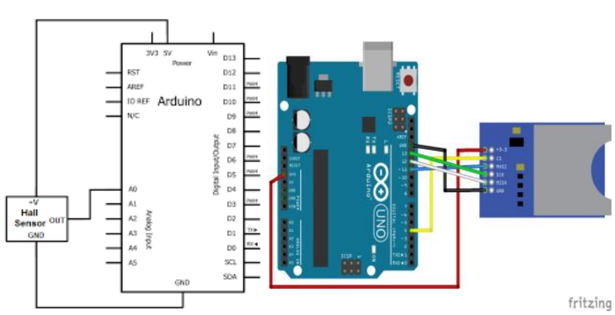

Fig. 8. Circuit diagram

B. Observation

While tuning it was observed that

- By increasing mass of the flyweight we can increase the centrifugal force applied by them, which results to early shifting of CVT than previous one.
- Stiffer the primary spring, late shifting of CV.
- High preloading of secondary helical spring will give better backshift.
- Lower the angle of Ram will give high initial torque to the vehicle due to suddenly engagement of CVT
- Lower the angle of helix gives higher the side force.

The table 3 shows the setting done while tuning the CVT

The best setting that fulfill our requirement is as follow:
Mas of the flyweights: 160 gm
Primary Ram: R-10-16
Helix(Degree): 45
Primary spring stiffness: 8.85 N/mm
Secondary spring spring Hole: 6^{th}

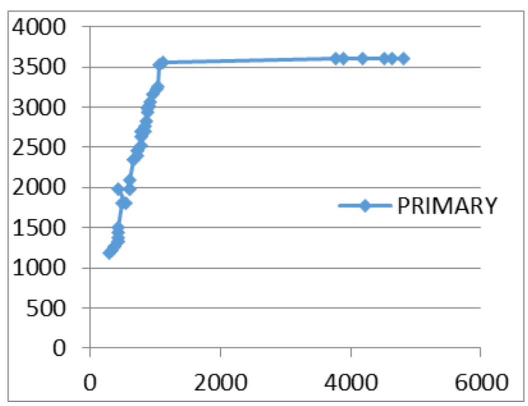

Fig. 9. Recorded CVT operation curve

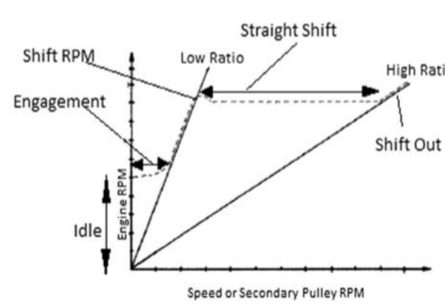

Fig. 10. CVT operation curve

Table 4
Hall sensor readings

Primary rpm	Secondary rpm	Gear ratio
1180	300	3.93333333
1210	340	3.55882353
1260	360	3.5
1260	360	3.5
1320	420	3.14285714
1320	420	3.14285714
1380	420	3.28571429
1440	420	3.42857143
1500	420	3.57142857
1800	480	3.75
1800	540	3.33333333
1980	600	3.3
2100	600	3.5
2340	660	3.54545455
2340	660	3.54545455
2400	720	3.33333333
2460	720	3.41666667
2460	720	3.41666667
2520	780	3.23076923
2640	780	3.38461538
2640	780	3.38461538
2700	780	3.46153846
2700	840	3.21428571
2700	780	3.46153846
2760	840	3.28571429
2820	860	3.27906977
2940	880	3.34090909
2979	890	3.34719101
3020	910	3.31868132
3070	920	3.33695652
3160	960	3.29166667
3230	1010	3.1980198
3260	1040	3.13461538
3520	1060	3.32075472
3550	1120	3.16964286
3600	3770	0.95490716
3600	3900	0.92307692
3600	4180	0.86124402
3600	4520	0.79646018
3600	4640	0.77586207
3600	4820	0.74688797

7. Drawings of CVT

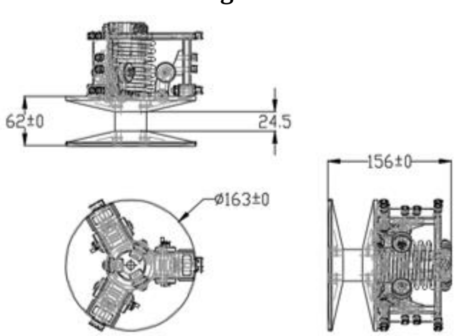

Fig. 11. Drawing 1: Primary pulley

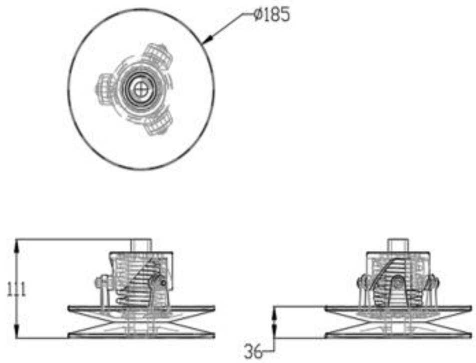

Fig. 12. Drawing 2: Secondary pulley

8. Conclusion

The optimized continuous variable transmission is designed step by step for desire variable range ratio of 3.9-0.5. This is suitable for most of the vehicles. Also we have increased the serviceability and ability to tune the CVT. Heating issues are minimized by providing the heat transfer area on both the sheaves and using a thermoelectric module. It will increase the performance of the CVT and life of its component. In addition to that weight of the CVT is reduced by 23-25% compare to market available CVT.

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