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Ball Transmission Analysis for ATV Application

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Abstract— ***A modified version of CVT (continuous variable transmission) is suggested for ATV (All-Terrain Vehicle) application. It is a ball transmission system used in vehicles to transfer rotational power between input and output shafts. This transmission mechanism utilizes a series of spherical rollers to facilitate smooth and efficient power transfer. The project aims to create a comprehensive mathematical model that captures kinematics of ball transmission systems. Parameters such as ball radius & disk size, material properties, contact angles are considered for accurate predictions according to ATV's operating conditions. For further validation, MSC ADAMS software is used to analyse the system's response. Performance parameters such as efficiency, torque capacity, and backlash are evaluated through simulation, enabling a detailed understanding of the system's behaviour under different operating modes such as neutral, underdrive and overdrive. Additionally, assembly analysis is performed to ensure proper integration and functioning of the system components. The extent and pattern of wear between components is studied by conducting a wear analysis study in ANSYS software. The study and results of this project contribute to optimizing system performance, enhancing reliability, and guiding design improvements in ball transmission systems for ATV's application. However, research shows that study of lubrication and wear reduction would be essential to practically implement this system.***

Index Terms— ***Ball transmission System for ATV's, Mathematical Modelling, Power Transmission, Stepless Transmission***

I. INTRODUCTION

Implementations of new emissions and fuel norms have led engineers to focus their works towards the modifications in the most economical and practical solution i.e., continuously variable transmissions. One such is a ball transmission system also known as Nuvinci in commercial application. It is highly adaptable and scalable continuously variable transmissions, enabling efficient power transfer and smooth torque control. A ball positioned around centre of two disk, tilting the ball changes their contact which gives variable ratios. A special fluid that fills inside the system occupies space between disks and ball, which under high pressure solidifies momentarily in that gap and act as rigid structure which allows torque transfer. This project focuses on the modification and analysis of this systems specifically in the context of its use in ATVs (All terrain Vehicles). The objective is to develop and validate a mathematical model that accurately captures the kinematics and behaviour of the ball transmission system. This model will be used to study the performance, efficiency and reliability to optimize the design of ball transmission systems in ATVs. Benefits of using ball transmission:

- Efficient power transmission
- Smooth torque control
- Compact and lightweight design
- Improved Fuel Efficiency
- Lower manufacturing cost

II. UNITS

Length- mm
Angle- Degrees
Angular speed – RPM

III. OVERVIEW OF BALL TRANSMISSION

The mechanism includes the following main parts: one input and one output disk, 4 number of equal spherical rollers of radius Rs, Idler and Power Screw.

- Spherical Rollers: The system consists of 4 equal spherical rollers. These rollers are positioned between the input and output disks, forming a contact interface with both disks. The spherical shape of the rollers allows for smooth rolling motion.
- Input and Output Disks: The ball transmission system includes one input disk and one output disk. The input disk is connected to the power source, while the output disk is connected to the load. These disks provide the contact surfaces for the spherical rollers.
- Idler Shaft: Two equal disks, the input and output disks, are radially and axially supported by a common idler shaft. The idler shaft ensures proper alignment and supports the disks during operation.
- Power Screw: A modified shifter mechanism, which is free to slide in the axial direction. The power screw aids in adjusting the position of the idler shaft, allowing for fine-tuning and alignment within the system.

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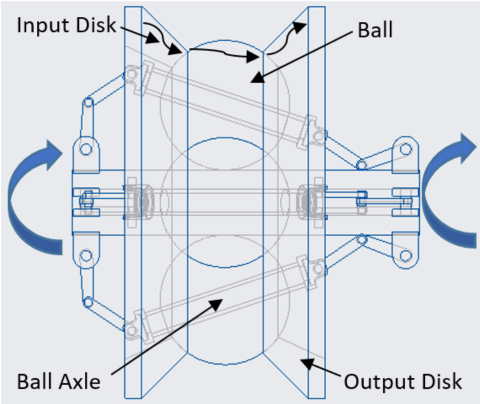

