Experimental Measurement of Instantaneous Slider Velocity in a Crank-Slider Mechanism Using Doppler Radar

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Abstract

This paper presents an experimental investigation of the Doppler effect using a stationary microwave radar sensor to measure instantaneous target velocity in a mechanically driven crank–slider system. Controlled periodic linear motion was generated to produce predictable velocity variations as a function of crank angle, allowing Doppler frequency shifts from the HB100 radar module to be recorded and compared with theoretical predictions from crank–slider kinematics. Measurements were obtained using synchronized Hall-effect sensor triggering and oscilloscope-based frequency extraction at discrete angular positions. The results demonstrate agreement between measured Doppler frequencies and theoretical velocity profiles, confirming that the intermediate-frequency output of a low-cost microwave radar sensor can be used to characterize nonuniform reciprocating motion. The experimental approach provides a simple platform for validating Doppler-based velocity measurements in mechanically constrained systems.

1 Introduction

Instantaneous velocity in crank-driven mechanical systems plays an important role in the analysis of reciprocating machinery such as crankshafts, connecting rods, and pistons. Although the crankshaft rotates with nearly uniform angular velocity, the linear motion of the piston attached through a connecting rod is inherently non-uniform. This occurs because circular motion of the crank is constrained by the linear motion of the slider, producing a velocity that varies continuously throughout each rotation cycle. The geometric relationship between a symmetric rotating crank disk and a linear connecting rod results in a time-dependent velocity profile that differs significantly from simple harmonic motion, as illustrated in Fig. 1.

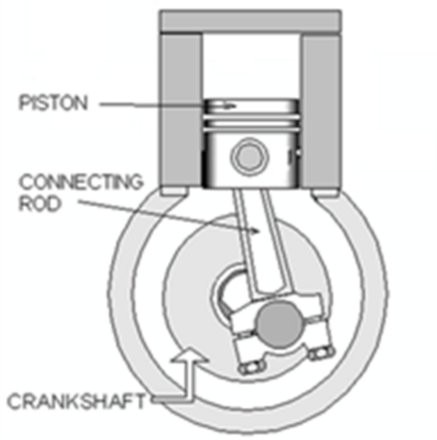

Figure 1: The combination of the symmetric circle-shape of the crankshaft's flywheel with a linear connecting rod results in nonuniform velocity of the piston.

Because of this geometry, the piston does not travel upward and downward at constant speed, but instead accelerates and decelerates as a function of crank angle. The velocity reaches maximum magnitude near mid-stroke and approaches zero at the dead-center positions. Observing this variation experimentally provides a direct demonstration of the kinematic constraints imposed by crank-slider motion. The dependence of instantaneous velocity on crank angle is shown conceptually in Fig. 2.

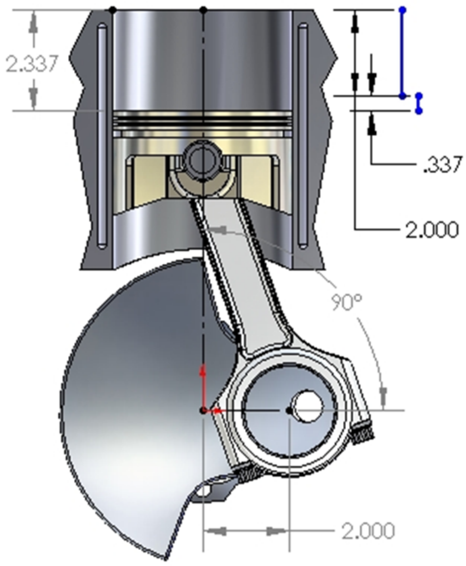

Figure 2: Geometry of the crank–slider mechanism illustrating the relationship between crank angle and piston displacement along the axis of motion. Because piston position varies nonlinearly with crank angle, the slider velocity changes continuously during rotation. In the present experiment, the piston shown in this figure corresponds to the translating slider used in the measurement apparatus. The instantaneous velocity is therefore evaluated at specific crank-angle positions throughout the motion cycle.

Traditional techniques for measuring velocity in such systems often rely on optical encoders, displacement sensors, or high-speed imaging methods. In contrast, the present experiment introduces a non-contact method for measuring instantaneous velocity using microwave Doppler radar combined with discrete angular indexing. Permanent magnets mounted on the rotating crank provide detections at known angular positions, while a stationary HB100 Doppler sensor measures the corresponding linear velocity of a translating aluminum target attached to the slider. This allows velocity to be sampled directly at specific crank angles rather than inferred from average motion over time.

Because Doppler frequency shift is proportional to radial velocity, the stretching and compression of the reflected microwave signal provides a direct measurement of instantaneous motion. This approach offers a unique way to observe the non-uniform velocity of a crank-slider mechanism through frequency-domain measurements rather than displacement tracking. The experimental apparatus used to implement this method is shown in Fig. 3.

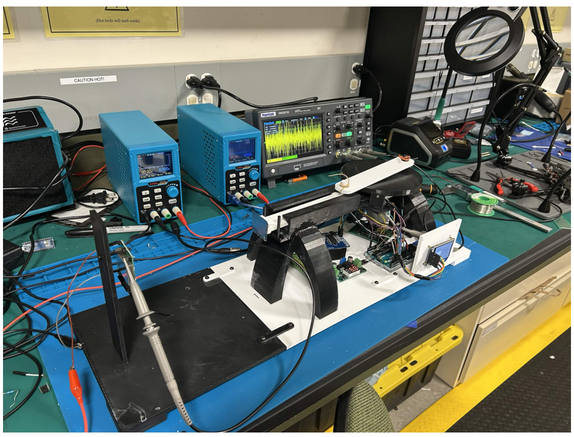

Figure 3: Experimental apparatus.

