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# Cam Based IVT

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**Abstract:** *There are several categories of CVTs in existence today, including traction, belt, and ratcheting types. Drives of these types, their attributes, and associated design challenges are discussed to frame the development of the Cam-based IVT. The operation of this transmission is kinematically similar to a planetary gear set, and therefore, its operation is described with that in mind including a description of the six major components of the transmission, those being the cam, followers, carriers, planet gears, sun gears, and one way clutches. The kinematic equation describing its motion is derived based on the similarities it shares with a planetary gear set. Additionally, the equations for the cam design are developed here as the operation of the CVT is highly dependent on the shape of the cam. There are six simple inversions of this device and each inversion has special characteristics and limitations, for example, the available gear range. A method was developed to select the most suitable inversion, gearing, and follower velocity for a given application.*

**Keywords**- *CVT (Continually variable transmission), IVT (Infinitely variable transmission)*

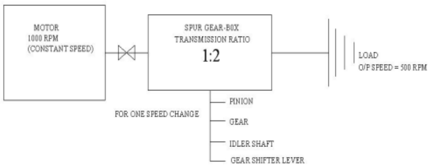
## I. Introduction

A specific type of CVT is the infinitely variable transmission (IVT), which has an infinite range of input/output ratios in addition to its infinite number of possible ratios; this qualification for the IVT implies that its range of ratios includes a zero output/input ratio that can be continuously approached from a defined "higher" ratio. A zero output implies an infinite input, which can be continuously approached from a given finite input value with an IVT. Low gears are a reference to low ratios of output/input which have high input/output ratios that are taken to the extreme with IVTs, resulting in a "neutral", or non-driving "low" gear limit. Most continuously variable transmissions are not infinitely variable.Most (if not all) IVTs result from the combination of a CVT with an epicyclic gear system (which is also known as a planetary gear system) that facilitates the subtraction of one speed from another speed within the set of input and planetary gear rotations. This subtraction only needs to result in a continuous range of values that includes a zero output; the maximum output/input ratio can be arbitrarily chosen from infinite practical possibilities through selection of extraneous input or output gear or sprocket sizes without affecting the zero output or the continuity of the whole system. Importantly, the IVT is distinguished as being "infinite" in its ratio of high gear to low gear within its range; high gear is infinite times higher than low gear. The IVT is always engaged, even during its zero output adjustment.

## II. Need of Infinitely Variable Transmission system

There are many machines and mechanical units that under varying circumstances make it desirable to be able to drive at an barely perceptible speed , an inter mediate speed or a high speed. Thus a infinitely variable (or step less speed variation in which it is possible to get any desirable speed. Some mechanicals hydraulic and electrical devices serve as such step less drives. However the torque Vs speed characteristics of these drives do not match that of step less drives at increased driving torque at low speeds. Hence the need of an step less drive with the following characteristics Step less or infinitely variable speed.

- Wide range of speed variation i.e.(Nmax to Nmin).
- Shifting form one speed to another should be shock less .
- Minimum no of controls for speed changing .
- Ease of operation.
- Compact construction .




As per above example 4 components are required per speed change, thus if we desire to achieve 1:4 reducer with speed change upto 0 ie, if i/p speed is thousand , o/p speed will vary from 250 rpm to 0 rpm , then Components in drive = 250 x 4 = 1000……This will make the drive extremely bulky, in weight and size, difficult to control and extremely costly.

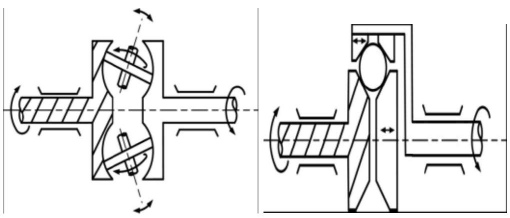
## III. Background

As mentioned previously, there is a substantial amount of prior work in the field of continuously variable transmissions. In general, these drives can be separated into 4 different categories traction, belt, ratcheting, and hydrostatic drives. Additionally, sometimes electrical couplings (generator/inverter/motor) are considered to be CVTs. Of these, only the hydrostatic and electrical drives depend on power transmission devices which are not mechanically linked and therefore less attention will be given to these.

