IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

The Performance of One-Way Clutch in a Cam-Based Infinitely Variable Transmission

To cite this article: Amjad Al-Hamood *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **671** 012008

IOP Conf. Series: Materials Science and Engineering **671** (2020) 012008 doi:10.1088/1757-899X/671/1/012008

The Performance of One-Way Clutch in a Cam-Based Infinitely Variable Transmission

Amjad Al-Hamood[1], Hazim U. Jamali[1], Oday I. Abdullah[2 3], J Schlattmann[3]

1- Mechanical Engineering Department, University of Kerbala, Kerbala, Iraq
2- Energy Engineering Department, University of Baghdad, Baghdad, Iraq
3- Hamburg University of Technology, Hamburg, Germany

ABSTRACT. Continuously variable transmission is the system which provides a step-less change in transmission ratio between two rotating shafts. When it can provide zero ratio, it is known as infinitely variable transmission (IVT). These systems are mainly classified into two categories; traction and non-traction types. In the traction type, the power is transmitted by friction force that develops between the active elements in the mechanism, while in the non-traction systems, the power is transmitted via direct contact. A very common type of non-traction IVT is the cam-based system. In this type, the rotating motion of the input element is converted to oscillatory motion with continuously variable amplitude. Eventually, the oscillatory motion is rectified to one-way rotational motion by means of a one-way clutch (rectifier). The rectifier is considered an essential element in the IVT system, as it is subjected to an extreme dynamical condition. In this study, the performance of one-way clutches (rectifiers) in a cam-based IVT is presented. The IVT system under consideration is a combination of two identical units and in each one, a rectifier is fitted at the output shaft. It is required that this rectifier is able to efficiently transmit the power during its engagement. It should also generate minimal power loss during disengagements, when aggressive relative motion is presented between its parts. It has been found that the operation of the one-way clutch is mainly determined by the designed cam profile. For this study, the profile is a combination of constant speed and trapezoidal forms. It was also concluded that the value of the selected transmission ratio controls the amount of fluctuation in the acceleration, velocity and displacement and hence, the energy lost due to slippage of the clutches.

Keywords: Continuously Variable, Transmission, One-way Clutch, Cam-Based

1. Introduction

Infinitely variable transmission (IVT) is the system which allows for continuous change (step-less) in speed ratio between two rotating elements. In IVT systems, the range of speed ratio includes zero value, when this is not the case, the system is called a continuously variable transmission (CVT), which is more common than the IVT. The importance of these systems is to provide the required speed ratio precisely, for application through large variety of conditions. In addition, they allow for smooth load changes that are applied to the mechanical elements within the machine, which serves to extend their life. Furthermore, applying these systems in some applications, for example in automotive, may contribute greatly to user comfort. Because of these advantages, the CVT and IVT systems are ideal for use instead of the traditional transmissions in transportation vehicles. Moreover, these new transmissions can also be integrated inside wind power electric generator systems [1]. This can help in maintaining the constant rotational speed of the electric generator part for variable speed wind turbines that depend on wind speed.

There are two main categories of the CVT; traction and non-traction, depending whether traction force is used in power transmission or not. The V-belt CVT is the most common traction type, where a V-belt is used to connect two pulleys on each of the movable sheaves [2-4]. A review on this type CVT can be seen in [5]. Toroidal transmission [6-8] is another traction CVT type, where the power is transmitted between two contacting surfaces by means of friction force or viscous fluid shearing strength. As these systems rely on traction force in their power transmission main, this is considered as one of their main limitations.

In the non-traction CVT, the power is transmitted by direct contact between the contacted surfaces: the mechanisms in [9, 10] are examples of this type. In general, the non-traction CVT include a ratchet or one-way clutches in their combination. Benities et al [11, 12] developed a ratcheting IVT which includes a number of one-way clutches and two epicyclical gear train. A non-traction IVT system using one-way clutches (ratchet) was introduced in [13]. This system contains number of identical units where each unit is based on a three-dimensional cam and follower mechanism. In general, ratchets (one-way clutches) are the weakest links in the ratcheting IVT systems. Morales and Benitez [14] proposed several rectifying designs in their study. Analytical and numerical studies were applied in order to determine the most applicable design.

