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Influence Of Kinematic Parameters on Wear Reduction in Cam-Follower System

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Abstract: Cam-follower mechanisms are often used in mechanical systems to change rotary motion into reciprocal motion. Nevertheless, wear at the cam-follower interface has a large influence on performance, accuracy, and lifetime. In this research, the impact of kinematic parameters: displacement, velocity, acceleration and jerk on wear in cam-follower systems are examined. Mathematical models for different types of motion are created and their kinematic behaviour is analysed mathematically such as uniform velocity, simple harmonic motion (SHM), cycloidal motion etc. This study relates these parameters with wear based on a theoretical model of the interaction forces and motion sliding. The findings prove that profiles featuring gentler transitions and at lower values of jerk are favourable in reducing impact forces along with wear. As a result of data analyses, the cycloidal motion has been determined to be best among all analysed profiles due to its smooth acceleration and almost jerk-free characteristics. The study highlights the importance of kinematic optimization in improving durability and reliability of cam-follower systems.

Introduction

Cam-follower mechanisms have found use in many applications including but not limited to, mechanical systems that convert rotary motion into reciprocating motion such as internal combustion engines and automated machinery. Cam-follower wear, caused mainly by repeated contact stresses and sliding motion, leads to significant degradation of performance and reliability in these systems.

Kinematic parameters which influence wear in cam-follower systems are displacement, velocity, acceleration and jerk. Sudden variations in these parameters creates dynamic force and impact load, result in more surface damage and less endurance. Although the wear induced by contact kinematics can be reduced with lubrication and proper material selection, it cannot be entirely avoided.

Hence, it is used to obtain a smooth motion by minimizing the wear; thus, kinematic designing of cam profile has to be optimized. Here different motion laws, namely uniform velocity, simple harmonic motion and cycloidal motion are analysed in order to study their impact on both kinematic behaviour and wear. It seeks to find the motion profiles with reduced dynamic effects and increased durability of cam-follower systems.

Literature Review

Wear in cam-follower systems has been extensively studied due to its significant impact on performance, efficiency, and durability of mechanical systems. Researchers have analysed the problem using theoretical, numerical, and experimental approaches, focusing on the role of kinematic parameters, contact stresses, and lubrication conditions.

The modelling work done by Zhang et al. (2006) on the cam wear in diesel engine valve trains makes use of a multi-body dynamic analysis coupled to an elastohydrodynamic lubrication (EHL) model. They study found that cam-follower contacts are operating on high loads and mixed lubrication conditions so any wear was unavoidable. Kinematic parameters (velocity and acceleration) have a significant effect on oil film thickness and contact pressure, as demonstrated by the results. Adhesive wear was significantly reduced, and system reliability enhanced with smoother motion profiles.

Patel and Desai (2010) did FEA to analyse the stress distribution in a cam-follower system for different cam profiles. Anyone who has used a camshaft for any reasonable length of time knows that the shape of the cam can have quite an effect on how much wear it experiences, as opposed to gradual changes in geometry which give rise to localized stress concentrators. On the other hand, optimized cam profiles allow for more even stress distribution while minimizing wear. The research highlighted the significance of not only material and lubrication design, but also kinematic design.

Kumar et al. (2012) applied a simple Archard wear model modified to predict adhesive wear in pairs of cam-follower. In their study, they demonstrated that wear was linearly dependent on contact load and distance slid, but inversely proportional to the hardness of the material. They also emphasized that the variation of sliding velocity, which is controlled by kinematic motion, are key factors for wear development. Theoretical background for relating kinematic parameters with wear behaviour was provided by this work.

This is an experimental investigation on the cam-follower systems used in the valve-trains of vehicles which was carried out by Singh and Rao (2014). In a test rig, they measured the wear rate for different working conditions and motion laws. The outcome showed that cycloidal and polynomial motion laws showed less wear as compared to the simple harmonic motion. It was concluded that cycloidal and polynomial motion rules result less wear due to smooth acceleration and jerk resulting less impact load.

