RESSTECH

Vol. 3, No. 2, pp. 29-39, 2026
RESEARCH ON INSTRUMENTATION
https://rin.resstech.org/

Air Column Length Measurement in a Sound-Wave Resonance Experiment Using HC-SR04 Ultrasonic Sensor

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ARTICLEINFO

Article history:
Received September 7, 2026
Revised September 21, 2026
Accepted September 23, 2026
Available online September 24, 2026

Keywords:
Ultrasonic sensor; Air column length; sound-wave resonance; Precision; HC-SR04;

ABSTRACT

This study evaluates the performance of the HC-SR04 ultrasonic sensor for measuring air column length in a sound-wave resonance experiment at 512 Hz. The sensor's accuracy and precision were assessed through comparison with a ruler as a reference instrument and repeated measurements. The characterization results show excellent linearity with R^2 = 0.99822. The accuracy test results show an average error of 1.156% and accuracy of 98.85%. The precision test at 10 cm yielded an average precision of 96.19%, while the precision test at 512 Hz (first resonance order) produced an average precision of 98.02%. In the resonance experiment at 512 Hz, the sensor was applied to measure air column lengths at the first, second, and third resonance orders. The measured values were compared with theoretical calculations, yielding an average accuracy of 98.26%. The measurements were conducted in an air-conditioned laboratory at 20 °C. Therefore, the results should be interpreted within the tested experimental conditions and the limitations of the measurement conditions.

1. INTRODUCTION

Sound-wave resonance experiments are commonly conducted by adjusting the air column length to identify resonance conditions. Conventional measurements generally rely on a ruler and visual observation of the water level, which may introduce measurement variations due to the limitations of manual measurement and the difficulty in identifying the position corresponding to maximum resonance amplitude [1], [2]. These limitations can affect the consistency of air column length measurements and the determination of resonance conditions during the experiment. The use of an ultrasonic sensor provides an alternative approach for measuring air-column length without requiring direct visual observation of the water level. The application of ultrasonic sensors for dimensional measurement has also been demonstrated in instrumentation systems, including diameter measurement using dual opposing ultrasonic sensors [17].

The HC-SR04 is a low-cost ultrasonic sensor that determines distance based on the time required for an ultrasonic pulse to travel to an object and return to the sensor [3]. Previous studies have investigated the measurement performance of the HC-SR04 in terms of accuracy, precision, linearity, and measurement error under different measurement conditions [4]–[10], [14]. These studies indicate that the measurement performance of the HC-SR04 can vary depending on measurement distance, target characteristics, sensor configuration, and experimental conditions. Similarly, sensor-based experimental instruments have been evaluated in terms of linearity and measurement accuracy to assess their measurement performance in physics experiments [18]. Therefore, characterization of the HC-SR04 is necessary before applying the sensor to air column length measurements in a sound-wave resonance experiment.

In sound-wave resonance experiments, the air column length corresponding to successive resonance orders is related to the wavelength and frequency of the sound-wave. Previous studies have investigated resonance phenomena using resonance tubes and electronic measurement systems to determine air column length and the speed of sound [11], [12]. Iskandar and Pramudya [12] investigated sound resonance using an Arduino-based ultrasonic sensor and a 512 Hz sound source, demonstrating the application of ultrasonic measurement for determining air column length in a resonance experiment. Their study reported air column measurements under different water-level adjustment conditions, demonstrating the potential of ultrasonic sensing for resonance experiments. Other resonance tube studies have also demonstrated the relationship between air column length, frequency, and the speed of sound [11].

Environmental conditions also need to be considered because temperature affects the speed of sound in air and can consequently influence ultrasonic distance measurements [13], [15]. Previous research has demonstrated that temperature variation can contribute to measurement errors in ultrasonic sensors. Such variations may affect the accuracy of distance measurements and should therefore be considered when evaluating sensor performance. Therefore, reporting the experimental conditions is important when evaluating the performance of an ultrasonic sensor for air column length determination.

Based on these considerations, this study aims to characterize the measurement performance of the HC-SR04 ultrasonic sensor for measuring air column length in a sound-wave resonance experiment at a frequency of 512 Hz. The characterization includes linearity, error, accuracy, and precision using a ruler as the reference instrument. The characterized sensor is subsequently applied to measure the air column lengths corresponding to the first, second, and third resonance orders. This approach provides a quantitative evaluation of the HC-SR04 measurement performance and its applicability to air column length measurement in a sound-wave resonance experiment.

