Simulation of cam-based infinitely variable transmission

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Abstract. Infinitely variable transmission (IVT) is a system that gives a continuous (non-discrete) variation that includes zero in transmission ratios between two rotating elements. In this paper, a cam based IVT mechanism was designed and simulated using SolidWorks software containing two identical units. Each unit included a cam with a follower and oscillatory slotted links pivoted at a hinge that could be moved vertically by altering the transmission ratio, achieved by using a hydraulic ram or a power screw. System units also include a grooved wheel and a follower or actuator. During operation, the grooved wheels displayed an oscillating rotational motion, so that they are connected to the output shaft via one-way clutches (ratchets) to give the output shafts one-way directional motion. The cam profiles are designed and investigated within the system with regards to performance. A combination of uniform velocity and 1-5 polynomial profiles where selected and designed for the current study. In general, the results obtained from the simulation showed compatibility with the expected theoretical results derived from the design of the current IVT system. These results indicated uniform velocity during the power stroke in each unit for all parts in the units. However, the ratchets used in this study produced a noticeable fluctuation in the angular velocity of the output shaft, and further work on the selection and development of more efficient ratchets is thus strongly recommended.

Keywords: Infinitely variable transmission, Cam, Ratchet.

1. Introduction

Infinitely variable transmission (IVT) refers to a system which allows for continuous variation (stepless) in transmission ratios between input and output rotating elements. The IVT system differs from a continuously variable transmission (CVT) due to its ability to produce a zero-transmission ratio, however. The feature of continuous variation in transmission ratio gives IVT systems the ability to utilise the most appropriate transmission ratio during operation. In addition, the smoother variation of ratio results in smooth loading on machines that use IVT systems, which may thus be used in automobiles, wind turbines, and any other machines that involve variation in transmission ratio.

For wind turbine applications, Mangialardi and Mantriota (1993) [1] suggested using CVT to respond to changes in air velocity, as a CVT provides a constant speed for the generator regardless of wind speed. Lang (2000) [2] and Bertini (2014) [3] presented analytical studies for the power loss in V-belt CVTs, the most common type of CVT, while Srivastava (2009) [4] made a dynamic model for a control CVT that worked based on the principles of friction developed by using mathematical models. Lee (2004) [5] and Verbelen (2018) [6] manufactured a Full-Toroidal IVT transmission and tested it practically to determine the possibility of using the device in vehicles and similar applications; the
results showed high capacity, although there were also various stresses. Ramanujam (2018) [7] introduced a CVT which did not support the transmission of friction power, unlike conventional transmission. Aliukov et al. (2017) [8] and Aliukov et al. (2018) [9] introduced a CVT-type transmission device, using a mathematical model for comparison, while Benitez and Madrigal (2004) [10] implemented an IVT type model with two planetary gear sets, one-way clutches, and free wheels; they also created a mathematical model to match the theoretical results with the observed operation. Lahr and Hong (2006) [11] presented practical and mathematical models of an IVT transmission device with cams, followers, a planetary gear group, and unidirectional clutches. The results showed that the rotational speed of the output shaft was more stable compared with other types of transmission. Abood (2010) [12] presented a novel cam based IVT system that provided uniform output for uniform input. Finally, Al-Hamood et al. (2018) [13] and Al-Hamood et al. (2020) [14] presented a theoretical study of a cam-based infinitely variable transmission system (IVT). In this study, that IVT system was geometrically designed and modelled using SolidWorks software in order to develop an alternative kinematics analysis for the system. The cam profile was investigated with regard to the desired performance of the system and, accordingly, the linear or angular position, velocity and acceleration are evaluated for all major parts of the system.

2. IVT System.

The IVT system under consideration consisted of two identical units, as shown in Figure 1. Each unit consisted of the following parts:

1. A cam-follower mechanism fixed to the input shaft of the system.
2. An oscillatory slotted link connecting the reciprocating movement from the cam-follower to the groove wheel follower. The slotted link was fixed at a hinge that provided vertical movement by means of a power screw.
3. A grooved wheel-follower mechanism. The grooved wheel is and its follower is considered as cam follower mechanisms with profiles that covered an angular displacement larger than 2π, as seen in Figure 1.
4. A one-way clutch (ratchet) which connected the grooved wheel to the output shaft. The function of this was to ensure that the output shaft rotated only in one direction despite the oscillatory motion of the grooved wheel.

