

Kinematic Modeling and Analysis of a Cam Based CVT

For a Capstone Design Project Experience

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ABSTRACT

This paper presents a *Capstone Design Project* at Oakland University, a CAD model of a cam based CVT (Continuously Variable Transmission).

The *Capstone Design Project* at Oakland University covers a broad range of mechanical engineering core disciplines of kinematics, dynamics, material properties and mechanics, machine design, and serves as an integration course before mechanical engineering students' graduate. It takes students through the entire taxonomy of the design process: from searching for ideas, proposal, survey, knowledge, comprehension, application, to analysis, synthesis, and finally evaluation and modification.

This project was performed by a group of mechanical engineering senior students, to demonstrate their engineering training and capabilities to search for ideas, to formulate a proposal and modify it to get the approval from the department curriculum committee, to conduct literature survey, to understand the descriptions of a new mechanism, to design and construct a virtual prototype in the computer environment, and finally to propose modifications to improve the original design.

This project is to investigate a novel cam based CVT which was proposed in US patent # 4,603,240, which has a cam input to drive an angle dependent, clutch actuated output shaft. This patent was published 15 years ago, but unfortunately there was no detailed design or analysis ever presented. Based on this patented CVT, a CAD (Computer Aided Design) model utilizing three dimensional CAD software (CATIA®) was conducted, creating a visualization and analysis model to ascertain system performance and feasibility. This paper describes the mechanism designed and created, limitation of the modeling software and the approach utilized to overcome these limitations. The resultant motion is then analyzed to ascertain the performance and determine the viability of the design concept. Finally, some key improvements to the system are proposed to the design.

INTRODUCTION

Many machines can produce an output that is rotational in nature. Some examples include internal combustion engines, wind mills, and electric motors. In order to effectively use this output, from these machines, often a modification of the angular velocity is necessary. There are many types of transmissions that can perform this function, from a simple gear reduction to the recent development of continuously variable transmissions.

Merriam-Webster defines a transmission as: "an assembly of parts including the speed-changing gears and the propeller shaft by which the power is transmitted from an engine to a live axle; *also*: the speed-changing gears in such an assembly"^[1]. Any reductions or increase in angular velocity of an input machine, for use as output, can be termed a transmission. For a transmission to be useful to end users, traditionally more than one gear ratio is desired. A typical four speed with overdrive transmission, used in automobile applications, is arranged with the following gear ratios, Table 1.

Table 1 – A Typical Four Speed with Overdrive and Reverse Transmission

| Gear | Gear Ratio |
|------|------------|
| 1 | 1:2.8-3.1 |
| 2 | 1:2.1-2.5 |
| 3 | 1:1.5-1.7 |
| 4 | 1:1 |
| OD | 0.695:1 |
| R | 1:-3 |

The other main option of transmission, the manual transmission, would use similar gear ratios, relying on the operator to determine the shift points. As these are the two primary options in today's automobiles, alternative approaches are often overlooked. A relatively under investigated type is the continuously variable transmission. This design utilizes new technology and in turn yields viable advantages over automatic transmissions. Further research will only help to expand the overall potential of these systems in future years. One example is the United States Patent, patent number 5,603,240, which describes a MECHANICAL TRANSMISSION CONTINUOUSLY VARIABLE FROM FORWARD TO REVERSE^[2]. It is the intent of this project to explore this patent by modeling the design, kinematics, and determining the viability and possibility of future applications.

ADVANTAGES AND DISADVANTAGES OF CVT

In an automobile, the main purpose of the transmission is to convert input, rotational motion, from the engine into output, rotational motion. In an automatic transmission, the use of planetary gear sets is vital in producing a wide array of output speeds from a limited range of engine speeds. This change is done automatically without a clutch pedal^[3]. On the other hand, a continuously variable transmission accomplishes the same function without the use of a discrete gear set^[4]. Table 2 presents some of the benefits and downfalls of using a CVT in place of an automatic transmission.

Table 2 – Advantages and Disadvantages of CVT vs. Traditional Transmissions

| Advantages | Disadvantages |
|--|---|
| <ul style="list-style-type: none"> • More fuel efficient^[4,5] • Engine runs at optimum power range, increases performance^[4,5] | <ul style="list-style-type: none"> • Cost^[4] • Slow progression in development due to lack of demand^[4] |

| | |
|--|---|
| <ul style="list-style-type: none"> • Constant, step-less acceleration^[4,5] • Less engine fatigue from gear changes^[4] • Better response to speed and throttle changes^[5] | <ul style="list-style-type: none"> • Complicated control scheme^[4] • Generally low torque capabilities^[4] • Weight^[4] • Use of a torque converter, to generate power at zero or low speeds, decreases overall CVT efficiency^[4,6] |
|--|---|

With the ever increasing demand for more fuel efficient automobiles, a continuously variable transmission seems advantageous. While this innovation is quite new in relation to other transmission technologies, the benefits will keep expanding. Also, as this technology becomes more prominent in the market, the manufacturing infrastructure will increase and drive down the overall cost of these systems.