This paper presents an investigation of the motion and performance of one-way clutches used in a cam-based ratcheting type IVT [15]. This investigation studies the kinematics of the clutches installed at the IVT, and this will add to knowledge of the clutch features that are compatible with such applications.

2. Operation of the IVT System

The components and configuration of the IVT system under consideration is shown in Figure 1. As can be seen in this figure that the main components of the system are two cams, with their followers fitted to the input shaft, two slotted links, and two grooved wheels fitted to the output shaft by means of one way-clutches.

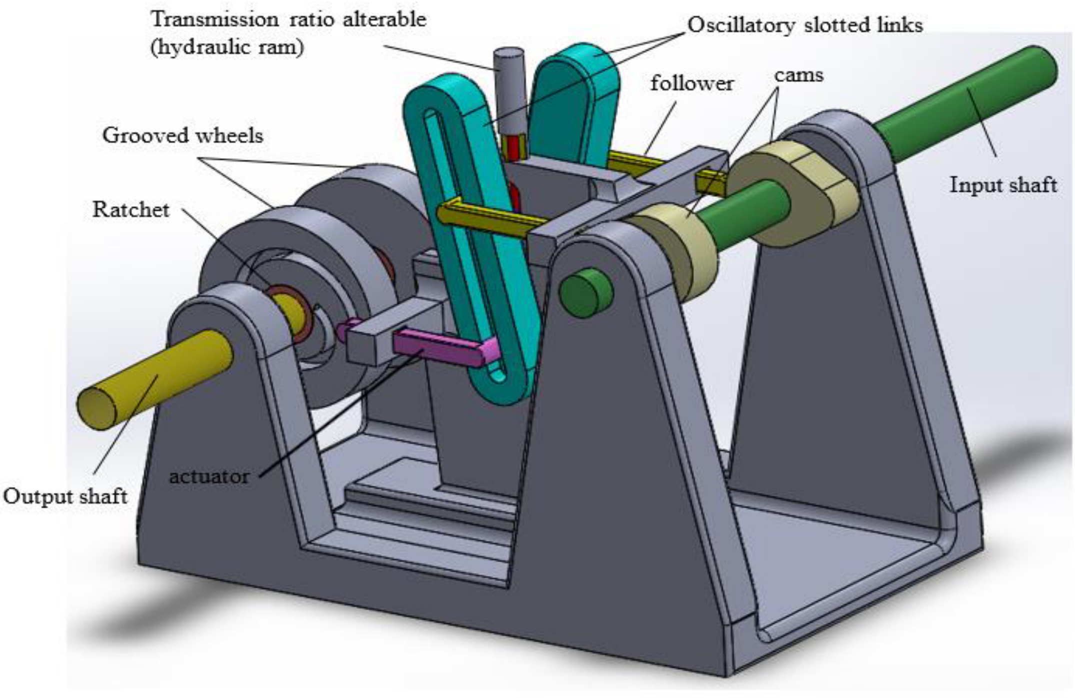

Figure 1: The infinitely variable transmission system under consideration [15].

The rotary motion of the input shaft is converted to reciprocating motion of the followers of both cams that fitted to the input shaft. This reciprocating motion makes the slotted links oscillate about their center of rotation, with continuously variable amplitude depending on the position of that center. At the other end of the slotted links, the grooved wheel actuators are connected and hence they reciprocate with amplitude that is independent of the amplitude of the cam followers.
These reciprocating motion (of the actuators) actuate the grooved wheel to move with two-way rotational motion (oscillatory). In order to achieve one-way rotation for the output shaft, the grooved wheels are connected to it, by means of one-way clutches. These clutches connect the wheels with the output shaft for one direction of motion and allow for relative rotational motion between them at the other direction.

There many types of one-way clutch, but they all provide the feature of connecting in one direction and disconnecting in the other direction. The type of clutch selected depends on the dynamics and performance of the system that the clutches are intended to be used in. The next sections provide an insight on the dynamics of the one-way clutches that are used in the cam based IVT described previously.

3. Kinematics of the IVT

In this section, a brief description on the kinematics of the whole IVT system is presented, which leads to the dynamics of the one-way clutches, which is the aim of this work.