Traction drives will be addressed first. Their single unifying characteristic is the transmission of power through rolling contact. As one can imagine then, much of their success depends upon the careful design of the contact patch geometry and kinematics through the gear range. The several most common and successful types of traction drives are the Full or Half Toroidal, the Kopp Variator, the Milner CVT and the Beier Variator .

The full and half torroidial drives are perhaps the oldest designs, dating back to the 1877 patent by Hunt. They are comprised of at least two traction discs with a toroidal shape connected through one or more rollers. By varying the angle at which the rollers contact the toroidal discs, the effective gear ratio can be changed. There has been an extensive amount of research on these drives, and some have been commercially successful. Both the Kopp Variator and the Milner CVT use planet balls instead of rollers to transmit power between the input and output races. While the Kopp Variator actively positions these rollers to control the transmission ratio, the Milner CVT moves the races axially instead. Finally, the Beier Variator relies on intermeshing disks whose radial separation can be adjusted to vary the transmission ratio.

There are several challenges which traction CVT designers face. One of the most significant is the high contact force necessary between the rotating elements required to transmit torque through a thin film of oil. Enormous pressures (up to 3.5[GPa]) are necessary to compress the film of oil to the point that it nearly solidifies, and only then can it efficiently transmit motion. Therefore the power transmission components must be manufactured from a suitably strong material (such as AISI 4340, 8620, or 9310) with suitably fine surface finish. In addition, care must be taken to reduce the losses in the bearings that generate the clamping forces between the elements. Great efforts are also taken to reduce the losses within that contact patch due to viscous sliding, the greatest culprit being spin, which is the rotation of the rolling elements about an axis perpendicular to the contact patch. The penalties which these drives incur in terms of cost, complexity, and weight were meant to be avoided while developing the Cam-based IVT.



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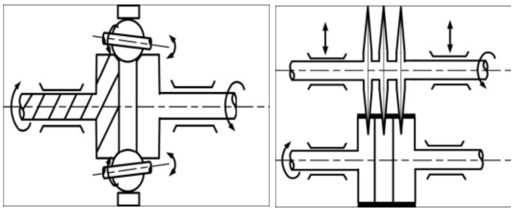


C D

Figure 3-1. A) Torroidal , B) Kopp, C) Milner, D) Beier CVTs

Belt drives are another class of continuously variable transmissions. They are notable because they are the most common CVT developed for commercial production, being used by Honda, Ford, Nissan and Toyota as well as many small tractor and ATV manufacturers. In principle, their operation has changed little since their inception. This transmission uses a pair of 'V' shaped pulleys arranged so that one half of the pulley can be moved axially in relation to the other to vary the gear ratio. A matching belt which rides in the pulleys transmit power between the driven and driving pulley, as can be seen in Figure 3-2.

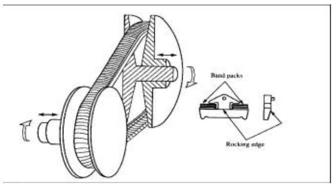



Figure 3-2. Schematic of a Belt type CVT.

Belt drives have been developed into a unique mechanical device, one in which a belt is pushed between two pulleys, as opposed to pulled. The problem is analogous to the cliché of "pushing a rope". Such a motion is accomplished with a number of flat plates mounted on a metal band or belt; when put under a load, the plates are compressed together and form a rigid column between the two pulleys. Unfortunately, with as much development as they have undergone, belt CVTs are still unable to produce efficiency gains in automobiles predicted by their makers. In fact, some are often worse than their manual transmission counterparts. The losses present in belt CVT's can be contributed to three sources. First, like the traction drives presented earlier, there are losses due to the viscous slip between the belt and the pulleys. Secondly, to generate the clamping forces on the belt while controlling the gear ratio often requires complex hydraulic systems whose pumping losses represent a significant energy cost. Finally, there are belt related frictional losses which occur as a result of the sliding motion of the belt as it enters and leaves the v-groove in the pulley. Regardless, because of the significant development these transmissions have undergone and the relative simplicity of low power versions, they have seen widespread acceptance. The ratcheting drive is the final class of mechanically driven continuously variable transmissions. All ratcheting CVTs, of which the Cam-based IVT is one, converts a rotary input into at least two out of phase oscillations of adjustable magnitude. Through the use of several one-way clutches, these oscillations are then converted back to a rotation. By varying the magnitude of the oscillations, the ratio between the input and output angular velocities can be changed. If these adjustments can be made infinitely small, the transmission will be continuously variable. Up to now, one of the main limitations of ratcheting CVT's has been their propensity for producing a nonuniform output for a uniform input; therefore, their applications have been limited, but there are several examples of such transmissions.