Lee et al. (2015) analysed the dynamic behaviour of cam follower system by finite element modelling. They said that the high dynamic loads from sudden changes in acceleration and jerk lead to a great wear and surface fatigue. In this analysis, it is shown that impacts with high jerk accelerate surface degradation and suggests that smooth kinematics transitions must be imposed.

Gupta and Sharma (2016) formulated optimization method for the design of cam profile with polynomial motion laws. They indicated that an optimized cam profile minimize vibration, balance load distribution, extend service life and supply practical information toward the design of wear-resistant cam mechanism by controlling parameters.

Wang et al (2017) examined lubrication behaviour of cam-follower system with elastohydrodynamic lubrication theory. They pointed out oil film thickness varies drastically with sliding velocity and contact condition, which in turn is related to the kinematic parameters. Better lubrication occurs when smoother motion is achieved, resulting in lower boundary contact and wear.

Reddy et al (2018) experimented to confirm wear prediction models of cam-follower system. Experimental results demonstrated that wear development is highly associated with the kinematic behaviour and operational conditions. The wear was drastically decreased when cam profile is optimized, which agreed with the result based on theory and simulation.

For the jerk in cam-follower mechanism, Chen and Li (2019) studied its impact and they found that jerk contributes to instantaneous change in acceleration. Such jerk causes impacts and greater surface wear, therefore decreasing the jerk would enhance the life-span of cam-follower mechanism.

From the above studies, it is evident that wear in cam-follower systems is strongly influenced by kinematic parameters, particularly velocity, acceleration, and jerk.

Research Gap

Most existing studies on cam-follower systems focus on material properties, lubrication, and stress analysis, while limited attention has been given to a comparative study of different kinematic motion laws. In particular, the influence of parameters such as velocity, acceleration, and especially jerk on wear behaviour is not analysed in an integrated manner. Therefore, a systematic evaluation of motion laws like uniform velocity, simple harmonic motion, and cycloidal motion is required to identify optimal conditions for minimizing wear.

Methodology

This study describes the investigation of the kinematic variables effect on cam-follower wear, using theoretical and simulation methods. First the literature related is explored and the various issues affecting wear and the function of different motion laws were found out. Then the mathematical expressions describing the expressions for displacement, velocity, acceleration and jerk of constant velocity, Simple Harmonic motion and cycloidal motion are developed mathematically. Then preliminary simulations were conducted to produce kinematic diagrams and compare them. The outcomes of the simulations are analysed to check for smoothness of motion and for dynamic forces experienced. Lastly the dependence of kinematic variables on wear were inferred from theoretical wear aspects and appropriate cam profile are determined.

Kinematic analysis

Assumptions:

Let:

- h= lift of follower
- β= cam angle for rise (in radians)
- θ= cam rotation angle
- ω= angular velocity of cam

1. Uniform Velocity Motion

- Displacement

In uniform velocity motion, the follower moves with constant velocity:

$$y = \frac{h}{\beta}\theta$$

- Velocity

$$v = \frac{dy}{dt} = \frac{h}{\beta} \cdot \omega$$

(Constant velocity)

- Acceleration

$$a = \frac{dv}{dt} = 0$$

- Jerk

$$j = \frac{da}{dt} = 0$$

2. Simple Harmonic Motion (SHM)

- Displacement

$$y = \frac{h}{2}\left(1 - cos\left(\frac{\pi\theta}{\beta}\right)\right)$$

- Velocity

$$v = \frac{dy}{dt} = \frac{h\pi\omega}{2\beta} sin\left(\frac{\pi\theta}{\beta}\right)$$

- Acceleration

$$a = \frac{h\pi^2\omega^2}{2\beta^2} cos\left(\frac{\pi\theta}{\beta}\right)$$

- Jerk

$$j = -\frac{h\pi^3\omega^3}{2\beta^3} sin\left(\frac{\pi\theta}{\beta}\right)$$

3. Cycloidal Motion

- Displacement

$$y = h\left(\frac{\theta}{\beta} - \frac{1}{2\pi} sin\left(\frac{2\pi\theta}{\beta}\right)\right)$$

