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Design and Load Analysis of an Orbital Shaker using a Keypad as Input Based on Arduino Uno

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Abstract

This study aims to develop an orbital shaker device with an Arduino Uno-based input system for rpm and time, utilizing a keypad as the input medium. The orbital shaker is designed to homogenize chemical solutions through circular motion, featuring display functions for rpm and mixing time. The device uses a NEMA 17 stepper motor as the main motor, a 4x4 membrane keypad for input, an Arduino Uno as the processor, and a TM1637 display for rpm and time readings. Testing of the orbital shaker includes calibration of rpm and time. Rpm calibration is performed using a laser tachometer to measure the conformity of the inputted rpm values, while time calibration uses a stopwatch to determine system error values. The rpm calibration results indicate an average error rate of 0.36%, with an accuracy of 99.62% and precision of 99.58%. In comparison, time calibration results show an average error rate of 0.15%, with an accuracy of 99.84% and precision of 99.88%. Further rpm measurements were conducted with solution loads ranging from 100 to 1000 g, increasing in increments of 100 g, and rpm testing was performed from 100 to 500 rpm. The test results demonstrate that the optimal performance of the designed orbital shaker occurs at rpm values between 100 and 450 with a load range of 100–600 g.

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Abstrak

Penelitian ini bertujuan untuk mengembangkan perangkat orbital shaker yang dilengkapi dengan sistem input rpm dan waktu berbasis Arduino Uno, yang menggunakan keypad sebagai media input. Orbital shaker dirancang untuk menghomogenkan larutan kimia melalui gerakan melingkar, dengan fitur tampilan nilai rpm dan waktu pengadukan. Perangkat ini menggunakan motor stepper NEMA 17 sebagai motor utama, keypad membran 4x4 untuk input, Arduino Uno sebagai prosesor, dan layar TM1637 sebagai penampil rpm dan waktu. Pengujian perangkat orbital shaker dilakukan dengan kalibrasi rpm dan waktu. Kalibrasi rpm dilakukan menggunakan tachometer laser untuk mengukur kesesuaian nilai rpm yang diinput, sementara kalibrasi waktu dilakukan dengan stopwatch guna menentukan nilai kesalahan sistem. Hasil kalibrasi rpm menunjukkan nilai kesalahan rata-rata sebesar 0,36%, dengan akurasi 99,62% dan presisi 99,58%. Sedangkan, kalibrasi waktu menghasilkan nilai kesalahan rata-rata 0,15%, dengan akurasi 99,84% dan presisi 99,88%. Selanjutnya, pengukuran rpm dilakukan menggunakan beban larutan seberat 100–1000 g dengan kenaikan setiap 100 g, serta pengujian rpm mulai dari 100–500 rpm. Hasil pengujian menunjukkan bahwa kinerja optimal dari orbital shaker yang dirancang adalah pada rpm 100–450 dengan beban 100–600 g.

1. Introduction

The current development of technology is rapidly growing across various sectors. Technology exists to simplify human work, and its utilization is nearly evenly distributed across all fields. The advancement of technology must be connected to the role of laboratories as a supporting facility for research and development. Certain laboratory activities require tools to facilitate tasks, including those needed to dissolve chemical or biological compound samples evenly and homogeneously, manually, or automatically. The tool used to mix solutions automatically is called a shaker. As the name suggests, a shaker is a device that functions to stir or mix one solution with another to achieve homogeneity. Using an automatic shaker increases time and energy efficiency. Some solutions can also be hazardous upon skin contact, so using a shaker enhances user safety. The shaking process in a shaker utilizes unidirectional (Abrianto, 2021) and orbital motion systems.