The prior work in ratcheting drives includes that by Benitez. He presents a transmission whose operation is similar to the concept presented here, but it is characterized by its non-uniform output for a uniform input. It is similar in that there is a device that varies the amount of rotation of several planetary gears with respect to a carrier. By varying the eccentricty, *e*, of the slotted plate with respect to the "guide groove", the angular velocity of the planet gears will vary as they travel around the sun. Each planet gear is connected to a second planet through a one way clutch; the planet with the largest velocity will then transmit motion to the ring gear. Similarly, Pires incorporates a number of levers, shafts, and a slotted plate to accomplish the same task. Similar in concept to both Pires and Benitez, but different in implementation, is a design used by Matsumoto which is commercially available under the name "Zero-Max". This transmission uses several reciprocating four bar linkages to oscillate the indexing clutches. An input is applied to the crank mechanism on the left which oscillates the first four bar mechanism. A second four bar loop converts these oscillations to a continuous output rotation through a number of one way clutches. Like Benitez's and Pires' CVTs though, it exhibits a non-uniform output for a uniform input.

Because of ratcheting drives unique power transmission mechanisms, they do not exhibit the typical loss mechanisms of other CVTs. For instance, the frictional elements which transmit power in all ratcheting CVTs are of the diode type. That is, they are either locked or freewheeling, and when transmitting power in the locked state they do so with no losses because there is no relative motion between components. The losses during freewheeling are also relatively small and independent of the transmitted power. Therefore large rolling frictional losses and viscous slipping losses are avoided. Secondly the clamping forces necessary to generate the friction is self-contained within commercially available sprag clutches. This keeps manufacturing costs and weight to a minimum. In addition, the shifting mechanisms can be designed to shift only the unloaded side of the drive, the particular mechanism which is freewheeling at that instant. Therefore the inefficient and complex shifting mechanisms of belt drives can be avoided.

While ratcheting drives avoid the common sources of inefficiencies, the limited amount of available research references and commercially available examples can in part be attributed to the nearly universal trait of these transmissions, their non-uniform output for a uniform input. That is, given a constant input velocity, the output of most ratcheting drives will exhibit some sort of rippling effect. Up to now this limitation has relegated these drives to vibration tolerant applications only, such as farm equipment. The Cam-based IVT presented within though has the ability to produce a continuous and uniform output. Therefore it is hoped that this transmission will be able to bridge the gap between research only studies and real world applications for both ratcheting drives and CVT's in general. It should be noted that only one other similar transmission as been recently developed, that by Jan Naude, covered under US and international patents although no academic literature is available. While similar, significant differences exist as both designs overcome problematic areas with different solutions.

The capability of the Cam-based IVT to produce a smooth and continuous output given a smooth input comes as the name suggests, from a cam and follower mechanism. Only this mechanism gives the designer sufficient freedom to eliminate any output velocity ripples unlike the linkage driven systems used by Benitez, Pires, and Matsumoto. Cams of course are not new in this regard, but the development of three dimensional cams with varying profiles along their lengths are a relative new development only made feasible with the development of computer controlled machining operations. Although not impossible, it would have been very difficult to achieve such a shape prior to the development of this technology.