- Velocity

$$v = \frac{dy}{dt} = \frac{h\omega}{\beta}\left(1 - cos\left(\frac{2\pi\theta}{\beta}\right)\right)$$

- Acceleration

$$a = \frac{2\pi h\omega^2}{\beta^2} sin\left(\frac{2\pi\theta}{\beta}\right)$$

- Jerk

$$j = \frac{4\pi^2 h\omega^3}{\beta^3} cos\left(\frac{2\pi\theta}{\beta}\right)$$

Motion Type	**Velocity**	**Acceleration**	**Jerk**	**Wear Effect**
Uniform Velocity	Constant	Zero (but sudden change)	Infinite at ends	High
SHM	Gradually changes	Finite	Moderate	Medium
Cycloidal	Gradually changes	Gradually changes	Minimum	Low

Table 1: Comparison

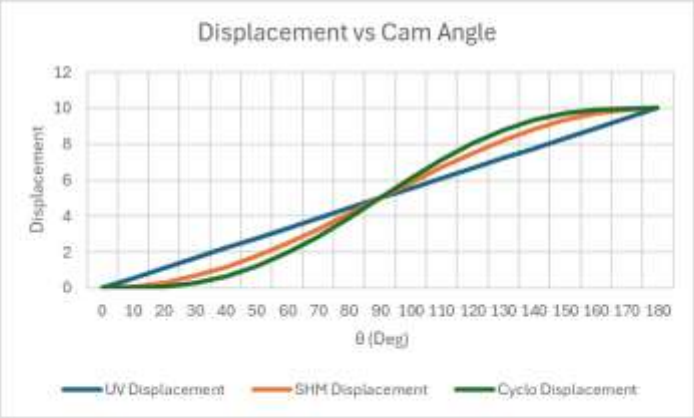
Wear in cam-follower systems is significantly influenced by jerk, and motion laws with smoother jerk variation, such as cycloidal motion, result in reduced impact forces and lower wear.

Simulation and Graph analysis

Objective: The analysis and comparison of kinematic behaviour of various motion laws uniform velocity, simple harmonic motion (SHM) and cycloidal motion based on variation of displacement, velocity, acceleration and jerk with respect to cam angle.

Method of simulation: Simulation of the motion of follower for each of the above-mentioned motion laws was carried out using the kinematic equations that were previously derived. Keeping the lift (h) and cam angle (θ) at fixed values for an unbiased comparison, the plot between the displacement, velocity, acceleration and jerk with respect to the cam angle (θ) were drawn. Simulation was performed using Microsoft Excel.

To perform the simulation and draw the kinematic graphs, some reasonable values have been assigned for kinematic parameters. These values are, Lift of follower, h = 10 mm; cam rotation angle for rise, = 180° ; angular velocity of cam = 1 rad/sec; and cam angle was varied from 0 to 180° get the plots of displacement, velocity and acceleration with respect to the cam angle for the three motion laws. All these values have been chosen such that it gives effective comparison and for easy calculations. Analysis was performed only for the rise portion, because, maximum wear is observed for cam follower mechanisms during the relative motion of cam and follower. During dwell motion does not occur so no wear takes place, return stroke will be somewhat similar to rise and analysis of rise will give the information which is necessary.