An Orbital Shaker is a type of shaker that operates with circular stirring movements (aligned with its orbit or axis). The orbital shaker is utilized for stirring processes during Dispersive Liquid-Liquid Microextraction (DLLME), which increases extraction efficiency by ensuring better mixing between the solvent and sample (Elik et al., 2024) for dispersive solid-phase microextraction of caffeine (Altunay et al., 2022), for segmenting the growth of endothelial cells (Pang et al., 2021), and for other applications. Additionally, there is an orbital shaker known as a thermal shaker, which can stir while maintaining an optimal temperature. This incubator shaker has two functions: to homogenize nutrients and to maintain the temperature conditions required for microbial growth (Vadiska, 2015).

The design of an orbital shaker involves either a DC motor or a stepper motor (Vicias, 2024). This system is designed with a control system from a controller device using various control methods and simulations (Wibowo et al., 2023; Shibalkina & Szabó, 2021; Alhinqari & Alhengari, 2021; Margirahayu et al., 2022; Mohini, 2016). In this study, the design uses a stepper motor as the main driver, with input for rotation speed and time from an Arduino-based 4x4 keypad. The display uses a seven-segment module to facilitate observation from a sufficient viewing distance.

The stepper motor actuator's transfer function describes the relationship between input voltage and the stepper motor's angular velocity. The stepper motor's dynamic model can be represented by a mathematical model involving mechanical and electromagnetic parameters, such as torque, moment of inertia, and motor constant. The equation expresses torque (Tm).

$$T_m = J\frac{d\omega}{dt} + B\omega \tag{1}$$

J is the rotor's moment of inertia, ω is the motor's angular velocity, and B is the friction coefficient. The input voltage equation (V) is:

$$V = L\frac{Di}{dt} + R\,i + K_e\omega \tag{2}$$

L is the motor's inductance, R is the motor's resistance, i is the motor current, and K_e is the electromotive force constant.

A stepper motor's torque (Tm) is typically proportional to the current flowing through its coils. The torque equation for a stepper motor can be written as:

$$T_m = K_t i \tag{3}$$

with K_t as the torque constant of the motor (Nm/A) and i as the motor current, we can describe the angular position (θ) or angular velocity of the stepper motor in the Laplace domain (s) as follows:

$$\theta(s) = \frac{Kt}{J\,s^2 + Bs}\,I(s) \tag{4}$$

The transfer function from the input current *I(s)* to the angular position *θ(s)* of the stepper motor, based on the given parameters, is:

$$\frac{\theta(s)}{V(s)} = \frac{K_t}{Ljs^3 + (RJ + BL)s^2 + B^2 s} \tag{5}$$

For the angular velocity ω(s) of the motor, the transfer function to the input current *I(s)* can be derived as follows:

$$\frac{\omega(s)}{V(s)} = \frac{K_t}{Ljs^2 + (RJ + BL)s + B^2} \tag{6}$$

The load on an orbital shaker is directly related to the moment of inertia, which increases as the load grows. This study conducts the design and performance analysis of the increased load on the orbital shaker.

It includes examining how higher moments of inertia affect the shaker's operational efficiency and stability and how to optimize the motor and control system to handle larger loads while maintaining consistent orbital motion and reliable mixing performance.

2. Methods

This research involves two manufacturing processes: hardware design and software. The devices used in this study are a Multimeter, Tachometer, Stopwatch, Solder, Protoboard, and others. The materials used in this study are Arduino Uno, Motor Stepper TB6560, Keypad 4x4, Seven-segment display, Driver Stepper Controller TB6560, and Step Down LM2596.

2.1 Hardware Design

The hardware design for the orbital shaker used a stepper motor as the main drive, a power supply circuit as an AC to DC voltage changer, an LM2596 step-down module to lower DC voltage, an on/off switch, a TB6560 stepper motor driver to adjust motor rotation, Arduino Uno as a process, a keypad as input, and seven segments as displays. The block diagram can be seen in **Figure 1.**