THE CLASSES OF CVT – LITERATURE SURVEY

In the field of continuously variable transmissions, there are several different types that have been developed. The main mechanical variants include: friction, ratcheting, hydrostatic, and positive drive^[6]. Each design yields an improved efficiency when compared to standard automatic transmissions and succeeds in eliminating discrete gear ratios^[5]. Many CVTs are currently in production and are used by some of the major companies in the automotive market.

1. Friction Class - Push Belt Type

The most frequently used CVTs, especially in the automotive industry, use the friction class. There are two sub-systems that make up this class, in which the most common is the push belt design, Figure 1 and Figure 2. The push belt type, utilizes a strong belt which acts between two pulleys, one fixed and one movable, connected to the input and output shafts^[6]. Sensors read the engine output, and electronically vary the distance between the pulleys and in turn drive the belt tensioner^[4]. “The continuously changing distance between the pulleys-their ratio to one another-is analogous to shifting gears”^[7]. Honda uses this type of push belt design in its CVT model for the 2012 Insight. In combination with their Drive-by-Wire™ throttle system, this transmission adjusts constantly to provide the highest efficiency drive ratio without the use of conventional gears. This translates into better acceleration and an excellent fuel economy rating at 41 city/44 highway/42 combined miles per gallon^[8].

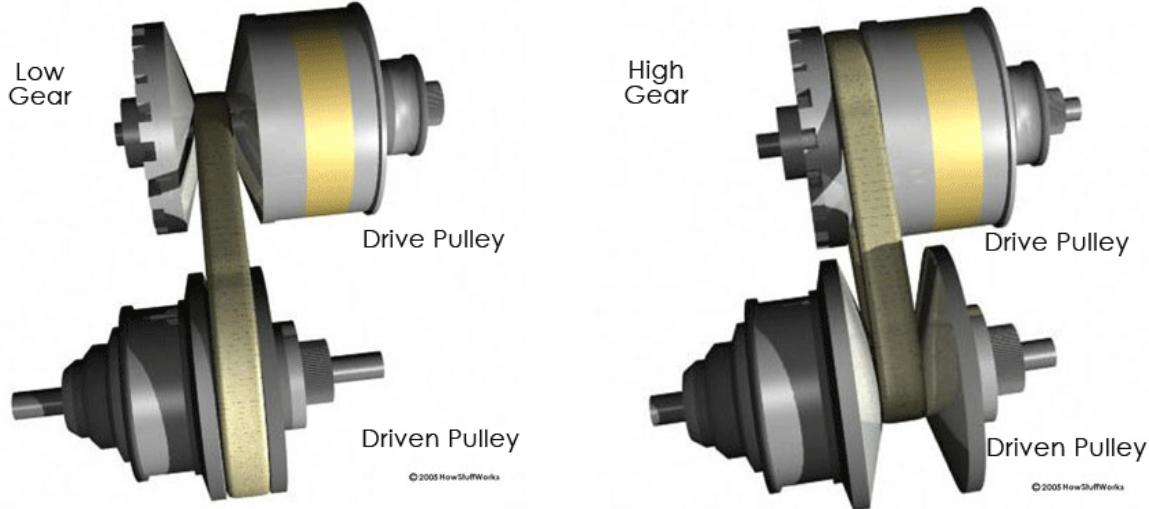


Figure 1 – Low Gear of Push Belt CVT^[5]

Figure 2 – High Gear of Push Belt CVT^[5]

2. Friction Class - Torodial Type

Also within the friction class of CVTs, is the torodial traction-drive design, shown in Figure 3. This system attaches one torus^[4], or curved disc, to the input shaft and another to the output shaft. Rollers connected between these two discs, allow for torque transmission from one to the other. The infinitely adjustable gear ratio is caused by the changing of the angle of the rollers in relation to the axis of the shaft^[6]. When the non-stationary torus slides linearly, it varies the angle^[4]. Nissan's "Extroid", Figure 4, utilizes the torodial design and has made many breakthroughs in the world of continuously variable transmissions. Installed in the Nissan Gloria and Cedric, it has the highest torque capability of all CVTs in current production at a torque capacity of 390 Newton meters^[6]. The company boasts three superb benefits for the "Extroid": quick response and smooth ratio changes, high torque capacity, and improved fuel economy. This CVT is reported to be ten percent more efficient when compared to conventional automatic transmissions^[9].