Graph 1: Displacement vs Cam Angle

Observation:

a) Uniform Velocity: Linear variation (straight line)

b) SHM: Smooth sinusoidal curve

c) Cycloidal: Smooth curve with gradual start and end

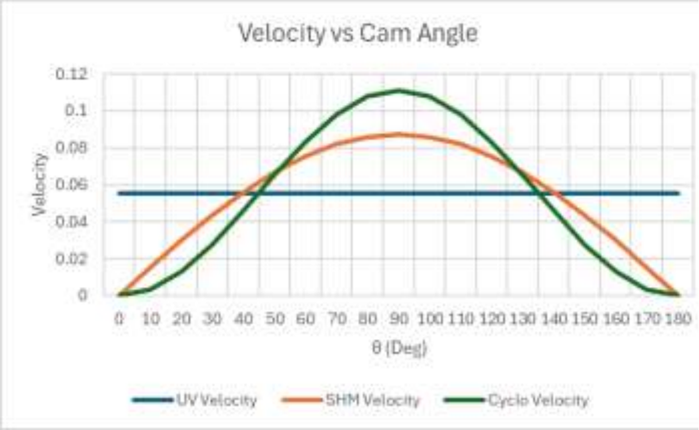
Analysis:

a) Uniform velocity shows constant rate of rise

b) SHM and cycloidal provide smooth transition

c) Cycloidal motion shows better smoothness at boundaries

Smooth displacement reduces sudden contact changes and reduces wear.



Graph 2: Velocity vs Cam Angle

<u>Observation:</u>

a) Uniform Velocity Constant velocity line

b) SHM Sinusoidal curve (zero at start & end, max at mid)

c) Cycloidal Smooth curve (gradual rise and fall)

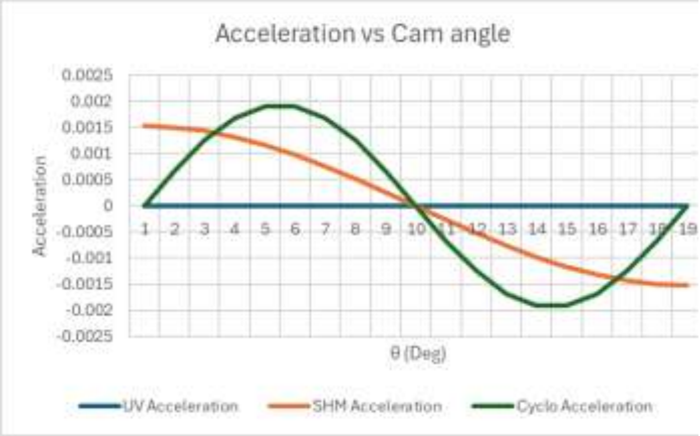
<u>Analysis:</u>

a) Uniform velocity has instant start/stop - shock

b) SHM reduces sudden velocity change

c) Cycloidal provides gradual velocity variation

Sudden velocity change - high friction - more wear.



Graph 3: Acceleration vs Cam Angle

<u>Observation:</u>

a) Uniform Velocity - Zero (except at boundaries)

b) SHM - Cosine curve (positive & negative)