2. MATERIAL AND METHODS

This study employs an experimental method to measure air column length in a sound-wave resonance experiment using the HC-SR04 ultrasonic sensor. The measurement system is designed to acquire sensor readings automatically and display the results through a dashboard. The block diagram of the measurement system is shown in Figure 1.

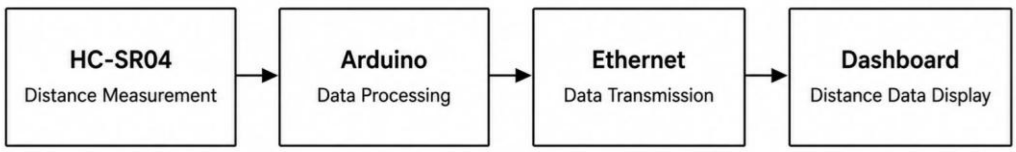

Figure 1. Block diagram of the measurement system.

Figure 1 illustrates the data acquisition flow, beginning with sensor measurement and continuing through data processing and transmission to the dashboard. Ethernet is used as the data transmission medium, allowing the measurement results to be monitored remotely. The HC-SR04 ultrasonic sensor is a low-cost module commonly used for distance measurement. The sensor operates at 5 V DC, with an operating current of 15 mA, an operating frequency of 40 kHz. It has a measurement range of 2-400 cm and a resolution of 0.3 cm [16]. It measures distance by emitting an ultrasonic pulse and then measuring the time taken for the echo to return from a target. This time-of-flight measurement allows the sensor to calculate the distance to an object. The resonance tube used in this experiment is a transparent acrylic tube with a length of 100 cm and an inner diameter of 5 cm. A speaker connected to a signal generator with a frequency of 512 Hz serves as the sound source. Air column length is measured by placing the HC-SR04 sensor at the top of the resonance tube and directing it toward the water surface. The sensor position relative to the resonance tube is shown in Figure 2.

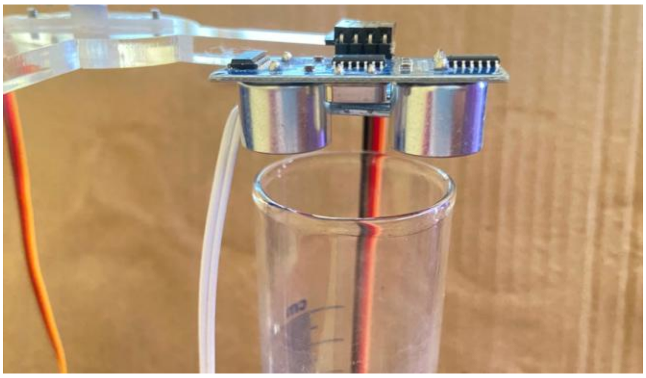

Figure 2. Position of the HC-SR04 sensor for air column length measurement.

As shown in Figure 2, the HC-SR04 measures the vertical distance between the sensor and the water surface without physical contact. The sensor is positioned at a fixed reference point, and the measured distance is used to determine the air column length inside the resonance tube. The distance measurement is based on the travel time of the ultrasonic wave from the sensor to the water surface and back to the sensor, as expressed in Equation (1):

$$d = \frac{vt}{2} \tag{1}$$

where d is the distance between the sensor and the water surface, v is the speed of ultrasonic waves in air, and t is the travel time of the ultrasonic wave from the sensor to the water surface and back to the sensor. The speed of sound in air was taken as 343 m/s, corresponding approximately to the laboratory temperature of 20 °C. The experiment was conducted in an air-conditioned laboratory with the air conditioner set to 20 °C. Relative humidity was not recorded during the measurements. The measurement and data acquisition processes were performed repeatedly throughout the experiment. The measurement procedure is illustrated in Figure 3.

