EXPERIMENTAL INVESTIGATION ON CONTACT FORCE ANALYSIS OF ECCENTRIC CAM WITH ROLLER FOLLOWER

A Project report submitted in partial fulfilment of the requirements for the award of the degree of

Bachelor of Technology
in
Mechanical Engineering

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CERTIFICATE

This is to certify that the Project Report entitled "**EXPERIMENTAL INVESTIGATION ON CONTACT FORCE ANALYSIS OF ECCENTRIC CAM WITH ROLLER FOLLOWER**" has been carried out by **SUNKARA MADHUKAR (319126520112), GIDUTHURI MANU (319126520078), PAILA SHYAM VENKAT (319126520101), BOLAGANA JASWANTH KUMAR (319126520068), MATCHA SAI KUMAR (319126520092)** to the Department of Mechanical Engineering, ANITS is a record of the bonafide work carried out by them under the esteemed guidance of **Dr. B. NAGARAJU.** The results embodied in the report have not been submitted to any other University or Institute for the award of any degree or diploma.

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# ABSTRACT

Experimental verifications of cam–follower contacts are very important owing to the difficulties faced during a reliable simulation due to the continuous variation of load, speed and geometry of the contact. Some experiments have been carried out with cam-follower system, and realized sfor investigation on cam–follower and contacts, in order to test its capability to contact forces. Circular eccentric cam has been used because of its lower transient effects and comparison of the results with the theoretical/numerical ones is easier. The test have been performed using eccentric cam with Roller follower. The behavior of the cam–follower contacts at several different rotational speeds, ranging from 50 to 500 rpm, and different pre-loads have been investigated. The apparatus can also be used for testing the occurrence of abnormal operating condition known as jump phenomenon which has an Adverse effect on the life span of the cam and follower. The values of displacement, velocity , acceleration and contact forces are found verifying the equations generated with practical values. Hertz equation is used in contact force analysis of cam and Follower system for finding Contact stress and Shear Stress.

Keywords: Cam, Follower, Contact Forces, Shear Stress, Contact Stress

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CHAPTER -I

INTRODUCTION

1.1 CAM

A higher pair is created when two links are joined, either at a point or along a line. A cam-follower system will have two of these higher pair devices. Cam and follower is the name of a higher pair mechanism.

A cam-follower system must operate smoothly in order for the follower to move without jamming. This means that the follower must move without requiring excessive input power.

The timing of all these timing activities can be simply set by having cam-follower devices. In an IC engine, the valves must be kept open; first, close it, and keep it closed.

1.2 FOLLOWER

A mechanical component that follows the motion of the cam is known as a follower. Followers can translate or oscillate. It might be spring-loaded or it can touch the cam's surface profile. It may move with uniform acceleration or uniform velocity. The follower motion can be used to create complex output motion.

1.3 TERMINOLOGY OR NOMENCLATURE FOR CAM AND FOLLOWER:

The terminology for Cam and Follower is as follows:

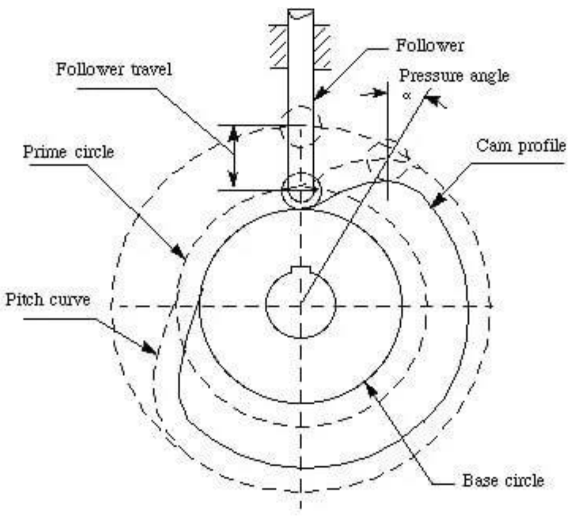


Fig 1.1 Terminology of Cam and Follower

- Pitch Curve
- Prime Circle
- Base Circle
- Trace Point
- Pressure Angle

1.3.1 Trace point:

A trace point on the follower is a location that encapsulates follower motion. It is the roller's centre for a roller follower. As a result, the roller centre serves as the trace point, and the motion of the follower will therefore be defined in terms of of this roller centre.

If it is a flat face follower, then the trace point we use is the point on the follower's face that is in contact with the cam surface when the follower is at one of the extreme positions we normally use that extreme position when the follower is closest to the cam centre.

1.3.2 Base circle:

The base circle is the smallest circle that can be drawn with the cam centre as the centre and touching the cam profile, this circle we call a base circle. So the radius of the base circle we call, Rb, is called the base circle radius.

1.3.3 Pitch curve:

Consider kinematic inversion when defining the pitch curve. This four-link system has a fixed link, a cam, a roller, and a follower in the kinematic inversion.In this four-link system, this link is fixed, but if we build a kinematic inversion holding cam fixed, it will move in the kinematic chain. A curve parallel to the cam profile will be produced by the location of the roller's centre.This is where the roller centre or trace point is located following kinematic inversion with a fixed cam.

1.3.4 Prime circle:

The centre of the smallest circle can be the cam centre, which is tangential to the pitch curve. This circle is perpendicular to the pitch curve and has its centre at the camshaft axis. The prime circle is this particular circle. The prime circle radius is Rp = Rb + Rr if the base circle radius is Rb and the roller radius is Rr.

1.3.5 Pressure angle:

The roller and cam's common normal runs through the roller's centre and parallel to the cam profile.

1.4 CAM AND FOLLOWER WORKING PRINCIPLE:

Two normal forces, one acting in the X direction and the other in the Y direction, balance the cocking moment, or the moment brought on by this force Fn.

This vertical motion will be attempted to be stopped by a friction force that is times the usual force. This will be less than N if the normal force is N. The follower must overcome the spring force while moving upward in addition to these two friction forces.

1.5 APPLICATION OF CAM AND FOLLOWER SYSTEM:

Applications for Cam and Follower systems are countless. Which are:

1.5.1 The exit valve and intake valve are closed and opened by an internal combustion engine. The cam and follower system turns the inlet and exhaust valves of an IC engine in a reciprocating motion.

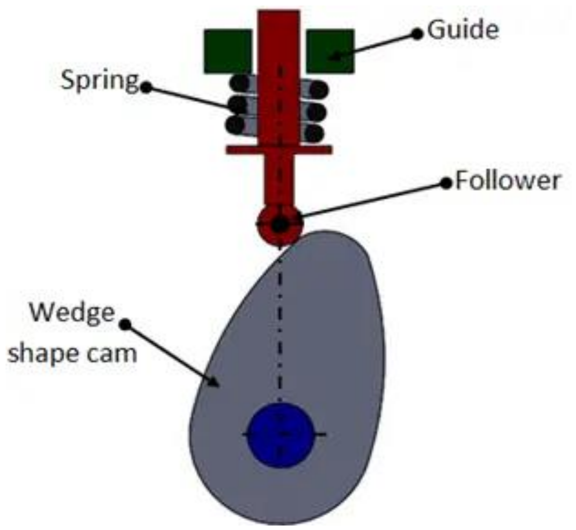


Fig.1.2 Internal combustion Engine

1.5.2 Cam and Follower are utilised in various automated motion parts of various automated types of machines.

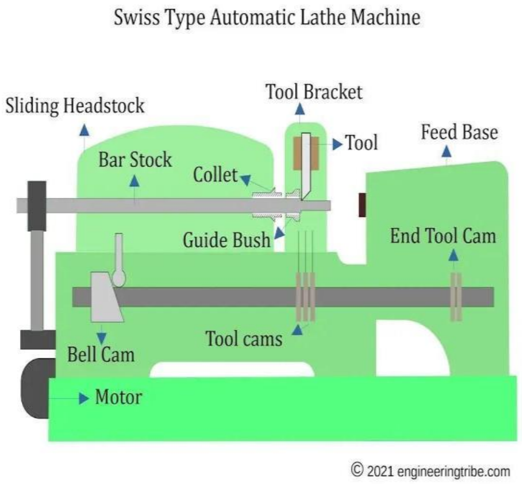


Fig.1.3 Swiss Type Automatic Lathe Machine

1.5.3 The primary mechanism in hydraulic systems is the Cam and Follower mechanism. In that situation, fluid pressure affects the mechanism..

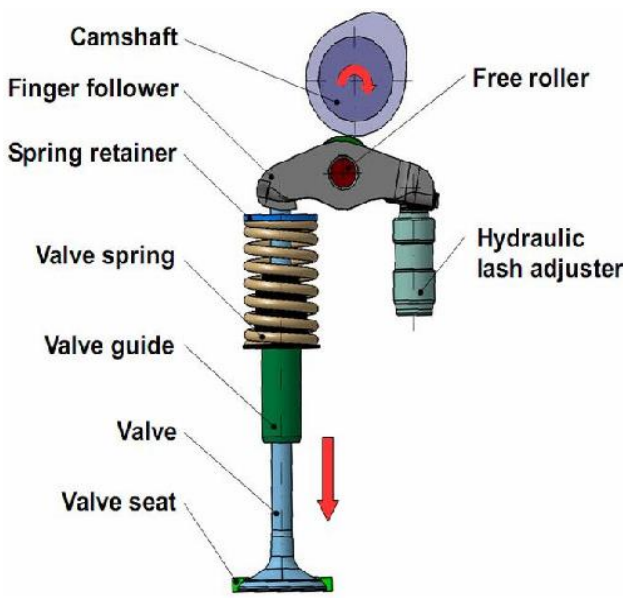


Fig.1.4 Hydraulic System

1.6 CAM PROFILE DESIGN FOR A TRAIN OF ROLLER FINGER FOLLOWER VALVES:

1.6.1 Printing equipment: The Cam and Follower system aids in the printing of the screen. Pull and push work together to move into the location where printing will take place.

Fig.1.5 Die cutting machine

1.6.2 Gear-Cutting Machines: To help with the construction of a conjugate cam, the motion law of an oscillating follower was examined using a cam mechanism. A parameter selection strategy using the parametric proportional coefficient method is provided for the conjugate cam cutting mechanism with oscillating follower. The dynamic performance of a dynamic model with clearance is examined..

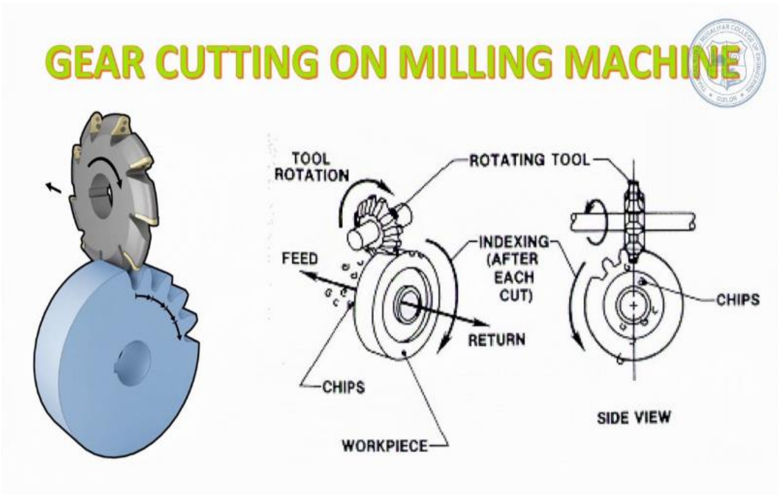


Fig.1.6 Gear Cutting On Milling Machine

1.6.3 Wall Clocks: The driving member is the cam, and the driven member is the follower. Internal combustion engines frequently use the cam and follower mechanism to control the inlet and exhaust valves. They are utilised in wall clocks and the automatic lathe machines' feed mechanisms..