c) Cycloidal - Smooth sinusoidal curve

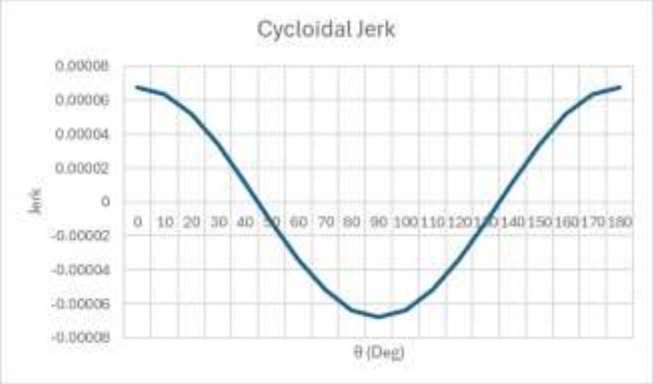
<u>Analysis:</u>

a) Uniform velocity has infinite acceleration at start/end

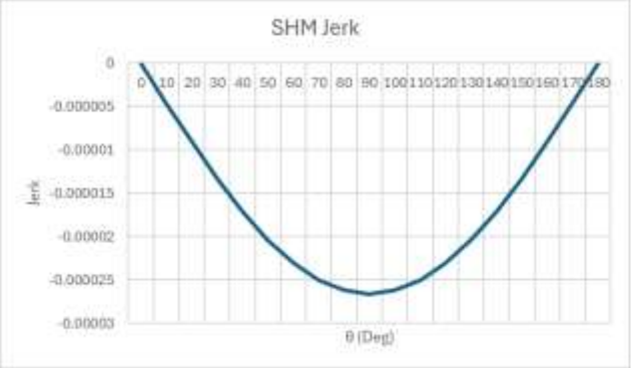
b) SHM has finite but noticeable peaks

c) Cycloidal has smooth acceleration distribution

High acceleration - high contact force - increases wear



Graph 4: Cycloidal Jerk vs Cam Angle



Graph 4: SHM Jerk vs Cam Angle

Of greatest importance is the jerk graph as it indicates rate of change of acceleration and is responsible for impact forces and wear. Graph of variation of jerk shows the transition is smoothest in cycloidal motion and thus dynamically controlled while SHM has lesser but non uniform jerk. Constant velocity graph which is not plotted results in infinite jerk.

Parameter	**Uniform Velocity**	**SHM**	**Cycloidal**
Displacement	Linear	Smooth	Very smooth
Velocity	Constant	Smooth	Gradual
Acceleration	Sudden at ends	Moderate	Smooth
Jerk	Infinite	Moderate	Minimum

Table 2: Kinematic parameters comparison from graphs

The simulation results clearly indicate that cycloidal motion provides the smoothest variation in all kinematic parameters, particularly minimizing jerk, which significantly reduces impact forces and wear in cam-follower systems.

Wear Analysis of Cam-Follower System

Introduction

Continuous sliding contact and the cyclic loading at the interface of the cam surface and the follower produce wear in the cam-follower system. Material is removed from the contact surfaces, which results in diminished precision, increased vibration, and a shorter life for the mechanism. The intensity of wear varies with the dynamic nature of motion and the resulting dynamics at the contact point.

Theoretical Background

Wear in such systems can be described using the Archard wear model:

$$W = \frac{K \cdot L \cdot S}{H}$$

where $W$is the wear volume, $K$is the wear coefficient, L is the normal load, S is the sliding distance, and H is the hardness of the material. In cam-follower mechanisms, the values of load and sliding distance vary with the motion characteristics, influencing the overall wear behaviour.

Wear Calculation Using Archard's Wear Model

Assumptions

For the purpose of analysis, the following standard values are considered:

- Wear coefficient, $K = 1 \times 10^{-8}$
- Normal load, $L = 500\, N$
- Material hardness, $H = 2000\, N/mm^2$
- Follower lift, $h = 10\, mm$
- Cam rotation for rise = 180°

Sliding Distance Estimation

The sliding distance for each motion law is derived from the kinematic velocity expressions using the Root Mean Square (RMS) sliding velocity, which represents the wear-effective contact severity over the full rise stroke. The RMS velocity is given by:

$$v_{rms} = \sqrt{\frac{1}{\beta}\int_0^{\beta} [v(\theta)]^2\, d\theta}$$

1. Uniform Velocity

$$v(\theta) = \frac{h\omega}{\beta}\, v_{rms,UV} = \sqrt{\frac{1}{\beta}\int_0^{\beta} \left(\frac{h\omega}{\beta}\right)^2 d\theta} = \frac{h\omega}{\beta}$$

$$= \frac{10 \times 1}{\pi} \approx 3.183\, mm/s$$

2. Simple Harmonic Motion

$$v(\theta) = \frac{h\pi\omega}{2\beta} sin\left(\frac{\pi\theta}{\beta}\right) v_{rms,SHM}$$

$$= \sqrt{\frac{1}{\beta}\int_0^{\beta} \left(\frac{h\pi\omega}{2\beta}\right)^2 sin^2\left(\frac{\pi\theta}{\beta}\right) d\theta}$$

$$= \frac{h\pi\omega}{2\beta} \cdot \frac{1}{\sqrt{2}} = \frac{10\pi}{2\pi\sqrt{2}} \approx 2.221\, mm/s$$

