Doppler Radar Measurements of Periodic Motion

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Abstract

This paper presents an experimental investigation of the Doppler effect using a stationary microwave radar sensor and a mechanically driven crank–slider system to produce controlled periodic target motion, with measured Doppler frequency shifts compared to theoretical predictions.

1 Introduction

The Doppler effect describes the change in observed frequency of a wave due to relative motion between a source and an observer or reflecting object. The effect applies to electromagnetic waves and forms the basis of radar-based velocity measurements [Nol20, Web93]. In continuous-wave radar systems, Doppler shifts arise from the reflection of transmitted microwaves from moving targets, allowing radial velocity to be inferred from measured frequency changes.

Low-cost microwave Doppler modules such as the HB100 operate at approximately 10.525 GHz and are commonly used in motion detection systems [Man21, ?]. Prior studies have demonstrated their ability to detect motion and measure frequency shifts, but many implementations focus on practical sensing applications rather than experimental validation of Doppler theory [?].

The objective of this work is to experimentally measure Doppler frequency shifts produced by a target undergoing controlled periodic linear motion and to compare the measured shifts with theoretical predictions. By combining a stationary HB100 radar sensor with a mechanically driven crank–slider mechanism, this experiment provides a simple laboratory validation of Doppler radar principles.

Doppler radar sensors are widely used for motion detection due to their ability to directly measure velocity without requiring physical contact or optical tracking. Low-power microwave Doppler modules, such as the HB100 radar sensor, operate by transmitting a continuous-wave signal and producing an intermediate-frequency (IF) output proportional to the radial velocity of a reflecting target. These sensors are commonly employed in security systems and motion detectors, and their signal characteristics have been well documented in prior studies [Man21, LLC07]. Despite their widespread use, Doppler radar sensors are often treated as black-box devices, with limited emphasis on experimental validation of the underlying Doppler theory in controlled laboratory settings.

The objective of this project is to experimentally verify Doppler radar theory by measuring frequency shifts produced by a target undergoing controlled periodic linear motion. A stationary HB100 microwave radar sensor is used to record Doppler signals generated by a mechanically driven crank–slider system, which converts rotational motion from a motor into repeatable linear motion toward and away from the sensor. A lightweight aluminum reflective deflector is mounted to the slider to provide a consistent radar cross-section while minimizing mechanical load on the system. Aluminum is chosen for its high electrical conductivity, low mass, and common use as a radar reflector in experimental and applied settings.

To enable accurate data acquisition, the low-amplitude IF output of the HB100 sensor is amplified using an LM358 operational amplifier circuit and digitized by an Arduino microcontroller. The recorded Doppler signal is then analyzed to extract frequency information as a function of time, allowing experimental Doppler shifts to be compared directly with theoretical predictions based on the known kinematics of the crank–slider mechanism. By combining a simple mechanical system with accessible electronics, this experiment provides a clear and quantitative demonstration of Doppler radar principles while highlighting the relationship between target velocity, signal processing, and measured frequency shifts.

2 Theoretical Background

2.1 Doppler Radar Theory

The Doppler effect describes the change in observed frequency of a wave due to relative motion between a source and an observer. While originally derived for sound waves, the same principle applies to electromagnetic radiation and is widely used in radar velocity measurements [**?**, **?**].

In a continuous-wave microwave radar system such as the HB100 module used in this experiment, a signal of frequency f_0 is transmitted toward a target. When the target moves with radial velocity v, the reflected wave experiences a frequency shift due to the Doppler effect. The Doppler frequency shift is given by

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

(1)

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

The HB100 microwave module operates near 10.525 GHz. The corresponding wavelength is

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

where c is the speed of light. At this wavelength (approximately a few centimeters), even small target velocities produce Doppler frequencies in the audio range, allowing them to be measured using amplification and signal processing circuits [**?**].

In this experiment the motion of the reflector 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 is directly proportional to the radial velocity of the moving reflector. Accurate control and understanding of the reflector velocity is therefore essential for validating Doppler measurements experimentally.

2.2 Crank–Slider Theory

To generate controlled periodic linear motion, a crank–slider mechanism is used. A crank–slider converts rotational motion into reciprocating linear motion and is commonly used in mechanical systems such as engines and pumps [Nig15, Nor99].