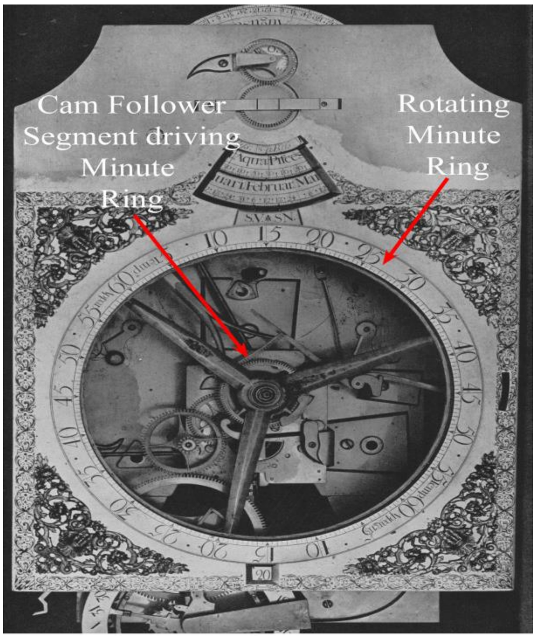


Fig.1.7 Wall Clocks

1.7 TYPES OF CAMS:

By direct contact, a rotating device called a cam causes the follower, another component of this machine, to oscillate or reciprocate. This component is mostly utilised to convert rotary motion into linear motion for another component. It is a component of a machine that can be a shaft that strikes various points on a lever in a circular route or a rotating wheel (such as an electric wheel). There are numerous varieties of cams available, including the following:

According to the shape of the cam

- Heart-shaped cams
- translating cams
- wedge cams
- spiral cams
- disc or plate cams
- cylindrical cams

1.7.1 Disc Or Plate Cam: A precise motion cannot be transmitted to the follower by a disc (or plate) cam since it lacks a regular contour..

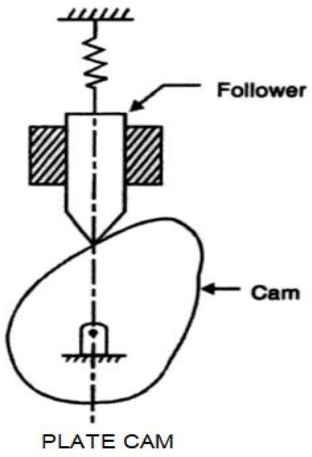


Fig.1.8 plate cam

1.7.2 Cylindrical Cam: The follower of a cylindrical cam runs parallel to the cylinder's axis on a cylindrical surface that has a groove in it..

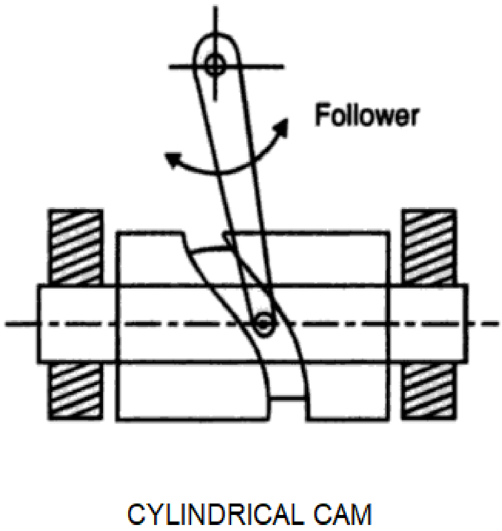


Fig.1.9 cylindrical cam

1.7.3 Translating Cam: A translating cam has a plate that has been grooved or contoured, and its follower oscillates on the plate's face. The shape or groove has defined the follower's movements.

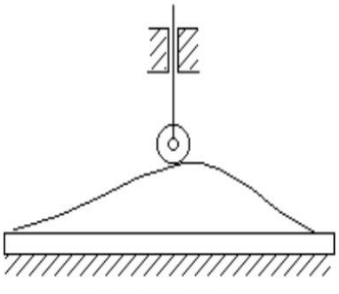


Fig.1.10 Translation Cam

1.7.4 Wedge Cam: The wedge cam imparts a particular motion to the follower by the use of an angled flat regular contour..

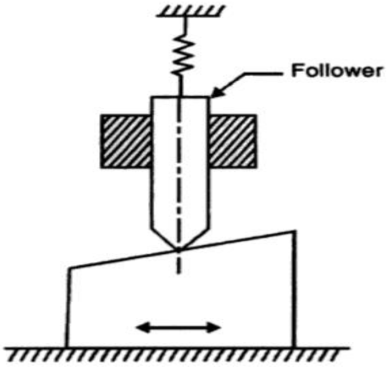


Fig.1.11 Wedge Cam

1.7.5 Spiral Cam: The spiral cam operates in a reciprocating motion and has a half-circular or spiral-shaping grooved contour. The follower moves vertically to the cam's axis.

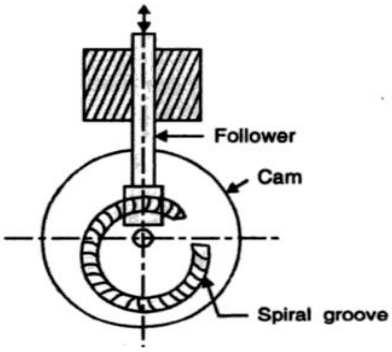


Fig.1.12 Spiral Cam

1.7.6 Cam in the shape of a heart: This style of cam has an asymmetrical heart shape. It is mostly used to return a shaft to hold the cam in a predetermined position with the help of a roller's pressure..

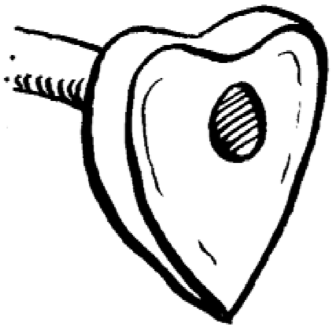


Fig.1.13 Heart shaped Cam

1.8 TYPES OF FOLLOWERS:

A follower is a revolving or oscillating component of a device that directly follows the motion of a cam. If a cam moves back and forth, the follower moves vertically with regard to the cam's axis. The major function of this component of the machine is to follow the cam, which may be oscillating or reciprocating. It alters the cam's rotating motion so that it now oscillates or reciprocates..

There were various types of follower which are as follows:

1.8.1 Based on the Shape:

- Offset Follower
- Radial Follower
- Spherical Follower
- Flat-faced Follower
- Knife Edge Follower
- Roller Follower

1.8.1.1 Knife-Edge Follower: kind of follower makes contact with the cam at a sharp angle. This is the simplest of all the followers, and due to its sharp edge, these types of followers are not used when applying something quickly.

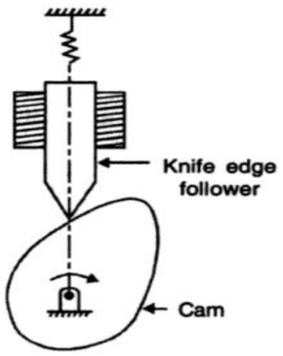


Fig.1.14 Knife Edge Follower

1.8.1.2 Roller Follower: This kind of follower has a smooth touch with the surface, making it ideal for high-speed operation. Compared to other followers, this kind experiences less wear and tear.

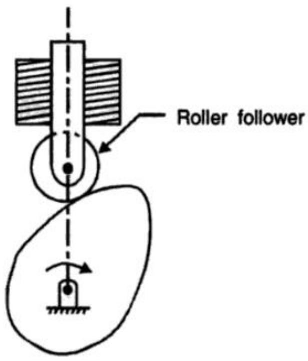


Fig.1.15 Roller Follower

1.8.1.3 Flat-Faced Follower: This kind of follower has an unsteady cam that resembles a smooth surface. When space is at a premium, this kind of cam is utilised since the follower can withstand more side thrust. A precise application can also make use of this follower..

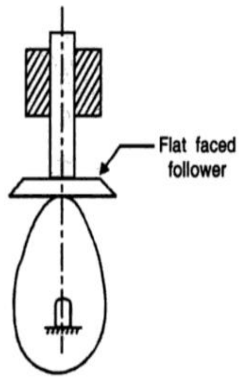


Fig.1.16 Flat Faced Follower

1.8.1.4 Spherical Follower: This kind of follower also has a cam and a curved conventional follower. This is an altered version of a follower with a flat face.

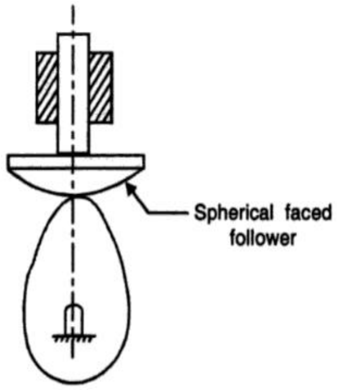


Fig.1.17 Spherical Faced Follower

1.8.1.5 Radial Follower: The path of motion in this kind of follower runs across the camshaft's middle. Generally speaking, the follower moves in step. The follower is moving reciprocally..

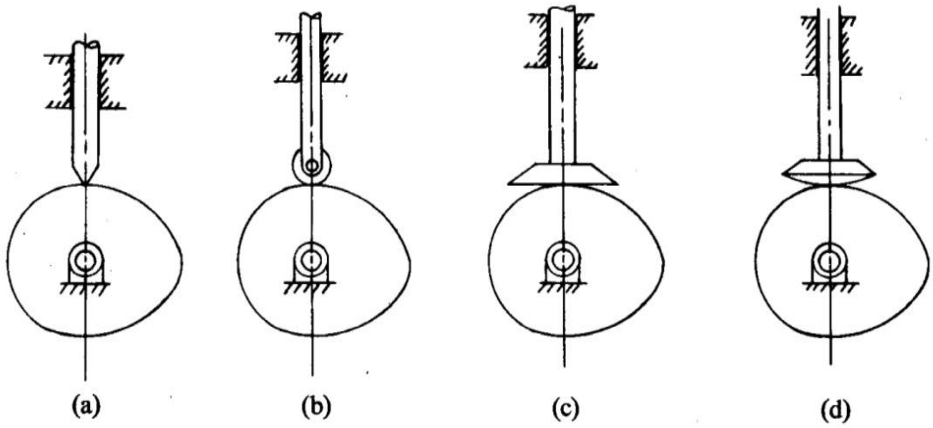


Fig.1.18 Radial Follower

1.8.1.6 Offset Follower: The movement of the follower's axis in this sort of follower is not parallel to the cam axis..

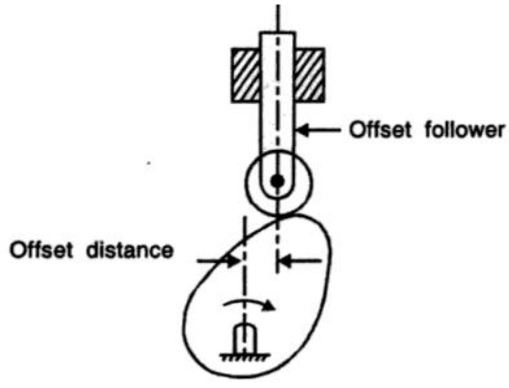


Fig.1.19 Offset Follower

1.8.2 Depending on the Position:

- Inline Follower: In an inline follower, the follower's axis lines up with the cam's centre.
- Offset Follower: An offset follower has an axis that is slightly out of alignment with the cam's centre.

1.8.3 Depending on the Motion:

- Transforming Follower: A translating follower is a cam that moves in a straight path.
- Follower that oscillates: This type of follower pivots and moves in an oscillating manner. They are known as oscillating followers.

1.9 ECCENTRIC CAM:

An eccentric cam is a disc with an off-center rotational axis. This implies that the flat follower rises and falls at a steady pace as the cam rotates. The most straightforward cam to create, yet one of the most effective. It is frequently used in steam engines to operate sliding valves or pump rams by converting rotary energy into linear reciprocating motion.