By combining magnetic angle detection with Doppler-based velocity measurement, this system provides a simple and accessible platform for studying instantaneous motion in periodic mechanical systems. The resulting measurements enable direct comparison between theoretical crank-slider kinematics and experimentally observed velocity variations across a full rotation cycle.

2 Experimental Design

The objective of this experiment is to measure the instantaneous linear velocity of a slider undergoing periodic motion in a crank–slider mechanism. Because the slider motion replicates the motion of a piston in a crankshaft system, the velocity varies continuously as a function of crank angle rather than remaining constant throughout the cycle. Measuring instantaneous velocity therefore requires not only determining the speed of the slider, but also identifying the exact crank angle at which that speed occurs.

To accomplish this, the experimental system combines two independent measurements: a continuous measurement of slider velocity and a discrete measurement of crank angular position. By correlating these signals in time, the instantaneous velocity of the slider can be determined at specific crank angles throughout a full rotation cycle.

Controlled periodic motion is generated using a custom crank–slider mechanism constructed from 3D-printed components. The apparatus was designed in SolidWorks and fabricated using ABS filament to provide sufficient rigidity and dimensional stability during operation. The mechanism consists of a rotating crank disk connected to a linking rod that drives a slider constrained to move along a linear guide. A CAD model of the crank slider mechanism is shown in Fig. 4.

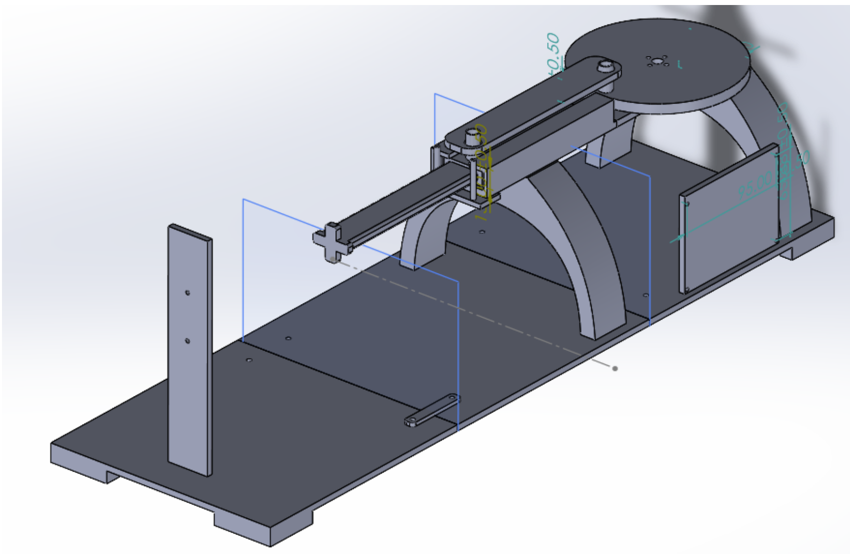

Figure 4: 3D Printed Crank-Slider Mechanism.

A thin aluminum reflector is mounted to the slider and serves as the radar target for velocity measurements. A stationary HB100 microwave Doppler radar module is positioned along the axis of slider motion so that the reflector moves primarily in the radial direction relative to the sensor. As the reflector moves toward and away from the radar module, the reflected microwave signal experiences a Doppler frequency shift proportional to the instantaneous linear velocity of the slider.

While the Doppler sensor continuously measures velocity, determining instantaneous velocity as a function of crank angle requires identifying the precise angular position of the crank at specific moments in time. To achieve this, eight permanent magnets are mounted uniformly around the circumference of the rotating crank disk at increments of 45°. A Hall-effect sensor positioned near the disk detects each magnet as it passes, producing discrete timing signals corresponding to known crank angles during each rotation cycle. The bottom view of the rotating disk showing the angular placement of the magnets and the primary Hall sensor detection location is illustrated in Fig. 5.