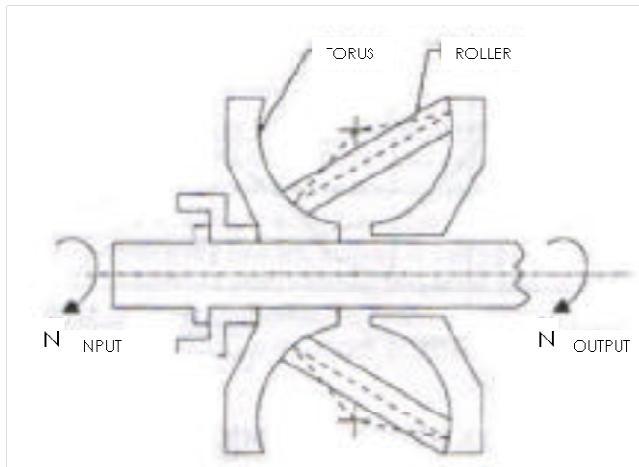


Figure 3 – Torodial CVT^{[4][17]}

Ratio change mechanism of the EXTROID CVT

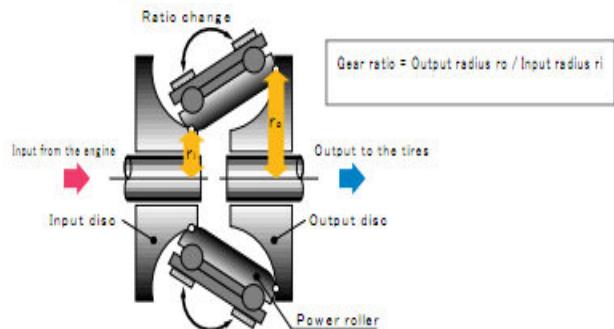


Figure 4 – Nissan Extroid^[9]

3. Ratcheting Class

Another variant in the current CVT market includes the ratcheting class. In these types, there are multiple power paths which translate input motion into output motion by the use of ratchets, sprags, or one-way clutches. There are two basic functions of this class. The first function is to generate multiple oscillations, or stroke variations. This can be done by utilizing a simple crank using a variable throw or pivot. The second is to select the appropriate portion of the oscillations to drive the output, or clutching. For general cases, a portion of each power path is connected to the output and engages at various times. This alternating engagement allows one to carry the load while the other is disengaged and thus produces constant, smooth motion. Although there are some drawbacks to this system, there have been several designs put into production^[10]. One such is the "Zero-Max Adjustable Speed Drive."

"The general principle of operation of the "Zero-Max Adjustable Speed Drive", Figure 5, gives infinitely adjustable speed by changing the distance that four or more one-way clutches rotate the output shaft when they move back and forth successively. The number of strokes per clutch per minute is determined by the input speed. Since one rotation of the input shaft causes each clutch to move back and forth once, it is readily apparent that the input speed will determine the number of strokes or urges the clutches give the output shaft per minute"^[11].

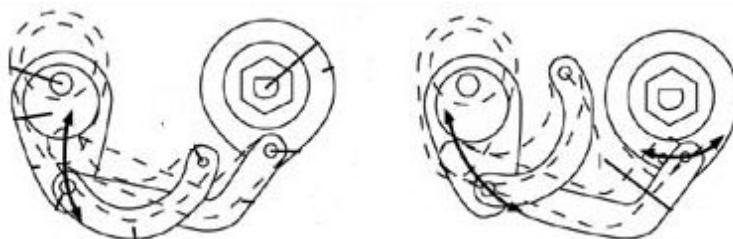


Figure 5 – Ratcheting Mechanism of the Zero-Max Adjustable Speed Drive^[11]

4. Hydrostatic Class

The third variant in the world of CVTs is the hydrostatic class. In this design, pumps are used to vary the fluid flow through hydrostatic motors. The input motion from the engine operates a hydrostatic pump and subsequently turns the rotational motion into fluid flow. This process is then reversed after passing through the hydrostatic motor, which is positioned on the output side. Overall, the cycle undergoes two phases: rotational to fluid flow and fluid flow back to rotational^[5], Figure 6. The most common types of hydrostatic pumps include: the bent axis pump, the radial piston pump, and the vane pump^[13], Figure 8.

With this type of CVT, a planetary gear-set and clutches can be included. This hybrid design, called a hydro-mechanical transmission, has three different modes of converting input motion into output motion. “At a low speed, power is transmitted hydraulically, and at a high speed, power is transmitted mechanically. Between these extremes, the transmission uses both hydraulic and mechanical means to transfer power.” The use of this CVT is best fitted for heavy-duty applications^[8]. John Deere utilizes the Tuff Torq® hydrostatic transaxle, Figure 7, in some of their riding lawn mowers. This design is said to be very efficient and by placing the transmission components in the same housing as the differential and axle housings, it reduces the potential for leakage^[13].

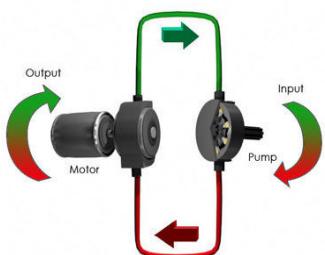


Figure 6 – Basic Concept of Hydrostatic CVT^[5]



Figure 7 – John Deere Kanzaki® K46 Transaxle^[13]

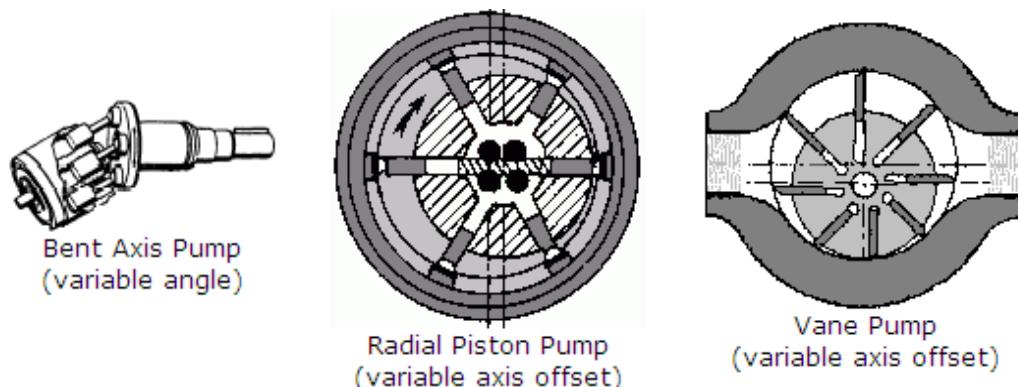


Figure 8 – Common Pump Types for Hydrostatic CVT^[13]