An eccentric cam typically has a groove around its circumference where a circular collar (eccentric strap) is tightly fitted and linked to an eccentric rod. The rod is suspended so that the other end of it may provide the necessary reciprocating motion.

1.9.1 Velocity, Acceleration and Jerk in an Eccentric Cam:

A detailed mathematical formulation to derive the velocity, acceleration and jerk in a eccentric cam is discussed below.

Let,

a = eccentricity

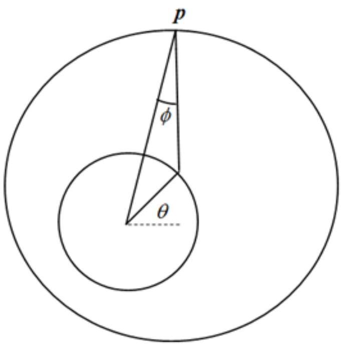
r = radius of circular cam

θ = angular position of cam

θ = angular position of eccentric cam with respect to normal

ω = angular velocity of the cam (assumed to be constant)

With respect to the Figure, the position of the follower of the elliptical cam is given by:



position p in an eccentric cam is given by,

$$p = a\sin\theta + r\cos\phi \qquad (1)$$

where,

$$p = \sin^{-1}(\frac{a}{r}\cos\theta) \qquad (2)$$

The velocity of reciprocation v, of the follower is the derivative of position p and is given by:

$$v = a\omega(cos\theta + \sin\theta\tan\theta) \qquad (3)$$

The acceleration of the follower acc, is also a derivative of velocity and it written as,

$$acc = a\omega^2\left[(-\sin\theta + \cos\theta\tan\phi - \frac{a}{r}\left(\frac{\sin 2\theta}{\cos\phi}\right)^2\right] \quad (4)$$

The jerk is rate of change of acceleration and it is given by:

$$jerk = a\omega^3\left(\begin{array}{l} -\sin\theta + \cos\theta\tan\phi - \frac{a}{2r}\frac{\sin 2\theta}{\cos\phi^3} - \frac{a}{r}\frac{\sin 2\theta}{\cos\phi^2} + \\ 2\left(\frac{a}{r}\right)^2 \frac{\sin\theta^3 * sin\phi}{\cos\phi^4} \end{array}\right) \quad (5)$$

1.10 ROLLER FOLLOWER:

The bearing system known as the Roller Follower is small and incredibly stiff. It serves as a guide roller for cam discs and linear motion and comprises needle bearings. This device has robust walls and is made to withstand an impact stress since its outer ring spins while remaining in contact with the mating surface. A precise cage and needle rollers are integrated into the outer ring. This achieves a fantastic rotation performance and prevents the product from skewing. And as a result, the product can easily endure rotation at high speeds. Roller followers can be classified as either separable or non-separable, depending on whether the inner ring can be split. The outer ring comes in two shapes: cylindrical and spherical. When the cam follower is placed, the spherical outer ring easily absorbs a distortion of the shaft centre and aids in reducing a biassed load.

Fig.1.20 Roller follower

1.11 ADVANTAGES OF ECCENTRIC CAM:

- Internal suspension is absent
- No internal flexible discharge tube
- motor operating at low temperatures
- High level of contamination tolerance
- Gas free oil pump
- Flooded start liquid with high tolerance
- High liquid defrost tolerance
- Low stress valve
- Valve actuation

1.11.1 Internal suspension is absent: A suspension could be thought of as a heterogeneous mixture of several particles that are mixed in a solution but still visible to the naked eyes. Its diameter ranges around 1000 nm. In such a mixture, every component is thoroughly combined, and every particle is visible under a microscope. Additionally, the solid particles in this type of mixture are large enough to allow for sedimentation. Consider a solvent (let it be water) and mix a solute (let it be flour). After mixing it thoroughly, what we see is it does not mix completely. Whereas, after some time it gets settled down at the bottom of the jar containing the solution. This is called suspension.

1.11.2 No internal flexible discharge tube: Discharge tubes are frequently the last parts of a compressor to be developed, thus even under strict geometrical boundary restrictions, they must fit inside the shell's remaining volume. Manufacturing, assembly, and brazing must be permitted in the discharge tube arrangement since they are essential to component quality.

1.11.3 motor operating at low temperatures: Low temperature motor operation refers to running an electric motor at lower temperatures than its rated operating temperature. Electric motors are typically designed to operate within a certain temperature range, which is specified by the manufacturer. Running a motor at a lower temperature than its rated temperature can have several advantages**:**

- **Reduced wear and tear:** Running a motor at a lower temperature reduces the wear and tear on its components, which can extend the life of the motor and reduce maintenance costs.

- **Improved efficiency:** Electric motors are typically less efficient at high temperatures, so running a motor at a lower temperature can improve its efficiency and reduce energy consumption.
- **Increased reliability:** High temperatures can cause insulation breakdown and other types of damage that can lead to motor failure. Running a motor at a lower temperature can increase its reliability and reduce the risk of failure.
- **Improved performance:** Some types of motors, such as permanent magnet motors, can actually deliver more power at lower temperatures.

1.11.4 High level of contamination tolerance: High contaminant tolerance refers to the ability of a system, component, or material to operate effectively and efficiently in the presence of contaminants such as dust, dirt, debris, or other foreign particles. High contaminant tolerance can offer several advantages, including:

- **Increased reliability:** Systems that are designed to tolerate contaminants are less likely to experience breakdowns or failures due to clogging, corrosion, or other damage caused by particles or debris.
- **Longer lifespan:** Components that are built to withstand contaminants can last longer and require less maintenance, which can reduce the overall cost of ownership over time.
- **Lower maintenance costs:** Systems that can operate in contaminated environments often require less cleaning, repair, and replacement of parts, which can result in lower maintenance costs.
- **Enhanced safety:** In some applications, such as in manufacturing or industrial settings, high contaminant tolerance can help prevent accidents and ensure worker safety by reducing the risk of equipment failure.
- **Improved performance:** Systems that are designed to tolerate contaminants can often maintain their performance even in harsh environments, leading to more consistent and reliable operation.

1.11.5 Gas free oil pump: A gas-free oil pump is a type of pump used in the oil and gas industry to transfer oil without the presence of gas. The pump is designed to remove gas from the oil before it is transferred, which can reduce the risk of explosions and other safety hazards. The advantages of gas-free oil pumps include:

- **Increased safety:** Gas-free oil pumps are designed to minimize the risk of explosions and other safety hazards that can occur when gas is present in the oil being transferred.
- **Improved efficiency:** By removing gas from the oil before it is transferred, gas-free oil pumps can improve the efficiency of the transfer process and reduce the amount of time required to complete the task.
- **Reduced downtime:** Gas-free oil pumps can help prevent downtime and production losses that can occur when equipment malfunctions or safety incidents occur.
- **Enhanced quality:** Gas-free oil pumps can help maintain the quality of the oil being transferred, which can be important in applications where the oil must meet certain standards or specifications.
- **Cost savings:** By reducing the risk of safety incidents, improving efficiency, and reducing downtime, gas-free oil pumps can result in cost savings for companies in the oil and gas industry.

1.11.6 Flooded start liquid with high tolerance: High flooded start liquid tolerance refers to the ability of a motor or other electrical equipment to operate effectively and efficiently in the presence of liquid, even if the equipment is completely flooded. High flooded start liquid tolerance can offer several advantages, including:

- **Increased reliability:** Electrical equipment that is designed to tolerate flooding is less likely to fail due to moisture or liquid intrusion.
- **Reduced maintenance costs:** Equipment that is designed to tolerate flooding typically requires less maintenance, repair, and replacement of parts, which can result in lower maintenance costs.
- **Improved safety:** In some applications, such as in water treatment facilities or sewage pumping stations, high flooded start liquid tolerance can help prevent accidents and ensure worker safety by reducing the risk of equipment failure.
- **Enhanced performance:** Electrical equipment that is designed to operate in flooded conditions can often maintain its performance even when exposed to liquid, leading to more consistent and reliable operation.

- **Increased flexibility:** High flooded start liquid tolerance can allow equipment to be used in a wider range of applications, including those with high humidity, moisture, or liquid exposure.

1.11.7 High liquid defrost tolerance: High defrost liquid tolerance refers to the ability of a refrigeration system or other equipment to withstand the presence of liquid during the defrost cycle. During defrost, ice or frost that has accumulated on the equipment is melted, and the resulting water or liquid can potentially damage the equipment. High defrost liquid tolerance can offer several advantages, including:

- **Increased reliability:** Equipment that is designed to tolerate liquid during defrost is less likely to fail due to moisture or liquid intrusion.
- **Reduced maintenance costs:** Equipment that is designed to tolerate liquid during defrost typically requires less maintenance, repair, and replacement of parts, which can result in lower maintenance costs.
- **Improved efficiency:** High defrost liquid tolerance can allow for more effective defrost cycles, resulting in better performance and energy efficiency.
- **Enhanced safety:** In some applications, such as in food processing or pharmaceuticals, high defrost liquid tolerance can help prevent contamination and ensure product safety by reducing the risk of equipment failure.
- **Increased flexibility:** High defrost liquid tolerance can allow equipment to be used in a wider range of applications, including those with high humidity or moisture exposure.

1.11.8 Low stress valve: A low stress valve is a type of valve that is designed to operate with minimal stress or strain on its components, even under high-pressure conditions. Low stress valves can offer several advantages, including:

- **Increased durability:** Low stress valves are designed to withstand high-pressure conditions without experiencing damage or wear, resulting in a longer lifespan and reduced maintenance requirements.
- **Improved safety:** By reducing stress on valve components, low stress valves can help prevent valve failure or leakage, which can lead to safety hazards in some applications.

- **Enhanced performance:** Low stress valves can maintain their performance even under high-pressure conditions, leading to more consistent and reliable operation.
- **Reduced maintenance costs:** Low stress valves typically require less maintenance, repair, and replacement of parts, which can result in lower maintenance costs.
- **Energy efficiency:** By maintaining tight seals and reducing leakage, low stress valves can improve energy efficiency and reduce operating costs.

1.1.9 Valve Actuation: Valve actuation refers to the process of opening and closing valves using an actuator or other mechanism. Valve actuation can offer several advantages, including:

- **Improved efficiency:** Valve actuation can allow for remote or automated operation of valves, reducing the need for manual intervention and improving efficiency.
- **Enhanced safety:** In some applications, such as in hazardous environments or in emergency situations, valve actuation can improve safety by allowing valves to be operated from a distance.
- **Greater control:** Valve actuation can allow for precise control over valve position, flow rates, and other parameters, leading to improved performance and more efficient operation.
- **Reduced maintenance costs:** Valve actuation can help prevent valve damage or wear by ensuring that valves are operated within their intended parameters, reducing the need for maintenance or replacement.
- **Increased flexibility:** Valve actuation can allow for greater flexibility in process design and control, allowing valves to be placed in locations that may be difficult or impossible to access manually.

CHAPTER -II

LITERATURE REVIEW

For this project we collect some relevant information about cam-follower analysis, from this we did not found any investigation on contact force analysis of eccentric cam with roller follower.

Ciulli, Enrico *et al*.[1] studied on circular eccentric cam-follower pairs provides valuable insights into the behavior of cam-follower contacts at different rotational speeds and pre-loads and utilized a new apparatus specifically designed for investigating cam-follower and gear teeth contacts and used circular eccentric cams for easier comparison with theoretical/numerical results. It involved testing cams with different eccentricities and surface roughness and two different followers, and data of all contact force and moment components were acquired at high acquisition frequency.

D Vela *et al*.[2]studied the complexity of cam-follower contact and emphasizes the importance of experimental verifications. The behavior of fundamental components of the rig has been investigated through tests and theoretical/numerical simulations. The results provided important insights for the design of a new apparatus specifically aimed at measuring film thickness and contact forces in cam-follower contacts. The new apparatus can reproduce a cam-follower mechanism that uses a rocker as a link device between the cam follower set and the valve.

