DESIGN AND DEVELOPMENT OF A GOVERNOR TEST DEVICE TO ANALYZE THE EFFECT OF SPEED VARIATION ON CENTRIFUGAL FORCE

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Abstract. *A governor is a mechanical control device that functions to maintain engine speed stability through a response mechanism to changes in centrifugal force. This study aims to design and develop a governor test device to analyze the effect of rotational speed variation on centrifugal force, both visually and measurably. The research process includes literature review, device design using CAD software, physical fabrication, and experimental testing at various rotational speeds (RPM). The data collected involves the displacement of the governor sleeve (ball position), which is directly proportional to the magnitude of the centrifugal force. The test results show that the higher the speed, the greater the centrifugal force generated, as indicated by the increased radial distance of the ball from the axis of rotation. This research contributes as a practical learning tool to understand the working principles of governors and their applications in mechanical control systems.*

Keywords: *Centrifugal Force; Governor; Mechanical Control; Rotational Speed; RPM; Test Device.*

1. INTRODUCTION

The development of automatic control systems technology began during the Industrial Revolution. One important milestone in the history of automatic control was the invention of the governor by James Watt in 1769. A governor is a mechanical device used to automatically regulate the speed of a steam engine without human intervention. This system works on the principle of mechanical position changes based on the rotational speed of the shaft, which is then used to regulate the power supply to the engine to maintain stability (Kristyadi et al., 2020).

Technically, a governor is a dynamic system capable of adapting to changes in the main system. In this case, changes in the shaft rotational speed will cause changes in the position of the governor element (usually a ball or rocker arm), which in turn will affect the energy flow control mechanism (such as a steam valve). (Yogi Saputra et al., 2022) In other words, the governor position directly reflects the response to changes in engine speed, so this system has the ability to maintain engine stability automatically (Febrian et al., 2023).

The operating principle of a governor is closely related to centrifugal force, which is the force that appears on a rotating object due to centripetal acceleration (a change in the direction of velocity). Centrifugal force acts away from the center of rotation and is perpendicular to the linear velocity.(Muharni et al., nd)As the rotational speed increases, the centrifugal force acting on the governor element also increases, causing it to move away from the axis of rotation. This movement is then used as a mechanical signal to regulate the energy supply to the system, such as partially closing a steam valve to reduce the speed back to a steady state (Hapsari et al., 2023).

Changes in rotational speed will affect the magnitude of the centrifugal force generated, causing the governor arm to change position. Therefore, the governor system is not static, but rather highly responsive to changes that occur during the engine's operation. This capability makes the governor one of the earliest forms of automatic control systems that is still widely used today, both in purely mechanical form and in combination with electronic and digital systems (Kadaryono et al., 2020).

However, in practice, the performance of the governor tester can vary depending on the applied rotational speed. Therefore, it is necessary to test and optimize the governor tester to determine how the system reacts to various rotational speeds and to determine the most stable and efficient operating conditions (Digdoyo et al., 2020).

This study aims to analyse the response of a governor tester to variations in rotational speed and to find the optimal operating point that provides maximum stability. With a deeper understanding of the behaviour of the governor system, it is hoped that the results of this study can contribute to the development of more effective and efficient mechanical control systems (Suryono et al., 2021).

2. LITERATURE REVIEW

2.1 Centrifugal force

Centrifugal force doesn't actually exist. It's just an apparent effect that occurs when an object moves in a circle, but centrifugal itself isn't a force. Centrifugal means moving away from the center. When an object or particle moves in a circle, a centripetal force acts on it, directed toward the center of the circle. Many people are tempted to add a force directed away from the center, whose role is to balance the centripetal force. The magnitude of the centrifugal force is equal to the magnitude of the centripetal force, while the direction of the centrifugal force is opposite to the centripetal force. This is intended to keep the object in circular motion in a state of equilibrium. The force directed away from the center is called the centrifugal force (Fhasya et al., 2023).

If there is a centrifugal force acting on an object in circular motion, then Newton's first law is violated. According to Newton's first law, if there is a net force acting on an object, the object will either be at rest or moving at a constant speed along a straight line. When an object is in circular motion, a centripetal force acts on it, directed toward the center of the circle (Hau & Nuri, 2019).

If there were a centrifugal force directed away from the center, there would be a net force causing the object to move in a straight line. In reality, the object continues to move in a circular motion. Therefore, it can be concluded that there is no centrifugal force.

2.2 Governor

The first automatic feedback controller used in industrial processes generally refers to James Watt's flyball governor, developed in 1769 to control the speed of a steam engine. Therefore, the governor is the earliest automatic control device used to regulate and control the process with a mechanical system, to measure and regulate the speed of an engine, hence it is also called a speed limiter. The governor works to regulate speed based on the balance of centrifugal force with gravity or spring force ("I. On Governors," 1868).

2.3 Governor Working Principle

A governor is a device used to control the speed of a prime mover from over speeding and stabilize the desired engine rotational speed. The governor regulates the average speed of the engine or prime mover when there is a variation in the speed of the load frequency. If the motor load is constant, then the motor speed remains constant from one cycle to the next. If the load increases, the motor speed decreases and the governor angle will increase with the change, thus moving the valve open to increase the working fluid which increases the load (Simanjorang et al., 2021).