The schematic diagram shown in Figure 2 illustrates the motion of a single unit in the infinitely variable transmission (IVT).

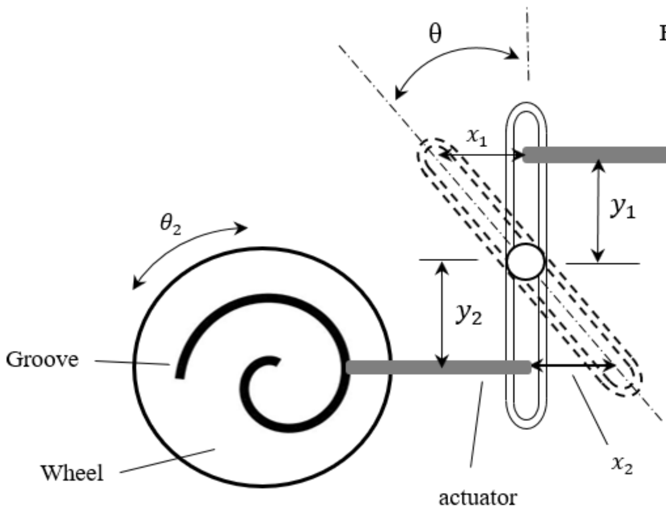

Figure (2): motion of a single unit in the IVT system.

This system is designed to deliver a uniform output angular velocity for uniform input, so that the relation between cam angle of rotation, θ_1 and the follower displacement, x_1 can be written as:

$$x_1 = c_1\theta_1 \qquad (1)$$

Where $c_1$is constant of proportionality for the cam.

In the same way and similar designation, the relation between wheel angle of rotation, θ_2 and the actuator displacement, x_2 is written as: the relation between groove profile and the actuator is written as follows:

$$x_2 = c_2\theta_2 \qquad (2)$$

Where c_2 is a constant of proportionality for the wheel.

It is known that the velocity and acceleration are obtained by first and second derivative of the displacement relation with respect to time, respectively. So that, the velocity of the cam profile is equal to c_1 and the acceleration is zero. If uniform speed profile is used for out and return stroke of the cam profile, the displacement, velocity and acceleration of the cam follower for one revolution can be seen in Figure 3.

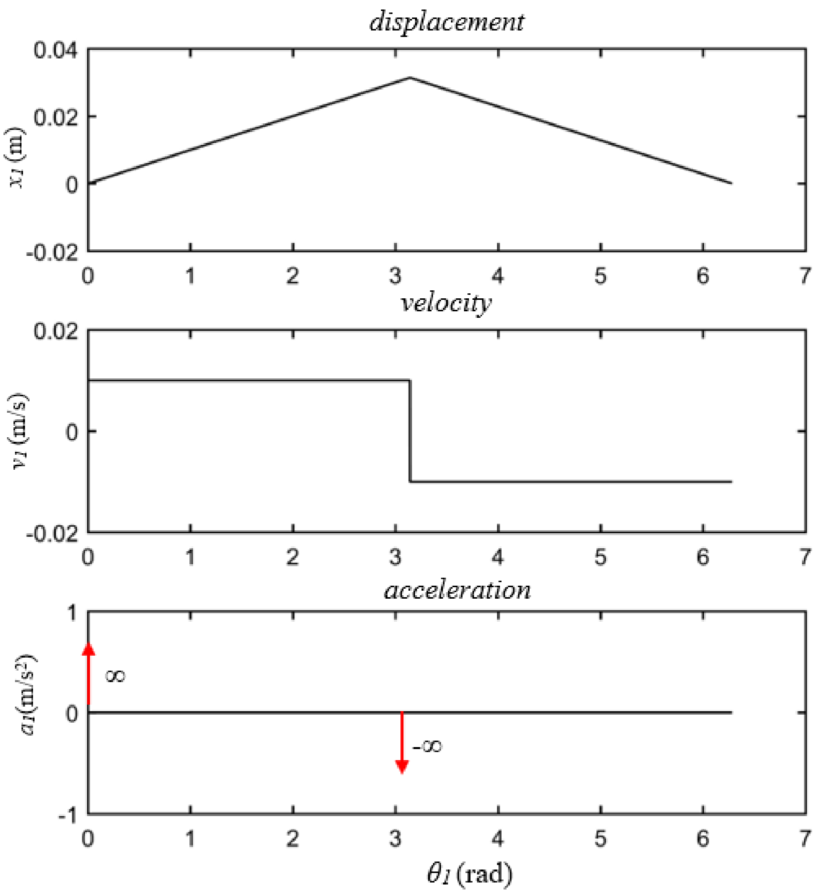

Figure 3. Displacement, velocity, and acceleration of uniform speed cam for one revolution ($c_1=0.01$).