Enrico Ciulli *et al*.[3]investigated that it makes use of a brand-new instrument for measuring film thickness and contact forces to examine the behavior of cam-follower contacts. Tests were carried out at various rotational speeds and pre-loads with mixed lubrication using steel and glass followers and circular eccentric cams with variable eccentricities and surface roughness. The findings, which include information on the components of contact force and moment, driving torque, and optical interference pictures, point to the experimental setup's potential for revealing important details about cam-follower contact behavior.

H.S. Yan *et al.*[4] This study proposes an alternative approach for improving the motion characteristics of cam-follower systems by varying the cam input driving speed, and demonstrates the feasibility of this approach through experimental data. A polynomial speed trajectory is found to reduce peak values of motion characteristics, and systematic design procedures for generating an appropriate trajectory are developed. Design examples are given to illustrate the procedure for getting an appropriate speed trajectory as variable speed cam-follower systems.

Louay S. Yousuf *et al*. [5] investigated that the detachment between the cam and follower for different cam speeds and internal distances of the follower guide. The study uses various techniques, such as the largest Lyapunov exponent parameter, power density function of FFT, and Poincare' maps, to detect detachment heights. The study also utilizes multi-degrees of freedom systems to improve dynamic performance and reduce detachment. The results show a significant reduction in the peak of nonlinear response after using multi-degrees of freedom systems. The study employs SolidWorks program for numerical solution and a high-speed camera for data collection. Overall, the study provides valuable insights into nonlinear dynamics phenomena in cam and follower systems.

Francis J. Sisk *et al*. [6] investigated a dual capacity refrigerant compressor with an eccentric cam that rotates on a crankpin between two positions to obtain two different stroke lengths. The study shows that by providing lightening cavities and eccentric weightings, the center of mass of the cam can be shifted to obtain centrifugal torque in the proper direction at both maximum and reduced stroke positions. The cam moves through an angle of about 270° around the crankpin, providing a centrifugal force torque that holds the cam in place in the reduced stroke length position. Overall, this study provides valuable insights into the design and operation of dual capacity refrigerant compressors.

Ali Hasan *et al*. [7] examined and selected the optimal combination of cam and follower to avoid jumping phenomenon during the required task. The study is conducted in the dynamics laboratory of the mechanical engineering department using an experimental setup to record the critical jumping speed. The study is divided into two parts, one recording the jumping speed with various weights on the follower assembly under compression, and the other recording the jumping speed with constant weight on the follower assembly under gradual compression of the spring. Overall, this study provides valuable insights into the optimization of cam and follower combinations for efficient and reliable operation.

Cemil Kozkurta *et al*. [8] presented an experimental approach for determining cam profiles based on a graphical method, aiming to improve accuracy and eliminate the need for certain determination parameters. The proposed approach includes equations and algorithms for both flat face and roller translating follower mechanisms. Results demonstrate that the approach provides highly precise results compared to conventional analytical and CAD systems. Overall, this study provides a valuable contribution to the field of cam profile determination.

Hazim U. Jamali *et al*. [9] examined a numerical study on the effects of various factors, such as radius of curvature, surface velocities, applied load and lubrication, on the contact problem between a cam and a flat-faced follower. The study includes the introduction of an axial modification of the cam depth and analyzes its impact on film thickness and pressure distribution using a point contact model. The results indicate that the cam form of modification significantly affects the predicted film thickness, pressure distribution, and surface deformation, highlighting its importance in the design of such systems. Overall, this paper provides valuable insights into the characteristics of contact problems in cam and follower mechanisms.

B.S.Thakkar *et al*. [10] explained that cam and follower mechanism is a fundamental component of modern machinery due to its ability to produce various motions. Cams are rotating elements that impart reciprocating or oscillating motion to followers, and they can also convert rotary motion into translation or oscillation. Cam mechanisms are preferred over other types because they offer an unlimited variety of motions. This study aims to determine the critical jumping speed of the cam using an experimental setup. The results were verified using three methods, including analytical calculations, simulation software, and C programming, and the percentage of deviation was calculated to justify the accuracy of the findings

Tsiavis *et al*. [11] designing an optimal cam mechanism can be a time-consuming process due to numerous considerations, including design parameters and optimization criteria. In this study, the problem of designing a cam mechanism with a translating flat-face follower is approached from a multi-objective perspective. The optimization criteria for determining design parameters, such as cam base circle radius, follower face width, and follower offset, involve minimizing cam size, input torque, and contact stress. The optimization procedure takes into account various constraints, such as pressure angle and contact stress, while utilizing genetic algorithms to find optimal solutions that meet kinematic requirements. Finally, the dynamic behavior of the cam mechanism is investigated, considering frictional forces.

Enrico Ciulli *et al.* [12] Cam-follower contacts are complex due to the continuous changes in operating parameters, such as speed, load, and geometry. Numerical simulations and experimental measurements are required to understand the behavior of cam-follower pairs. An experimental apparatus has been designed to measure contact forces with a dynamometer and lubricant film thickness and shape with optical interferometry. This paper reviews experimental works on cam-follower pairs, describes the test rig used in the study, and presents trends in contact forces during the rotation of circular eccentric and engine spline cams. The friction trends are associated with mixed and boundary lubrication regimes, and unattended friction peaks are found in tests with the spline cam, with possible explanations provided.

2.1 SUMMARY:

Based on the above literature lot of gaps which were identified in case of eccentric cam-roller follower system. The objectives are drawn and discussed briefly in the next chapter to fulfill the gaps.

CHAPTER -III

OBJECTIVES

From the previous chapter there are some literature gaps which were identified. Basing on the gaps identified, the following objectives of an eccentric cam- roller follower were derived:

1. Motion parameter analysis: Analyzing the motion parameters such as displacement, velocity, and acceleration is crucial for designing an efficient and reliable cam-follower system. This information allows engineers to select appropriate materials, lubrication, and other design factors to ensure that the system operates smoothly.
2. Jump phenomenon analysis: The jump phenomenon occurs when the follower suddenly transitions from one part of the cam profile to another. This can lead to abrupt changes in contact force and vibration, which can negatively impact the performance and reliability of the system. Analyzing the jump phenomenon allows engineers to design cam-follower systems that minimize these effects.
3. Contact force determination: The maximum and minimum contact forces between the cam and follower affect the wear and tear of their surfaces, as well as the power and efficiency of the cam-follower mechanism. By determining these forces, engineers can design systems that are durable and efficient.
4. Contact stress determination: To determine the maximum and minimum contact stresses between the cam and the follower because they affect the wear and tear of cam and follower surfaces.
5. Shear stress determination: To determine the maximum and minimum shear stress between the cam and follower as it effect the surfaces of cam and follower to reduce the wear and tear.
6. Model validation: Validating analytical models with experimental results helps to predict the contact forces and behavior of the cam-follower mechanism more accurately. Comparing the experimental results with the theoretical analysis can be used to validate the accuracy of the theoretical model used to predict the behavior of the eccentric cam-follower mechanism.
7. Design optimization: By identifying sources of error and discrepancies between the experimental and theoretical results, engineers can optimize the design of the

eccentric cam-follower mechanism for improved performance, reduced wear and tear, and increased durability. This optimization may involve changing the material properties, adjusting lubrication, or modifying the shape of the cam profile to achieve better results.

CHAPTER -IV

EXPERIMENTATION DETAILS

4.1 EXPERIMENTATION SET UP:

4.1.1 A circular eccentric cam with a roller follower is a mechanical system used to convert rotational motion into linear motion. The system consists of a circular eccentric cam and a roller follower that rolls along the cam's surface. As the cam rotates, the follower's position and motion are determined by the shape of the cam.

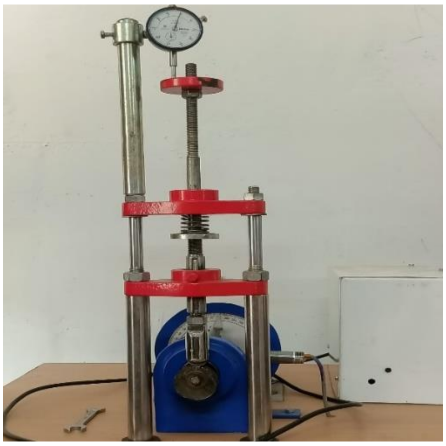


Fig.4.1 Experimentation set up

4.1.2 In an experiment with this system, the cam and follower are typically set up on a test rig, and the cam is rotated by a motor or other power source. The motion of the follower is then measured using sensors or other instrumentation. By analyzing the follower's motion, engineers and researchers can study the behavior of the system and optimize its design for specific applications.

Fig.4.2 Eccentric cam follower system

4.1.3 One key advantage of a circular eccentric cam with a roller follower is its ability to produce precise linear motion with minimal friction and wear. This makes it well-suited for applications such as machine tools, robotics, and automated manufacturing, where precise positioning and motion control are essential.

4.1.4 The roller follower provides a constant contact point with the cam surface, which helps to distribute forces and minimize wear. It also allows for a smooth and consistent motion, making it useful in applications where jerk or sudden changes in acceleration could be problematic.

4.1.5 The design of the cam profile can be customized to produce a variety of motion profiles, including constant velocity, acceleration, deceleration, and complex waveforms. This flexibility makes it useful in a wide range of applications, from simple linear motion systems to complex robotic mechanisms.

4.1.6 Circular eccentric cams with roller followers are also well-suited for use in harsh environments or applications where other types of motion systems may be prone to failure. This is because the roller follower can operate with minimal lubrication and is less sensitive to dirt, debris, and other contaminants.

4.1.7 However, there are also some limitations and challenges associated with circular eccentric cams with roller followers. One of these is the potential for cam wear or deformation over time, which can cause changes in the motion profile of the follower. This can be mitigated through careful design and material selection, as well as regular maintenance and inspection.

4.1.8 Another challenge is the need to ensure proper alignment between the cam and follower. Misalignment can cause excessive wear, vibration, and noise, and can ultimately lead to failure of the system.

4.2 CALCULATIONS USING PYTHON PROGRAMES:

4.2.1 Python is a high-level, interpreted programming language that was initially made available in 1991. One of the most widely used programming languages in use today, it is renowned for its simplicity, readability, and adaptability. Python has a wide range of uses, including machine learning, scientific computing, web development, and data analysis.

4.2.2 One of the main strengths of Python is its ease of use and readability. Its syntax is designed to be intuitive and easy to understand, making it accessible to both beginners and experienced programmers alike. Python code is also highly readable, thanks to its use of whitespace and a lack of complex syntax, which can make it easier to maintain and modify over time.

4.2.3 Another key feature of Python is its flexibility and modularity. It includes a vast standard library of modules and functions, which can be used to perform a wide range of tasks without the need for additional libraries. Additionally, there is a large and active community of developers who have created a wide range of third-party libraries and tools for Python, making it easy to extend and customize for specific use cases.

4.2.4 Also, Python programming is a popular choice for numerical computation and data analysis, and it can be used to perform calculations of acceleration and velocity in a variety of applications, from physics and engineering to finance and biology.

4.2.5 To calculate acceleration and velocity using Python, one approach is to use the equations of motion from classical mechanics, which describe the relationship between , velocity, acceleration, and time. These equations can be implemented in Python using variables, functions, and mathematical operators.

4.2.6 Overall, Python is a strong and flexible programming language that is appropriate for a variety of applications. Its readability and simplicity make it a great option for newcomers, while its modularity and flexibility make it a favourite among seasoned developers and academics.

4.3 GRAPHICAL REPRESENTATIONS USING MATLAB SOFTWARE :

4.3.1 MATLAB (short for "matrix laboratory") is a high-level programming language and interactive environment widely used in engineering, science, and mathematics. It was developed by MathWorks and initially released in 1984. MATLAB provides a flexible and powerful platform for numerical computation, data analysis, visualization, and algorithm development.