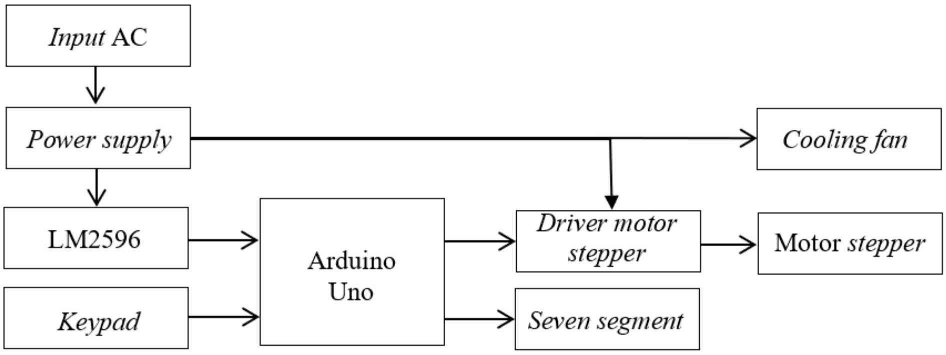


Figure 1. Orbital shaker block diagram

In **Figure 1**, it can be explained that the input from AC 220 V voltage is converted to DC using a power supply circuit with an output of 24 Volts to provide voltage to the stepper motor. The DC voltage of 24 V will be lowered to 12 V using the LM2596 module as the voltage input for the Arduino Uno. The keypad 4x4 serves as input data, the value of rotation per minute or rpm, and the time to be processed by the orbital shaker. Arduino Uno will process the input and produce an output through stepper motor movement and seven segments to display the shaker's rpm and time values. The electrical diagram is shown in **Figure 2.**