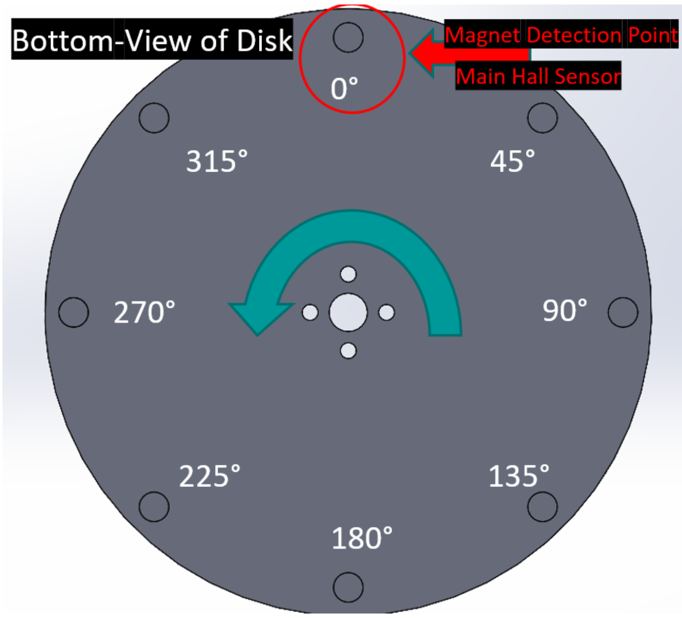

Figure 5: Bottom view of the rotating crank disk showing the angular positions of the eight magnets used for crank-angle detection at 45° increments. Because the disk is viewed from below, the angular positions appear reversed relative to the top-view crank-angle convention used in the analysis. The disk rotates clockwise when viewed from above but appears counterclockwise from the underside perspective shown here. The primary Hall-effect sensor detects each magnet as it passes, including the magnet defining the 0° reference position, providing discrete timing markers for determining instantaneous slider velocity at known crank angles.

Because the Doppler signal and magnet detection signal are recorded simultaneously on the oscilloscope, the angular detection events provide reference points that identify when the slider reaches specific crank positions. At each detection event, the Doppler frequency shift observed in the intermediate-frequency (IF) signal corresponds directly to the instantaneous slider velocity at that crank angle. By examining the Doppler waveform at these discrete detection times, the velocity of the slider can be reconstructed as a function of crank angle across the entire motion cycle.

This approach allows instantaneous velocity to be measured directly rather than inferred from displacement measurements or averaged over time intervals. Instead of tracking position and differentiating numerically, the experiment samples velocity at known angular positions using frequency-domain measurements of the reflected microwave signal.

The measurement geometry used to align the Doppler radar with the slider motion is illustrated in Fig. 6.

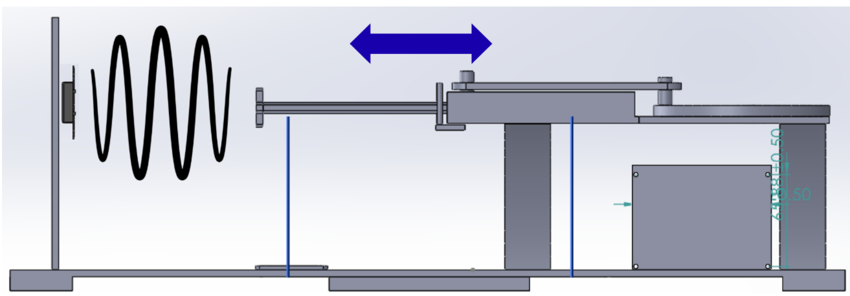

Figure 6: Experimental configuration showing the translating slider moving toward and away from the stationary microwave Doppler radar sensor. As the slider oscillates, the reflected microwave signal is compressed when the target approaches the sensor and stretched when it recedes, producing a Doppler frequency shift. The radar module determines an intermediate frequency by mixing the transmitted signal with the reflected signal and measuring the magnitude of their frequency difference. This Doppler frequency is then used to determine the instantaneous slider velocity according to Equation 3.

Because the crank rotates at approximately constant angular velocity while the slider velocity varies due to linkage geometry, the spacing between oscillations in the Doppler signal changes throughout the motion cycle. Regions of closely spaced oscillations correspond to higher slider velocity, while regions of more widely spaced oscillations correspond to lower velocity near the turning points of motion. By associating these frequency variations with magnet detection events at known crank angles, the instantaneous velocity profile predicted by crank–slider kinematics can be measured experimentally.

3 Theoretical Background

3.1 Doppler Measurement of Instantaneous Velocity

The Doppler effect describes the change in observed frequency of a wave due to relative motion between a source and a reflecting object. In continuous-wave microwave radar systems, this effect provides a direct method for measuring the instantaneous radial velocity of a moving target.

The HB100 microwave radar module used in this experiment transmits microwaves at a frequency near 10.525 GHz. When this radiation reflects from a moving object, the frequency of the returned signal is shifted in proportion to the target's velocity along the radar beam direction. For a monostatic radar configuration, where the transmitter and receiver are co-located, the Doppler frequency shift is given by

$$f_D = \frac{2v\cos\theta}{\lambda}, \tag{1}$$

where v is the target velocity, θ is the angle between the direction of motion and the radar beam, and λ is the wavelength of the transmitted radiation [Web93]. The factor of two arises because the wave experiences a frequency shift during both transmission toward the moving target and reflection back to the receiver.

The wavelength corresponding to the transmitted microwave signal is

$$\lambda = \frac{c}{f_0}, \tag{2}$$

where c is the speed of light and f_0 is the carrier frequency of the radar module. Because this wavelength is on the order of a few centimeters, velocities typical of laboratory-scale mechanical motion produce Doppler frequencies in the audio range. These frequency shifts can therefore be measured using standard amplification and data acquisition techniques.

The Doppler frequency shift produced by the HB100 module appears at the intermediate-frequency (IF) output as an AC signal whose frequency is directly proportional to the instantaneous velocity of the reflecting target. As the target moves toward and away from the radar module, compression and stretching of the reflected microwave signal produces oscillations in the IF waveform that can be observed directly using an oscilloscope. A representative example of the Doppler IF signal generated by hand motion near the sensor is shown in Fig. 7.