4.3.2 MATLAB is widely used in academia and industry for a variety of applications, including data analysis, signal processing, image analysis, control systems, machine learning, and scientific computing. It provides a comprehensive set of functions and toolboxes that can be used to develop complex applications and systems.

4.3.3 One of the key strengths of MATLAB is its ability to handle matrix operations efficiently. The language has built-in support for vectors and matrices, and many operations can be performed on them without the need for explicit loops. This makes MATLAB particularly useful for tasks such as linear algebra, signal processing, and image analysis.

4.3.4 One of the key strengths of MATLAB is its ability to handle matrix operations efficiently. The language has built-in support for vectors and matrices, and many operations can be performed on them without the need for explicit loops. This makes MATLAB particularly useful for tasks such as linear algebra, signal processing, and image analysis.

4.3.5 MATLAB has an interactive command-line interface that allows users to enter commands and receive immediate feedback. This makes it easy to explore and manipulate data, and to quickly prototype and test algorithms. In addition, MATLAB provides a graphical user interface (GUI) that includes tools for creating plots, designing graphical user interfaces, and managing data.

4.3.6 MATLAB can be used to develop complex systems and applications, including control systems, signal processing systems, and machine learning systems. MATLAB provides a variety of tools and functions for system modeling, simulation, and design, as well as for code generation and deployment.

4.3.7 MATLAB is widely used in academia and research, and is often used to develop and prototype new algorithms and techniques. MATLAB provides a flexible and powerful platform for exploring and testing new ideas, and can be used to develop algorithms in a wide range of areas, including computer vision, natural language processing, and robotics.

4.3.8 In conclusion, MATLAB is a powerful and flexible programming language and environment that is widely used in engineering, science, and mathematics. It provides a comprehensive set of functions and tools for numerical computation, data analysis, visualization, and algorithm development. With its rich set of features and extensive toolboxes, MATLAB is an essential tool for researchers, scientists, engineers, and students working in a wide range of fields.

CHAPTER -V

RESULT AND DISCUSSION

5.1 THEORATICAL APPROACH

$co_1 = po_1 + cp$

$cp = op - oc$

$cp = R - e$

$po_1 = r$

$\therefore co_1 = r + R - e$

$co_2 = ?$

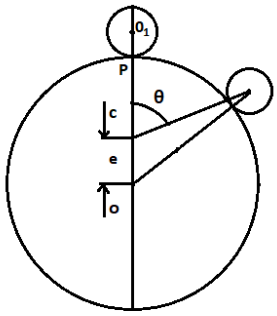


Fig. 5.1 Diagrammatic representation of eccentric cam with roller follower

5.1.1 SINE RULE:

$$\frac{R+r}{\sin\theta} = \frac{e}{\sin\beta} = \frac{co_2}{\sin\emptyset}$$

$$\frac{R+r}{\sin\theta} = \frac{e}{\sin\beta}$$

$$\sin\beta = \frac{e.\sin\theta}{R+r}$$

$$\beta = \sin^{-1}(\frac{0.004}{R+r}).\sin\theta$$

$$(180° - \theta) + \emptyset + \beta = 180°$$

$$\emptyset = \theta - \beta$$

$$co_2 = \frac{e.\sin\emptyset}{\sin\beta} = \frac{e.\sin(\theta-\beta)}{\sin\beta}$$

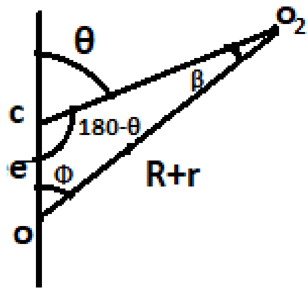


Fig 5.2 Sine rule

5.1.2 DISPLACEMENT OF THE CENTRE OF THE ROLLER:

$$y = co_2 - co_1$$

$$y = \frac{e.\sin(\theta-\beta)}{\sin\beta} - (r+R-e)$$

$\sin\beta = \left(\frac{e}{r+R}\right) sin\theta$

Let $c=\frac{e}{r+R}$

$\mathrm{Sin}\,\beta = c.sin\theta$

$cos\beta.\frac{d\beta}{dt} = c.cos\theta\,\frac{d\theta}{dt}$

$cos\beta.\frac{d\beta}{dt} = c.cos\theta.r.\omega$

$\frac{d\beta}{dt} = \frac{c.\omega.cos\theta}{cos\beta}$

$\boldsymbol{y = \frac{e.\sin(\theta-\beta)}{\sin\beta} - (r+R-e)}$ ———————— **(A)**

5.1.3 VELOCITY:

$\dot{y} = e[\frac{\mathrm{Sin}\,\beta.\cos(\theta-\beta)\left(\frac{d\theta}{dt}-\frac{d\beta}{dt}\right)-\sin(\theta-\beta)cos\beta.\frac{d\beta}{dt}}{sin^2\beta}$

$\dot{y} = \frac{e}{sin^2\beta}[\cos(\theta-\beta).\mathrm{Sin}\,\beta\left(\omega - \frac{c.\omega.cos\theta}{cos\beta}\right) - \sin(\theta-\beta)cos\beta.\frac{c.\omega.cos\theta}{cos\beta}$

$\dot{y} = \frac{e}{sin^2\beta}[\cos(\theta-\beta).\mathrm{Sin}\,\beta\,.\,\omega - \cos(\theta-\beta).\mathrm{Sin}\,\beta\,\frac{c.\omega.cos\theta}{cos\beta} - \sin(\theta-\beta)cos\beta.\frac{c.\omega.cos\theta}{cos\beta}\,]$

$\dot{y} = \frac{e}{sin^2\beta}[\cos(\theta-\beta).\mathrm{Sin}\,\beta - \frac{c.\omega.cos\theta}{cos\beta}\,[\,\sin(\theta-\beta)cos\beta + \cos(\theta-\beta)\,\mathrm{Sin}\,\beta]$

$\boldsymbol{\dot{y} = \frac{e}{sin^2\beta}[\omega.\cos(\theta-\beta)\sin\beta - \frac{c\,\omega\,cos\theta\,sin\theta}{cos\beta}]}$ ———————— **(B)**

5.1.4 ACCELERATION:

$\frac{d}{dt}(\dot{y}) = \frac{d}{dt}\;[\frac{e}{sin^2\beta}(\omega\cos(\theta-\beta)\sin\beta - \frac{c\,\omega\,cos\theta\,sin\theta}{cos\beta})]$

$$\frac{d}{dt}\left[e.\frac{1}{sin^2\beta}\right]$$

$= e.\frac{d}{dt}\left[\frac{1}{sin^2\beta}\right]$

$$= e.\left[\frac{-2ec\omega cos\theta}{sin^3\beta}\right] \qquad \text{———————} \quad 1$$

$$\frac{d}{dt}[\omega.\cos(\theta-\beta).\,\text{Sin}\beta]$$

$$= \omega.\frac{d}{dt}[\cos(\theta-\beta).\,\text{Sin}\beta]$$

$$= \omega.\frac{d}{dt}[2.\cos(\theta-\beta).\,\text{Sin}\beta]$$

$$= \frac{\omega}{2}.\frac{d}{dt}[\sin(\theta-\beta+\beta)-\sin(\theta-\beta-\beta)]$$

$$= \frac{\omega}{2}\frac{d}{dt}[\sin(\theta)-\sin(\theta-2\beta)]$$

$$= \frac{\omega}{2}[\frac{d}{dt}\sin(\theta)-\frac{d}{dt}\sin(\theta-2\beta)]$$

$$= \frac{\omega}{2}\left[cos\theta.\frac{d\theta}{dt}-cos(\theta-2\beta)\frac{d}{dt}(\theta-2\beta)\right]$$

$$= \frac{\omega}{2}[cos\theta.\frac{d\theta}{dt}-cos(\theta-2\beta)(\frac{d\theta}{dt}-2\frac{d\beta}{dt})]$$

$$= \frac{\omega}{2}[cos\theta.\omega-cos(\theta-2\beta)(\omega-2\frac{c.\omega.cos\theta}{cos\beta})]$$

$$= \frac{\omega}{2}[cos\theta.\omega-\omega.cos(\theta-2\beta)(1-2\frac{c.cos\theta}{cos\beta})]$$

$$= \frac{\omega^2}{2}[cos\theta-cos(\theta-2\beta)(1-2\frac{c.cos\theta}{cos\beta})] \qquad \text{———————} \quad 2$$

$$\frac{d}{dt}\left[c.\omega\frac{cos\theta.sin\theta}{cos\beta}\right]$$

$$= c.\omega.\frac{d}{dt}\left[\frac{cos\theta.sin\theta}{cos\beta}\right]$$

$$= \frac{c.\omega}{2}\frac{d}{dt}\left[\frac{2.cos\theta.sin\theta}{cos\beta}\right]$$

$$= \frac{c.\omega}{2}\frac{d}{dt}\left[\frac{sin2\theta}{cos\beta}\right]$$

$$= \frac{c.\omega}{2}[\frac{cos\beta\frac{d}{dt}(sin2\theta)-sin2\theta\frac{d}{dt}(cos\beta)}{cos^2\beta}]$$

$$= \frac{c.\omega}{2}\left[\frac{cos\beta(2cos2\theta)\frac{d\theta}{dt} - sin2\theta(-\operatorname{Sin}\beta)\frac{d\beta}{dt}}{cos^2\beta}\right]$$

$$= \frac{c.\omega}{2}\left[\frac{2cos\beta(cos2\theta).\omega + sin2\theta\,.\operatorname{Sin}\beta\,.\frac{c.\omega.cos\theta}{cos\beta}}{cos^2\beta}\right]$$

$$= \frac{c.\omega^2}{2}\left[\frac{2cos\beta(cos2\theta)+c.sin2\theta.cos\theta.tan\beta}{cos^2\beta}\right] \text{———————} 3$$

From 1,2,3

$$\ddot{x} = e.\left(\frac{-2c\omega cos\theta}{sin^3\beta}\right)\left[\frac{\omega^2}{2}\left(cos\theta - \cos(\theta - 2\beta)\left(1 - \frac{2c\cos\theta}{cos\beta}\right)\right) - \left(\frac{c\omega^2}{2}\right)\left(\frac{2cos2\theta.cos\beta + csin2\theta.cos\theta.tan\beta}{cos^2\beta}\right)\right] \text{———} \mathbf{(C)}$$

5.1.5 DATA:

Stiffness K=660.02 N/m

e=0.004m

m=0.737 kg

R=23mm

R=10mm

5.1.6 FOR FINDING $\boldsymbol{\beta}$:

$$c = \frac{e}{R+r} = \frac{(0.004)(10^3)}{23+10} = 0.1212$$

$$\sin\beta = c\,.\ \sin\theta$$

$$\boldsymbol{\beta = \sin^{-1}(c\,.\sin\theta)} \text{ ———————————— } \mathbf{(D)}$$

5.1.7 VALUES OF β:

Table 5.1 Theoretical values of β

Θ (°)	β (°)
10°	1.2
20°	2.37
30°	3.47
40°	4.46
50°	5.22
60°	6.02
70°	6.53
80°	6.85
90°	6.96
100°	6.855
110°	6.539
120°	6.024
130°	5.327
140°	4.468
150°	3.474
160°	2.375
170°	1.2
180°	0
190°	-1.2
200°	-2.375
210°	-3.47
220°	-4.468
230°	-5.327
240°	-6.024
250°	-6.539
260°	-6.855
270°	-6.961
280°	-6.855
290°	-6.539
300°	-6.024
310°	-5.327
320°	-4.468
330°	-3.474
340°	-2.375
350°	-1.205
360°	0

The values of β are tabulated in the above table. By taking the relevant angle θ and substituting in the equation (D) we get the values of β at that angle θ. *As* θ varies from 10° to 360° ,the values of β are tabulated.