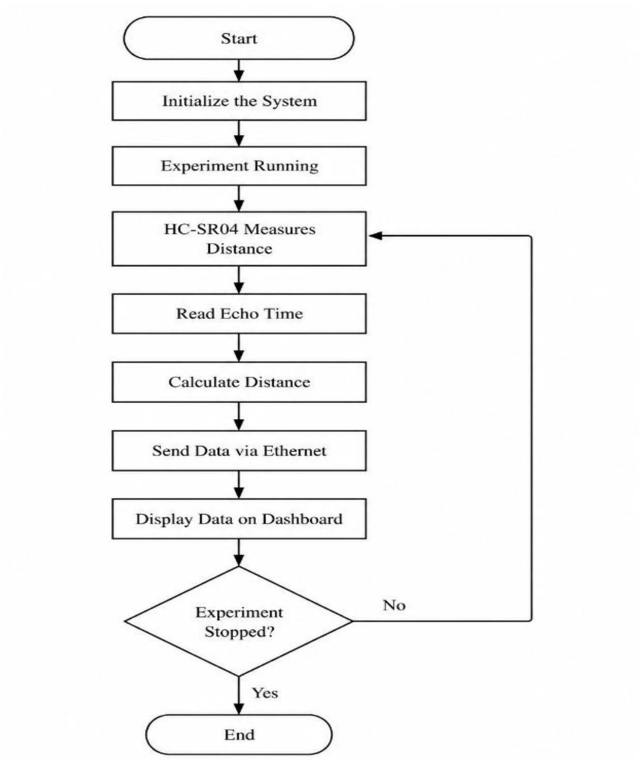

Figure 3. Flowchart of HC-SR04 measurement.

The flowchart in Figure 3 is designed in a continuous loop to ensure consistent data acquisition throughout the experiment. This looping mechanism is essential because each air column length variation is measured with two repetitions. The system automatically repeats the measurement cycle until the experiment is terminated by the user, thereby maintaining stable time intervals between successive data points to support the precision analysis.

The performance evaluation of the HC-SR04 is conducted in several stages. First, the sensor was characterized by comparing its distance measurements with a ruler as the reference instrument. 10 distance variations were set, ranging from 5 cm to 50 cm in 5 cm increments, with one measurement taken for each variation for linearity. The relationship between the sensor output and the reference distance was analyzed using linear regression to determine the linearity of the sensor. The accuracy of the HC-SR04 was evaluated by comparing the sensor measurements with a ruler as the reference instrument. 10 air column length variations were set, ranging from 5 cm to 50 cm in 5 cm increments. For each variation, two measurements were taken using the HC-SR04, and the average value was calculated. The percentage error is calculated using Equation (2):

$$\text{Error} = \left|\frac{Yn-Xn}{Xn}\right| \times 100\% \tag{2}$$

where Y_n is the HC-SR04 measurement result and X_n is the measurement value obtained from the ruler. Accuracy is calculated using Equation (3):

$$\text{A\%} = \left(1 - \left|\frac{Yn-Xn}{Xn}\right|\right) \times 100\% \tag{3}$$

where Y_n is the HC-SR04 measurement result and X_n is the measurement value obtained from the ruler. An A value approaching 100% indicates higher measurement accuracy.

The precision of the HC-SR04 was evaluated by performing 10 repeated measurements at a fixed distance of 10 cm. Precision is determined based on the consistency of repeated measurements relative to their average value using Equation (4).

$$\text{P\%} = \left(1 - \left|\frac{Xn-\bar{X}n}{\bar{X}n}\right|\right) \times 100\% \tag{4}$$

where X_n is the n-th measurement result, n is the number of measurements, and $\bar{X}_n$ is the average measurement value. A precision value approaching 100% indicates higher consistency among repeated measurements**.** Linearity is determined from the relationship between the HC-SR04 measurement results and the reference values using linear regression and the coefficient of determination (R^2). An R^2 value approaching 1 indicates a strong linear relationship between the sensor measurements and the reference values.

The resonance test was conducted at a frequency of 512 Hz. A speaker placed near the open end of the resonance tube generated sound waves at a frequency of 512 Hz. The water level was gradually lowered until the sound intensity reached its maximum, indicating the first resonance condition. At this point, the HC-SR04 measured the air column length. The process was repeated for the second and third resonance orders. For a tube with one end closed by the water surface, the theoretical air column length at resonance is expressed in Equation (5):

$$L = \frac{(2n-1)}{4}\,\lambda \tag{5}$$

where L is the air column length, n is the resonance order ($n = 1,2,3,\ldots$), and λ is the wavelength. The wavelength is determined using the relationship $\lambda = v/f$, where v is the speed of sound in air (343 m/s) and f is the sound source frequency (512 Hz). The measured values were then compared with the theoretical values. The precision of the HC-SR04 was also tested at 512 Hz (first resonance order) with 10 repeated measurements under the same experimental conditions. The average value and precision were calculated using Equation (4).