Table 1: Follower displacement, velocity, and acceleration through one cam revolution.

$\boldsymbol{\theta_1}$	**Displacement**	**Velocity**	**Acceleration**
$[0, \pi]$	$c_1\theta_1$	c_1	0
$[\pi, (9/8)\pi]$	$\frac{-4A}{3\pi}\theta_1^3 + 4A\theta_1^2 + (-4A\pi + c_1)\theta_1 + \frac{4}{3}A\pi^2$	$\frac{-4A}{\pi}\theta_1^2 + 8A\theta_1 - 4A\pi + c_1$	$\frac{-8A}{\pi}(\theta_1 - \pi)$
$[(9/8)\pi, (11/8)\pi]$	$-\frac{A}{2}\theta_1^2 + (\frac{17}{16}A\pi + c_1)\theta_1 - 0.56A\pi^2$	$-A\theta_1 + \frac{17}{16}A\pi + c_1$	$-A$
$[(11/8)\pi, (13/8)\pi]$	$\frac{4A}{3\pi}\theta_1^3 - 6A\theta_1^2 + \left(\frac{69}{8}A\pi + c_1\right)\theta_1 - 4A\pi^2$	$\frac{4A}{\pi}\theta_1^2 - 12A\theta_1 + \frac{69}{8}A\pi + c_1$	$\frac{8A}{\pi}\theta_1 - 12A$
$[(13/8)\pi, (15/8)\pi]$	$\frac{A}{2}\theta_1^2 - \left(\frac{31}{16}A\pi - c_1\right)\theta_1 + 1.69A\pi^2$	$A\theta_1 - \frac{31}{16}A\pi + c_1$	A
$[(15/8)\pi, 2\pi]$	$\frac{-4A}{3\pi}\theta_1^3 + 8A\theta_1^2 - (16A\pi - c_1)\theta_1 + \frac{32}{3}A\pi^2 - 2\pi c_1$	$\frac{-4A}{\pi}\theta_1^2 + 16A\theta_1 - 16A\pi + c_1$	$\frac{-8A}{\pi}(\theta_1 - 2\pi)$

It can be noted from Figure 3 that the acceleration moves toward $+\infty$ and $-\infty$ when θ_1 equal to zero and π respectively, because of the step change of velocity for these positions. The infinite value of acceleration needs an infinite value of force to be applied throughout the whole mechanism, especially at the contact regions. Accordingly, this will increase the chance of damage of these regions. For solving this issue, a combination of uniform speed and trapezoidal profile is designed for the cam outstroke and return-stroke respectively. The follower displacement, velocity and acceleration relations for one revolution of the cam is shown in table (1) and are depicted in Figure 4.