3. Cycloidal Motion

$$v(\theta) = \frac{h\omega}{\beta}\left(1 - cos\,\frac{2\pi\theta}{\beta}\right) v_{rms,CYC}$$

$$= \sqrt{\frac{1}{\beta}\int_0^{\beta} \left(\frac{h\omega}{\beta}\right)^2 \left(1 - cos\,\frac{2\pi\theta}{\beta}\right)^2 d\theta}$$

Expanding $(1 - cos\,\frac{2\pi\theta}{\beta})^2 = 1 - 2cos\,\frac{2\pi\theta}{\beta} + cos^2\frac{2\pi\theta}{\beta}$, and integrating over $[\beta]$:

$$\int_0^{\beta} cos\,\frac{2\pi\theta}{\beta}\, d\theta = 0, \int_0^{\beta} cos^2\frac{2\pi\theta}{\beta}\, d\theta$$

$$= \frac{\beta}{2} v_{rms,CYC} = \frac{h\omega}{\beta}\sqrt{\frac{1}{\beta}\cdot\frac{3\beta}{2}} = \frac{h\omega}{\beta}\sqrt{\frac{3}{2}}$$

$$= \frac{10}{\pi}\sqrt{1.5} \approx 1.952\, mm/s$$

Normalisation and Sliding Distance

The geometric sliding distance for all three profiles is equal to the follower lift, h = 10 mm. To account for wear-effective contact severity, the sliding distance is scaled proportionally using the RMS velocity ratio, normalised to the SHM value as the reference:

$$S = h \times \frac{v_{rms}}{v_{rms,SHM}}$$

Motion Type	V_{rms} mm/s	Ratio to SHM	Sliding distance (s) mm.
Uniform Velocity	3.183	1.433	14.33
SHM	2.221	1.000	10.00
Cycloidal	1.952	0.879	8.79

Table 3: RMS Velocity and Effective Sliding Distance

Wear volume calculations

- **Uniform Velocity**:

$W = (1\times10^{-8} \times 500 \times 14.33) / 2000$

$= 3.58\times10^{-8}$ mm^3

- **SHM**:

$W = (1\times10^{-8} \times 500 \times 10.00) / 2000$

$= 2.50\times10^{-8}$ mm^3

- **Cycloidal**:

$W = (1\times10^{-8} \times 500 \times 8.79) / 2000$

$= 2.20\times10^{-8}$ mm^3

Discussion

From the results it can be seen that the type of motion greatly affects wear. Motion at uniform velocity creates wear at maximum because the rapid start and stop motions cause impact forces and greater sliding distances. Motion at simple harmonic causes less wear due to easier transition despite the acceleration being varied to a certain extent.

The least wear is recorded by motion at cycloidal which can be attributed to smooth and continuous changes in displacement, velocity and acceleration. This reduces the jerk and thereby the dynamic loads experienced and also the sliding distances resulting in nearly 38.5% reduced wear as compared to uniform velocity motion.

Wear Analysis Conclusion

The wear analysis results proved to be true as it concludes that cycloidal motion produces minimum wear in cam follower mechanisms. The test also proves to select the jerk-free motion profile for reducing the overall wear of mechanism.

Wear Behaviour Under Different Motion Laws

The different types of motion with respect to their effect on the wear between the cam and follower pair are discussed below:

Uniform velocity motion: The follower velocity is constant throughout the rising part. The starting and stopping part is an instantaneous. The abrupt starting and stopping cause impact load between cam follower pair.

The impact load on the cam follower pair leads to high localized stresses and impact load on the contact surfaces, therefore, the wear occurs at very faster rate, increased friction loss and rapid surface degradation, also leads to large material removal rate and thus the uniform velocity motion wear condition is very severe. It is therefore generally unsuitable for smooth and continuously operating applications.