5.1.8 PYTHON CODE FOR FINDING VELOCITY:

```
In [4]: import math
theta=float(input("enter theta=:"))
beta=float(input("enter beta:"))
w=1
e=4
c=0.1212
x=w*(math.cos(theta-beta))*math.sin(beta)
y=(c*w*math.cos(theta)*math.sin(theta))/math.cos(beta)
z=e/((math.sin(beta))**2)
print(z*(x-y))

enter theta=:20
enter beta:2.37
2.4920049629676546

In [ ]:
```

Fig 5.3 Python code for finding velocity value.

A python code is generated for finding the values of velocities at different values of θ and β. The generated values are tabulated in the table-

5.1.9FOR ACCELERATION:

```
jupyter Untitled Last Checkpoint: 4 minutes ago (unsaved changes)    Logout
File Edit View Insert Cell Kernel Widgets Help    Trusted    Python 3 (ipykernel)
Run Code

In [3]: import math
theta=float(input("enter theta=:"))
beta=float(input("enter beta:"))
w=1
e=4
c=0.1212
x=((w*2)/2)*(math.cos(theta)-math.cos(theta-(2*beta)))*(1-((2*c*math.cos(theta))/math.sin(beta)))
y=(((c*w)*2)/2)*(((2*math.cos(2*theta)*math.cos(beta))+c*math.sin(2*theta)*math.cos(theta)*math.tan(beta))/((1+math.cos(2*theta)
z=((-2)*e*math.cos(beta))/((3*math.sin(beta)-math.sin(3*beta))/4)
print(z*(x-y))

enter theta=:20
enter beta:2.37
7.677445783797455

In [ ]:
```

Fig 5.4 Python code for finding acceleration value.

A python is generated for finding the values of acceleration at different values of θ and β. The generated values are tabulated in the table-

Table 5.2 Theoretical values:

Θ	β	y	$\dot{y}$	$\ddot{y}$
20°	2.37	0.296	2.475	5.187
40°	4.46	0.899	4.386	0.925
60°	6.02	1.84	10.973	15.586
80°	6.85	3.09	4.668	0.517
100°	6.855	4.462	4.194	-3.141
120°	6.024	5.826	14.451	-15.46
140°	4.468	6.968	3.2554	-16.35
160°	2.375	7.744	4.81	-0.4757
180°	0	-	0	-17.53
200°	-2.375	7.744	-4.838	-13.32
220°	-4.468	6.968	-0.793	-9.62
240°	-6.024	5.826	-13.934	-7.642
260°	-6.855	4.462	-3.17	-2.9683
280°	-6.855	3.07	-4.72	0.542
300°	-6.024	1.826	-4.503	7.513
320°	-4.468	0.84	-4.37	2.67
340°	-2.375	0.2266	-2.1477	5.2474
360°	0	-	-	-

Y=Displacement of the follower(mm)

$\dot{y}$= Velocity of the follower(*mm/s)*

$\ddot{y}$= Acceleration of the follower mm/s^2

The above table comprises of cam rotation angle (θ), β , Displacement(y),velocity(**$\dot{y}$),** Acceleration (**$\ddot{y}$).** The values obtained in the above table are theoretical values which are obtained by substituting the values of θ to get the angle β and to find the displacement(y), Velocity ($\dot{y}$) , Acceleration ($\ddot{y}$). At each angle of θ and βsubstituting in the corresponding equation (A), (B) and (C) the values of displacement, velocity and acceleration are found.

5.2 PRACTICAL APPROACH

5.2.1 DISPLACEMENT VALUES

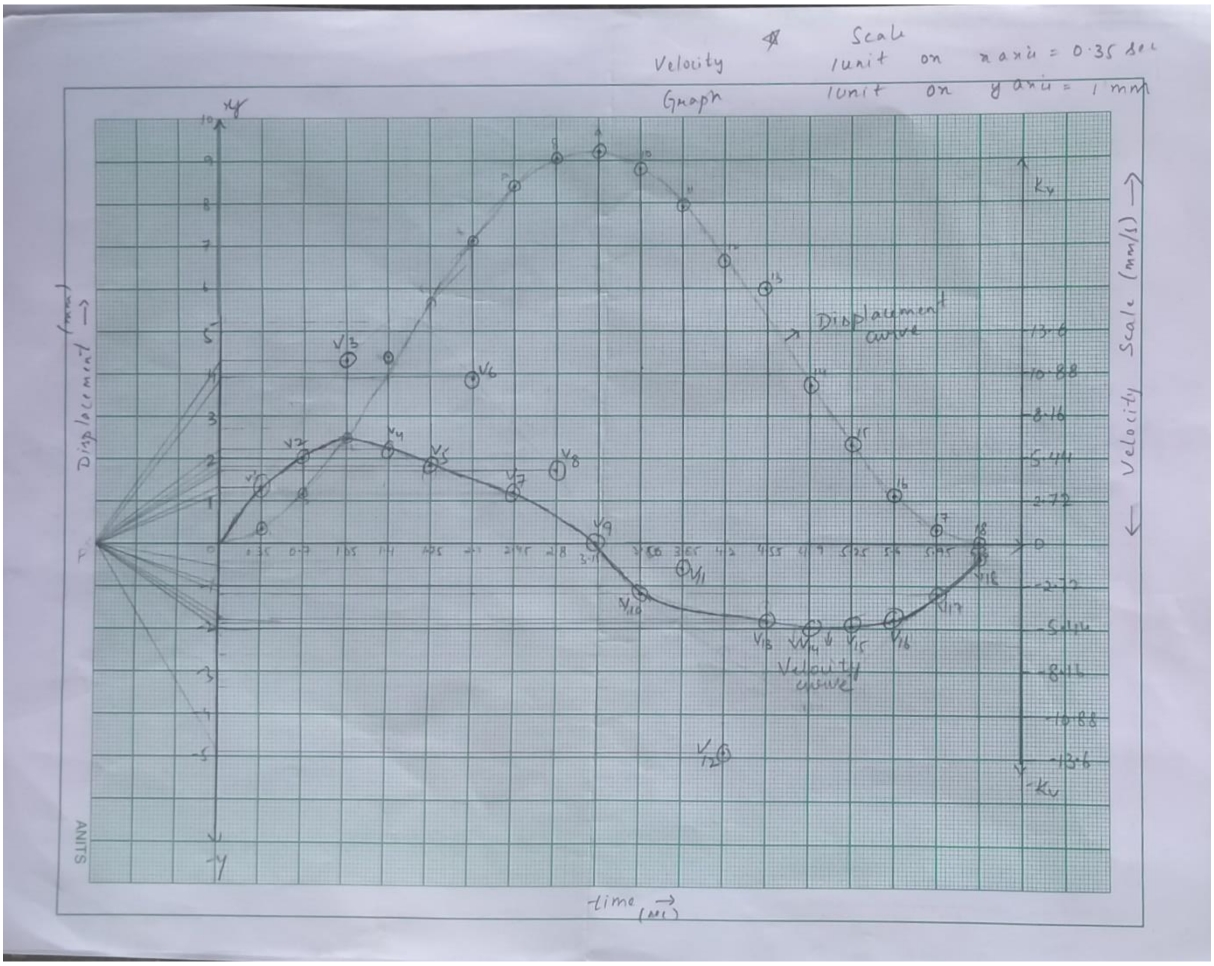
Table 5.3 Displacement values from experiment

Θ (°)	**Displacement Y (mm)**
10°	0.1
20°	0.325
30°	0.64
40°	1.15
50°	1.72
60°	2.45
70°	3.31
80°	4.4
90°	4.83
100°	5.65
110°	6.41
120°	7.12
130°	7.8
140°	8.39
150°	8.78
160°	9.06
170°	9.19
180°	9.21
190°	9.03
200°	8.79
210°	8.48
220°	7.92
230°	7.3
240°	6.64
250°	6
260°	5.28
270°	4.55
280°	3.72
290°	3.03
300°	2.32
310°	1.69
320°	1.08
330°	0.63
340°	0.27
350°	0.17
360°	0.1

These are the values obtained from doing it practically. Select eccentric cam & roller follower. Fix the follower to the Push rod and the fix Cam to the cam shaft. 3) Keep the cam at the lower most position. (Nose of the cam in downward position) Now tighten the follower in such a way that the follower and cam are in just contact. Fix the Dial Gauge to the Stand and rotate the base plate, in order to touch the displacement rod of gauge. See that the gauge is showing zero position. Also, note while fixing the cam position, the angular scale pointer is at zero and even the dial gauge pointer is at zero position. (Rotate the outer ring of gauge to make the pointer at zero position). Now, gradually go on rotating the cam shaft by hand through 10° to 20° , and note down the dial gauge reading for every position. Likewise, readings are to be taken up to 360°.

5.2.2 VELOCITY VALUE(Graphical Method)

Fig 5.5 Velocity- time graph from displacement- time graph

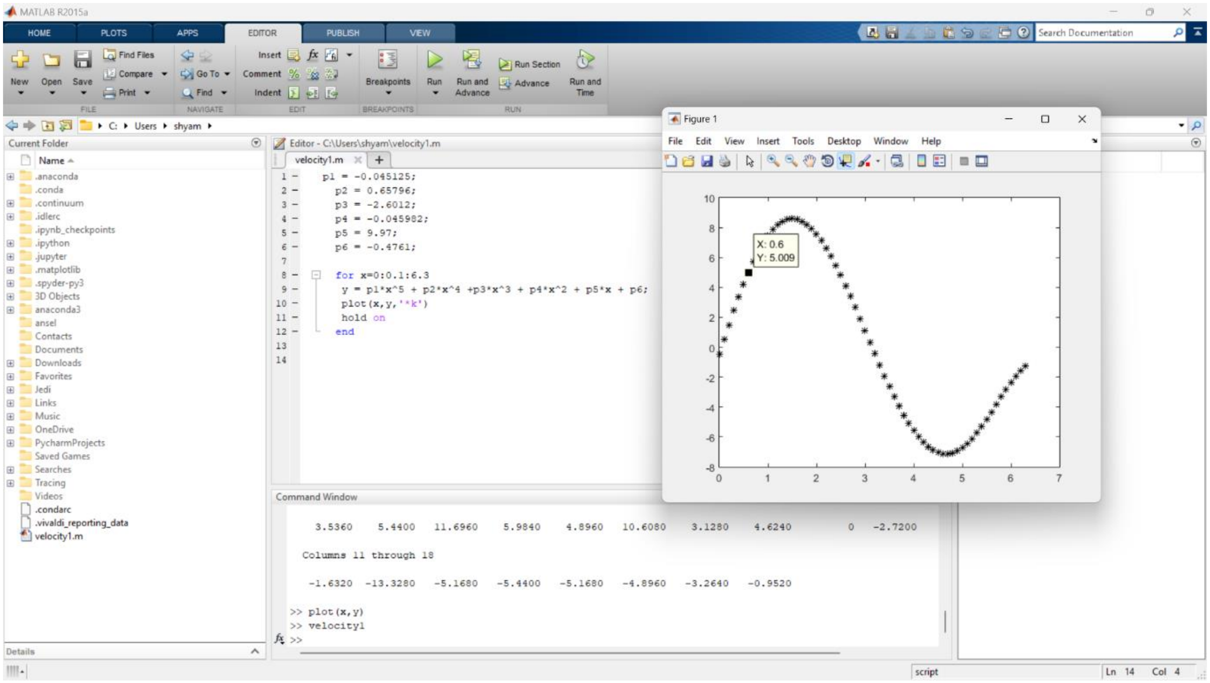


Draw the displacement-time/angular displacement curve and obtain the velocity-time curve. Graphical differentiation method can be used to determine the velocity and acceleration for a moving point on a mechanism at various instants utilizing the displacement- time data. Velocity is the derivative of displacement with respect to time and is proportional to the slope of the tangent to the displacement-time curve for any instant. To plot the velocity time curve, select a convenient point P (known as pole point) as shown and draw a line parallelly.

