# Stress Analysis of Half Toroidal Continuously Variable Transmission System

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*Abstract*— The continuously variable transmission, or CVT, continues to emerge as a key technology for improving the fuel efficiency of automobiles with internal combustion (IC) engines. A toroidal continuously variable transmission (CVT) has an elliptical shape in the contact area, which resulting high contact stress and transmits the power. Many parameters affect the contact stress of the half toroidal CVT, which include the properties of the contacting material (Young's modulus), operating parameter (input load) and geometrical parameters (aspect cavity ratio, curvature ratio and half cone angle of the power roller, transmission ratio). In this paper, the contact between the input disk and the power roller are formulated using the classical Hertzian contact theory. Based on the formulated equations, different system parameters, which affect the maximum Hertzian contact stresses, are compared with the simulated results generated in ANSYS. The comparative results will provide some observations of the relations between the maximum Hertzian stresses and input load in the form of graphs for different materials (i.e. 100Cr6/Si3Ni4, 100Cr6/Ni75%, Cr 14%, Fe 10%, 100Cr6/100Cr6, 100Cr6/Ni70 %, Cu 30 %). These graphs give useful information for designer to know the maximum Hertzian stress during operation in such systems.
***Key words:*** CVT, Half Toroidal, Elliptical Contact, Hertzian Contact Stress, Operating Parameters

## I. Introduction

The word "transmission" is used for a device that is located between the clutch and shaft. A transmission allows power to be sent from a power source, most often an engine or motor, to a drive mechanism. Transmissions use gears and a clutch to convert the speed of the power source into torque. A basic automotive transmission system or auto transmission system comprises of various transmission components such as gears, shafts and other parts, which function together to enable the movement of an automobile. Automobile or automotive transmission system consists of various devices that help in transmitting power from the engine through the drive shaft to the live axle of an automobile. Gears, brakes, clutch, fluid drive and other auto transmission parts work together for transforming the speed ratio between the engine and wheels of a vehicle.

Toroidal CVTs can potentially reduce the fuel consumption because the engine can run under most efficiently attributed to its smooth power delivery without any shift shock and robust acceleration as the power is delivered continuously with little loss of driving force during its ratio changes compared with traditional transmissions [1]. Toroidal CVTs research has led to more powerful transmissions and wider automotive application, which has increased the demand for further development and ultimately given a rigid foundation for toroidal CVTs in the world of automotive infrastructure. A toroidal continuously variable transmission (CVT) that uses a traction drive to transmit torque has a vastly larger torque capacity than a conventional CVT. This transmission technology has attracted considerable interest owing to its capability in substantially improving vehicle fuel economy and power performance [1]. The half toroidal CVT transmits torque by means of contact between the input disk, the power roller and the output disk which resulting contact stress between disc and roller [2-3]. The analysis of elliptical contact of elasto- hydrodynamic lubrication (EHL) considering a spin effect was performed [4]. Also the influence of spin motion combined with rolling or sliding motion on the pressure distribution and the film thickness of EHL contacts was discussed [5].The stress calculations of the contacts of the toroidal CVT for fatigue life analysis were performed by using Hamrock's method [6].The performance of the drive depends to a large extent on the maximum value of Hertzian stress in the elliptical contact area, where different aspects such as material, operating, geometrical parameters must be considered in such a contact.

## II. Geometry and Operation Principles of Toroidal CVT

A half-toroidal CVT consists of three basic elements: an input disk, an output disk and a power roller. The geometry and dimensions of a CVT are determined by four design parameters, i.e. the aspect cavity radius $r_0$, the aspect ratio of cavity $K_0$, the half cone angle of the power roller $\theta$ and the profile radius of the power roller $R_{22}$roller. $R_1$ is the radius of input disc at the contact rolling circle and $R_3$ is the radius of output disc at the contact rolling circle, $R_{12}$ is the principle curvature radius of the input disk in parallel direction to the plane space and$R_{11}$ is the Principle Curvatures radius of the input disc in perpendicular to the plane space, $R_{22}$ is the principle curvature radius of power roller in the direction parallel to the plane space , which is along the profile tangent to the axial direction of the output disk, $R_{21}$ is the principle curvature radius of the power roller in the perpendicular direction to the plane space, which is along the profile tangent to the cross section direction. The parameters are shown in fig. 1.