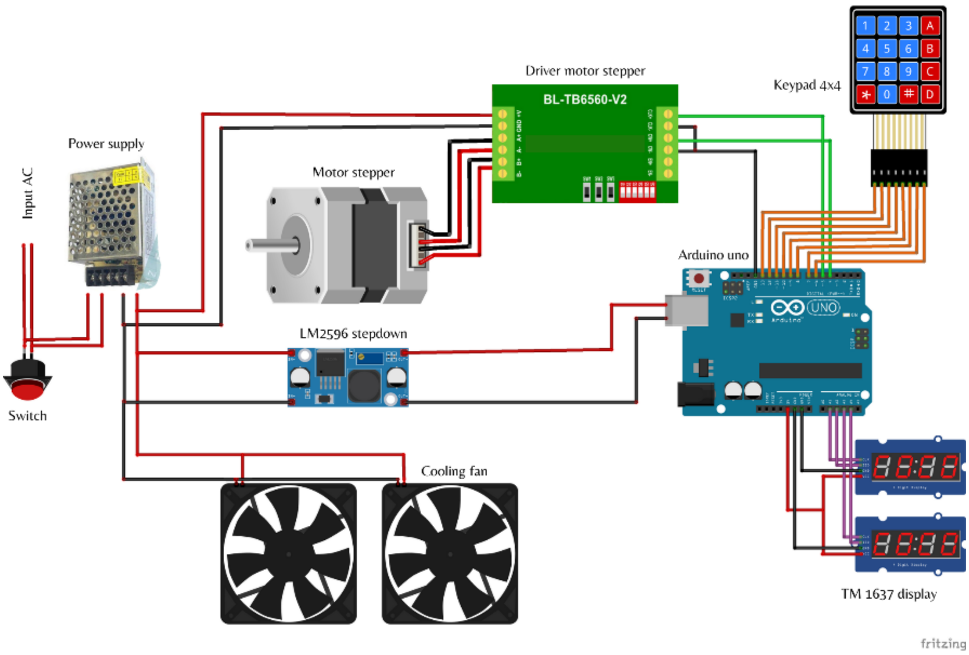


Figure 2. Electrical diagram

Furthermore, the step-down module LM3596 will change the output of 24 V DC from the power supply to 12 V DC and then connect to Arduino Uno as the input voltage. Arduino Uno will be connected with a 4x4 keypad and two pieces in seven segments. The 4x4 keypad has eight pins: R1, R2, R3, R4, C1, C2, C3, and C4, which will all be connected to Arduino digital pins in order, digital pins numbers 13, 12, 11, 10, 9, 8,7, and 6. Furthermore, 2 seven segments are used to display rpm and time. Seven segments have four pins: CLK, DIO, GND, and VCC. The first seven segments, CLK & DIO, will be connected with Arduino analog pins A1 and A2. At the same time, the second CLK & DIO seven segment will be connected with the A3 & A4 pin on the Arduino. GND pins for ground and VCC pins will be connected to 5 V on Arduino. There are also two pieces of 12 V DC cooling fan for air intake and removing hot air from the motor. This DC cooling fan is directly connected to the LM2596 stepdown, which provides a DC voltage of 12 V.

2.2 Software Design

Software design is made to support the system's performance in working correctly and obtaining the optimal output. Software design based on the Arduino IDE application. The "A" button is used to input the rpm value, and the "B" button is the time input. Then press the "#" button on the keypad, and the orbital shaker will operate. Arduino will process the input received by the keypad and then display it in seven segments. Moreover, the stepper motor driver will start according to the rpm input given on the keypad. For more details, the programming flowchart can be seen in **Figure 3**.

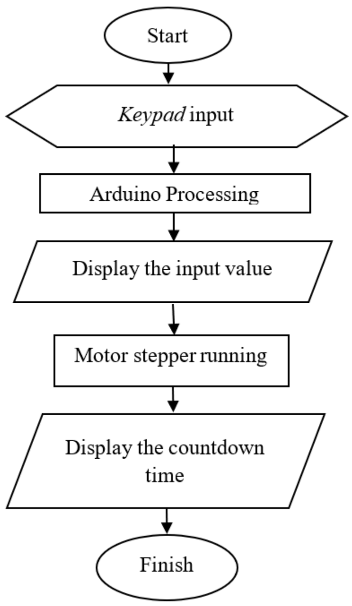


Figure 3. Programming flowchart

2.3 Hardware Testing

Hardware testing is performed on each component to determine its ability to perform its functions. Testing begins with calibrating the motor rotation and the timer on the orbital shaker to determine its ability to execute commands through Arduino. Calculate the percentage value of errors, accuracy, and precision using **Equations 7-9**.

$$\%E = \left|\frac{Y - X_n}{Y}\right| \times 100\% \tag{7}$$

$$\%A = \left[1 - \left|\frac{Y - X_n}{Y}\right|\right] \times 100\% \tag{8}$$

$$\%P = \left[1 - \left|\frac{X_n - \bar{X}_n}{\bar{X}_n}\right|\right] \times 100\% \tag{9}$$

With Y as the Reference parameter value, X_n as the measured Parameter Value to-n, and $\bar{X}_n$ as the Average of the measured parameter value. Furthermore, calibration of rpm or revolutions per minute of the orbital shaker is carried out to determine the suitability of the measured rpm, whether by input on the tool. The rpm calibration was carried out by running an orbital shaker without a load, and the rotational speed was measured using an rpm measuring tool, a tachometer.

Next is the timer calibration on the orbital shaker tool. This calibration ensures that the stirring process is appropriate and there is no delay.

The rpm and time calibration process were repeated three times for each variation. The calibration results are calculated to obtain the percentage error value in **Equation 7**, the percentage of accuracy in **Equation 8**, and the percentage of precision in **Equation 9**. A graphic between the measured RPM and the input RPM was also obtained.