Fig. 1: Schematic diagram of Ball Transmission

IV. MATHEMATICAL MODELLING

In the given figure, the following relations and geometric parameters can be observed:

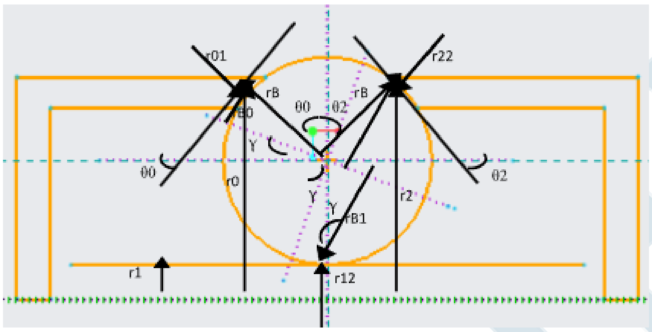

Fig. 2: 2D representation of Ball Transmission

The following are notations for different parameters mentioned in the above figure.

1. **αi**: Angle between the horizontal axis and the tangent at the roller passing through the point of contact with the input disk.
2. **αl**: Angle between the horizontal axis and the tangent at the roller passing through the point of contact with the idler.
3. **αo**: Angle between the horizontal axis and the tangent at the roller passing through the point of contact with the output disk.
4. **γ** (Tilt Angle): Angle between the horizontal axis and the rotation axis of the roller. It represents the inclination of the roller with respect to the horizontal plane.
5. **ri**: Input Disk Radius
6. **rl**: Idler Radius, which is free to move. It is responsible for maintaining contact between the rollers and the disks.
7. **ro**: Output Disk Radius
8. **rb**: Ball Radius
9. **rbl**: Perpendicular distance from the tilt axis to the point of contact between the ball and the idler.
10. **rbi**: Perpendicular distance from the tilt axis to the point of contact between the ball and the input disk.
11. **rbo**: Perpendicular distance from the tilt axis to the point of contact between the ball and the Output disk.
12. **ωi**: Angular velocity of input disk
13. **ωl**: Angular velocity of idler
14. **ωo**: Angular velocity of Output Disk
15. **ωb**: Angular Velocity Of ball

Four Points of Contact: The disks meet each roller at four distinct points. These points represent the locations where the rollers come into contact with the disks.

The mentioned geometric parameters and relations are essential in understanding the behaviour and characteristics of the ball transmission system. They define the angles, curvature, and contact points necessary for deriving the equations of desired reduction ratios for effective power transmission between the input disk, idler, and output disk.

V. EQUATIONS

In the given equations, the following relationships describe the values of rbi, rbi, and rbo:

$$rbi = rb * \cos\,(\,\alpha 1\, +\, \gamma) \qquad 1$$

$$rbl = rb * \cos\,(\gamma) \qquad 2$$

$$rbo = rb * \cos\,(\alpha 2 - \gamma) \qquad 3$$

Additionally, the values of ri and ro can be expressed as follows:

$$ri = rl + rb + rb * \cos(\alpha i) = \mathrm{rb} * (1 + \mathrm{k} + \cos(\alpha i)) \quad 4$$

$$ro = rl + rb + rb * cos(\alpha 0) = \mathrm{rb} * (1 + \mathrm{k} + \cos(\alpha o)) \quad 5$$

Here, rb represents a common term involving the radius of the Ball radius, k represents a constant, and αi, αo, and γ represent the angles as previously defined.

These equations provide the standard expressions for calculating the values of rbi, rbi, rbo, ri, and ro based on the given geometric configuration of the ball transmission system.

The aspect ratio, represented by k = r1/rb,

Under ideal conditions, the following equations hold true:

$$\omega 0 \mathrm{ri} = \omega \mathrm{brbi} \qquad 6$$

$$\omega 2 \mathrm{ro} = \omega \mathrm{brbo} \qquad 7$$

These equations express the product of angular velocities (ωi, ωo) and radii (ri, ro) at the points of contact between the rollers and the disks.