![Figure 1. The IVT system under consideration](image-url)
3. System operation

The operation of the IVT system begins with the rotational velocity of the input shaft. The input rotational motion of the input shaft and the cam is converted to reciprocating linear motion by the follower connected to the cam. This cam-follower motion then turns into oscillatory rotational motion at the slotted link. As shown in figure 1, the slotted link is hinged with a variable position pivot that allows a variable transmission ratio. The position of the hinge can be controlled by a hydraulic ram or a motor connected to a power screw. Linear reciprocating motion is obtained again from the groove follower which is connected to the slotted link on one side and the grooved wheel on the other, allowing the grooved wheel to develop oscillatory rotational motion. The value of angular displacement in the grooved wheel thus depends on the position of the pivot of the slotted link. The oscillatory motion of the grooved wheel is then converted to one-way angular motion in the output shaft via the one-way clutch (ratchet).

The active stroke for each unit is represented by the cam outward stroke as explained above; however, in order to complete the cycle for each unit, a return stroke must be achieved using a rotational spring fitted to the slotted link. The main function of this spring is to maintain contact between the cam and its follower. To change the transmission ratio in the IVT system, a power screw was used to change the position of the pivot of the slotted link, offering a range of output angular speeds for specific values of input angular velocity. Theoretically, this system provides a zero-transmission ratio within its continuous range, allowing it to be classified as an infinitely variable transmission system.

4. IVT system simulation

In this work, SolidWorks software version 2018 was used to simulate the IVT system, allowing kinematic analysis for all parts of the IVT system. The linear and rotational displacement, velocity, and acceleration were thus determined after the geometrical design of all parts in the system was carried out during simulation. The selection and design of the cam profile and the grooved wheel profile played important roles in the development of this study. SolidWorks was used in the analysis and simulation in this study due to its potential in the field of 3D drawing and simulation to facilitate simultaneous work (Wang, Li, and Zhu 2017) [15]. The program is also used by more than a million engineers globally, and several international universities rely on it in their work.

It is essential for any transmission system to provide uniform output angular speed for uniform input. The cam was therefore designed to give constant speed during the active stroke of each unit. However, for the return stroke, it is not practical to use a uniform speed profile due to the problem of sharp edges, which could lead to an infinite value of acceleration. More practically, this mean that very large values of contact forces are generated in the contact region between the cam and the follower. To deal with this, a fifth order polynomial function was selected for the cam profile as shown in figure 2. The constant velocity profile thus covers the angle (0-π) and the polynomial curve for angle (π-2π).
The theoretical displacement, velocity, and acceleration equations for a knife-edge follower connected to the cam shown in figure 2 along one revolution are listed in table 1.

**Table 1.** Theoretical kinematic equations representing the motion of a knife-edge follower connected to the cam used in the study, with $H$ as the follower stroke.

| Angle of cam rotation ($\theta$) | Displacement | Velocity | Acceleration |
|---------------------------------|--------------|----------|--------------|
| [0- $\pi$]                     | $\frac{\theta}{\pi}$ | $\frac{H}{\pi}$ | 0 |
| [\pi-2\pi]                     | $H - H \left[ -\frac{\theta - \pi}{\pi} + 20 \left( \frac{\theta - \pi}{\pi} \right)^3 - 30 \left( \frac{\theta - \pi}{\pi} \right)^4 + 12 \left( \frac{\theta - \pi}{\pi} \right)^5 \right]$ | $H \left[ (1 - 60 \left( \frac{\theta - \pi}{\pi} \right)^2 \right] + 120 \left( \frac{\theta - \pi}{\pi} \right)^3 - 60 \left( \frac{\theta - \pi}{\pi} \right)^4$ | $H \left( \frac{\theta - \pi}{\pi} \right) \left[ -120 + 360 \left( \frac{\theta - \pi}{\pi} \right) - 240 \left( \frac{\theta - \pi}{\pi} \right)^2 \right]$ |

The grooved wheel used in the simulation is shown in figure 3. This wheel acts as a cam with the capacity to produce a curve over a range larger than $2\pi$ with a uniform velocity profile similar to that used in the cam. The profile shown covers a range of $8\pi$, allowing the introduction of large values of transmission ratios.
5. Results

The results presented below were obtained using kinematic simulation of the IVT system as modelled using SolidWorks software as described previously.