Let kv = $velocityscale$ Then, vc = $k_v TO$

$$k_v = \frac{k_s}{k_t} \cdot \frac{1}{PO}$$

Fig 5.6 Velocity – Time Graph



MATLAB software is used to draw the Velocity- Time Graph in order to avoid human errors and to get accurate values.

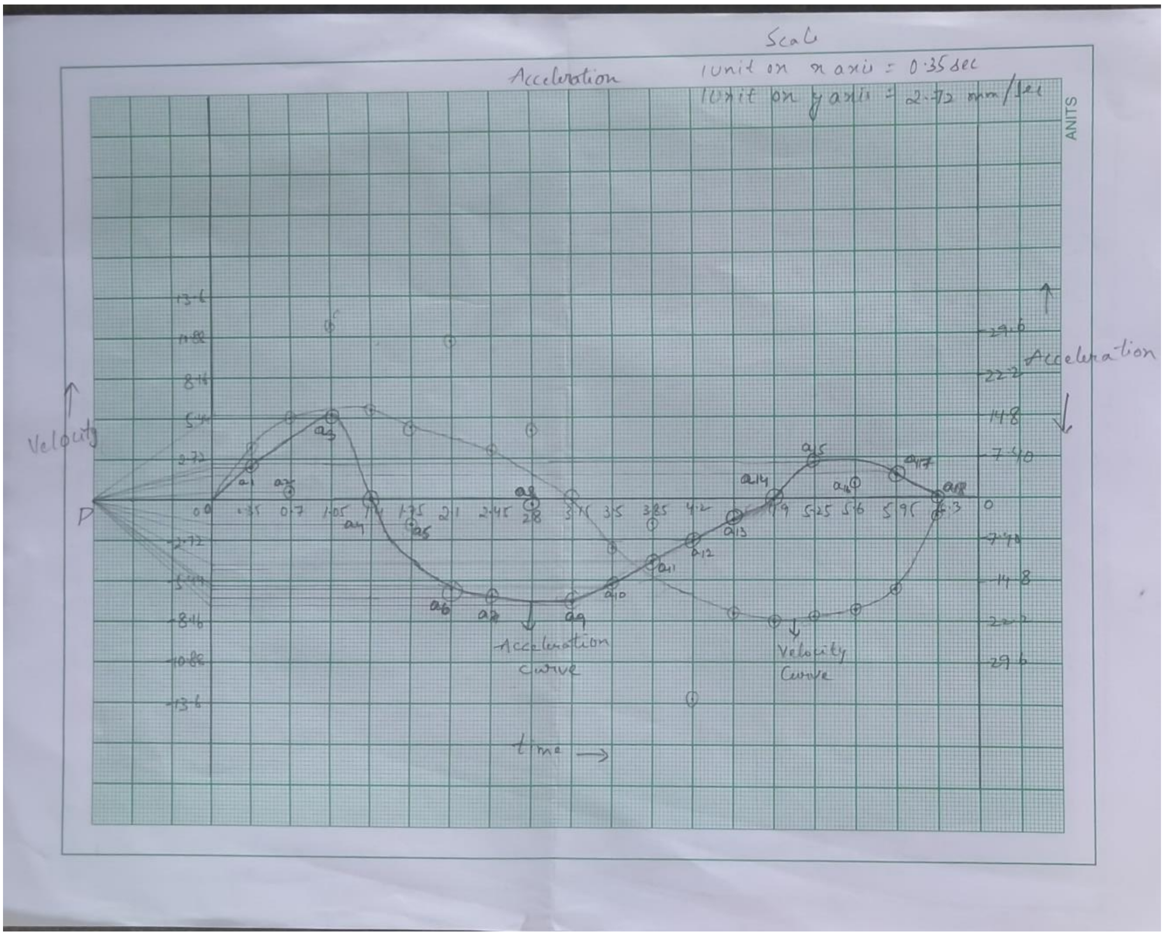
Table 5.4 Velocity values (Graphical Method)

$\dot{y}_i$	ϴ	**Velocity**
$\dot{y}_1$	20°	2.9
$\dot{y}_2$	40°	5.009
$\dot{y}_3$	60°	11.696
$\dot{y}_4$	80°	5.984
$\dot{y}_5$	100°	4.896
$\dot{y}_6$	120°	10.608
$\dot{y}_7$	140°	3.264
$\dot{y}_8$	160°	4.624
$\dot{y}_9$	180°	0
$\dot{y}_{10}$	200°	-3.264
$\dot{y}_{11}$	220°	-1.632
$\dot{y}_{12}$	240°	-13.328
$\dot{y}_{13}$	260°	-5.1
$\dot{y}_{14}$	280°	-5.44
$\dot{y}_{15}$	300°	-5.22
$\dot{y}_{16}$	320°	-4.896
$\dot{y}_{17}$	340°	-3.264
$\dot{y}_{18}$	360°	0.952

The above velocity values are obtained from the graph which is drawn in graph sheet.In order to get the accurate values of velocity MATLAB software is used to draw the velocity-time graph from displacement-time graph in order to avoid human error.The values are taken for every 20°of angular rotation.

5.2.3 ACCELERATION VALUES (Graphical Method)

Fig 5.7 Acceleration - time graph from displacement- time graph

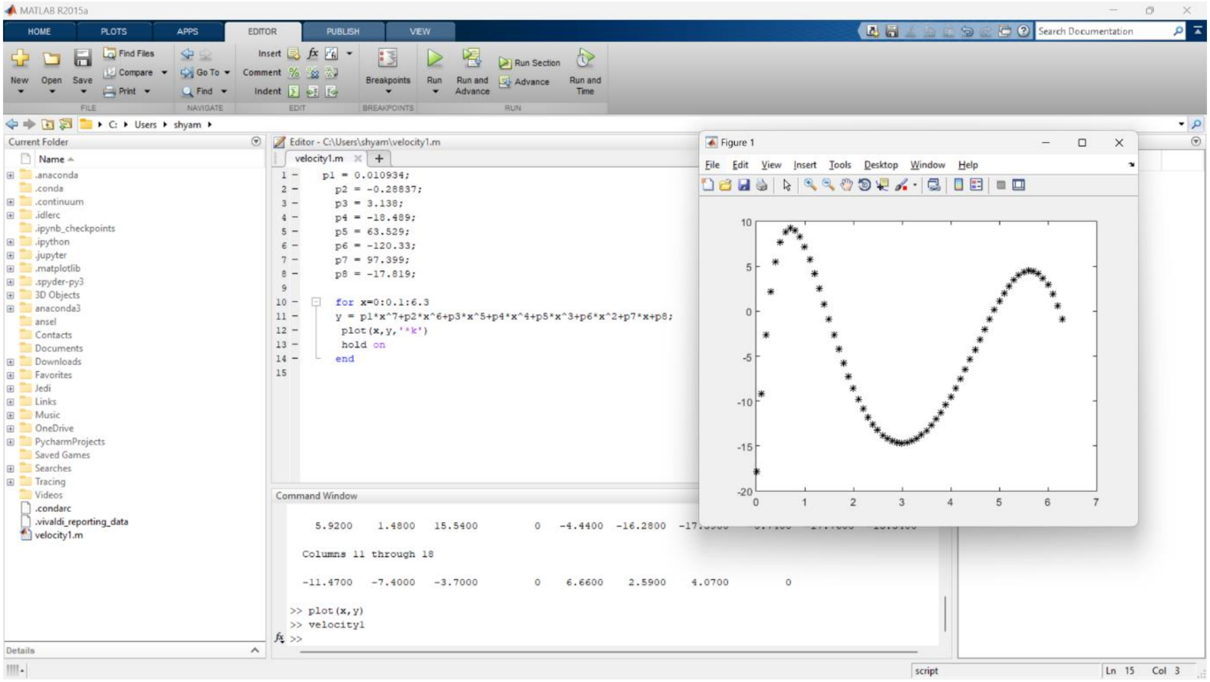


Draw the velocity-time curve and obtain the acceleration-time curve. Graphical differentiation method can be used to determine the velocity and acceleration for a moving point on a mechanism at various instants utilizing the displacement- time data. Velocity is the derivative of displacement with respect to time and is proportional to the slope of the tangent to the displacement-time curve for any instant. To plot the velocity time curve, select a convenient point P (known as pole point) as shown and draw a line parallelly.

Let k_a = Acceleration $scale$ Then, ac = $k_a T$O

$$k_a = \frac{k_v}{k_t} . \frac{1}{PO}$$

Fig 5.8 Acceleration – Time Graph



MATLAB software is used to draw the Velocity- Time Graph in order to avoid human errors and to get accurate values.

Table 5.5 Acceleration values (Graphical Method)

$\ddot{y}_i$	**Ө**	$(mm)/s^2$
$\ddot{y}_1$	20°	5.92
$\ddot{y}_2$	40°	1.48
$\ddot{y}_3$	60°	15.54
$\ddot{y}_4$	80°	0
$\ddot{y}_5$	100°	-4.44
$\ddot{y}_6$	120°	-16.28
$\ddot{y}_7$	140°	-17.39
$\ddot{y}_8$	160°	-0.74
$\ddot{y}_9$	180°	-17.76
$\ddot{y}_{10}$	200°	-15.54
$\ddot{y}_{11}$	220°	-11.47
$\ddot{y}_{12}$	240°	-7.4
$\ddot{y}_{13}$	260°	-3.7

$\ddot{y}_{14}$	280°	0
$\ddot{y}_{15}$	300°	6.66
$\ddot{y}_{16}$	320°	2.59
$\ddot{y}_{17}$	340°	4.07
$\ddot{y}_{18}$	360°	0

The above acceleration values are obtained from the graph which is drawn in graph sheet by drawing tangents at each point and drawing parallelly from Pole point P. In order to get the accurate values of velocity MATLAB software is used to draw the acceleration-time graph from velocity-time graph in order to avoid human error. The values are taken for every 20° of angular rotation.

5.3 VELOCITY VALUES

Table 5.6 Comparing practical and theoretical values of velocity.

Θ	**$\dot{y}$ (mm/s) (PRACTICAL VALUE FROM GRAPH)**	**$\dot{y}$ (mm/s) (THEORATICAL VALUE FROM FORMULAE)**
20°	2.9	2.476
40°	5.009	4.386
60°	11.696	10.973
80°	5.984	4.668
100°	4.896	4.194
120°	10.608	14.451
140°	3.264	3.2554
160°	4.624	4.81
180°	0	0
200°	-3.264	-4.838
220°	-1.632	-0.793
240°	-13.328	-13.934
260°	-5.1	-3.17
280°	-5.44	-4.72
300°	-5.22	-4.503
320°	-4.896	-4.37
340°	-3.3264	-2.1477
360°	0.952	0

From table-5.2 and table-5.4 We got theoretical and practical values of velocity using derived formula and Graph. On comparing the Theoretical and Practical Values there is a less difference between the two values.

5.4 ACCELERATION VALUES

Table 5.7 Comparing practical and theoretical values of Acceleration.

ϴ	**$\ddot{y}$(mm/s) (PRACTICAL VALUE FROM GRAPH)**	**$\ddot{y}$(mm/s) (THEORATICAL VALUE FROM FORMULAE)**
20°	5.92	5.187
40°	1.48	0.925
60°	15.54	15.586
80°	0	0.517
100°	-4.44	-3.141
120°	-16.28	-15.46
140°	-17.39	-16.35
160°	-0.74	-0.4757
180°	-17.76	-17.530
200°	-15.54	-13.32
220°	-11.47	-9.62
240°	-7.40	-7.642
260°	-3.7	-2.9683
280°	0	0.542
300°	6.66	7.513
320°	2.59	2.67
340°	4.07	5.2474
360°	0	0

From table-5.2and Table- 5.5, We got the theoretical and practical values using derived formula and from graphs. On comparing the Theoretical and Practical Values there is a less difference between the two values.