5. Positive Drive Class

The final class of continuously variable transmissions is the positive drive design. As a relatively new class, the Naudic iCVT, from Varibox CVT Technologies, is said to be the world's first positive drive CVT. It succeeds in maintaining a mechanically positive drive, even through the shifting cycle. Also with this prototype design, smooth shifting is accomplished without the use of clutches or even a torque converter, which can be considered an advantage over other CVT classes. With a mechanical efficiency compared to a manual transmission, the fuel economy is improved. By not having any type of hydraulic control, the Naudic iCVT is said to be less complex than a conventional automatic, but still more intricate than a manual. Its applications include passenger vehicles, trucks, and construction equipment and can be scaled to meet a wide range of torque or power requirements^[14].

The purpose of a continuously variable transmission is to infinitely change the gear ratio without the use of gears. This allows for a smoother and steadier acceleration. Each of the four classes of CVT achieves a higher level of efficiency when compared to standard automatic transmissions and allow the vehicle's engine to run within its optimum performance range. As seen in Table 3 and Table 4, the improvement is quite evident. A prime example of this enhancement, in the mainstream automotive market, is the use of CVTs in the Honda Civic. This vehicle equipped with a standard automatic has a fuel economy rating of 28/35 city/highway miles per gallon, but when using a CVT increases to 34/38 city/highway miles per gallon. Other system benefits include less engine fatigue, due to the elimination of harsh gear shifting, and a quicker acceleration^[4].

Table 3 – Automatic Transmission Gear Ratio Efficiency^[4]

| Gear | Efficiency Range |
|------|------------------|
| 1 | 60 - 85% |
| 2 | 60 - 90% |
| 3 | 85 - 95% |
| 4 | 90 - 95% |
| 5 | 85 - 94% |

Table 4 – Efficiency of Different CVT Designs^[4]

| CVT Mechanism | Efficiency Range |
|-------------------|------------------|
| Rubber Belts | 90 - 95% |
| Steel Belts | 90 - 97% |
| Toroidal Traction | 70 - 94% |
| Nutating Traction | 75 - 96% |
| Variable Geometry | 85 - 93% |

THE CAD MODEL

The rotational input to the transmission is transferred to the system by a series of cams on a shaft. The number of cams is defined as N, and can vary per the specific application. In its preferred configuration N should be even. Each cam is offset rotationally by 360° divided by N. As the input cam shaft subassembly spins, the rotational motion is transferred into linear motion via push and pull cam followers. These cam followers are positioned so that there is always contact between the cam and a follower, either pushing or pulling the Input Linear Displacement Multiplier (ILDM). This converts the input rotational motion into linear motion. The ILDM is connected to the Output Linear Displacement Multiplier (OLDM) by the Input/Output Pin (I/O Pin). This pin is fixed in the ILDM and is able to slide in a slot within the OOLDM.

As the ILDM moves in and out, the OOLDM is also pushed and pulled in a linear motion. The end of the OOLDM contains a rack and pinion gear design. This rack and pinion converts linear motion into an oscillating rotational motion. Another device must be used to convert the oscillating rotational motion into continuous rotational motion. A control unit can be used electronically, hydraulically, or mechanically to engage and disengage the calipers. This can be programmed or designed to engage the calipers when the oscillating rotational motion is moving in the desired direction. These calipers engage and disengage with disks that are attached to the output shaft. The design will be such that the calipers will disengage before the oscillating rotation comes to a stop and reverses direction. In this way an output shaft rotation occurs by only engaging the calipers when the oscillating motion is rotating in the desired direction. By adding multiple layers a smooth continuous rotational movement can be achieved.

In order to change the gear ratio, the output assembly rotates. The amount of rotation is defined as the phi (Φ) angle shown in, Figure 9. The patent authors have envisioned the Φ angle to range from 0° to 180° . When the $0^\circ \leq \Phi < 90^\circ$ the output will spin in a specific direction, clockwise or counterclockwise, as defined by the control scheme. When the phi angle is at 90° the transmission will be in neutral. When the $90^\circ < \Phi \leq 180^\circ$ the output will spin in the opposite direction than the lower phi angles. For references visuals of this cam based CVT assembly, see Figure 10, and the original design is shown in Figure 11.