In the same vein as other ratcheting drives, Cam-based IVT uses such a three dimensional cam to produce oscillations in a number of followers. By varying the profile on which the followers travel, the magnitude of these oscillations can be changed, thereby producing a different transmission ratio. And through the careful design of the cam profiles, the smoothness of the output velocity can be ensured.

## IV. Theory of Cam Based Infinitely Variable Transmission System

4.1. Components

In its simplest form, this transmission contains six unique components. Each component is described here briefly and illustrated in the following figures. While their function may be alluded to here. The heart of this transmission is a centrally located three dimensional cammoid. It is sometimes referred to as simply "cam" but this is somewhat undescriptive as a cammoid has a continuously varying profile along its length. The cammoid is most often fixed to ground, but can also serve as the input or output. Around the cammoid are a number of followers. Each follower interacts with the cammoid through a spherical or ellipsoidal roller mounted on said follower. The followers are held to the cam surface when not under load by a return spring. The followers are rotatably mounted to one or two carrier plates, the third major unique component of the transmission. The carriers are used to support the followers as well as transmit the input and output torques in some inversions.

This is analogous to a carrier's function in a planetary gear set. When designed to rotate, the carriers do so about the central axis of the cam. On each follower, is fixed a planet gear or pulley which meshes with a sun gear. The sixth and final unique component of the Cam-based IVT is a one way clutch located inside each of the planet gears or the sun gears. These clutches are responsible for rectifying the oscillations generated by the cam and followers and can be connected on the race opposite the sun gear to either the input, output, or ground depending on the inversion specified. The shaft connected to this inner race of the sun gears is simply called the sun gear shaft and its sole purpose is to transmit torques from an external source to both of the sun gears (however usually not at the same time). If however the sprag clutches are located in the planet gears, the sun shaft is directly connected to only one sun gear. These components are labeled on both a simplified representation and a prototype CAD model in

4.2. Operation

Attention is now given to the operation of the Cam-based IVT, specifically, how the major components detailed above interact to generate a smooth output motion at infinitely many transmission ratios. There are six different inversions of the Cam-based IVT, and while the majority of this work is focused on one particular inversion, the operation of the transmission is better first illustrated with a dynamically simpler one. Therefore the configuration first presented here uses the cam as the input and the sun gear shaft as the output.

Consider now the simplest inversion the Cam-based IVT which can be thought of as simply a cam and follower system with an attached gear train. Therefore the cam will serve as the input and the sun gear shaft as the output while

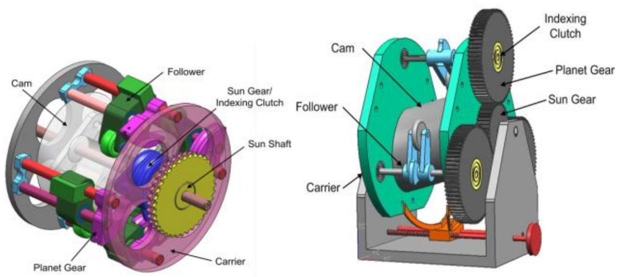
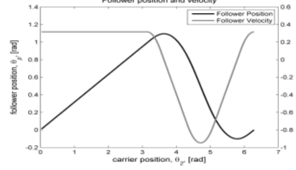



Figure 4-1. The complete prototype of the Cam-based IVT planet rears and the version has its sprag clutches in the sun gears.

the carriers remain fixed to ground. In such a configuration, a rotational input to the cam causes the followers to simply oscillate up and down as they are held to the cam with the return springs. In this case the followers do not rotate around the cam because the carrier is fixed. Due to the shape of the cam and the position of the followers around the cam, the followers oscillate out of phase of one another, that is, one follower will rotate clockwise, while the other rotates predominately counter clockwise. The out of phase oscillations of the followers drives the planet gears and their respective sun gears back and forth. It follows then that one direction of the oscillations of the sun gears will be transmitted to the sun gear shaft through the one way clutches. Because one sun gear will always be moving faster in the locking direction of the clutches, one sun will transmit torque to the sun gear shaft. With a carefully designed cam profile, the velocity of the sun gears can be shaped to produce a smooth and continuous output of the sun gear shaft with no velocity ripples. Such a velocity profile would look something like that in Figure 4-2. When overlaid with the velocity profile of the other out of phase followers, it would appear as in Figure 4-3.