5.5 Contact Force Analysis

Contact force equation.

$$\boldsymbol{F_c = m\ddot{y} + sy + \dot{}mg}$$

We know.

$$y = \frac{e.\sin(\theta-\beta)}{\sin\beta} - (r + R - e)$$

$$\ddot{y} = e.\left(\frac{-2c\omega cos\theta}{sin^3\beta}\right)\left[\frac{\omega^2}{2}\left(cos\theta - \cos(\theta - 2\beta)\left(1 - \frac{2c\ cos\theta}{cos\beta}\right)\right) - \left(\frac{c\omega^2}{2}\right)\left(\frac{2cos2\theta.cos\beta + csin2\theta.cos\theta.tan\beta}{cos^2\beta}\right)\right]$$

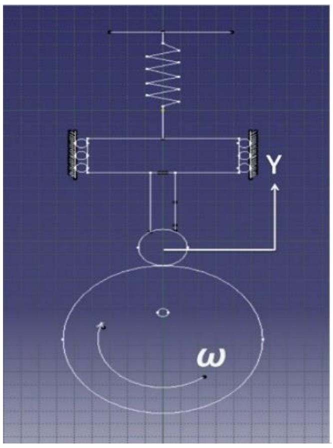


Fig.5.9 Free body diagram of cam follower

Substitute y and $\ddot{y}$

We get

$$\boldsymbol{F_c = m * \left(\frac{-2*e*\omega*c*\cos\theta}{\frac{3*\sin\beta - \sin 3\beta}{4}}\right) * \left[\left(\frac{\omega^2}{2}\right) * \left(\cos\theta - \cos(\theta - 2\beta) * \left(1 - \frac{2*c*\cos\theta}{\cos\beta}\right)\right) - \left(\frac{c*\omega^2}{2}\right) * \left(\frac{2*\cos\theta*\cos\beta + c*\sin 2\theta*\cos\theta*\tan\beta}{cos^2\beta}\right)\right] + s * \left(\frac{e*\sin(\theta-\beta)}{\sin\beta} - (R + r - e)\right) + mg}$$

Table 5.8 Contact forces values at each angle of rotation of cam on follower.

$\boldsymbol{\theta_i}$	**Force Values (N)**
θ_1	7.3485 (F_{min})
θ_2	7.4467
θ_3	7.6107
θ_4	7.871
θ_5	8.164
θ_6	8.5072
θ_7	8.919
θ_8	9.33
θ_9	9.77835
θ_{10}	10.2371
θ_{11}	10.695
θ_{12}	11.1328
θ_{13}	11.528
θ_{14}	11.8745
θ_{15}	12.1535

θ_{16}	12.353
θ_{17}	12.5277
θ_{18}	-
θ_{19}	12.74 (F_{max})
θ_{20}	12.4543
θ_{21}	12.2366
θ_{22}	11.909
θ_{23}	11.54
θ_{24}	11.143
θ_{25}	10.7
θ_{26}	10.2381
θ_{27}	9.7752
θ_{28}	9.3214
θ_{29}	8.8944
θ_{30}	8.503
θ_{31}	8.1538
θ_{32}	7.8620
θ_{33}	7.633
θ_{34}	7.4827
θ_{35}	7.434
θ_{36}	-

The values of θ and β are substituted in F_c equations to get the values of F_c corresponding to its angles. The above table is of contact force values.From this we can find the maximum and minimum contact force of cam on the follower.

From the table we observed that Minimum contact force is 7.34N which is obtained at $\theta = 10°$ and Maximum contact Force is 12.74N which is obtained at $\theta = 190°$

$$\boldsymbol{F_{max} = 12.74\ N}$$
$$\boldsymbol{F_{min} = 7.34\ N}$$

5.6 HERTZ EQUATION:

The Hertz equation is an important tool used in contact force analysis of cam and follower systems. It is a mathematical equation that allows us to calculate the contact force that results from the elastic deformation of two bodies in contact under a compressive load.

For a cam-and-follower contact, the Hertz equation can be applied using the following steps:
Determine the contact radius of the follower roller, which is the radius of the circular area where the cam and roller are in contact.

Calculate the contact stress at the contact radius using the Hertz equation:
Hertz equation for cam follower analysis

$$\boldsymbol{\sigma = \sqrt{\frac{F}{\pi . a}}}$$

where σ is the contact stress, F is the force applied to the cam, a is the contact radius, and π is the mathematical constant pi.
Calculate the maximum shear stress using the following equation:
Maximum shear stress equation for cam follower analysis

$$\boldsymbol{\tau_{max} = \frac{\sigma}{2}}$$

where τ max is the maximum shear stress.

5.6.1 CONTACT STRESS:

$$\boldsymbol{\sigma = \sqrt{\frac{F}{\pi . a}}}$$

Where a=contact radius =2.3 cm = 0.023 m

Table 5.9 Contact stress values

$\boldsymbol{\sigma_i}$	**Contact Stress values.**
σ_1	10.0846
σ_2	10.1515
σ_3	10.2629
σ_4	10.4370
σ_5	10.6294
σ_6	10.8506
σ_7	11.1101
σ_8	11.3632
σ_9	11.6330
σ_{10}	11.9028

σ_{11}	12.1661
σ_{12}	12.4126
σ_{13}	12.6310
σ_{14}	12.8195
σ_{15}	12.9691
σ_{16}	13.0751
σ_{17}	13.1673
σ_{18}	-
σ_{19}	13.2784
σ_{20}	13.1286
σ_{21}	13.0134
σ_{22}	12.8380
σ_{23}	12.6375
σ_{24}	12.4183
σ_{25}	12.1689
σ_{26}	11.9033
σ_{27}	11.6311
σ_{28}	11.3579
σ_{29}	11.0945
σ_{30}	10.8479
σ_{31}	10.6228
σ_{32}	10.4310
σ_{33}	10.2785
σ_{34}	10.1763
σ_{35}	10.1431
σ_{36}	-

5.6.2 SHEAR STRESS:

$$\tau_{max} = \frac{\sigma}{2}$$

Table 5.10 Shear Stress Values

$\tau_{max\ i}$	**Shear stress N/m^2**
$\tau_{max\ 1}$	5.0423
$\tau_{max\ 2}$	5.0759
$\tau_{max\ 3}$	5.1314
$\tau_{max\ 4}$	5.2185
$\tau_{max\ 5}$	5.3147

$\tau_{max\ 6}$	5.4253
$\tau_{max\ 7}$	5.5557
$\tau_{max\ 8}$	5.6816
$\tau_{max\ 9}$	5.8165
$\tau_{max\ 10}$	5.9514
$\tau_{max\ 11}$	6.0838
$\tau_{max\ 12}$	6.2063
$\tau_{max\ 13}$	6.3155
$\tau_{max\ 14}$	6.4097
$\tau_{max\ 15}$	6.4845
$\tau_{max\ 16}$	6.5375
$\tau_{max\ 17}$	6.5836
$\tau_{max\ 18}$	-
$\tau_{max\ 19}$	6.6392
$\tau_{max\ 20}$	6.5642
$\tau_{max\ 21}$	6.5067
$\tau_{max\ 22}$	6.4190
$\tau_{max\ 23}$	6.3187
$\tau_{max\ 24}$	6.2091
$\tau_{max\ 25}$	6.0844
$\tau_{max\ 26}$	5.9516
$\tau_{max\ 27}$	5.8155
$\tau_{max\ 28}$	5.6789
$\tau_{max\ 29}$	5.5472
$\tau_{max\ 30}$	5.4239
$\tau_{max\ 31}$	5.3114
$\tau_{max\ 32}$	5.2155
$\tau_{max\ 33}$	5.1395
$\tau_{max\ 34}$	5.0885
$\tau_{max\ 35}$	5.0715
$\tau_{max\ 36}$	-

CHAPTER -VI

CONCLUSION AND FUTURE SCOPE

Table 6.1 Theoretical and Practical values

Θ (°)	**B** (°)	y **(theoretical)** ***(mm)***	y **(Practical)** ***(mm)***	$\dot{y}$ **(Theoretical)** ***(mm/s)***	$\dot{y}$ **(practical)** ***(mm/s)***	$\ddot{y}$ **(theoretical)** mm/s^2	$\ddot{y}$ **(Practical)** mm/s^2
20°	2.37	0.296	0.325	2.475	2.9	5.187	5.92
40°	4.46	0.899	1.15	4.386	5.009	0.925	1.48
60°	6.02	1.84	2.45	10.973	11.696	15.586	15.54
80°	6.85	3.09	4.4	4.668	5.984	0.517	0
100°	6.855	4.462	5.65	4.194	5.984	-3.141	-4.4
120°	6.024	5.826	7.12	14.451	4.896	-15.46	-16.28
140°	4.468	6.968	8.39	3.2554	10.608	-16.35	-17.39
160°	2.375	7.744	9.06	4.81	3.264	-0.4757	-0.74
180°	0	-	9.21	0	0	-17.530	-17.76
200°	-2.375	7.744	8.79	-4.838	-3.264	-13.32	-15.54
220°	-4.468	6.968	7.92	-0.793	-1.632	-9.62	-11.47

240°	-6.024	5.826	6.64	-13.934	-13.328	-7.642	-7.4
260°	-6.855	4.462	5.28	-3.17	-5.1	-2.9683	-3.7
280°	-6.855	3.07	3.72	-4.72	-5.44	0.542	0
300°	-6.024	1.826	2.32	-4.503	-5.22	7.513	6.66
320°	-4.468	0.84	1.08	-4.37	-4.896	2.67	2.59
340°	-2.375	0.2266	0.27	-2.1477	-3.264	5.2474	4.07
360°	0	-	0.1	-	0.952	-	-

The following conclusions were drawn from theoretical and practical values :

1. Motion parameter analysis is carried out and it is analyzed that the motion parameters such as displacement, velocity and acceleration is crucial for designing an efficient and reliable cam-follower system. This information helps the Engineers to choose suitable materials, lubrication, and other design factors to ensure for smooth operation.
2. It is identified that the jump phenomenon helps an engineers to design cam-follower systems effectively whichwill minimizes an abrupt changes in contact force and vibration. This leads to better performance and reliability of the system.
3. It is inferred from the Table 5.8 that the maximum contact force is 12.74N at $\theta = 190°$ and minimum contact force is 7.34N at$\theta = 10°$ between the cam and follower. This information plays a vital role in the selection of appropriate materials and lubrication.As the maximum and minimum contact forces between the cam and follower affect the wear and tear of their surfaces, as well as the power and efficiency of the cam-follower mechanism.
4. It is inferred from the Table 5.9 that the maximum contact stress is 13.2784 N/m^2 at $\theta = 190°$ and minimum contact stresses is 10.0846 N/m^2 at $\theta = 10°$ between the

cam and the follower is essential to prevent wear and tear on their surfaces. This information helps engineers to choose appropriate materials and lubrication to minimize the effects of contact stress.

5. It is inferred from the Table 5.10that the maximum shear stress is 6.639 N/m^2 at $\theta = 190°$ and minimum shear stress is 5.043 N/m^2 at$\theta = 10°$between the cam and follower is essential to reduce wear and tear on their surfaces. This information helps engineers to select appropriate materials and lubrication to minimize the effects of shear stress.
6. The analytical results were validated with experimental results which helps the Engineers to predict the contact forces and behavior of the cam-follower mechanism more accurately. This information is essential for designing cam-follower systems that operate reliably and efficiently.

FUTURE SCOPE OF THE WORK:

An analysis is carried out to optimize the experimental results by using Artificial neural networks to determine the optimal set of parameters so that the engineers can optimize the design of the eccentric cam-follower mechanism. This optimization may involve changing material properties, adjusting lubrication, or modifying the shape of the cam profile to achieve better performance, reduced wear and tear, and increased durability.

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