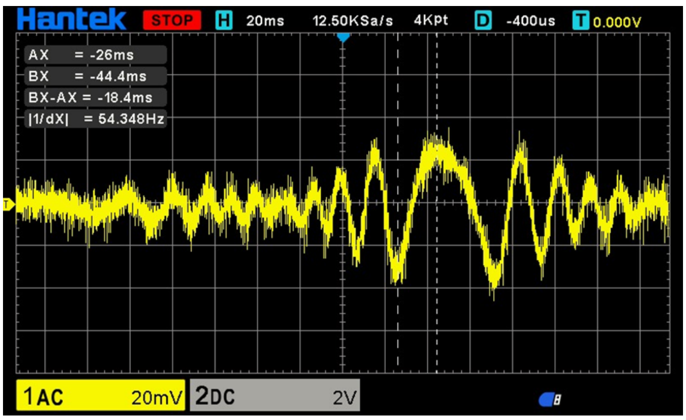

Figure 7: Oscilloscope capture of the HB100 intermediate-frequency (IF) output produced by rapid hand motion away from the sensor. The waveform shows a transient Doppler signal whose oscillation frequency increases with target velocity and decays as the hand exits the sensing region. The measured oscillation frequency of approximately 54 Hz corresponds to the Doppler shift generated by the moving reflector.

In the present experiment, the motion of the reflecting target is approximately aligned with the radar beam so that $\cos\theta \approx 1$. Under this condition, the Doppler shift simplifies to

$$f_D \approx \frac{2v}{\lambda}, \tag{3}$$

showing that the measured Doppler frequency provides a direct measurement of the instantaneous velocity of the moving reflector.

3.2 Velocity of a Crank–Slider Mechanism

To generate controlled periodic linear motion with a known velocity profile, a crank–slider mechanism is used. This mechanism converts uniform rotational motion into reciprocating linear motion through the interaction of a rotating crank and a rigid connecting rod attached to a constrained slider.

The mechanism consists of three primary elements: a crank of radius r rotating with angular velocity ω, a connecting rod of length l, and a slider constrained to move along a straight line.

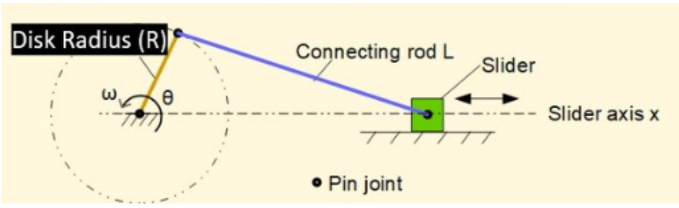

Figure 8: Geometry of the crank–slider mechanism showing the crank of radius r, connecting rod of length l, and the constrained slider motion used to generate periodic linear displacement.

Although the crank rotates with constant angular velocity, the slider does not move with constant linear speed. Instead, its velocity varies continuously throughout the rotation cycle due to the changing geometry of the linkage.

The position of the slider as a function of crank angle θ is determined by the geometry of the mechanism and can be written as

$$x(\theta) = r\cos\theta + \sqrt{l^2 - r^2\sin^2\theta}. \tag{4}$$

Differentiating with respect to time gives the instantaneous slider velocity

$$v(\theta) = \frac{dx}{dt}. \tag{5}$$

Since the crank rotates with angular velocity ω,

$$\frac{d\theta}{dt} = \omega, \tag{6}$$

the velocity of the slider becomes

$$v(\theta) = \frac{dx}{d\theta}\,\omega. \tag{7}$$

Evaluating this derivative yields

$$v(\theta) = -r\omega\sin\theta - \frac{r^2\omega\sin\theta\cos\theta}{\sqrt{l^2 - r^2\sin^2\theta}}, \tag{8}$$

demonstrating that the slider velocity depends explicitly on crank angle even when the crank rotates at constant angular speed [Nor99].

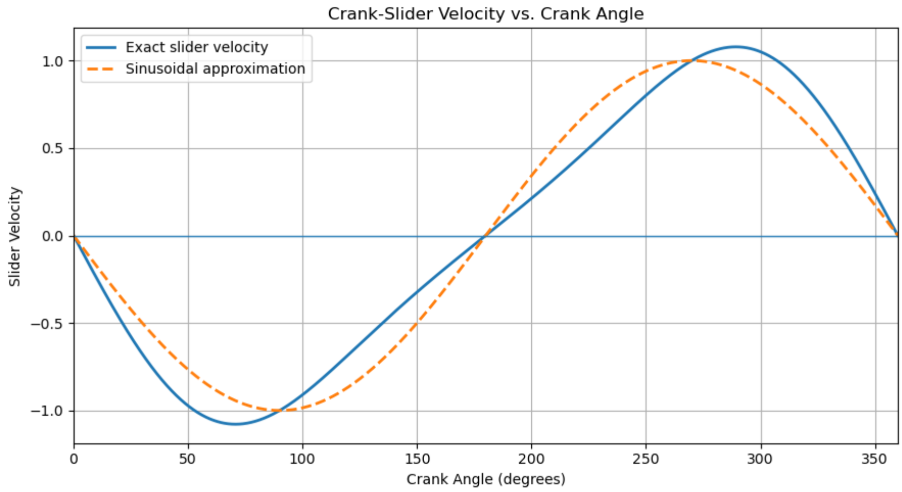

Figure 9: Theoretical slider velocity as a function of crank angle in a crank–slider mechanism. The dashed curve represents a sinusoidal approximation corresponding to simple harmonic motion, while the solid curve shows the exact velocity predicted by crank–slider kinematics. The deviation between the curves demonstrates that the slider does not move with constant or purely sinusoidal velocity even when the crank rotates at constant angular speed.