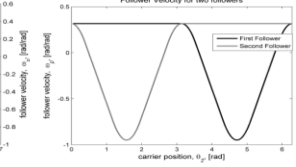




Figure 4-2. Displacement and Velocity profile.

Figure 4-3. Three velocity profiles overlaid out of phase.

The inversion studied for the majority of this work utilizes the sun gear shaft as the input, and the carriers as the output. As will be elaborated on later, this particular inversion was chosen because it provides higher gear ratios as well as a larger gear ratio range for a given cam eccentricity. It has been experienced that this inversion is more difficult to visualize then others, but much clarity can be gained by picturing something similar and much more familiar, a planetary gearset. To fully describe its motion, first a circular cam is considered. This will decouple the motion of the carrier and the followers around the cam, from the oscillations of the followers. Once these dynamics are understood, it is only a small step to superimpose follower oscillations and their effects on the carrier motion to understand the full system. To begin, first consider a perfectly circular cam as in Figure 4-4. A clockwise rotation applied to the sun gear is transmitted by all one way clutches as a counter clockwise rotation on the planet gears. Such a motion will force the follower down onto the cam and because they cannot rotate in this direction (due to the cam reaction force) the carrier will then rotate around the cam. The carrier rotates with a 1:1 ratio to the sun gear.

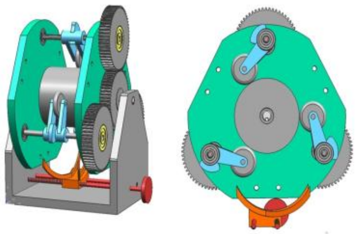


Figure 4-4. Schematic of IVT with round cam. One of the carriers and the base has been removed from the figure on right for clarity.

Now consider a non-circular cam. The operation is nearly the same as above; a clockwise rotation on the sun gear shaft forces one of the followers down onto the cam. Since the follower cannot rotate in this direction, the sun gear rotation causes the carrier to rotate about the cam just as above. Except this time, as the carrier rotates around the cam, the follower will rotate in relation to the carrier as it follows the lobes of the cam. For example, when the follower moves up onto a cam lobe, it and the attached planet gear will rotate in a clockwise direction in relation to the carrier. Here the operation is similar to a planetary gear set, where the rotation of the carrier depends upon both the sun gear and the planet gear rotations. Specifically, the relative clockwise rotation of the planet gears forces them to rotate (or walk) around the sun gear in a clockwise direction. As the planet gears orbit the sun gear they move the carrier along with them, advancing its position with respect to the sun gear. Because the carrier is the output, a non circular cam will create transmission ratios greater than unity. Note that only one follower was considered in the above analysis. This follower, the one under load, is called the active follower. This is because while the active follower is moving up a cam lobe, the second or third followers, called the inactive followers, should be moving down a lobe and will be rotating in a counterclockwise direction with respect to the carrier as a result. A counterclockwise rotation of the attached planet gear will rotate the meshing sun gear further clockwise, in a direction that disengages the one way clutch. (Because the sun gear shaft rotates clockwise, they are installed such that they lock up with a counter clockwise application of torque on the sun gear race.) Therefore as one sun gear transmits torque to the carrier and cam, the second is freewheeling faster in the same direction, but one gear is always engaged with the sun gear shaft.

5.3. Shifting

The shifting capabilities of the Cam-based IVT are particularly unique, especially when compared to those of traction drives. Specifically, many traction drives require large and powerful shifting mechanism to reposition components in relation to one another as they transmit power. For traction drives this can be particularly problematic because of the large normal forces necessary to generate traction. However, as with all ratcheting drives, at least one of the drive components (the follower in the case of the Cam-based IVT) is unloaded for some time. Repositioning these components when unloaded eases the task of shifting. This is a characteristic unique to the Cam-based IVT even amongst other ratcheting drives.