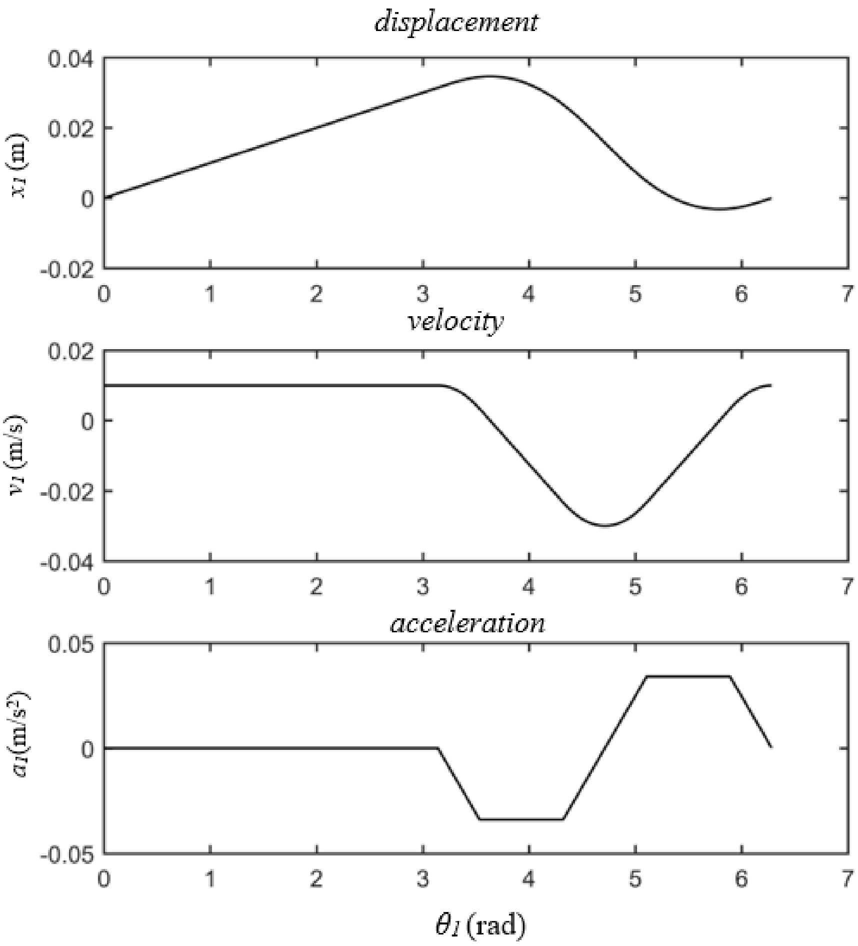

Figure 4. Displacement, velocity, and acceleration for a combination of uniform speed and trapezoidal cam profile.

4. One-Way Clutch Kinematics

As described previously, the grooved wheels are mounted on the output shaft via one-way clutches, so that the function of these clutches is related to the motion of the wheels and the output shaft. The wheels' motion is of two-way oscillation with different amplitude depending on the selected value of transmission ratio. Unlike the cam, the groove profile is designed to have a uniform speed profile only, as it may have variable amplitude of angular displacement for different transmission ratio. Accordingly, for particular transmission ratios, the angular displacement, θ_2 , velocity, ω_2 , and acceleration, α_2 , of the one-way clutches can be written as follows:

$$\theta_2 = \frac{1}{c_2}\frac{y_2}{y_1}x_1 \qquad (3)$$

$$\omega_2 = \frac{1}{c_2}\frac{y_2}{y_1}v_1 \qquad (4)$$

$$\alpha_2 = \frac{1}{c_2}\frac{y_2}{y_1}a_1 \qquad (5)$$

Where:

x_1, v_1, a_1 are the linear displacement, velocity and acceleration of the cam follower detailed in table (1).

y_1 and y_2 are the displacement of the follower and actuator from the slotted link pivot, respectively.

Figure 5 shows the angular displacement of the wheel versus the cam angle of rotation for a range of y_2/y_1. It can be noted that when this ratio is equal to zero, the groove wheel is stationary while the input shaft is rotating. As y_2/y_1 is increased, the amplitude of the angular displacement is also increased including minus values. These values imply that the wheel moves in reverse direction than the input and output shaft and it represents the slippage stroke of the one-way clutch.