By combining equations (1)-(7) and incorporating the aspect ratio, the reduction ratio (τID) can be defined as a function of the tilt angle γ:

$$\tau\mathrm{ID} = \omega\mathrm{o}/\omega\mathrm{i} = (\mathrm{rbori})/(\mathrm{rbiro}) = (\cos(\alpha 2 - \gamma)(1 + \mathrm{k} + \cos(\alpha\mathrm{i})))/(\cos(\alpha\mathrm{i} + \gamma)(1 + \mathrm{k} + \cos(\alpha\mathrm{o}))) = \tau 0\cos(\alpha\mathrm{o} - \gamma)/\cos(\alpha\mathrm{i} + \gamma) \qquad 8$$

In the scenario where αi = αo = α, the reduction ratio simplifies to:

$$\tau = \cos(\alpha - \gamma)/\cos(\alpha + \gamma) \qquad 9$$

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These equations provide the reduction ratio in the ball transmission system by considering the given geometric configuration and parameters. Iteration for different parameters were done according to design constraints of ATV. The reduction ratio is influenced by the tilt angle γ which was also iterated for desired gear ratio at output, as well as the angles αi and αo, indicating the relationship between input and output angular velocities.

VI. REDUCTION RATIO

By plotting the graph for αi = αo = α (where α is 30°, 45°, or 60°) with a fixed ball radius of 25 mm and an aspect ratio (k) of 0.5, we can observe the series of reduction ratios for different tilt angles. This analysis helps in understanding how the tilt angle affects the reduction ratio and the overall performance of the ball transmission system.

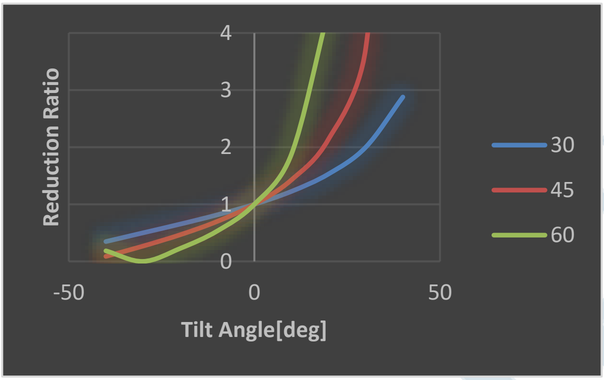
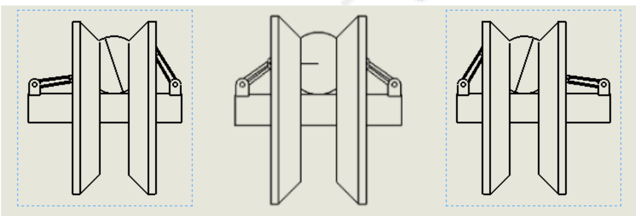


Fig. 3: Reduction ratio at different values of αi =αo

The specific selection of α = 45° is often chosen for analysis and comparison purposes because it represents a balanced configuration where the forces and contact between the rollers and disks are evenly distributed. Additionally, α = 45° provides a symmetrical and stable operation of the ball transmission system.

I. Relation between α and γ

Reduction ratio	Tilt angle (α = 45°)
0.5	-18.43494882
1	0
2	18.43494882



rbi>rbo Underdrive (τ=0.5) rbi=rbo Neutral (τ=1) rbi<rbo Overdrive (τ=2)

Fig. 4: Representation of different cases in Ball Transmission

VII. WEAR ANALYSIS

Wear analysis of the ball transmission system between the ball and the disk involves studying the effects of friction and contact forces on the surfaces of the balls and disk over time.

In Mechanical APDL, the material loss due to wear is approximated by repositioning the contact nodes at the contact surface. The new coordinates of wear are determined by wear model. Arched Wear model is used for defining wear.