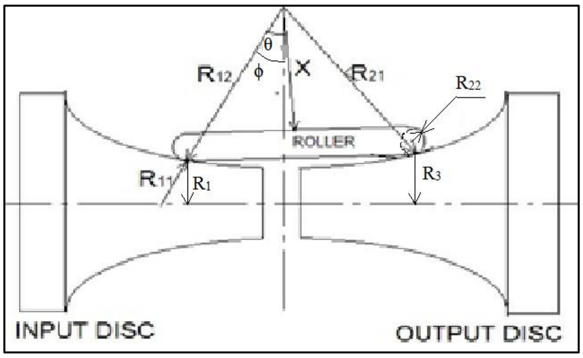


Fig. 1: Geometry of the Half Toroidal CVT

 

Dimension of the discs and roller are taken from the research paper [8] and after draw the geometry of the half toroidal CVT.

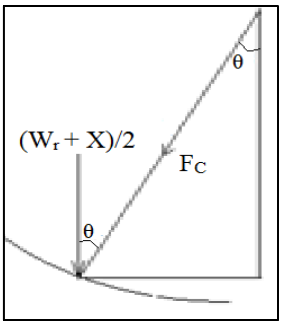


Fig. 2: Normal Force Acting On the Disc

The schematic diagram in fig. 2 shows the loading spring of a half toroidal CVT. The loading spring is a mechanism that uses spring to create axial load as shown in fig.2 where θ is the half cone angle, $W_r$ is the weight of roller and X is the spring force $F_c$ is the normal force [9].
The equation of normal force acting on the disc is

$$Fc = \frac{(W_r + X)}{2} \times \cos\theta$$

## III. EXPRESSIONS FOR CONTACT STRESS ANALYSIS OF HALF TOROIDAL CVT

Due to elasticity, the contact patches between the roller and disks will take the shape of ellipse centered at the points of contact as depicted in fig.1. The size and the orientation of the contact ellipses depend on the contact force Fc. The material property and the geometry of the roller and disk surfaces. For a revolution surface, such as the roller or the disk, the two principle directions are respectively along the profile tangent to the axial section and that tangent to the cross section.

Based on the Hertzian contact theory [7] the size of the contact ellipse and the maximum contact stress that occurs at the center of the contact ellipse at the input side of the half toroidal CVT,

$$b = \beta\left[\frac{3F_c}{4(B+A)}\left(\frac{1-v_1^{\,2}}{E_1} + \frac{1-v_2^{\,2}}{E_2}\right)\right]^{\frac{1}{3}} \ldots\ldots\ldots\ldots\ldots \quad [4.1]$$

$$a = \frac{b}{k} \ldots\ldots\ldots\ldots\ldots\ldots \quad [4.2]$$

$$\sigma_{max} = \frac{1.5\,F_c}{\pi ab} \ldots\ldots\ldots\ldots\ldots\ldots \quad [4.3]$$

where a and b are respectively the length of the long and short axes, within the crosswise rolling direction and b in the traction rolling direction; $\sigma_{max}$ is the maximum contact stress; $v_1$ and $v_2$ are the Poisson ratios of the disk and roller materials respectively; and $E_1$ and $E_2$ are the Young's modulus of the disk and roller materials. The quantity (B+A) and (B-A) related with the surface principal curvatures of the disk and the power roller, can be determined by the following Equations

$$B + A = \frac{1}{2}\left[\frac{1}{R_{12}} + \frac{1}{R_{11}} + \frac{1}{R_{22}} + \frac{1}{R_{21}}\right] \ldots\ldots\ldots\ldots\ldots\ldots \quad [4.4]$$

$$B - A = \frac{1}{2}\left[\left(\frac{1}{R_{12}} - \frac{1}{R_{11}}\right)^2 + \left(\frac{1}{R_{22}} - \frac{1}{R_{21}}\right)^2 + 2\left(\frac{1}{R_{12}} - \frac{1}{R_{11}}\right)\left(\frac{1}{R_{22}} - \frac{1}{R_{21}}\right)\cos 2\Psi\right] \ldots\ldots [4.5]$$

In the case of half Toroidal CVT, the principle curvatures and are containing in the same plane, i.e., ψ equals to zero. The two coefficients, β and k depend on the surface principal curvatures of the disk and the roller and can be calculated by elliptical integration, and approximated with enough accuracy by linear relations with respect to the value (B+A) and (B-A) which is as follows [9]:.