Figure 4 shows the linear displacement, velocity, and acceleration of the cam-follower with a rotational speed of 500 rpm on the input shaft. Figure 4a, which shows the displacement versus time, indicates a relatively smooth and continuous curve along more than one cycle, including the connection between two types of profiles as described in table 2.

Figure 4b shows the linear velocity of the follower; in this figure, the two parts of the cam profile (uniform speed and the polynomial form) can be seen clearly. The active stroke is represented by the uniform speed stroke; the negative value shown in the figure for this stroke is due to the axis used in the SolidWorks model, which emphasises the importance of having two units for each system, as during the return stroke for the unit, the other unit should work at constant uniform speed.

Figure 4c shows the linear acceleration of the cam follower; this curve thus represents the time derivative of the velocity profile shown in figure 4b. The zero value represents the uniform velocity profile, and the curve is smooth and no sudden changes.

Figure 3. The grooved wheel.
Figure 4. Displacement, velocity, and acceleration of the cam follower.
Figure 5 shows the velocity of both followers of the both units together, highlighting that, throughout the operation, the units’ actions create a uniform speed stroke (at approximately -0.5 mm/s) that acts as the active stroke as the other follower does its return stroke.

Figure 5. Linear velocity of the cam followers for both units

Figure 6 shows the angular velocity of the slotted links of both units, highlighting that there is no uniform speed portion over the cycles shown. This is due to changes in angle in the slotted link during operation.

Figure 6. Angular velocity of slotted links of both units.
Figure 7 shows the linear velocity of the two grooved wheel followers. This figure is similar to figure 4, but with reversed values, as the grooved wheel followers move in the opposite direction to the cam followers. The mirroring is relatively accurate, as the pivot of the slotted link for this study was fixed at the middle of the allowable vertical position.

**Figure 7.** Linear velocity of the two grooved wheel followers.

Figure 8 shows the angular velocity of both grooved wheels during system operation, showing that the system produces uniform output angular velocity for uniform input. In this figure, the angular velocity of each wheel oscillates between opposing directions, which supports the use of ratchets to connect the grooved wheel to the output shaft, as this permits only the uniform speed to be transferred to the output shafts.

**Figure 8.** Angular velocity of grooved wheels during system operation.
Figure 9 shows the output angular velocity of the output shaft based on connecting the grooved wheels to the shaft using ratchets. The figure shows that the output angular velocity is almost uniform, with very small values of fluctuation at the end of each uniform speed period. This behaviour may have resulted from the particular type of ratchet used in this study, and further work should thus be done to investigate improving or replacing this with another type of ratchet that is more suitable.

6. Conclusions.

The main goal of the current study was to model and simulate the kinematics of a cam based on a ratchetting type infinitely variable transmission system. This model was thus built and run in SolidWorks Software version 2018.

The results showed that the system kinematics can be modelled and simulated efficiently in SolidWorks software, and that the type and features of the cam profile are the critical factors affecting the design success of these IVT systems. The simulation results further indicated that a combination of uniform velocity profile and a fifth order polynomial profile gives smooth and continuous trends for displacement, velocity, and acceleration for the cam-follower, allowing the other parts of the IVT system to have similar trends during operation.

The results of this study thus support the idea that, in these types of systems, two identical units working on opposing frequencies produce efficient system operation. In this study, the units were oriented without any overlap in the working stroke; future research regarding overlap might thus offer interesting results.

Another major finding related to the design of the grooved wheel profile. The simulation showed that, to obtain uniform output angular velocity for uniform input, a uniform velocity profile should be applied. Additionally, the value of the total angle covered by the groove profile affects the largest transmission ratio that system can produce.
Finally, this study determined that the ratchets selected for the modelled IVT system produced a noticeable fluctuation in the output angular velocity. Further research to effect the selection and operation of more efficient ratchets is thus strongly recommended.

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