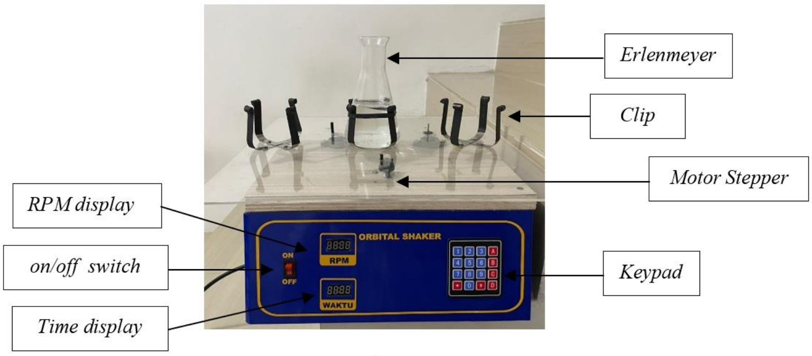
2.4 Overall Orbital Shaker Tool Test

Overall tool testing is carried out to determine the overall performance of the designed tool. At this stage, hardware and software testing is also carried out. The hardware is tested on each component used to determine the ability of these components to carry out their functions. Testing on the software is carried out to determine the tool's performance by the program implemented on the tool. After calibration, the next step is measuring the suitability of rpm when given a load. The load is a water solution weighing 100 g to 1000 g with a 100 to 500 rpm variation. The rpm measurement using the load was repeated 3 times.

3. Results and Discussion

3.1 Result of the Orbital Shaker Tool

Figure 4 shows the result of the orbital shaker tool. The shaker tool is 35 cm long, 25 cm wide, and 14 cm high.



(a)

(b)

Figure 4. Orbital shaker; (a) Front view; (b) Rear view

The shaker tool's frame is made using iron hollow material covered with acrylic with a thickness of 3 mm. The front of the tool has an on/off switch, 2 TM1637 displays, a 4x4 keypad, and information on device specifications. Two cooling fans are on the back of the device for air intake and hot air exit. This fan maintains the stepper motor's optimal temperature. **Figure 5** shows the tool's display from the inside.

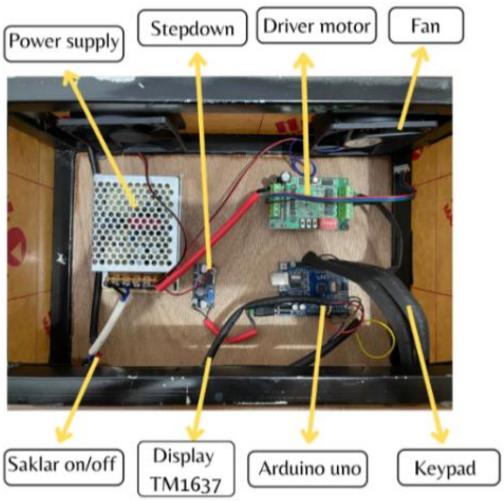
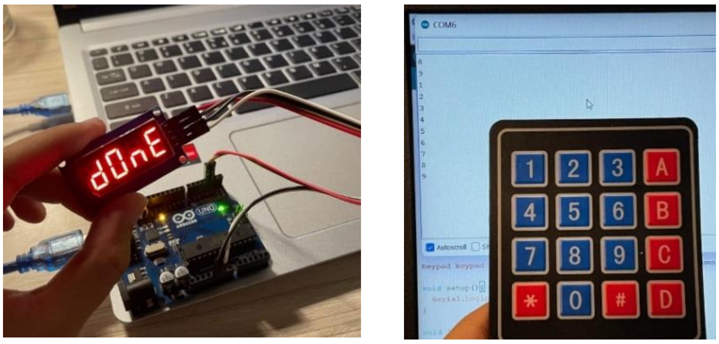


Figure 5. Inside view of the orbital shaker

On the inside, there is an electronic circuit to run the tool. The electronic components used are a 24 V 3 A power supply, stepper motor driver, Arduino Uno, stepper motor 2-seven-segment TM1637, two fans, and a 4x4 membrane keypad.