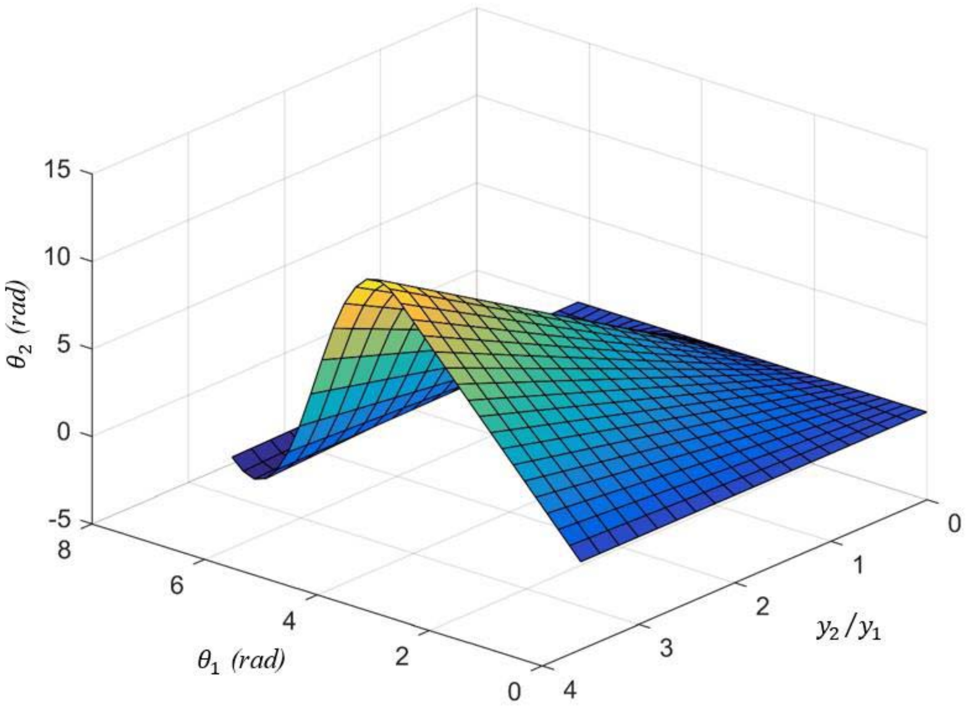

Figure 5. The angular displacement of the grooved wheel versus the input shaft angular position and a range of y_2/y_1

Figure 6 shows the wheel angular velocity for a range of y_2/y_1 through one revolution of the input shaft. When y_2/y_1 is zero, the velocity of the wheel is also equal to zero, which means that it is stationary, where that is compatible with the behavior depicted in Figure 5. The amplitude of the angular velocity is increased when y_2/y_1 is increased. For the particular value of this ratio, the velocity is constant for $0 \leq \theta_1 \leq \pi$. For the rest of the revolution, the velocity varies according to the relation mentioned in Table 1 that includes minus value representing the reverse direction of the wheel.

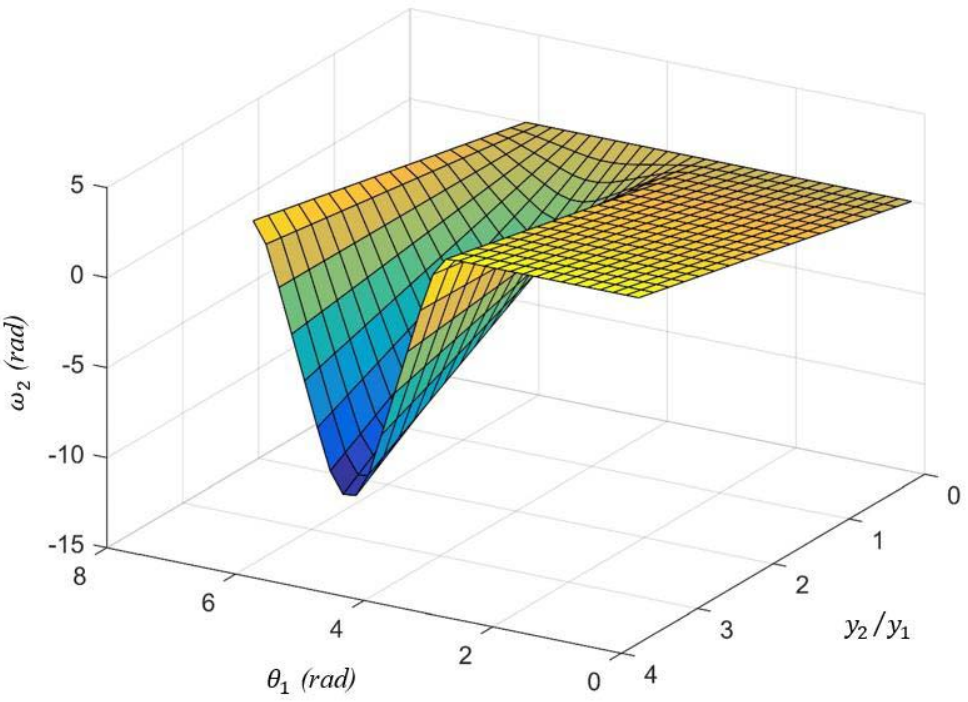

Figure 6. The angular velocity of the grooved wheel versus the input shaft angular position and a range of y_2/y_1