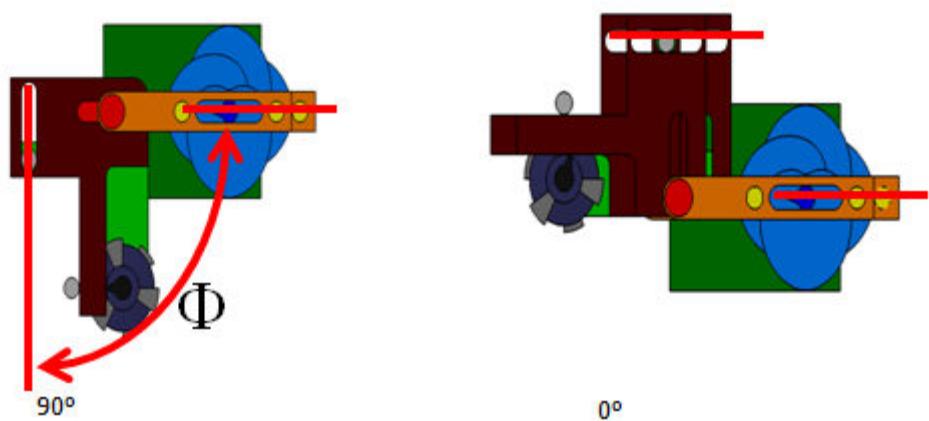


Figure 9 - Φ Angle Orientation

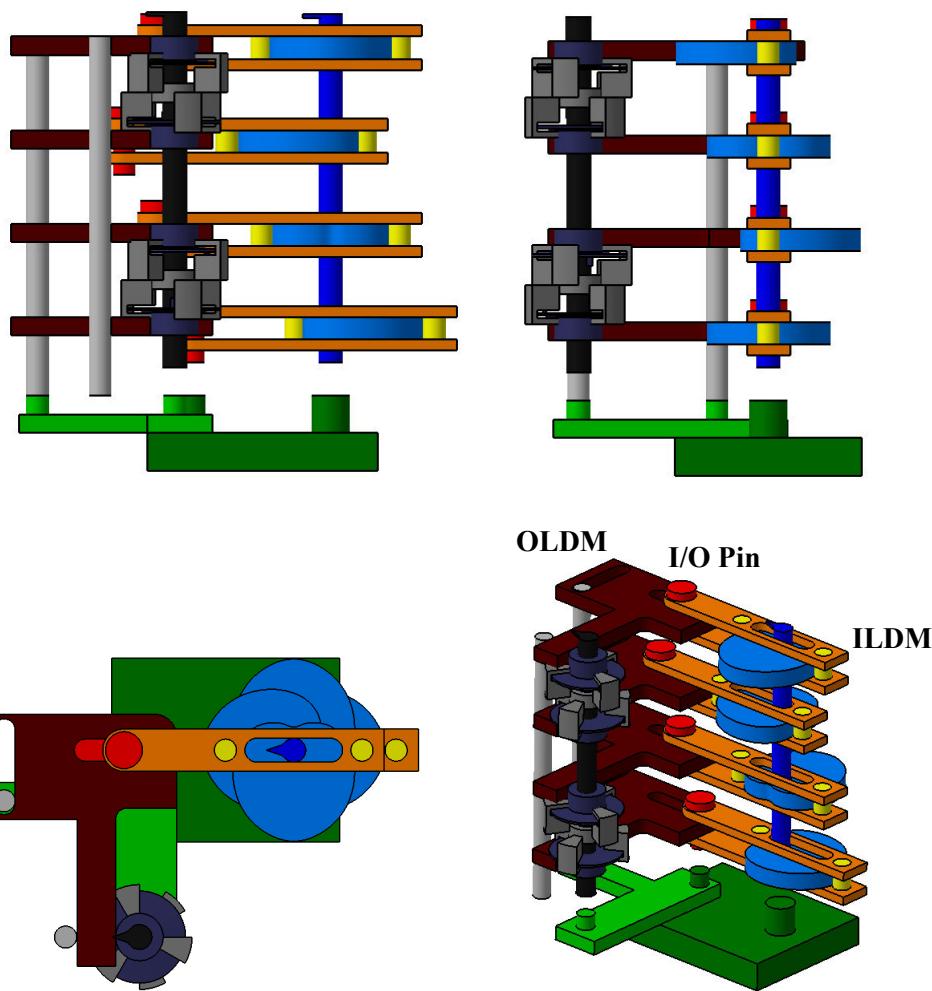


Figure 10 – Cam Based CVT CAD Model

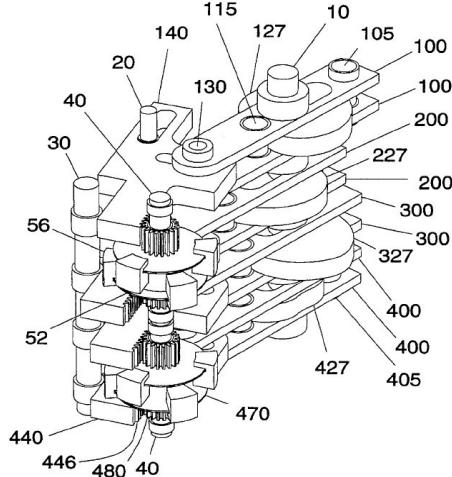


Figure 11 – US patent # 4,603,240 Cam Based CVT Original Design^[2]

GEAR RATIO ANALYSIS

In order to understand the potential gear ratios from the CVT mechanism being designed, an analysis of the motion was conducted to determine the equation of motion of the output shaft as a function of the geometry and the input angular velocity. The dimensions of the geometry impact the resultant gear ratios and the design space is analyzed here in order to ascertain proper dimensions for these components.