3.2 System Test

The results will be displayed using 2 pcs TM1637 displays and 1 pcs 4x4 membrane keypad connected to the Arduino Uno. The TM1637 display is connected to Arduino to pins A1, A2, A3, A4, 5V, and GND, and a 4x4 keypad is connected to Arduino digital pins from pins 2 to 9. The testing results on the TM1637 display and 4x4 keypad can be seen in **Figure 6.**



(a) (b)

Figure 6. Display and keypad test results; (a) TM1637 display; (b) Keypad 4x4

Figure 6 shows the results of the TM1637 display test on a screen that prints the words "done." It indicates that the TM1637 display is in good condition and can display the measurement results. The keypad testing is done by activating the serial monitor on the Arduino IDE application and testing the input that will appear on the serial monitor.

3.3. Testing the RPM of the Orbital Shaker tool

The stepper motor used in this shaker is a NEMA 17 type with serial number 17HS3401. NEMA 17 is a hybrid-type stepper motor with a step angle of 1.8°, 200 steps per 1 revolution, and a 3.2 kg/cm torque value. It has the advantage of producing reasonably high torque with a low voltage.

A driver/controller is needed to drive this stepper motor, which functions as a regulator of the motor rotation so that it works stably. The NEMA 17 stepper motor driver is TB6560, the most used driver on NEMA17. In addition to adjusting the motor rotation, TB6560 can reduce noise when the motor is working, smooth the motor rotation, and improve the stepper motor's work performance.

Furthermore, the stepper motor rotational speed is measured using a tachometer. The type of tachometer used is a photo or laser tachometer that uses a light sensor sensitive to rotating objects. The type of tachometer used is DT-2234C+, with an rpm range of 2.5 to 100 thousand rpm, a size of 130x70 mm, and an accuracy rate of 0.05%. Measurements are made between 50 and 100 cm from the rotating point.

The initial test is rpm calibration, which involves running the tool from 100 rpm to 500 rpm without load. **Table 1** shows the RPM value calibration test data**.**

Table 1. RPM Calibration Results

No.	Input rotating speed (rpm)	Rated rotating speed (rpm)	Average error (%)	Accuracy (%)	Precision(%)
1.	100	99.7	0.3	99.69	99.55
2.	150	149.9	0.06	99.94	99.95
3.	200	199.4	0.3	99.69	99.55
4.	250	249.8	0.08	99.85	99.87
5.	300	298.4	0.53	99.47	99.45
6.	350	347.2	0.62	99.38	99.42
7.	400	397.5	0.62	99.38	99.42
8.	450	447.5	0.55	99.45	99.46
9.	500	498.9	0.22	99.78	99.58

Based on the results of the RPM calibration test, it is known that the error value obtained is minimal, ranging from 0.06% to 0.62%, and the accuracy and precision value is 99%. The measurement of the RPM value was repeated 3 times. The input rpm data is from 100 to 500 in multiples of 50. Furthermore, the test result data can be presented in graphical form, as shown in **Figure 7.**

