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Development of a Digital Cam-Follower Test Rig for Simple Harmonic Motion Studies

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Abstract – *Traditional cam-follower test rigs rely on manual measurement techniques using tachometers, vernier scales, and protractors to analyze simple harmonic motion (SHM). These conventional methods are prone to human error, limited in precision, and unable to provide real-time data visualization. This research presents the development of an advanced digital cam-follower test rig integrating sensor-based data acquisition, automated measurement, and real-time computational analysis. The system employs a Royal Enfield Bullet cam-follower mechanism with a rotary encoder for RPM and angular position measurement, and a Linear Variable Differential Transformer (LVDT) for follower displacement measurement. An Arduino microcontroller transmits data to a custom Python software platform which implements signal processing algorithms to generate kinematic graphs: cam angle vs. follower displacement, velocity, and acceleration. The system also automatically reconstructs the complete cam profile. Experimental validation demonstrates measurement accuracy improvement of 95%, data acquisition time reduced by 80%, and the capability to analyze complex motion patterns previously undetectable with manual methods. This digital test rig serves as a modern pedagogical tool bridging theoretical concepts with Industry 4.0 measurement technologies.*

Keywords—*Cam-follower mechanism, simple harmonic motion, LVDT sensor, rotary encoder, data acquisition, Arduino, kinematic analysis, Python software.*

I. INTRODUCTION

Cam and follower mechanisms represent one of the most fundamental and widely utilized mechanical systems in modern engineering applications. From internal combustion engines and textile machinery to automated assembly lines and packaging equipment, cam mechanisms provide precise motion control through elegantly simple mechanical designs. The cam-follower system converts rotary motion into a predetermined reciprocating or oscillating motion of the follower, enabling complex motion profiles to be achieved through careful geometric design of the cam surface.

Analysis of cam-follower motion traditionally involves theoretical calculations based on cam geometry, followed by experimental validation. However, conventional test rigs in mechanical engineering laboratories have relied on manual measurement techniques that introduce significant errors and provide limited insight into dynamic behavior. Existing test rigs employ vernier calipers or dial gauges for displacement measurement, tachometers for speed, and protractors for angular position—each introducing reading errors due to parallax, interpolation uncertainty, and operator judgment. Cumulative errors can reach 5-10% in displacement and higher in velocity/acceleration calculations.

This research develops a comprehensive digital test rig that integrates modern sensor technology, microcontroller-based data acquisition, and real-time computational analysis to provide an advanced platform for studying cam-follower kinematics with significantly improved accuracy and efficiency.

II. LITERATURE REVIEW

Merticaru et al. (2023) presented a comprehensive analytical, numerical, and experimental analysis of a positive displacement cam mechanism, emphasizing the need for multi-method validation and establishing benchmarks for measurement accuracy. Chang (2023) investigated vibration behavior of flexible followers with time-dependent boundary effects, demonstrating that traditional rigid-body assumptions significantly underestimate dynamic effects at high speeds and validating the need for high-frequency data acquisition systems.

Yousuf (2023) conducted a nonlinear dynamics investigation revealing complex chaotic contact force behaviors, validating the importance of continuous data acquisition over discrete sampling. De Groote et al. (2022) pioneered physics-based neural network models for cam-follower dynamics prediction, suggesting that digital test rigs serve as active learning platforms contributing to design optimization and predictive maintenance.

Aathif Akmal and Jiang (2022) studied effects of cam rotational speeds on system performance using modern data acquisition systems, validating the need for variable-speed capability and real-time RPM measurement. Chang et al. (2022) developed fault identification methodologies for clearance in cam mechanisms using vibration signature analysis, demonstrating the educational value of enabling students to explore condition monitoring through experimentation. The literature identifies key gaps: lack of accessible digital educational test rigs, absence of real-time analysis platforms, and limited documentation of practical Arduino-based implementation for mechanical engineering laboratories.

III. METHODOLOGY

The digital test rig operates through synchronized measurement of cam angular position and follower linear displacement. The system architecture follows a unidirectional signal flow: Physical Motion → Sensors → Arduino → Python Analysis → Graphical Display.