Since the output shaft is driven by a clutch/plate mechanism, the angular velocity of this component will drive the resultant angular velocity for the output shaft. The angular velocity of a pinion gear, (ω_{pinion}) in a rack and pinion configuration, is a function of linear velocity (v_{rack}) of the rack and the pinion pitch radius (r_{pinion}):

$$\omega_{pinion} = \frac{\nu_{track}}{r_{pinion}} \quad (1)$$

For an effective transfer of motion from the clutch plate to the output shaft a control scheme will be developed. Engagement between the components is restricted to the uniform angular velocity portion of the clutch/plate rotation, and will be disengaged at all other instants of time.

The velocity of the rack is defined as a function of half the input angular velocity of the cam shaft, the cam travel, and the angle between the input and output beams:

$$v_{rack} = \left(\frac{\omega_{cam\ shaft}}{2} \right) (d_{travel}) [\cos(\Phi)] \quad (2)$$

Combining Equations (1) and (2), the output angular velocity, as a function of the input angular velocity and the Φ angle between the transmission halves an equation is derived as:

$$\omega_{pinion} = \frac{(\omega_{cam\ shaft})}{z} \frac{(d_{travel})[\cos(\Phi)]}{r_{pinion}} \quad (3)$$

By varying the values of the travel distance and the pinion radius for the rack and pinion interface, the gear ratio range would be influenced. An inspection of this design space is performed later in this section.

The gear ratio is the relationship between the input angular velocity and the output angular velocity defined below:

$$GR = \frac{\omega_{cam\ shaft}}{\omega_{pinion}} \quad (4)$$

By combining Equations (1) and (2), the equation is derived for determining gear ratios as a function of the Φ angle, pinion radius, and stroke length:

$$GR = \frac{2r_{pinion}}{(d_{travel})[\cos(\Phi)]} \quad (5)$$

The gear ratio equation shows that the radius of the pinion gear and the length of the stroke contribute to the possible gear ratios. Since there have been no any specific dimension proposed from the original design in the patent, a design study was performed here with three values of each design factor, in order to understand the design space. First, three pinion radii were examined; 10, 14 and 18mm, with a 37mm stroke. The results of this analysis were plotted, Figure 12, showing the possible gear ratios with each configuration.

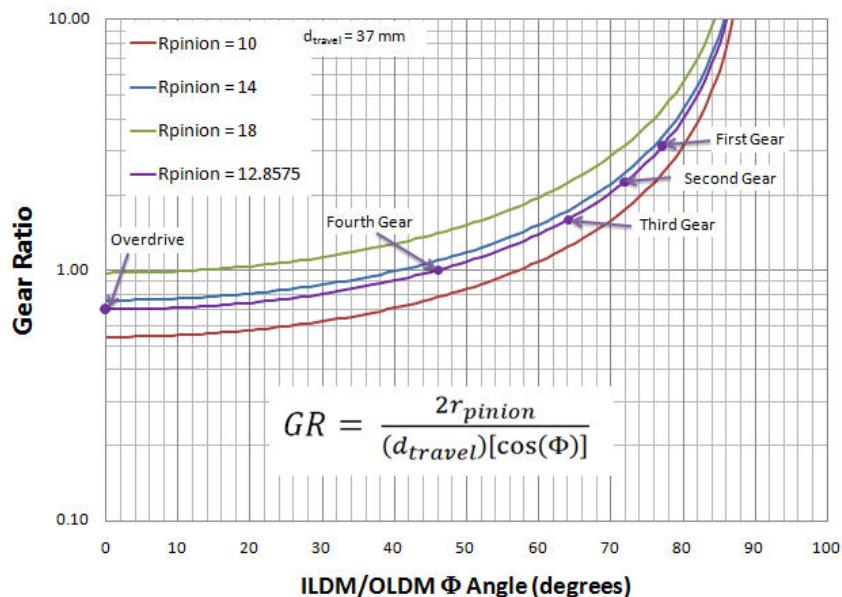


Figure 12 – Effect of Pinion Radius on Gear Ratio

Having determined that none of the three chosen pinion radii would produce the desired overdrive condition (0.695:1) at a Φ angle of zero degrees, a fourth radius was calculated.

Applying Equation (5) with the stroke value set to 37mm, the resultant pinion radius was determined to be 12.86mm. Figure 12 is plotted with this configuration and the resultant Φ angles for each of the simulated gear ratios is plotted.

Next, the three stroke lengths were calculated that corresponded to the design factor pinion radii at a Φ angle of 0° . Another simulated gear ratio plot is created using a pinion radius of 14mm to examine this design space, Figure 13.