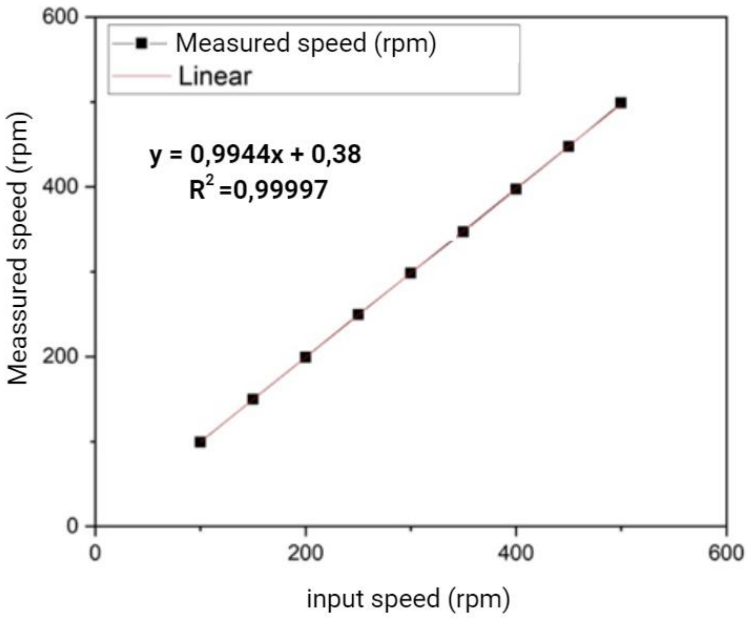


Figure 7. Stepper motor RPM calibration chart

In **Figure 7**, the stepper motor rpm calibration test results are linear. It indicates that the rpm measurement value is close to the input rpm value, with an R-value of 0.99997.

Furthermore, it tests the value of RPM with a load. The load used in this test is a solution of water in an Erlenmeyer tube weighing 100 g to 1000 g in multiples of 100 g. The weight before being filled with the water solution is 820 g, the weight of the Erlenmeyer and the acrylic in which the water solution is placed. Each multiple of 100 g was tested in several rpm variations, at 100 to 500 rpm. The test was repeated 3 times. The table of rpm test results with a load can be seen in **Table 2.**

Table 2. RPM Test Results with load

RPM Value / **Load (g)**	100	150	200	250	300	350	400	450	500
100	98.6	147.9	197.5	246.6	292.8	344.6	398.5	445.7	478.8
200	97.9	144.9	192.6	248.8	294.5	339.5	388.2	448.8	460.2
300	98.8	145.1	195.7	242.3	288.8	345.7	384.5	435.2	454.7
400	96.9	138.4	182.5	236.6	280.2	336.2	374.3	437.7	452.8
500	96.1	131.3	177.7	237.1	286.7	325.6	375.1	432.7	446.4
600	95.8	137.7	178.3	233.7	285.5	334.9	363.7	428.8	440.5
700	93.7	132.6	165.7	228.2	272.4	327.6	365.8	414.6	428.8
800	94.1	125.5	166.2	225.2	277.8	315.4	357.2	408.5	437.3
900	92.7	128.3	163.8	219.5	268.6	292.2	352.3	395.9	418.9
1000	92.2	126.7	158.2	201.7	256.2	286.4	345.6	388.2	421.4

Based on the results of the rpm test with load, it is known that the measured rpm value begins to decrease as the load increases. The input rpm value also affects the measured rpm data. Therefore, it is essential to know the working function of the shaker tool that is made and the rpm and load limits so that it works correctly. The graph of data and work functions is presented in **Figure 8.**