3. RESULTS AND DISCUSSION

3.1 Sensor Characterization

The HC-SR04 ultrasonic sensor was characterized by comparing the reference distance measured using a ruler with the corresponding ECHO pulse duration obtained from the sensor. 10 distance variations were set, ranging from 5 cm to 50 cm in 5 cm increments. The results are presented in Table 1.

Table 1. Characterization results of the HC-SR04 ultrasonic sensor

No	Distance (cm)	ECHO Pulse Duration (μs)
1	5	292
2	10	583
3	15	879
4	20	1166
5	25	1458
6	30	1750
7	35	2042
8	40	2332
9	45	2755
10	50	2914

Table 1 presents the reference distances measured using a ruler and the corresponding ECHO pulse durations obtained from the HC-SR04 ultrasonic sensor. The ECHO pulse duration shows an increasing trend as the reference distance increases. These data were subsequently used to evaluate the linearity of the sensor. The relationship between the reference distance and the ECHO pulse duration was further analyzed using linear regression. The resulting graph is presented in Figure 4.

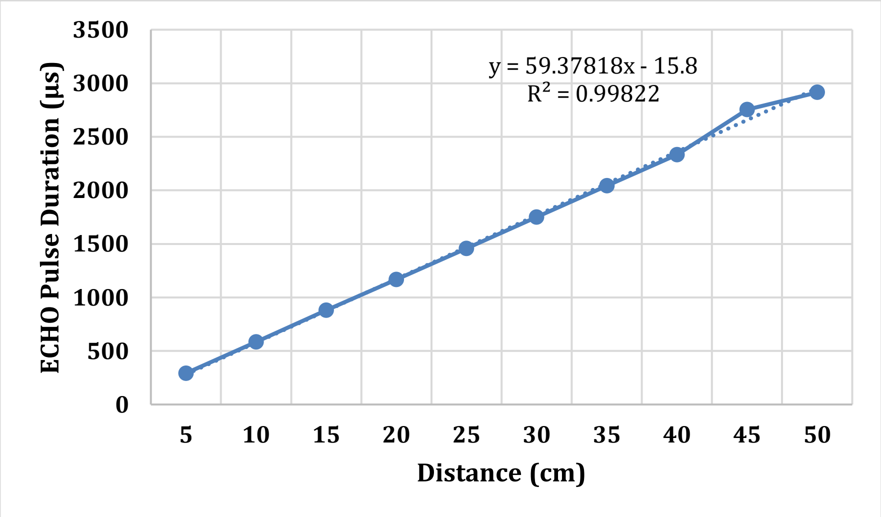

Figure 4. Graph of the relationship between distance and ECHO pulse duration.

The graph in Figure 4 shows the relationship between the reference distance and the ECHO pulse duration through a linear regression line. The obtained regression equation is $y = 59.37818x - 15.8$, with a coefficient of determination of $R^2 = 0.99822$. The R^2 value, which approaches unity, indicates a strong linear relationship between the reference distance and the ECHO pulse duration. This result indicates that the HC-SR04 sensor produces an ECHO pulse duration that varies linearly with the measurement distance across the tested range.

3.2 Accuracy Sensor

The accuracy of the HC-SR04 was evaluated by comparing the sensor measurements with a ruler as the reference instrument. 10 air column length variations were established, ranging from 5 cm to 50 cm in 5 cm increments. For each variation, two measurements were recorded using the HC-SR04, and the average value was computed. The results are presented in Table 2.

Table 2. Accuracy test results of the HC-SR04 ultrasonic sensor using a ruler as the reference instrument

Measurement	Ruler (cm)	HC-SR04 (cm)	Error (%)	Accuracy (%)
1	5.00	4.94	1.20	98.80
2	10.00	9.75	2.55	97.45
3	15.00	14.85	1.00	99.00
4	20.00	19.86	0.73	99.28
5	25.00	24.85	0.62	99.38
6	30.00	29.05	3.18	96.82
7	35.00	34.80	0.57	99.43
8	40.00	39.83	0.44	99.56
9	45.00	44.95	0.11	99.89
10	50.00	49.42	1.16	98.84
Average	-	-	1.156	98.85

Table 2 presents the measurement results of the HC-SR04 in comparison with the reference distances. The differences between the sensor readings and the reference values were used to determine the measurement error and accuracy. The measurement error varied across the tested distances, with the highest error of 3.18% observed at 30 cm and the lowest error of 0.11% recorded at 45 cm. These variations may be attributed to minor reflections or ambient noise affecting the reception of the ultrasonic waves. The comparison between the ruler distance and the sensor distance is presented in Figure 5.