Figure 7 shows the angular acceleration of the grooved wheels for a range of y_2/y_1 and a revolution of the input shaft. Similar to Figures 5 and 6, Figure 7 implies that the wheel is stationary when y_2/y_1 equal to zero. The acceleration continues to have zero value for the range $0 \leq \theta_1 \leq \pi$ even when y_2/y_1 increased. On the other hand, when $\pi \leq \theta_1 \leq 2\pi$, the angular acceleration fluctuates with trapezoidal form which its amplitude is increased when y_2/y_1 increased.

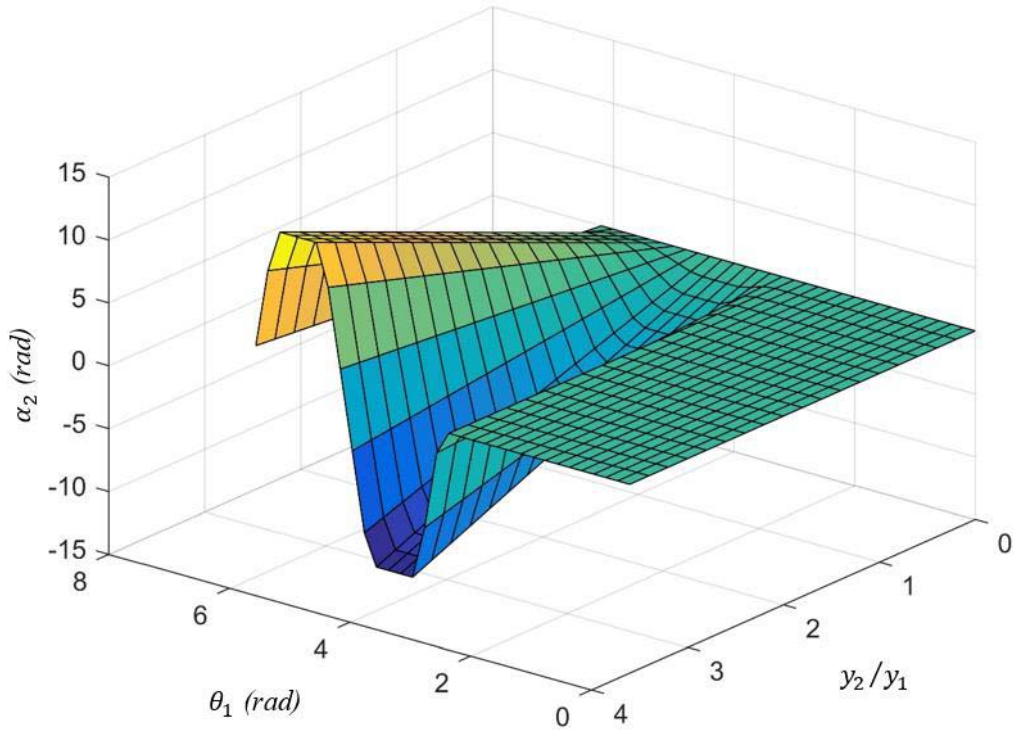

Figure 7. The angular acceleration of the grooved wheel versus the input shaft angular position and a range of y_2/y_1

5. Conclusions

This work focused on the kinematic analysis of the one-way clutches that are used in a cam-based infinitely variable transmission. The kinematics of the whole IVT led to the fact that for achieving uniform output angular velocity and acceleration for uniform input, the cam profile should be designed of a constant velocity type for cam outstroke and similar to this, is designed for the groove profile of the wheels. It was also concluded that to avoid infinite values of forces through the system elements and at the contact regions, a trapezoidal profile is designed for the return stroke of the cams.

The one-way clutches are used to engage the grooved wheels with the output shaft during one direction of rotation, and disengage them in the other direction. This process is applied periodically for the two wheels, keeping at least one engaged wheel throughout the time of operation. During disengagement, the one-way clutches' outer and inner races are slipped to each other. The relative angular displacement, velocity, and acceleration between the two races of each clutch depend on the features of the cam return stroke and on the selected transmission ratio of the IVT system.