Working Principle: A 24V DC gear motor (Yalu MY1016Z3, 350W) rotates the cam at variable speed (100-1000 RPM) via PWM driver. The Royal Enfield Bullet cam (base Ø30mm, lift 7mm) causes the spherical roller follower to reciprocate vertically following SHM. An EN-47 spring (OD=25mm, free length 90mm) maintains continuous cam-follower contact. The rotary encoder, coupled to the cam shaft, generates quadrature pulses for direction-aware angle measurement and an index pulse for zero reference once per revolution. Arduino firmware counts pulses to compute θ (degrees) and N (RPM). The LVDT core, mechanically coupled to the follower stem, produces an output voltage proportional to instantaneous displacement s (mm). Arduino's 10-bit ADC samples LVDT voltage at 100 Hz. Each cycle, Arduino transmits a CSV packet: TIME(ms), ANGLE(°), RPM, DISPLACEMENT(mm) over USB serial at 115,200 baud.

Table 1: System Block Diagram – Component Functions

BLOCK	FUNCTION	OUTPUT
Yalu MY1016Z3 Motor	Rotates cam at variable speed (100–1000 RPM)	Rotational shaft motion
Cam (Royal Enfield)	Base Ø30mm, lift 7mm; converts rotation to reciprocation	Mechanical displacement
Rotary Encoder	Measures cam angle (θ) and speed (RPM) via quadrature pulses	Digital pulse train (A/B/Z)
LVDT Sensor	Measures follower displacement (s), range ±10mm	Analog voltage (0–5V DC)
Arduino Uno	ADC conversion + encoder counting; USB serial @ 115200	Serial CSV data packets
Python Software	Receives data; computes v & a; plots 3 graphs + cam profile	Real-time visualization

Sensor Selection: LVDT was selected for displacement measurement due to its contactless operation (zero mechanical friction), infinite resolution (continuous analog output), high linearity (±0.25% FS over ±10mm range), and excellent frequency response up to 500 Hz. The incremental optical rotary encoder provides high angular resolution, quadrature output for direction detection, and an index pulse for absolute zero reference, enabling RPM computation via $N = (f_{pulse} \times 60) / PPR$.

Table 2: Comparison: Conventional vs Digital Measurement System

Parameter	Old Manual Method	New Digital System
Displacement	Vernier scale (±0.5mm error)	LVDT (±0.01mm)
Angular resolution	Protractor (±5° error)	Encoder (<1° resolution)
Speed measurement	Tachometer (±50 RPM)	Encoder-derived (±1 RPM)
Data points/revolution	10–15 manual readings	100–600 automated samples
Time per experiment	45–60 minutes	5–10 minutes
Acceleration calc.	Not feasible manually	Automatic (2nd derivative)

IV. DESIGN

The cam design uses a Royal Enfield Bullet cam with base diameter 30 mm, base radius R_b = 15 mm, follower lift h = 7 mm, maximum radius R_{max} = 22 mm, and rise angle β = 90°. The SHM displacement equation governing follower motion is:

$$s = (h/2)[1 - \cos(\pi\theta/\beta)]$$

The velocity and acceleration of the follower are derived by differentiating the displacement:

$$v = (\pi h\omega/2\beta)\sin(\pi\theta/\beta) \qquad a = (\pi^2 h\omega^2/2\beta^2)\cos(\pi\theta/\beta)$$

Motor Selection: Required power was calculated from spring force ($F_{spring} = 15 \times 3 = 45$ N), inertial force at 1000 RPM ($F_{inertia} = 0.15 \times 1526 = 229$ N), giving total force $F_{total} = 274$ N. Required torque $T = 274 \times 0.0035 = 0.96$ N·m. Power $P = 0.96 \times 104.7 = 100.5$ W. Applying safety factor 3 gives $P_{selected} = 300$ W. Selected: Yalu MY1016Z3, 24V DC, 350W rated.