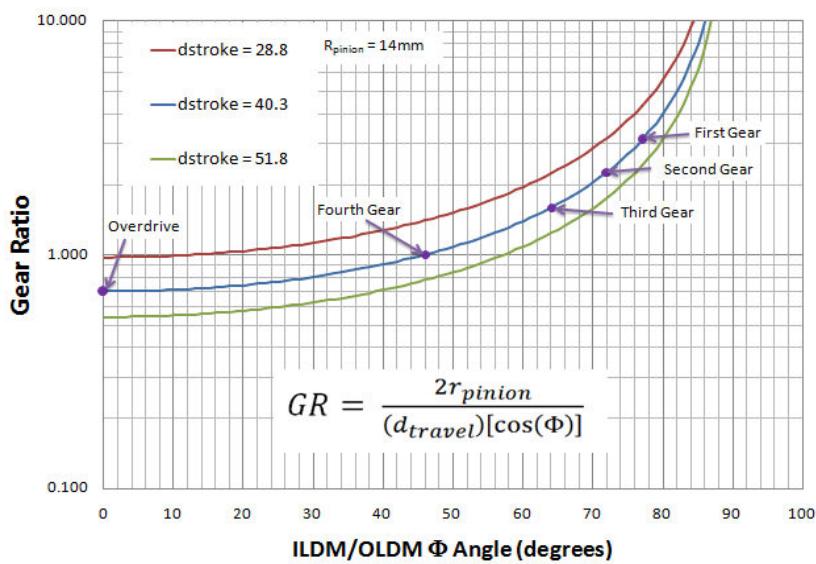


Figure 13 – Effect of Stroke Length on Gear Ratio

Having validated an appropriate design space, a response surface analysis was performed using the three pinion radii and three stroke lengths. Figure 14, is a three dimensional plot of this response with the black solid line showing potential dimensions for each design factor. Since the model had been previously designed with a 37mm stroke length and the pinion radius calculated for this length was reasonable, it was determined to continue with those values.

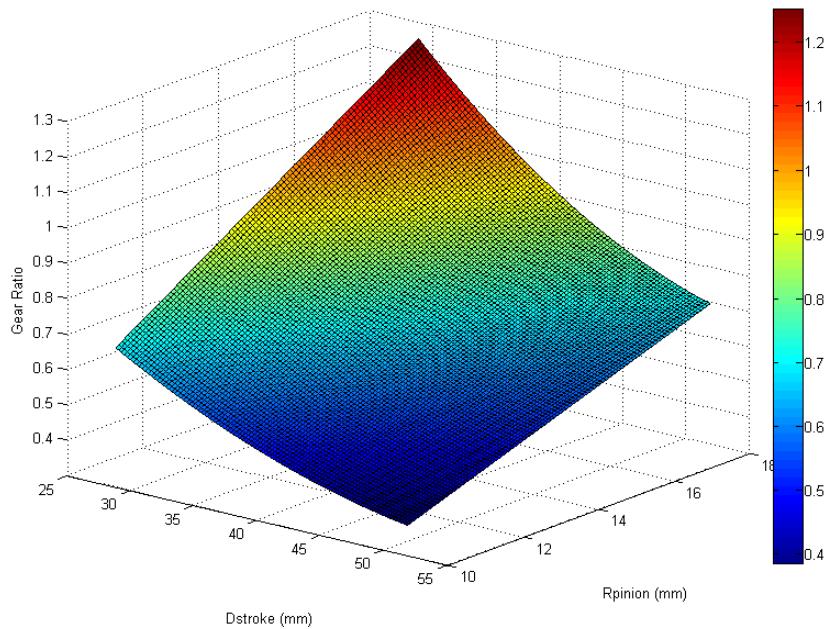


Figure 14 – Gear Ratio Geometry Design Space

Having determined the desired parameters, the Φ angles were determined to produce the equivalent gear ratios to an automatic transmission, with this CVT. Table 5 below shows the resulting gear ratios at specific values of Φ .

**Table 5 – Gear Ratios for Pinion Radius
(12.86mm)**

| Phi (Φ) Angle (degrees) | Input Angular Velocity (RPM) | | | | | | Gear Ratio |
|-----------------------------------|-------------------------------|---------|---------|---------|---------|---------|------------|
| | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | |
| | Output Angular Velocity (RPM) | | | | | | |
| 0 | 719.42 | 1438.85 | 2158.27 | 2877.70 | 3597.12 | 4316.55 | 0.695 |
| 46 | 499.75 | 999.51 | 1499.26 | 1999.02 | 2498.77 | 2998.53 | 1.00 |
| 64.24985 | 312.55 | 625.10 | 937.66 | 1250.21 | 1562.76 | 1875.31 | 1.60 |
| 72.40444 | 217.48 | 434.96 | 652.44 | 869.92 | 1087.40 | 1304.87 | 2.30 |
| 76.37377 | 169.49 | 338.97 | 508.46 | 677.95 | 847.44 | 1016.92 | 2.95 |
| 90 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | neutral |

While the purpose of a CVT is to produce relatively infinite gear ratios, the simulation work that was performed was at the above values in order to be able to analyze the output. This analysis shows that at longer strokes the pinion radius needs to increase. This infers that the strength of the pinion will be a major contributing factor to the robustness of this design. As a larger radius is required, a larger overall transmission size, to accommodate the stroke, will also be required.