The mechanism consists of three main elements:

- a rotating crank of radius r,
- a rigid connecting rod of length l,
- a slider constrained to move along a straight line.

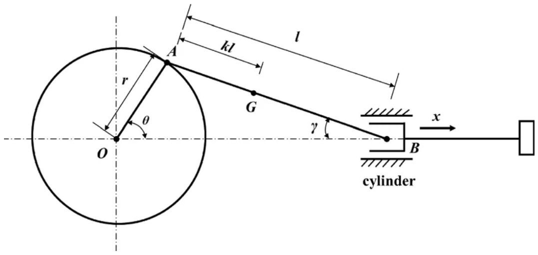


Figure 1: Geometry of the crank–slider mechanism used to generate periodic linear motion. The crank of radius r rotates with angular velocity ω and drives the slider through a connecting rod of length l.

As the crank rotates with angular velocity ω, the slider moves back and forth along its linear path. The geometry of the mechanism determines the displacement of the slider as a function of crank angle. For typical crank–slider systems, the peak-to-peak displacement of the slider is approximately

$$\Delta x \approx 2r, \tag{4}$$

meaning the crank radius directly determines the total travel distance of the slider.

An important feature of the crank–slider mechanism is that the slider does not move with constant velocity. Even if the crank rotates at a constant angular speed, the slider velocity varies continuously during each cycle. This occurs because the geometric relationship between the crank and connecting rod changes as the crank rotates [Nig15, Nor99].

Near the midpoint of the stroke, the motion of the slider is primarily influenced by the tangential component of the crank motion, causing the slider velocity to reach a maximum. In contrast, near the ends of the stroke the crank motion becomes nearly perpendicular to the direction of slider motion. At these positions the slider momentarily slows before reversing direction. As a result, the slider undergoes continuous acceleration and deceleration throughout the cycle.

This non-uniform motion is important for the present experiment because the Doppler frequency produced by the radar sensor depends directly on the instantaneous velocity of the reflector. When the slider velocity is highest, the Doppler frequency shift is largest. Near the turning points of the motion, where the slider velocity approaches zero, the Doppler shift correspondingly decreases.

The crank radius also plays a key role in determining the measurable Doppler signal. Increasing the crank radius increases the slider displacement and the maximum linear velocity, since the tangential speed of the crank is

$$v_{\max} \approx r\omega. \tag{5}$$

Larger crank radii therefore produce larger Doppler frequency shifts. However, excessively large displacements can introduce mechanical vibration or instability in the experimental apparatus. For this reason the crank radius must be selected to balance mechanical stability with the ability to produce measurable Doppler frequencies.

Understanding the kinematics and geometry of the crank–slider mechanism is therefore essential for predicting the velocity profile of the moving reflector and interpreting the Doppler signals measured during the experiment.