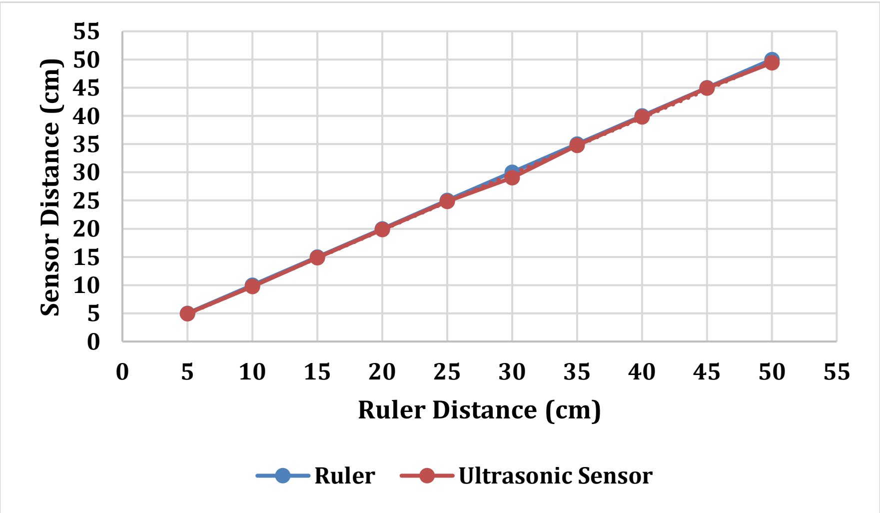

Figure 5. Graph of the relationship between ruler distance and sensor distance.

The graph in Figure 5 shows the comparison between the ruler distance and the HC-SR04 sensor distance. The sensor measurements generally follow the reference distances, with small differences observed at several measurement points. Based on the measurement results, the HC-SR04 obtained an average error of 1.156% and an average accuracy of 98.85% across the tested range.

3.3 Precision Sensor

The precision of the HC-SR04 was evaluated by performing 10 repeated measurements at a fixed distance of 10 cm. The results are presented in Table 3.

Table 3. Precision test results of the HC-SR04 at 10 cm distance.

Measurement	HC-SR04 (cm)	Precision (%)
1	10.60	94.10
2	10.50	95.10
3	10.84	91.70
4	9.45	94.50
5	9.79	97.86
6	9.90	99.00
7	9.81	98.06
8	9.45	94.50
9	9.81	98.06
10	9.90	99.00
Average	10.005	96.19

Table 3 displays the results of 10 repeated measurements conducted at a fixed distance of 10 cm. The average HC-SR04 was 10.005 cm, with an average precision of 96.19%. These findings indicate that the HC-SR04 produces consistent measurements with satisfactory repeatability. The observed variations in precision, ranging from 91.70% to 99.00%, may be attributed to minor fluctuations in measurement conditions during the repeated readings. The consistency of the sensor readings across 10 repetitions is visualized in Figure 6.

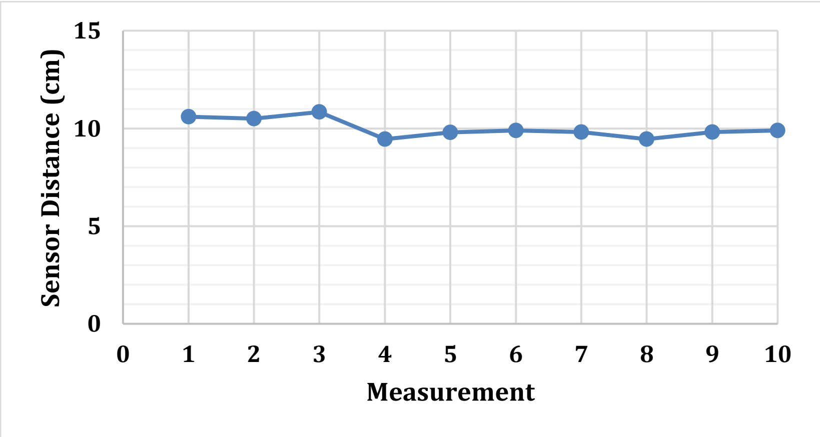

Figure 6. Graph of the precision test results at 10 cm distance.