Simple harmonic motion: The follower displacement follows a sinusoidal curve that leads to a comparatively smoother motion than in the case of uniform velocity. At the starting and stopping part there is gradual starting and stopping. There is thus no impact load.

Due to variation of dynamic condition, there are certain stresses generated between cam follower pair, so wear will occur between the two surfaces, the wear is moderate as compared to the uniform velocity motion wear conditions. Moderate stress fluctuation occurred at the contact surface due to variations in dynamic conditions at each instant during the period of travel. The wear is relatively lower as compared to uniform velocity motion. It gives reasonable operation at medium speed but does not prove to be best.

Cycloidal motion: The follower motion starts and stops smoothly and there is not impact at the contact surface so it does not have severe stresses between cam follower pair. Due to the continuous smooth variation, the stress is distributed uniformly on the contact surface and dynamic disturbance is relatively smaller than SHM and thus friction is less and wear at very slow rate. This is the most preferable type of motion for applications requiring reduced wear at very high speed.

Motion Type	**Nature of Motion**	**Contact Condition**	**Wear Level**
Uniform Velocity	Abrupt start/stop	High impact loading	High
SHM	Smooth but varying	Moderate stress variation	Medium
Cycloidal	Smooth and continuous	Uniform stress distribution	Low

Table 4: Comparative Wear Behaviour

Summary

The type of motion law used has an important role in the wear behaviour of cam-follower systems. If motion laws are causing rapid changes, the rate of wear increases; however, with smoother and continuous motion laws, it reduces the surface degradation. Amongst all the motion laws studied, cycloidal motion is the most preferable choice to reduce wear and to enhance the system endurance.

Result and Conclusion

Results: Kinematic analysis of the three different motion laws, viz, uniform velocity motion, SHM and cycloidal motion were done and simulated with the system parameters. Graphs of displacement, velocity, acceleration and jerk with respect to the cam angle were plotted and analysed.

Displacement analysis shows that for uniform velocity motion displacement profile shows linear variation while for SHM and cycloidal motion displacement shows continuous and smooth variation profile. Velocity analysis for uniform velocity shows constant velocity throughout whereas the SHM and cycloidal motion show slow varying velocity.

Acceleration plot shows that at beginning and end of motion for uniform velocity there is an abrupt change in acceleration whereas SHM shows a sinusoidal acceleration with mild peak. The cycloidal motion shows a smooth and continues variation of acceleration.

The jerk plot shows the major difference among the three motion laws. Theoretically the infinite jerk is experienced for uniform velocity motion at the boundaries hence there is very harsh impact conditions for this type of motion law. For SHM there is a mild jerk variation. Cycloidal motion shows slow varying jerk without sharp changes.

Conclusion: This work examines the impact of different kinematic motion law on a cam-follower system. In this work three motion laws have been analysed for a cam follower mechanism they are uniform velocity, simple harmonic motion (SHM) and cycloidal motion.

The result showed that the nature of the motion profile is a critical factor in performance and lifespan of the system. The abrupt change in the motion of the uniform velocity motion law caused the system to have an unstable operation and it increases the wear in the system. Simple harmonic motion was smoother than the uniform velocity motion but has variations which would affect its long-term operation. Cycloidal motion was observed to be the best motion law and offers a smooth and continued motion cycle. Thus, reducing the dynamic disturbances and increasing durability. It may be concluded that selecting appropriate motion law for any cam follower system is important for maximizing its performance.

Future Scope

While the current work has demonstrated a theoretical and simulation analysis of a cam-follower system, there are several directions where further work could be done:

- Sophisticated methods like finite element analysis could be implemented for accurate analysis of contact stresses and wear.
- A physical prototype of the cam-follower setup could be made to validate the theoretical results.
- Optimization of cam profile can be attempted using appropriate mathematical models and algorithms.
- Detailed analysis on the effect of different materials, coating and lubrication on wear could be performed.

- Study could be extended for high speed and load application, to gain industrial significance.

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