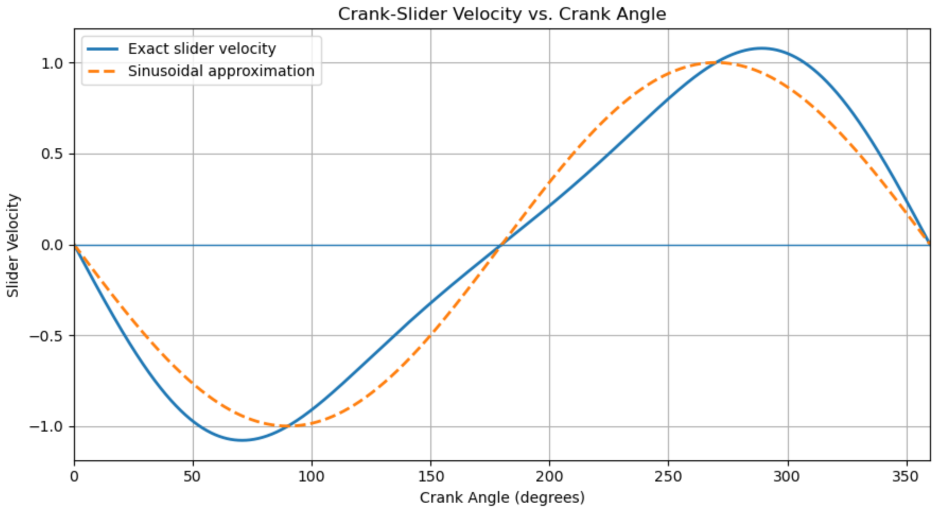
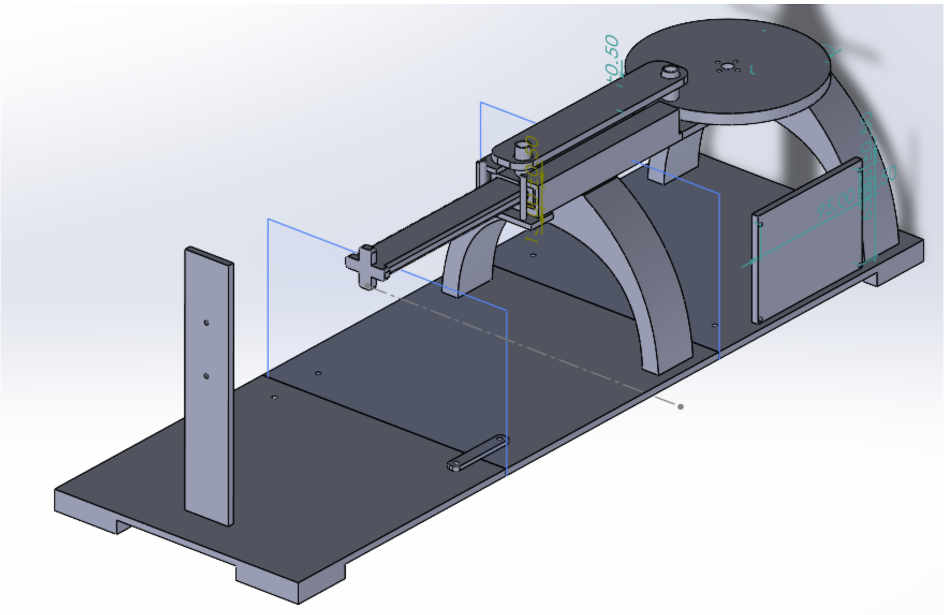


Figure 2: Theoretical slider velocity as a function of crank angle in a crank–slider mechanism. The dashed curve represents a sinusoidal approximation corresponding to simple harmonic motion, while the solid curve shows the exact velocity predicted by crank–slider kinematics. The deviation between the curves demonstrates that the slider does not move with constant or purely sinusoidal velocity even when the crank rotates at constant angular speed.

3 Experimental Design

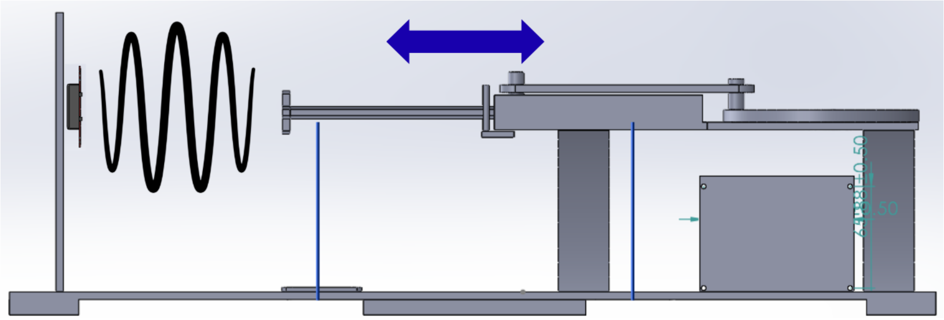
The goal of this experiment is twofold. First, the setup is designed to observe and measure Doppler frequency shifts using a low-cost microwave radar sensor. Second, the experiment is intended to demonstrate that the slider in a crank–slider mechanism does not move with uniform velocity during a rotation cycle. Because the Doppler frequency shift is directly proportional to the radial velocity of the reflecting object, variations in slider speed should produce corresponding changes in the measured Doppler signal.



To generate controlled linear motion, a crank–slider mechanism was constructed using custom 3D printed components. The parts were designed in SolidWorks and printed using ASA filament to provide sufficient rigidity and durability during operation. The mechanism consists of a rotating crank disk connected to a straight rod, which drives a slider constrained to move along a linear guide. When the crank rotates, the slider moves back and forth in a periodic linear motion.

A thin sheet of aluminum is mounted at the end of the slider and serves as the reflecting surface for the microwave signal. Aluminum was selected because it provides a strong reflection of microwave radiation, producing a clear Doppler signal when the reflector moves relative to the sensor.