$$k = 0.95 - 0.89\frac{(B-A)}{(B+A)} \ldots\ldots\ldots\ldots\ldots\ldots \quad [4.6]$$

$$\beta = 1.02 - 0.60\frac{(B-A)}{(B+A)} \ldots\ldots\ldots\ldots\ldots\ldots \quad [4.7]$$

The equations describing the Hertzian parameters such as semi major axis, semi minor axis and maximum Hertzian contact stress were solved, depend on the surface principal curvatures of the rolling elements of the half toroidal CVT. As shown in the equations, material property of rolling elements E and the load acting by the spring have effect on the maximum Hertzian stress. The calculated maximum Hertzian stress of the input contact for different material at different load is compared with the ANSYS result. [9]

The ratio of the sizes of the circles í corresponds to the ratio of the rotational speeds of input and output disks presented as the theoretical transmission ratio which is defined as the ratio of the radius of output disc at the contact rolling circle $R_3$andradius of input disc at the contact rolling circle $R_1$. The aspect cavity ratio $K_0$ defined as the ratio of the $e_0$ and $r_0$.

## IV. MODELING AND SIMULATION OF CVT MODEL

A modeling language is any artificial language that can be used to express information or knowledge or system in a structure that is defined by a consistent set of rules. Modeling of different parts of toroidal CVT is follows.

### *A. Input Disc & Output Disc*

Fig. 3: Input Disc & Output Disc

Input disc and output disc of half toroidal cvt is shown in fig. 3 and dimension of input disc and output disc as same as follows.

### *B. Roller*

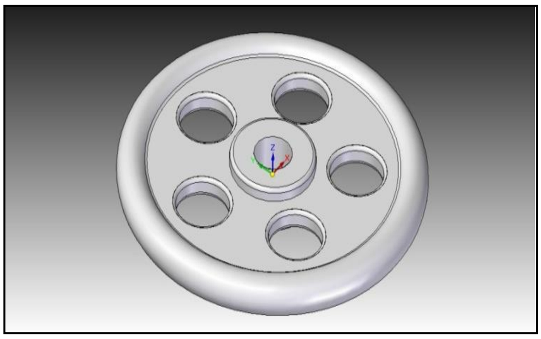

Fig. 4: Roller

Dimension of the discs and roller are taken from the research paper [8] and after draw the geometry of the half toroidal CVT.

Different parts of half toroidal continuously variable transmission system like input disc, output disc and roller are assembled as shown in fig. 5. transmission system like input disc, output disc and roller are assembled as shown in fig. 5.

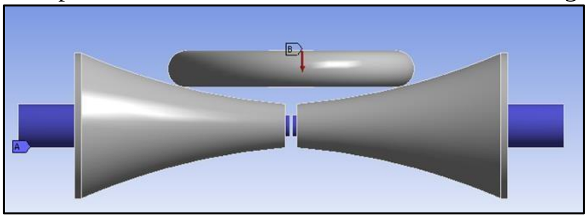

Fig. 5: Assembly of Toroidal CVT Model

After finishing modeling in PRO-E its time to analyze the model of half toroidal type continuously variable transmission system in ANSYS. The finite element method is a very powerful technique for the solution of a wide range of engineering problems. First Divide structure into pieces (element with nodes). Describe the behavior of the physical quantities on each element. Connect (Assemble) the element at the nodes to form an approximate system of equation for the whole structure. Solve the system of equations involving unknown quantities at the nodes (displacement).