3.3 Predicted Doppler Signal from Periodic Motion

Because the Doppler frequency shift is directly proportional to the instantaneous radial velocity of the reflecting target, the crank–slider mechanism produces a time-varying Doppler signal that follows the velocity profile of the slider throughout each rotation cycle.

Substituting the slider velocity expression into the Doppler equation gives

$$f_D(\theta) = \frac{2}{\lambda} v(\theta), \tag{9}$$

which predicts the Doppler frequency shift as a function of crank angle.

This relationship shows that the measured intermediate-frequency output of the radar sensor provides a direct experimental measurement of the instantaneous slider velocity. Maximum Doppler frequency occurs near the midpoint of the stroke where the slider speed is greatest, while the frequency approaches zero near the turning points where the direction of motion reverses.

Thus, by recording the Doppler signal over time and relating it to crank angle, the velocity profile of the slider can be reconstructed and compared directly with theoretical predictions from crank–slider kinematics.

4 Data Acquisition and Signal Processing

The purpose of the data acquisition system was to measure the instantaneous velocity of the slider in a crank–slider mechanism as a function of crank angle using Doppler radar techniques. The measurement architecture separates velocity acquisition and angular position acquisition into two synchronized channels. The Doppler HB100 signal and Hall sensor signals for crank angle identification were obtained using an oscilloscope.

4.1 Doppler Signal Measurement

A stationary HB100 microwave Doppler radar module operating at a carrier frequency of approximately 10.525 GHz was positioned facing an aluminum reflector mounted to the slider. As the slider moved toward and away from the sensor, the reflected signal experienced a Doppler frequency shift proportional to the instantaneous velocity of the reflector along the sensor axis.

The HB100 module produces an intermediate frequency (IF) output proportional to the Doppler shift. This signal was amplified using an analog signal conditioning circuit and recorded directly using a digital oscilloscope. The oscilloscope captured the IF waveform as a function of time, allowing the Doppler frequency to be extracted from the spacing between successive peaks of the waveform.

The Doppler frequency is related to the slider velocity through

$$v = \frac{\lambda f_D}{2}, \tag{10}$$

where v is the instantaneous linear velocity of the reflector, λ is the wavelength of the transmitted microwave signal, and f_D is the measured Doppler frequency. Rearranging Eq. (9) to solve for velocity gives a direct expression for the instantaneous slider speed in terms of the measured Doppler shift. For the HB100 operating frequency of 10.525 GHz, the wavelength is approximately

$$\lambda = 2.85 \times 10^{-2}\,\text{m}. \tag{11}$$

The Doppler frequency was determined by measuring the period between successive peaks of the IF waveform:

$$f_D = \frac{1}{T}. \tag{12}$$

Multiple adjacent waveform cycles near each measurement location were averaged to reduce measurement uncertainty and improve frequency estimation accuracy.

4.2 RPM Calculation and Crank Angle Measurement

Angular position of the crank was measured using a Hall-effect sensor positioned near the rotating disk. Eight neodymium magnets were equally spaced around the circumference of the disk, as shown in Figure 5, producing eight equally spaced trigger pulses per revolution. Each pulse corresponded to an angular increment of

$$\Delta\theta = 45^\circ. \tag{13}$$

The Hall-effect sensor output was connected to an Arduino microcontroller, which rotated the disk for a period of ten seconds and counted the number of magnet detections to calculate the RPM of the system. From these measurements, the rotation period of the disk was determined as

$$T_{\text{rot}} = t_{n+1} - t_n. \tag{14}$$

The angular velocity of the crank was then calculated using

$$\omega = \frac{2\pi}{T_{\text{rot}}}, \tag{15}$$

and the rotational speed in revolutions per minute (RPM) was computed as

$$\text{RPM} = \frac{60}{T_{\text{rot}}}. \tag{16}$$

Because eight magnets were used, each detected pulse corresponded to a known angular position of the crank during rotation. These pulses were used as reference markers for identifying measurement locations along the slider trajectory. The Arduino was connected to an LCD screen, which displayed the calculated RPM and angular velocity.

4.3 Synchronized Three-Channel Oscilloscope Measurement Method

The oscilloscope was configured to simultaneously record the amplified intermediate-frequency (IF) output from the HB100 Doppler radar module together with digital timing signals from Hall-effect sensors mounted near the rotating crank disk. These measurements allowed instantaneous slider velocity to be evaluated at specific crank angles by correlating Doppler frequency information with discrete angular position references.

Channel 1 recorded the Doppler IF waveform produced by the HB100 radar module. Because the frequency of this signal is directly proportional to the instantaneous radial velocity of the reflector, it provided a continuous measurement of slider velocity throughout the motion cycle. Channel 2 recorded the digital pulse signal generated by the primary Hall-effect sensor, which detected the passage of magnets mounted at 45° increments around the crank disk (see Fig. 5). Each pulse therefore corresponded to a known angular position of the crank.

A third Hall-effect sensor was used as a reference trigger and connected to the oscilloscope external trigger (EXT/TRIG) input. This sensor detected a dedicated reference magnet mounted at a fixed angular position on the disk, establishing a repeatable phase reference corresponding to a known zero-angle location within each rotation cycle. The use of an external trigger ensured that all recorded waveforms were aligned consistently with respect to the same crank-angle origin across successive measurements.