A stationary HB100 microwave Doppler radar module is positioned directly in front of the slider. The sensor continuously emits microwave radiation and detects the reflected signal from the moving aluminum reflector. As the reflector moves toward or away from the sensor, the reflected signal experiences a Doppler frequency shift that is proportional to the instantaneous radial velocity of



The HB100 module provides an intermediate frequency (IF) output that contains the Doppler signal. This IF output is connected to an oscilloscope in order to observe and record the signal waveform. The oscilloscope allows the Doppler frequency to be measured directly from the time-domain signal.

Because the crank–slider mechanism rotates at approximately constant angular velocity while the slider velocity varies due to geometric constraints, the Doppler signal is expected to vary throughout the motion cycle. When the slider moves faster, the Doppler frequency increases and the oscillations in the IF signal appear more closely spaced. When the slider slows down near the turning points of the motion, the Doppler frequency decreases and the signal oscillations become more spread out. Observing these variations in the IF waveform provides experimental evidence of the non-uniform velocity profile predicted by the 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 signal was recorded using an oscilloscope, while crank position information was obtained using a Hall-effect sensor and an Arduino microcontroller.

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

$$v = \frac{\lambda f_D}{2}, \tag{6}$$

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. For the HB100 operating frequency of 10.525 GHz, the wavelength is approximately

$$\lambda = 2.85 \times 10^{-2}\,\mathrm{m}. \tag{7}$$

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

$$f_D = \frac{1}{T}. \tag{8}$$

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

4.2 Crank Angle Measurement

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

$$\Delta\theta = 60^\circ. \tag{9}$$

The Hall-effect sensor output was connected to an Arduino microcontroller, which recorded the time between successive pulses using internal timing functions. From these measurements, the rotation period of the disk was determined as

$$T_{\mathrm{rot}} = t_{n+1} - t_n. \tag{10}$$

The angular velocity of the crank was then calculated using

$$\omega = \frac{2\pi}{T_{\mathrm{rot}}}, \tag{11}$$

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

$$\mathrm{RPM} = \frac{60}{T_{\mathrm{rot}}}. \tag{12}$$

Because six 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.

4.3 Synchronized Two-Channel Measurement Method

The oscilloscope was configured to simultaneously record the amplified IF output from the HB100 radar module and the digital pulse signal from the Hall-effect sensor using two independent channels. Channel 1 recorded the Doppler IF waveform, while Channel 2 recorded the Hall sensor trigger pulses corresponding to known crank angles.

Each Hall sensor pulse served as a timing reference indicating a known angular position of the crank. The Doppler frequency was then measured from the IF waveform in the immediate vicinity of each trigger pulse. This allowed the instantaneous slider velocity to be determined at specific angular locations throughout the crank rotation.

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

$$v = v(\theta). \tag{13}$$

This approach enabled direct comparison between experimentally measured 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

$$v(\theta) = R\omega \left(\sin\theta + \frac{R}{2L} \sin 2\theta \right), \tag{14}$$

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.

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 signal exhibits periodic frequency variations consistent with the back-and-forth motion of the crank–slider mechanism. Higher Doppler frequencies are observed when the reflector moves toward the sensor, while lower frequencies are observed when it moves away.

Measured Doppler frequencies are compared to theoretical predictions based on calculated target velocity. Preliminary results show general agreement between predicted and measured values, with deviations attributed to mechanical vibration and signal noise.

6 Discussion

The experimental results support the classical Doppler relationship for reflected electromagnetic waves. The observed Doppler frequencies scale with target velocity in a manner consistent with theoretical expectations.

Small discrepancies between measured and predicted values may arise from misalignment between the motion direction and radar beam, variations in motor speed, and electrical noise in the amplification circuit. Similar limitations have been noted in previous investigations of low-cost microwave radar sensors [**?**].

Improvements to mechanical stability and signal conditioning could further reduce measurement uncertainty and improve accuracy.

7 Conclusion

This experiment demonstrates the relationship between target velocity and Doppler frequency shift using a stationary microwave radar sensor and controlled periodic motion. Measured Doppler frequencies are consistent with classical Doppler radar theory.

The system provides a simple and accessible method for experimentally validating radar-based Doppler principles and offers opportunities for further refinement in both mechanical design and signal processing.

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