Camshaft Design: Bending moment $M_b = 274 \times 0.120/4 = 8.22$ N·m. Torsional moment $T = 350/104.7 = 3.34$ N·m. Equivalent moment $M_{eq} = \sqrt{(8.22^2 + 3.34^2)} = 8.87$ N·m. Required diameter using EN45 steel (Sys = 404 MPa, SF = 3): $d = [16 \times 3 \times 8.87 / (\pi \times 404 \times 10^6)]^{(1/3)} = 16.73$ mm. Selected standard diameter: 25 mm.

Bearing Selection: Load per bearing = 274/2 = 137 N. Required dynamic load rating $C = 137 \times [(20{,}000 \times 60 \times 1000)/10^6]^{(1/3)} = 1{,}456$ N. Selected: SKF 6205-2RS (C = 14,000 N, bore 25 mm, rated to 6000 RPM), exceeding requirement by 10×.

Data Acquisition: Arduino Uno's ATmega328P 10-bit ADC samples conditioned LVDT voltage at 100 Hz (Timer1 interrupt-driven), yielding 1024 levels over 0-5V → 0.024 mm displacement resolution. Hardware interrupts on D2/D3 count encoder pulses with microsecond precision. Python's PySerial receives CSV data at 115,200 baud. Savitzky-Golay filtering (window=11) reduces noise. NumPy gradient computes velocity and acceleration via 1st and 2nd order numerical differentiation.

V. RESULTS AND ANALYSIS

Experimental validation was conducted across cam speeds of 100–600 RPM. At each speed, displacement data was collected and compared against theoretical SHM predictions. The Python software automatically generated three kinematic graphs and reconstructed the cam profile in polar coordinates $[r(\theta) = r_{base} + s(\theta)]$.

Table 3: Validation Results – Experimental vs Theoretical SHM

Speed (RPM)	Max Disp. Measured (mm)	Max Disp. Theoretical (mm)	Max Velocity Measured (mm/s)	Error %
100	6.93	7.00	47.2	1.0%
200	6.87	7.00	94.6	1.9%
300	6.85	7.00	141.5	2.1%
400	6.79	7.00	189.2	3.0%
600	6.72	7.00	283.4	4.0%

The displacement profiles show excellent agreement with theoretical SHM curves at lower speeds (100-300 RPM), with minor deviations at higher speeds attributable to follower inertia and spring dynamics. The velocity graph confirms sinusoidal behavior with maximum velocity at mid-stroke ($\theta = 45°$), consistent with SHM theory. Acceleration data shows the cosine profile transitioning from maximum positive at $\theta = 0°$ to maximum negative at $\theta = 90°$, with zero crossing at mid-rise as theoretically predicted. The system successfully reconstructed the cam profile diagram in polar form, enabling direct comparison with the Royal Enfield cam's theoretical geometry.

Key Performance Improvements: Measurement accuracy enhanced by 95% (from ±0.5mm manual to ±0.01mm digital); data acquisition time reduced by 80% (from 45-60 min to 5-10 min); data density increased from 15 to 600 points per revolution; real-time visualization enables students to observe dynamic effects instantaneously.

VI. CONCLUSION

This research successfully developed and validated a digital cam-follower test rig that transforms the traditional mechanical laboratory experiment into a modern, sensor-integrated learning experience. The system achieves 95% improvement in measurement accuracy through LVDT-based displacement sensing and encoder-based angular measurement, while reducing experimental time by 80% through automated data acquisition and Python-based real-time analysis.

The integration of Arduino microcontroller interfacing, Python signal processing, and real-time Matplotlib visualization creates a complete measurement chain that exposes students to Industry 4.0 technologies within a familiar mechanical engineering context. The system's ability to automatically compute and display displacement, velocity, and acceleration profiles simultaneously, and to reconstruct the cam profile from experimental data, provides pedagogical value impossible with traditional manual methods.

The design calculations—motor selection (350W Yalu MY1016Z3), camshaft design (25mm diameter EN45 steel), and bearing selection (SKF 6205-2RS)—ensure structural integrity for continuous educational use. The system is replicable by other institutions at low cost using commercially available Arduino, LVDT, and encoder components, addressing the critical infrastructure gap identified in the literature review.

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