3.4 Resonance Test at 512 Hz

The resonance test was conducted at a frequency of 512 Hz. The water level was gradually lowered until the sound intensity reached its maximum, indicating the first resonance condition. At this point, the HC-SR04 recorded the air column length. This procedure was repeated for the second and third resonance orders. The measured values were subsequently compared with the theoretical air column lengths calculated using Equation (5). The results are presented in Table 4.

Table 4. Comparison of theoretical and HC-SR04 air column lengths at 512 Hz.

Resonance Order	Theoretical Air Column Length (cm)	HC-SR04 Measurement (cm)	Error (%)	Accuracy (%)
1	16.70	16.50	1.19	98.80
2	50.00	48.35	3.30	96.70
3	83.40	84.00	0.71	99.26
Average	-	-	1.73	98.26

Table 4 presents a comparison between the theoretical air column lengths and the HC-SR04 measurements at 512 Hz. The sensor readings closely approximate the theoretical values across all three resonance orders. The average error was 1.73%, corresponding to an average accuracy of 98.26%. The highest error 3.30% was observed at the second resonance order, while the lowest error 0.71% was recorded at the third resonance order. This observation suggests that the sensor's accuracy improves at higher resonance orders, possibly due to the reduced relative effect of surface perturbation at longer air column lengths. The comparison between the theoretical and HC-SR04 measurements at 512 Hz is presented in the graph in Figure 7.

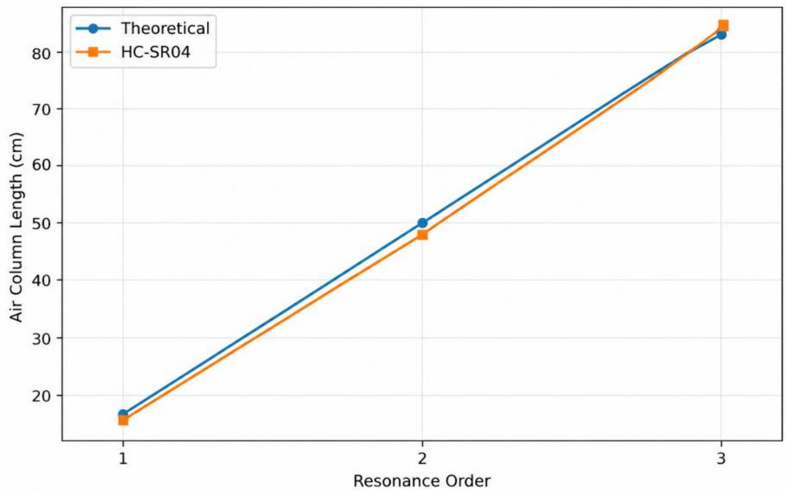

Figure 7. Graph of theoretical and HC-SR04 air column lengths at 512 Hz.

The graph in Figure 7 shows that the HC-SR04 measurements follow the increasing trend of the theoretical air column lengths as the resonance order increases. The measured values are close to the theoretical values, with slight differences observed at each resonance order. The sensor successfully detects the increase in air column length corresponding to successive resonance orders. These results demonstrate the applicability of the HC-SR04 ultrasonic sensor for air column length measurement in a sound-wave resonance experiment at 512 Hz.

Previous studies have demonstrated the application of the HC-SR04 ultrasonic sensor in sound-wave resonance experiments. Iskandar and Pramudya [12] applied an Arduino-based HC-SR04 system to measure air-column length and compare experimental resonance values with theoretical calculations at 512 Hz. Unlike previous studies, the present study systematically characterizes the HC-SR04 measurement performance for air column length determination before applying the sensor to resonance measurements. The characterization includes linearity, error, accuracy, and precision using a ruler as a reference instrument, followed by validation through resonance measurements at 512 Hz. The characterization results yielded an R^2 of 0.99822 and an average accuracy of 98.85%, while the resonance measurements achieved an average accuracy of 98.26%. This approach provides quantitative evidence of the sensor's measurement performance and its applicability to air-column length determination in a sound-wave resonance experiment.

3.5 Precision Test at 512 Hz

The precision of the HC-SR04 was also evaluated at 512 Hz (first resonance order) through 10 repeated measurements under identical experimental conditions. The results are presented in Table 5.