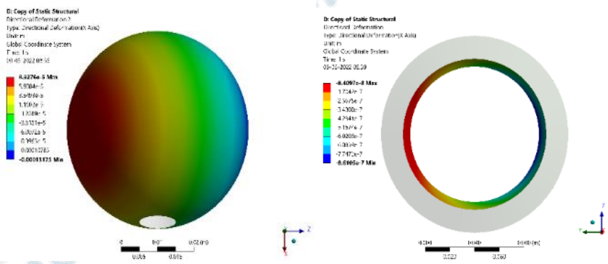
Arched Wear Model:

- Simulate the progressive loss of material from the contact surface.
- Assume rate of volume loss, w, due to wear is proportional to the surface pressure (P), & relative sliding velocity (Vrel) at the contact surface. Wear is in directly proportional to contact element normal.

W=K/H(P^m)*(Vrel^n)

Where:

K-Wear Coefficient
H-Material Hardness
m-Pressure Exponent
n-Velocity Exponent



Deformation of ball Deformation of disk

Fig. 5: Results of wear analysis

Through wear analysis, it was observed that the EN24 material demonstrated reduced wear characteristics, such as lower wear volume and slower wear rate, when in contact with the disk during the ball transmission operation. This indicates that the EN24 material is better suited for withstanding the friction and contact forces experienced in the ball transmission system.

VIII. SIMULATIONS

The CAD model was simulated in MSC Adams to validate velocities of output disk with ball at different tilt angles i.e., the three cases of Neutral, Overdrive and Underdrive. Ball is only free to rotate about its axis, which is titled to its extreme ends on both sides according to the design angle of tilt to get specific gear ration, thus results in creating conditions of underdrive and overdrive. Contacts are created between motion transferring elements i.e., between input disk and ball, ball and output disk. Three cases are discussed below. For simplicity on single ball models are simulated and with an input prime mover speed of 3500rpm. Further Multi-ball simulation was also conducted to check the stability of system.

CASE 1: NEUTRAL

In this case, tilt angle is zero (γ=0) giving a gear ratio of 1. Both input and output disk velocity must be equal i.e., the case of neutral drive.

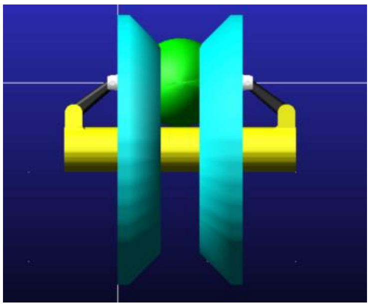


Fig. 6: Simulation for Tilt angle (γ=0)

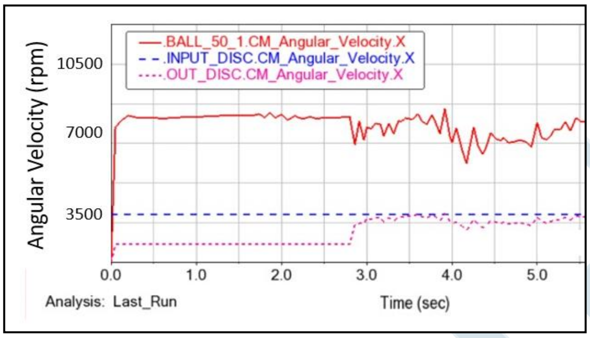


Fig. 7: Angular velocity of input disk, output disk, ball velocity V/s Time when γ=0.

Since there is no tilt in the ball; rbi = rbo. Therefore, there is less variations in velocity of input and output disk. Due frictional and wear losses there is certain deviation of input and output velocity rather being same giving an efficiency of 83.33%.

CASE 2: OVERDRIVE

In this case the ball was tilted to the right side with an angle of -18.43degrees (for which mechanism is designed to achieve required underdrive condition). Which gives a gear ratio of 0.5 i.e., the speed of output disk must be doubled.