At zero transmission ratio, the wheels and the output shaft are stationary. For non-zero transmission ratio, the clutches' slippage is developed with trapezoidal angular acceleration form and its corresponding angular velocity and displacement (during the cam return stroke only). The value of fluctuation of the acceleration, velocity and displacement are increased as the transmission ratio is increased. For the case studied in this research, when the ratio y_2/y_1 is equal to 3, the amplitude of the slippage angular displacement is reached about 11.3 *rad* while the total fluctuation of the angular acceleration is about ±10.2 rad/s^2. This means more friction losses within the clutches as a result of larger slippage angular displacement. It can be also concluded that for high relative angular acceleration, a higher amount of movement is required to return the wheel during the return stroke.

References

[1] Petković, D., Ćojbašić, Ž., Nikolić, V., Shamshirband, S., Kiah, M., Anuar, N., Abdul Wahab, A., 2014, Adaptive neuro-fuzzy maximal power extraction of wind turbine with continuously variable transmission, *Energy*, 64, pp. 868-874,

[2] Miyazawa, T., Fugii, T., Nonaka, K., and Takahashi, M., 1999, Power Transmitting Mechanism of Dry Hybride V-Belt for CVT-Advanced Numerical Model Considering Block Tilting Pulley Deformation paper No.1999-01-0751, *Transmission and Driveline System Symposium*, SAE, sp-1440, pp.143-153.

[3] Abo, K., Kobayshi, M., and Kurosawa, M., 1998, Development of a Metal Belt Drive CVT Incorporating a Torque Converter for Use 2-liter Class Engines, paper No.980823, *Transmission and Driveline System Symposium*, SAE, sp-1324, pp.41-48.

[4] Julió, G.Plante, J. S. 2011, An experimentally-validated model of rubber-belt CVT mechanics, *Journal of Mechanism and Machine Theory*, 46, (8), pp.1037-1053.

[5] Srivastava, N.,Haque, L., 2009, A review on belt and chain continuously variable transmissions (CVT): Dynamics and control, *Journal of Mechanism and Machine Theory*, 44, (1), pp.19-41.

[6] Lee,A. P., and Newall, J. P., 2004, Durability of a Compact Dual-Cavity Full-Toroidal IVT Variator SAE 01-0353.

[7] Tanaka, H., and Machida, H., 1996, Half-Toroidal Traction-Drive Continuously Variable Power Transmission, *Proc. Instn. Mech. Engrs*., vol.210.

[8] Verbelen, F., Derammelaere, S., Sergeant, P., Stockman, K., 2009, A comparison of the full and half toroidal continuously variable transmissions in terms of dynamics of ratio variation and efficiency, *Journal of Mechanism and Machine Theory*, 121, pp. 299-316.

[9] Nakagawa,M. (2017). *United State Patent No. US 2017/00029002*A1"Continuously variable transmission system"

[10] Rajendran, R. R. (2018). *United State Patent No. US 2018/0209523 A1*"Continuously variable transmission with uniform input-to-output ratio that is non-dependent on friction".

[11] Benitez, F. G., Madrigal, J. M., del Castillo, J. M., 2004, Infinitely Variable Transmission of Ratcheting Drive Type Based on One- way Clutches, *Journal of Mechanical Design*, **126**, pp.673-682.

[12] Benitez, F. G., Gutierrez, J., Campillo, G., Madronal, P., 2002, Variable Continuous Transmission System, US Patent 6,371,881.

[13] Abood, A., 2010, A Novel Cam-Based Infinitely Variable Transmission, *Journal of Kerbala University*, 8, (4), pp. 61-74.

[14] Morales, F. and Benitez, F., 2014, Basic Conceptual Designs for Rectifiers of Inertial Transmissions, SAE Technical Paper 2014-01-1737, https://doi.org/10.4271/2014-01-1737.

[15] Al-Hamood, A., Jamali, H., Imran, A., Kaleli, H., Senatore, A., Modelling and Theoretical Analysis of a Novel Ratcheting Type Cam Based Infinitely Variable Transmission System, [under review].