Table 5. Precision test results of the HC-SR04 at 512 Hz (first resonance order).

Measurement	Air Column Length (cm)	Precision (%)
1	16.29	99.91
2	16.29	99.91
3	15.52	95.36
4	16.17	99.35
5	16.50	98.62
6	16.29	99.91
7	15.64	96.09
8	16.16	99.29
9	16.94	95.92
10	16.96	95.80
Average	16.276	98.02

Table 5 displays the results of 10 repeated measurements conducted at 512 Hz (first resonance order). The average air column length was 16.276 cm, with an average precision of 98.02%. These findings indicate that the HC-SR04 maintains consistent measurement performance under resonance conditions. The variations in precision, ranging from 95.36% to 99.91%, may be attributed to minor fluctuations in water level or ambient conditions during the experiment. The consistency of the sensor readings across 10 repetitions at 512 Hz is illustrated in Figure 8.

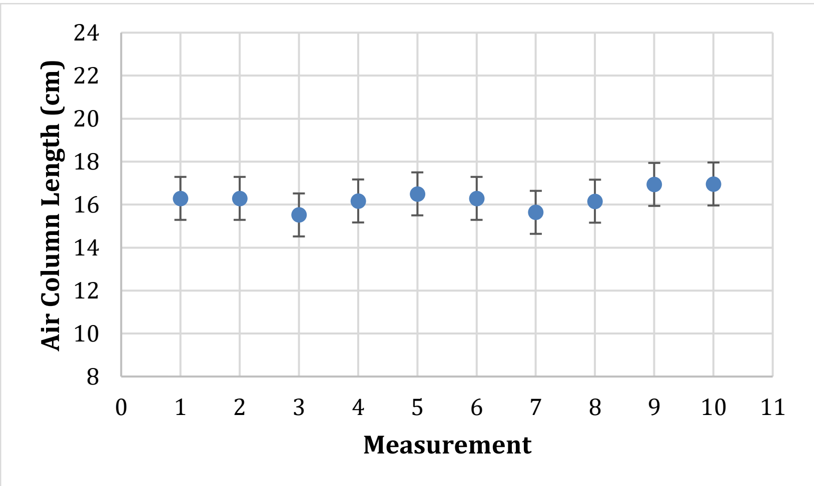

Figure 8. Graph of the precision test results at 512 Hz (first resonance order) with error bars.

Figure 8 shows the consistency of HC-SR04 measurements over 10 repetitions at 512 Hz (first resonance order). The readings are relatively stable, ranging from 15.52 cm to 16.96 cm, with an average value of 16.276 cm and a precision of 98.02%. This demonstrates that the sensor provides reliable and repeatable measurements under resonance conditions.

4. CONCLUSION

This study evaluated the performance of the HC-SR04 ultrasonic sensor for measuring air column length in a sound-wave resonance experiment at 512 Hz. The sensor characterization results showed excellent linearity (R^2 = 0.99822), an average error of 1.156%, accuracy of 98.85%, and precision of 96.19% at 10 cm. In the resonance experiment at 512 Hz, the sensor achieved an average accuracy of 98.26% with errors of 1.19%, 3.30%, and 0.71% at the first, second, and third resonance orders, respectively. The precision test at the first resonance order produced an average precision of 98.02%. These results indicate that the HC-SR04 can be used for air column length measurement in the tested sound-wave resonance conditions. However, the precision evaluation was limited to a single measurement distance and the first resonance order, and variations in repeated measurements indicate measurement uncertainty under the experimental conditions. Further studies should evaluate precision at multiple measurement distances and resonance orders, as well as consider temperature compensation, to provide a more comprehensive assessment of the sensor's measurement performance.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Department of Physics, specifically the Electronics and Instrumentation Laboratory at Universitas Negeri Padang, for providing the essential research facilities that supported this work. Appreciation is also extended to all colleagues for their assistance and valuable contributions toward the improvement of this article.

DECLARATIONS

Authorship contribution

Rahmadina Fitri: Conceptualization, methodology, formal analysis, software and writing-original draft.
Yulkifli and Mona Berlian Sari: Validation, Writing-review and editing.

Competing Interest

The author **declare** no conflict of interest in this study.

Funding statement

This work has not been funded by any person or organization.

Ethical Clearance

There are no human subjects in this manuscript, and informed consent is not applicable.

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