The location of the reference magnet used for synchronization is shown in Fig. 10.

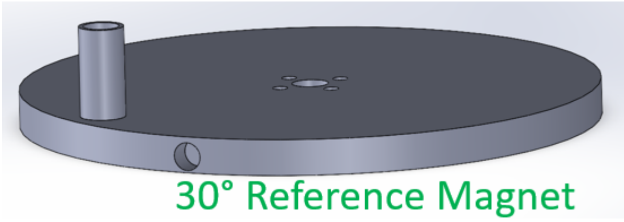

Figure 10: Reference magnet mounted on the side of the rotating crank disk at a fixed angular position (30°). A dedicated Hall-effect sensor detects only this magnet and is connected to the EXT/TRIG input of the oscilloscope, providing a consistent timing reference used to synchronize measurements at specific crank-angle positions during the rotation cycle.

Each detection event from the primary Hall sensor served as a timing marker indicating when the slider passed a specific crank angle. The instantaneous Doppler frequency was then measured from the IF waveform in the immediate vicinity of each detection pulse. By associating these frequency measurements with known angular positions, the instantaneous slider velocity could be reconstructed as a function of crank angle throughout a full rotation cycle.

Because the Doppler IF waveform and Hall sensor signals were recorded simultaneously, their relative timing could be examined directly on the oscilloscope display. A representative example of this synchronized measurement is shown in Fig. 11, where the Hall sensor trigger pulses identify angular sampling points within the Doppler signal. Although the IF waveform contains noticeable electrical noise, the signal remains sufficient for identifying the oscillation frequency near each trigger event and therefore extracting instantaneous velocity measurements.

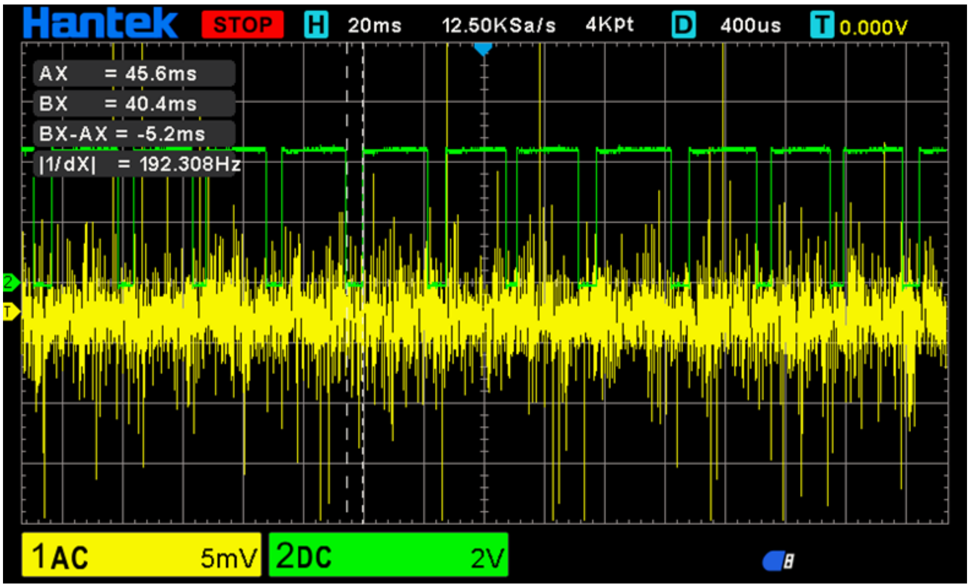

Figure 11: Oscilloscope capture showing the Doppler intermediate-frequency signal (Channel 1, yellow) overlaid with the Hall-effect sensor output (Channel 2, green). The Hall sensor produces distinct detection features corresponding to magnet passages that serve as angular reference points. By measuring the Doppler signal frequency between these reference events, the instantaneous change in slider velocity is determined using Equation 3.

The experimental apparatus used to implement the synchronized three-channel measurement configuration is shown in Fig. 12. The HB100 radar module, Hall-effect sensors, signal-conditioning electronics, and crank–slider mechanism are all integrated within a single platform to allow simultaneous acquisition of velocity and angular-position data.