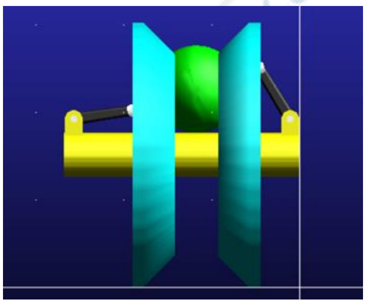


Fig. 8: Simulation for tilt angle (γ<0)-Overdrive condition

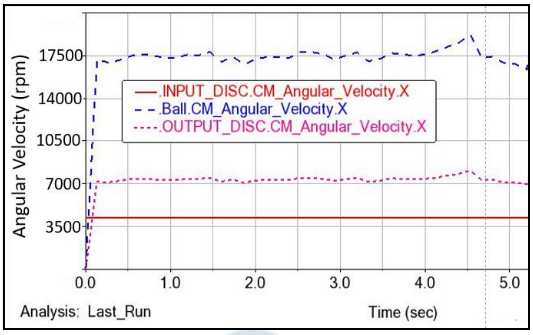


Fig. 9: Angular velocity of input disk, output disk, ball velocity V/s Time when γ<0.

Since the ball is tilted to the left side; rbo<rbi. Thus, output disk velocity is double than input disk.

CASE 3: UNDERDRIVE

In this case the ball was tilted to the left side with an angle of 18.43 degrees (for which mechanism is designed to achieve required underdrive condition). Which gives a gear ratio of 2 i.e., the speed of output disk must be half.

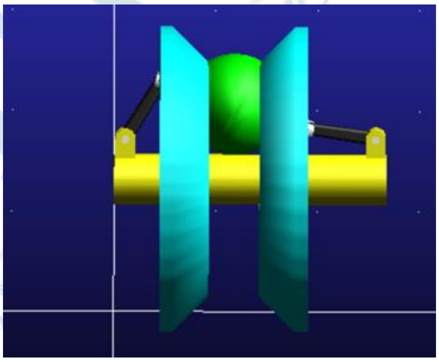


Fig. 10: Simulation for Tilt angle (γ>0) Underdrive Condition

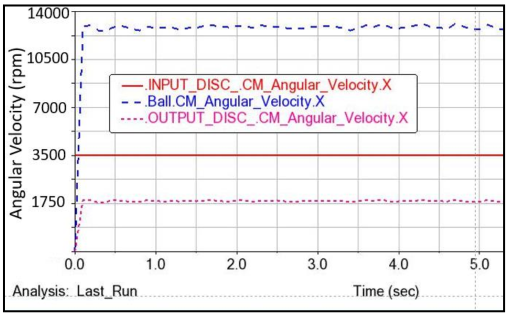


Fig. 11: Angular velocity of input disk, output disk, ball velocity V/s Time when γ>0.

Since the ball is tilted to the left side; rbo>rbi. Thus, output disks velocity is half than that of input disk.

IX. CONCLUSION

In this paper, we presented a mathematical model and analysis of a novel type of CVT in accordance to be used in ATVs. The proposed model considers the 4-link contact enabling the transfer of the torque through the transmission. With a power screw mechanism to change the ball axis. Control of power screw will be given to driver, any change from driver's end will be provide variable gear ratios just by titling of the ball axis, also there are no belts, chains or other mechanical constraints which reduces the manufacturing and maintenance cost. It is compact in size and can be used in automobile industry for various other application as well. The study from simulations in MSC ADAMS software shows that systems behave kinematically well but vibrations increase with increase in speed and thus lubrications parameters should be studied for increasing the efficiency of system and to avoid slippages. Also wear analysis in ANSYS shows the pattern of wear. Using this study further many design modifications can be done in design of ball to reduce the wear, use of different materials, use of different profiles for ball and disk to minimize wear. Also, 3D printed prototype was also validated these results practically as well. This study has demonstrated the potential of ball transmission for being used in ATVs. Further studies on lubrication, optimum number of balls and wear can be done to improve the efficiency of this system.

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