THE CONCERENS OF THE ORIGINAL DESIGN

Based on the analysis of the patent design, this a different way to achieve a ratcheting continuously variable transmission. The patented intent design suffers from some major concerns in regards to the long term viability of the design. Due to the speed of operation wear is a significant concern. Wear will occur within two distinct subsystems of this design, first in the input mechanism (cams) and secondly in the output mechanism (calipers). The second area of concern based on the patented design is the overall size of the transmission. Due to the control strategy utilized in the patent, the transmission requires 180° of rotation to achieve the desired gear ratios.

THE DISCUSSIONS AND DESIGN ALTERNATIVES

The concern for the cam system stems from the speeds at which the cams would be turning. Comparing it to current cam applications show a significant difference in rotational speed. For example, the wear characteristics of the cams of the patent transmission could be compared to a camshaft design in a standard combustion engine. The input shaft would rotate at the same speed as the engine's output shaft, or engine RPM. The rotational frequency of a camshaft in a current engine is exactly half the engine RPM. Thus, providing either a replacement of the cam system or an improvement on the current design would be desired before implementation. A suitable alternate of the cam design that still has a constant transition from rotational motion to linear motion has not yet been identified.

The current design for the output assembly poses many challenges. While the rack and pinion changes linear motion into oscillating rotational motion, the caliper opens and closes in order to grab a disk. While the implementation of a complicated control system would be necessary, the major concern lies with the break pad like design. Friction pads on standard vehicles must be serviced every 30,000 to 70,000 miles^[15]. The servicing of this component in the transmission would be costly for the consumer. In order to resolve this issue, another method to convert oscillating rotational motion into continuous rotational motion should be explored. However, this method must convert oscillating rotational motion into continuous rotational motion as uniformly as possible, as it is necessary to create a smooth rotational output assembly.

One such possible device is a sprag, which can be defined as a one way clutch that can be built for high torque applications. NSK, a manufacturer of sprags, claims that their products contain "wide cams with a larger radius of curvature than conventional models [which can] achieve high torque capacity under high loads for improved safety. A unique cam shape allows the GX series to withstand even shock loads without slipping."^[16]. The use of a sprag to replace the clutch system would not eliminate the need for a rack and pinion to convert linear motion to rotational motion, however it would eliminate the need for an externally controlled clutching system.

The current patent design includes a Φ that ranges from 0° to 180° as discussed previously. As a means to reduce the packaging size necessary for that much rotation, reverse could be achieved using an improved control system. In the case of an electrical control system, the code could simply be written to engage and disengage the calipers exactly opposite the forward setup

causing the output shaft to spin in reverse. This would eliminate the need for the Φ angle greater than 90° and thus significantly reduce the packaging size.

To further reduce the packaging size the geometry could be altered slightly. The same output can be achieved by making Φ of 180° the overdrive position. This would effectively fold the current design in half. The minimum 90° rotation required to achieve all gear ratios would still be possible by rotating the assembly in the opposite direction than the original design specified.

A balance of these changes should be implemented for future application, although not all of these changes can be made as some do not work with the other. For example if the output mechanism was changed to a sprag than the Φ angles greater than 90° would be necessary for reverse. However, a sprag does not eliminate the ability to rotate the overdrive position 180° . This would highly reduce the expected wear of the input and output shafts as well as reduce the packaging size.

CONCLUSION

In the world of automotive transmissions, continuously variable designs offer compelling advantages over more traditional designs. The cost prohibitive nature of these transmissions currently limits a sizeable integration into the automotive market. However, the improved fuel efficiency of these systems is an important aspect as governmental regulations become increasingly strict on raised fuel economy ratings. Therefore, continued research into these technologies is critical.

The cam based CVT, proposed by Klovstad and Fortune, was kinematically examined to understand the mode of operation and ascertain its ability to produce adequate gear ratios. This was necessary to determine its viability and potential applications. Analysis resulted in a design space definition with specific parameters for rack travel and pinion radius to achieve these gear ratios. The caliper – clutch/plate interface was determined that if the reciprocating motion could be induced to the clutch plate, uniformly over a significant region of the positive stroke of the rack, that the methodology of this design would be verified. The kinematic analysis demonstrates that this method of translating input rotational motion to output rotational motion through linear displacement is viable.

The cam based CVT defined in the patent, is theoretically viable through an analysis of motion, although not viable in its original embodiment. This is due to wear issues with the cam interface, and wear issues at the caliper – clutch/plate interface to name a few. Further development and investigation of this configuration would be necessary to address these known issues.

Additionally, the authors presented several key alternatives to improve this concept beyond the intent of the patent. Incorporation of reverse gearing into the zero to ninety degree configuration through a control strategy mechanism, thereby reducing the system packaging size, utilization of sprag clutches to eliminate the wear that the caliper – clutch/plate interface presents. While each of these offer some advantage over the patent, not all can be simultaneously implemented.

Overall, the concept presented in the patent offers promise as a potential CVT technology. With implementation of the proposed changes as well as optimization and development, a Cam based CVT could be realized.

ACKNOWLEDGMENTS

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