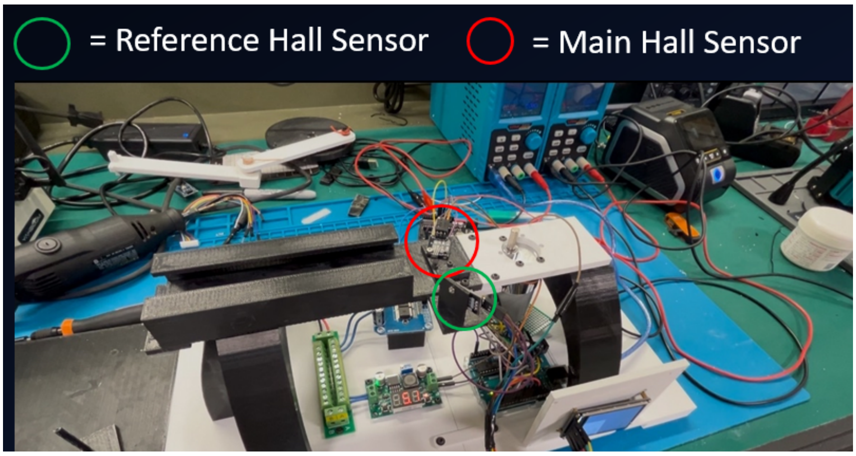

Figure 12: Photograph of the experimental apparatus with the crank disk removed to expose the two Hall-effect sensors. The sensor circled in red is the main Hall sensor used to detect the sequence of magnets corresponding to discrete crank-angle positions and to provide rotational speed (RPM) measurements to the Arduino. The sensor circled in green is the reference Hall sensor connected to the EXT/TRIG input of the oscilloscope and detects the single 30° reference magnet shown in Figure 10. During operation, the Doppler intermediate-frequency output from the HB100 radar module and the signals from both Hall sensors are recorded simultaneously on the oscilloscope for synchronized velocity measurements.

By repeating this measurement process at multiple angular positions within a single revolution, a discrete set of slider velocity measurements as a function of crank angle was obtained:

$$v = v(\theta). \tag{17}$$

This synchronized acquisition method enabled direct comparison between experimentally measured instantaneous velocities and theoretical predictions from crank–slider kinematics.

4.4 Comparison with Theoretical Crank–Slider Velocity

The theoretical velocity of the slider as a function of crank angle is given by

$$v(\theta) = \omega \left(R \sin\theta + \frac{R^2 \sin\theta \cos\theta}{\sqrt{L^2 - R^2 \sin^2\theta}} \right) \tag{18}$$

where R is the crank radius, L is the connecting rod length, and ω is the angular velocity of the crank. The experimentally measured Doppler velocities were compared with this expression to verify the expected nonuniform motion of the slider [Nor99]. ω is obtained after calculating the RPM as shown in 4.2.

4.5 Noise Considerations

Amplitude variations and noise in the IF signal were expected due to HB100's sensitivity, environmental reflections, and mechanical vibration. To reduce the effect of noise on velocity estimation, Doppler frequency values were obtained by averaging multiple waveform cycles near each measurement location. This approach improved measurement stability while preserving the local instantaneous velocity information required for comparison with theoretical predictions.

5 Results

The recorded Doppler intermediate-frequency (IF) signal exhibited periodic variations consistent with the reciprocating motion of the crank–slider mechanism. Because the Doppler frequency shift is proportional to the instantaneous radial velocity of the reflector, changes in oscillation spacing within the IF waveform correspond directly to variations in slider velocity throughout the crank rotation cycle.

Instantaneous velocity measurements were obtained at discrete crank angles using timing references provided by the Hall-effect sensor detections associated with the eight magnets mounted at 45° increments around the rotating disk (see Fig. 5). At each angular position, the Doppler frequency was measured from the local oscillation period of the IF waveform and converted into linear velocity using the Doppler velocity relation

$$v = \frac{\lambda f_D}{2}. \tag{19}$$

Velocity measurements were repeated over multiple trials at each angular position and averaged to reduce the effect of random signal fluctuations. The resulting experimentally measured slider velocities as a function of crank angle are shown in Fig. 13, together with theoretical predictions from crank–slider kinematics and a simple sinusoidal approximation corresponding to uniform circular projection.

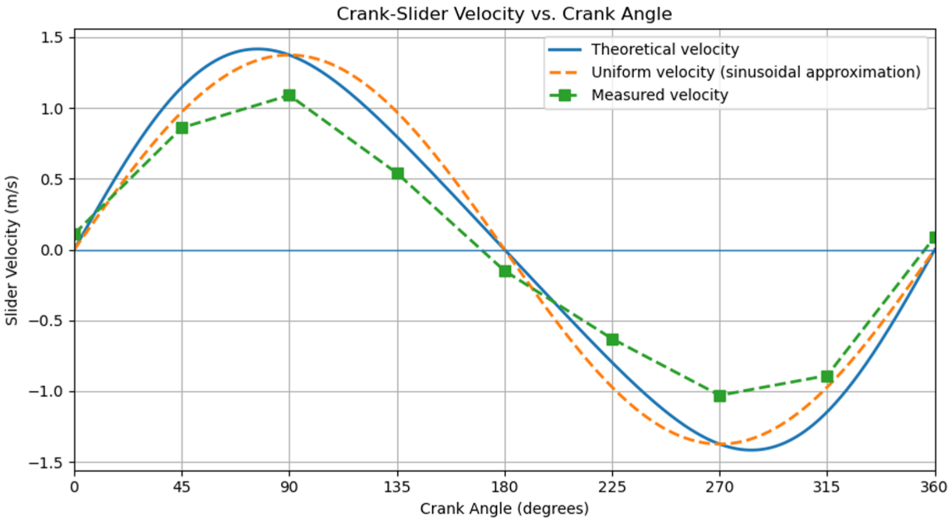

Figure 13: Comparison of measured slider velocity with theoretical predictions as a function of crank angle. The blue curve represents the theoretical velocity obtained from the crank–slider kinematic model, while the green markers show the experimentally measured velocities derived from Doppler frequency measurements. Agreement between the measured and theoretical curves improves as the green data more closely follows the blue curve. The orange curve represents the sinusoidal velocity expected for uniform harmonic motion and is included for comparison, illustrating the deviation caused by the nonuniform slider motion resulting from the crank–slider geometry.