## V. Result and Discussion

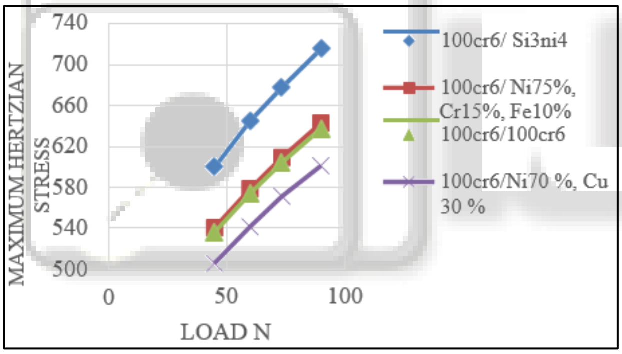


Fig. 6: (A) Theoretical Contact Stress for Different Material At Different Load

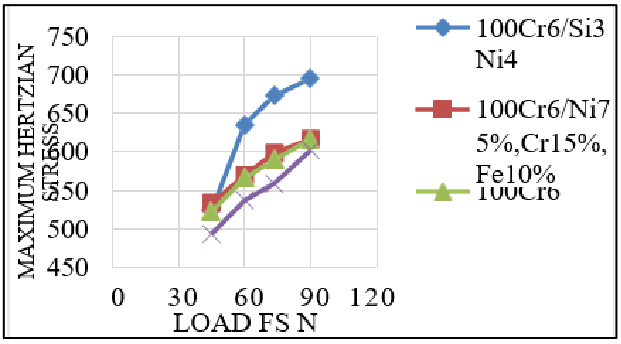


Fig. 6: (B) Contact Stress for Different Material at Different Load for ANSYS

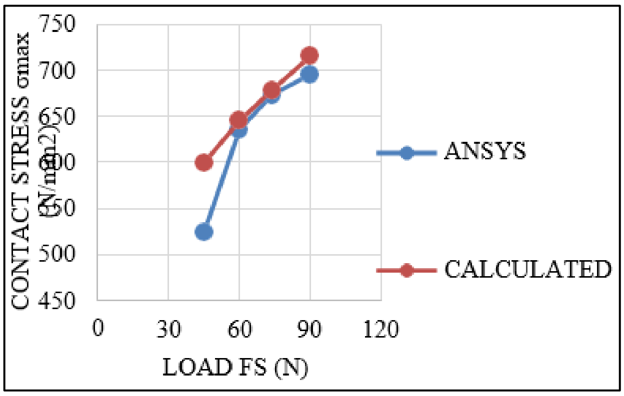


Fig. 6: (C) Comparison of Contact Stress Materia100cr6/Si3ni

Fig. (a) Presents the typical results concerning the variation of maximum Hertzian contact stress at different load for different material.

Properties of combination of different material like

| Combinations | Properties |
| --- | --- |
| 100Cr6/Si3Ni4 | ($E_1$=210 X $10^3$MPa, $\nu_1$=0.3) ($E_2$=315 X $10^3$MPa, $\nu_2$=0.26) 3 |
| 100cr6/ Ni75%, Cr15%, Fe10% | ($E_1$=210 X 10 MPa, $\nu_1$=0.3) ($E_2$=214 X $10^3$MPa, $\nu_2$=0.306) |
| 100cr6/100cr6 | ($E_1$= $E_2$=210 X $10^3$MPa, $\nu_1$= $\nu_2$=0.3) |
| 100cr6/Ni70 %, Cu 30 % | ($E_1$=210 X $10^3$MPa, $\nu_1$=0.3) ($E_2$=184X $10^3$MPa, $\nu_2$=0.239) |

Linear relations are obtained which can help the designer in evaluating the cyclic stresses created during the contact area. It can be observed that, the first combination has a higher maximum Hertzian contact stress in the selected ratio range compared with other combinations.

The basis for the design of a half toroidal CVT is to optimize the material, operating and geometrical parameters with the required speed ratio range efficiently

## VI. Conclusion

For contacts of the half toroidal CVT, the critical point of the maximum Hertzian stress is at the maximum deceleration position, i.e., at the initial rotation angle of power roller. The different system parameters material properties of different material and input parameter like input load play the major role in developing the Hertzian stress in the contacts of the half toroidal CVT.

The selection of the combination material with a moderate modulus of elasticity is preferable which reduce the maximum Hertzian stress to avoid fatigue failure. Useful graphs relating with material, operating and geometrical parameters are of help for a designer to determine the maximum Hertzian stresses within the speed ratio range in such systems.

The half toroidal type CVT model has been developed in PRO-Ethen it has been analyzed in ANSYS13. In addition to the various combinations of materials used for roller and discs, the materials combination100Cr6/Si3Ni4 with a moderate modulus of elasticity is preferable which reduce the maximum Hertzian contact stress to avoid fatigue failure. Useful graphs relating with material, operating and geometrical parameters are of help for a designer to determine the maximum contact stresses within the speed ratio range in such systems.

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