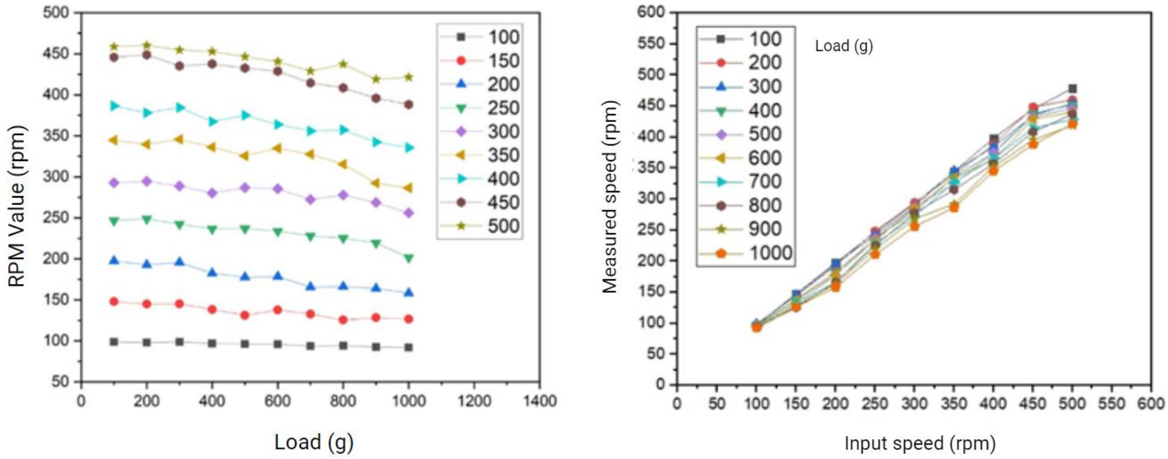


Figure 8. RPM test chart with load

There are visible differences based on **Figure 8** above; this is due to the additional load that is carried out. The red line shows the work function of the orbital shaker. It takes from 85% accuracy. The maximum rpm value for the tool to work optimally is 100-450 rpm with a load ranging from 100-600 g. After that, if the load is added to 700 to 1000 g, the rpm value will decrease from the rpm value inputted at the beginning of the stirring process.

3.4 Orbital Shaker Time Calibration Test

The countdown timer calibration test is carried out to determine the suitability of the inputted time compared to the actual time measured using a stopwatch. The suitability of the rotating time dramatically affects the mixed solution's results. The time test was repeated thrice with a time of 300, 600, and 900 seconds and a significant rpm of 100. The results of the spin time calibration test are presented in **Table 3.**

Table 3. Time Calibration Test Results

No.	Input time(s)	Measured time(s)			Average time (%)	Average error (%)	Accuracy (%)	Precision (%)
		1	2	3				
1.	300	300.79	299.50	300.75	300.34	0.11	99.89	99.93
2.	600	601.45	600.82	602.20	601.49	0.24	99.76	99.82
3.	900	900.40	902.80	900.20	901.13	0.12	99.88	99.90

Based on the measurement time calibration data above, it is known that the error value obtained is relatively small, which is 0.11% to 0.24%, with an accuracy and precision value of 99%. The shaker rotation time was measured with three repetitions with a time of 5, 10, and 15 minutes. Furthermore, the presentation graph of the shaker average rotation time calibration data can be seen in **Figure 9.**

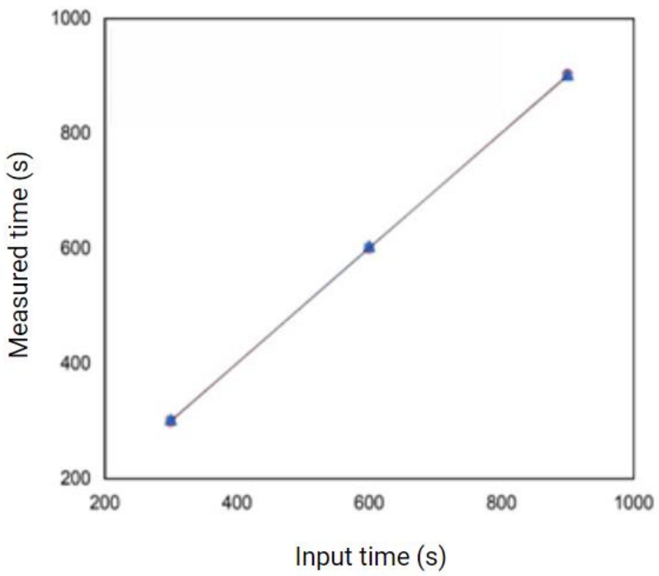


Figure 9. Chart timer calibration

In the graphic test timer of the orbital shaker tool, a linear graph is obtained, which means the measured timer value and the input time value are almost the same and appropriate. Testing the tool's rotating time is very important; if the rotation time does not match the input, it can damage the solution to be stirred.

4. Conclusions

The orbital shaker can be designed using a NEMA 17 stepper motor, with input using a 4x4 membrane keypad with TM1737 as a display based on Arduino Uno as the main processor. The stepper motor has a good level of accuracy and precision in performing revolutions per minute (RPM), with a no-load accuracy rate of 99%. In testing with a load, the most effective value for the tool to work properly is at 100-450 rpm and 100-600gr load.

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