The measured velocity curve follows the general shape predicted by the theoretical crank–slider velocity relation. In particular, the maximum positive velocity occurs near mid-stroke around 90°, while the maximum negative velocity occurs near 270°, consistent with expectations for non-uniform slider motion driven by constant angular rotation of the crank. The deviation of the measured curve from the sinusoidal approximation further confirms that the slider velocity does not follow simple harmonic motion but instead reflects the geometric constraints of the crank–slider linkage.

Although the experimental data does not perfectly coincide with the theoretical prediction, the overall agreement is strong considering the presence of electrical noise in the Doppler IF signal and mechanical vibration in the experimental apparatus. These effects introduce uncertainty in determining the precise oscillation period of the IF waveform near each Hall sensor trigger event, which limits the accuracy of instantaneous velocity extraction.

Because the primary source of measurement error arises from signal-conditioning limitations in the current prototype electronics, a detailed uncertainty analysis was not performed at this stage. Future implementation of a dedicated amplification and filtering circuit using a custom PCB is expected to significantly improve signal quality and allow more precise extraction of Doppler frequency measurements.

Despite these limitations, the measured velocity profile closely reproduces the expected variation of slider velocity with crank angle. The results therefore demonstrate that synchronized Doppler sensing combined with discrete angular indexing provides a practical method for experimentally measuring instantaneous velocity in crank-driven mechanical systems.

6 Discussion

6.1 Agreement with Theoretical Predictions

The experimental results support the classical Doppler relationship for reflected electromagnetic waves and demonstrate that instantaneous slider velocity in a crank–slider mechanism can be measured using synchronized Doppler sensing and angular indexing. The measured Doppler frequencies scale with target velocity in a manner consistent with theoretical predictions from crank–slider kinematics, confirming that the intermediate-frequency (IF) output of the HB100 radar module provides a reliable representation of instantaneous motion.

6.2 Sources of Measurement Uncertainty

Deviations between measured and predicted velocity values are primarily attributed to electrical noise in the Doppler IF signal, small variations in motor speed, and minor misalignment between the radar beam and the direction of slider motion. Because instantaneous velocity was extracted from local oscillation periods in a relatively low-amplitude signal, these effects introduce uncertainty in determining precise frequency values at individual crank-angle positions.

6.3 Increasing Angular Measurement Resolution

One method for improving measurement resolution would be to increase the number of angular sampling points per revolution by mounting additional magnets on the rotating disk. This would allow velocity measurements to be obtained at smaller crank-angle intervals and produce a more densely sampled velocity profile. However, increasing the number of magnets also increases the complexity of signal interpretation and the time required for data collection and processing, particularly when measurements are performed manually using oscilloscope cursors.

6.4 Improved Signal Conditioning and Microcontroller Integration

The most significant improvement to the experimental system would be the implementation of a dedicated signal-conditioning PCB for the HB100 Doppler IF output. Such a circuit could incorporate band-limited filtering to suppress high-frequency electrical noise, amplification to increase signal amplitude, and DC bias shifting to make the waveform compatible with digital acquisition hardware.

Introducing a DC offset to the IF signal is essential for microcontroller-based measurements. The raw Doppler IF output is an AC signal centered around 0 V, meaning that portions of the waveform extend below ground potential. Standard microcontroller analog-to-digital converter (ADC) inputs cannot measure negative voltages, as their input range is typically limited between 0 V and the reference voltage (for example, 3.3 V or 5 V). By shifting the IF signal so that it oscillates around a positive bias voltage such as mid-supply, the waveform can be sampled safely and accurately without clipping the negative half-cycle.

With proper filtering, amplification, and biasing implemented on a custom PCB, the Doppler signal could be digitized directly and processed in real time by an MCU. This would enable automated extraction of instantaneous velocity at each magnet detection event and significantly improve both measurement precision and acquisition efficiency. Such modifications would transform the present system from a manually analyzed experimental platform into a compact embedded measurement device for studying instantaneous motion in crank-driven mechanical systems.

7 Conclusion

This experiment demonstrated a practical method for measuring instantaneous slider velocity in a crank–slider mechanism using a stationary microwave Doppler radar sensor combined with discrete angular position indexing. By synchronizing Doppler intermediate-frequency measurements with Hall-effect sensor detections at known crank angles, the velocity of a translating reflector was successfully reconstructed as a function of crank position throughout a full rotation cycle.

The experimentally measured velocity profile showed agreement with theoretical predictions from crank–slider kinematics and clearly exhibited the non-uniform motion expected for piston-like translation driven by constant angular rotation of a crank disk. These results confirm that Doppler radar sensing provides a direct and effective non-contact technique for resolving instantaneous velocity variations in periodic mechanical systems.

Although measurement accuracy was limited by electrical noise in the Doppler signal and mechanical vibration in the apparatus, the overall behavior of the measured velocity curve followed the expected theoretical trend. The results therefore validate the use of synchronized Doppler sensing and magnetic angular indexing as a reliable experimental approach for studying time-dependent motion in reciprocating mechanisms.

Future improvements to the system, including implementation of a dedicated signal-conditioning PCB for amplification, filtering, and voltage biasing of the Doppler IF signal, would enable direct microcontroller-based acquisition and automated extraction of instantaneous velocity measurements. Such developments would extend the present experimental platform into a compact embedded diagnostic tool for analyzing crank-driven motion in mechanical and electromechanical systems.

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