As mentioned before, the cam is made up of an infinite number of profiles along its length; therefore, the cam's cross section continuously changes along its length, as can be seen in Figure 4-6. It changes from a circular shape on one end to an oblong or peanut shape on the other. Shifting the transmission between gears is accomplished by positioning the followers on different profiles along the cams length. This affects the magnitude of the follower’s oscillations and therefore the output of the transmission. This fact can be seen in

Equation, in which the followers' position along the cam determines the pressure angle, α, which thereby determines the torque applied to the carrier and therefore transmission ratio.

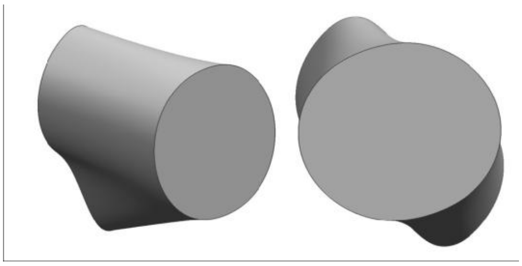


Figure 4-6. Isometric and front view of a 3-D cammoid model installed in the first prototype.

While shifting, to move either the cam or the followers under load, would require the shifter to overcome the high static friction between the roller and the cam. In addition, as a follower moves across the cam, it may also rotate as it moves onto a larger lobe. If this rotation is in the same direction required to activate the indexing clutches, the followers will then be transmitting torque to the output, and therefore part of the shifting load will be required to drive the output.

A unique advantage of a ratcheting drive though, is that the followers are unloaded on a portion of the cam as they rotate in a direction that disengages the one way clutches. This allows them to be repositioned with less force, and therefore, the shifting mechanism must only overcome the friction between the roller and the cam produced by the return spring. As the follower then enters the active profile of the cam, it will produce a different transmission ratio. One such concept for achieving this task can be seen in Figure 4-7. In this design, each follower is built with a guiding tab, and as the carrier rotates the followers through the shifter guides, those guides will drive the follower across the cam to the desired profile. A lead screw is used to reposition the shifter guides to select different profiles. Although this design was never implemented in a prototype, it demonstrates the necessary functionality required of a shifter. A complete description of the shifting mechanism actually implemented on the prototypes is presented in the mechanical design portion of this work.

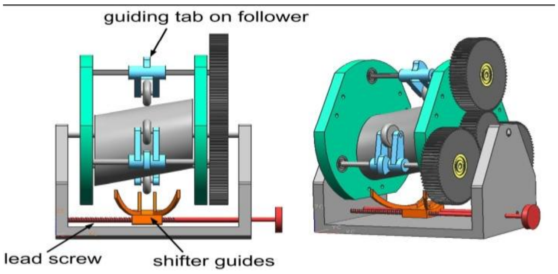



Figure 4-7**.** The front and isometric view of a concept transmission showing the shifting mechanism.

## V. Advantages

Step-less variation of speed: Any speed between Nmax to N min can be obtained. The conventional gives fixed speed ratios, that too in steps. This will help replace the costly electrical variable speed drives conventionally used

Wide range of speeds Ratio: The speed ratio can be varied one a wide range which is not possible in conventional gear box. This will be especially useful in spring making machinery, textile machinery, printing machinery and automatic transfer lines.

Compact size: The size of the gear less variable speed reducer is very compact; which makes it low weight and occupies less space in any drive.

Ease of operation: The changing of speeds is gradual one hence no calculations of speed ratio required for change gearing .Merely by rotating hand wheel speed can be changed.

Singular control: Entire range of speeds is covered by a single hand wheel control

## VI. Applications

Machine tool spindles are required to be driven out various speeds depending upon size of work & material to be cut in such cases the gearless variable speed reducer can be used along with the all geared head stock to give an infinitely variable speed reducer can be used along with the all geared head stock to give an infinitely variable speed conditions.

Machine tool slides can be moved at different speeds to impart feeding motion to the cutting tool using this drive.

Variable speed drive for conveyors in assembly line of automatic assembly plants
Variable speed drives in automatic transfer links & pick & place type robotic devices.
Bottle filling plants.
Indexing mechanism in automats

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