The forces acting on the governor are:

1. Centrifugal force
   It is a force that arises due to the movement of an object or particle along a curved path so that the force generated is outside the circle.
2. Centripetal Force
   This is the force required to keep an object moving in a circle. If the centrifugal force points outward, then the centripetal force points inward.
3. Tangential Force
   This is an internal force that works parallel to the cross-sectional plane or perpendicular to the axis of the rod.

2.4 Types of Governors

In general, governors can be classified into 2, namely based on their structure and how they work as follows:

1. Governor Based on Structure
   a. Mechanical Governor
   This governor is a centrifugal type; the balance is maintained by the centrifugal force of the fly ball and the spring tension.
   b. Pneumatic Governor
   This governor works according to the pressure difference between the vacuum pressure in the intake manifold and the atmosphere which is detected by a Pneumatic Governor diaphragm.

2. Governor Based on How It Works
   a. Centrifugal Governor
   This governor works based on centrifugal force, which is a force experienced by an object that moves in rotation, the direction of which is always away from the center of rotation.
   b. Inertial Governor
   An inertial governor operates based on the moment of inertia that arises from angular rotation, or can also be thought of as the sum of the mass of each particle in a rigid body multiplied by the square of its distance from the axis. Because it is considered more complicated, this type of governor is not widely used even though it produces faster reactions.

3. RESEARCH METHODS

This research was conducted using an engineering experimental approach, including the design, construction, and testing of a governor tester. The goal was to analyze the effect of rotational variations on the centrifugal force acting on the governor mechanism. The methodological steps are described as follows:

3.1 Literature Study

This activity aims to collect basic theories and technical references regarding:

1. The working principle of the governor (Watt, Porter, Proell, etc.)
2. The relationship between rotational speed (Rpm) and centrifugal force
3. Governor mechanism design and test system

3.2 Governor Test Equipment Design

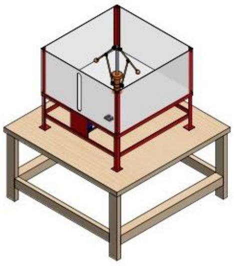

Figure 1. Governor test equipment design

At this stage the following is done:
1. Initial design of test equipment with CAD software (e.g. SolidWorks/AutoCAD)
2. Determining the type of governor used (e.g. Watt governor)
3. Principal component calculation:
   a. Governor arm, ball weight, arm length, spring (if any)
   b. Relationship between rpm and radius and centrifugal force
4. Creation of working drawings and tool specifications

3.3 Test Equipment Manufacturing
1. The test equipment fabrication and assembly process include:
   b. Main frame and motor mount
   c. Installing the governor and the rotary shaft
   d. Installation of the drive system (electric motor with speed controller)
   e. Addition of rpm measuring tool and ball radius/position change recording system.
2. Use of materials according to design specifications (iron, aluminum, transparent acrylic for visualization)

3.4 Tool Testing
Testing was conducted to determine the effect of variations in rotational speed on the centrifugal force on the governor. Testing steps:
1. Operate the tool at various rotational speeds (e.g. 300, 600, 900, and 1200 rpm)
2. Measure and record the change in radius (distance of the ball from the axis)
3. Calculate centrifugal force using the formula:
   F $= m \cdot r \cdot \omega 2$
   F = centrifugal force (N)
   m = mass of ball (kg)
   r = radius of gyration (m)
   ω = angular velocity (rad/s)
4. The test results data are recorded in a table and visualized in a graph of the relationship between speed and centrifugal force.

3.5 Data analysis
The data was analyzed to see the linear or quadratic relationship between rotational speed and centrifugal force:
1. Chart$Fs\ vs\ \omega$
2. Analysis of increasing trend of radius and force
3. Validation with theory

3.6 Tools used
In conducting this research, the use of appropriate tools and instruments is essential to support the successful design, manufacture, and testing of the governor test

equipment. The tools used are tailored to the testing requirements to observe the relationship between rotational variations and the resulting centrifugal force.

Each instrument is carefully selected to ensure accurate, consistent, and quantitatively analyzable experimental results. Furthermore, the instruments used support the assembly of mechanical components, measurement of physical parameters, and data recording during testing. Several instruments are used, including:

1. Drilling machine
   a. Voltage 220 V / 50 Hz
   b. 350 Watt Power
   c. No-Load Speed 2500 rpm
2. Welding machine
   a. Voltage 220 V / 50 Hz
   b. 900-Watt Electric Power
   c. Welding Wire Size 2 - 4 mm
3. Cutting Grinder
   a. Voltage 220 V / 50 Hz
   b. 670 Watt Power
4. Tachometer
5. Dynamo Machine
6. Ring spanners 10, 12, and 14

3.7 Materials Used

1. Alloy Steel
2. Iron elbow
3. Bearing
4. Dimmer
5. Bolt
6. White Melamine Plywood
7. Oil paint
8. Rod

4. RESULTS AND DISCUSSION

This study presents the test results and discussion of the governor test equipment that has been designed and made. The data obtained consist of rotation values (rpm) and sleeve rise height (mm) with different load variations, namely no load, 300 gram load, and 800-gram load. This discussion aims to explain the working pattern of the governor system, analyze the effect of load and rotation on the sleeve rise height, and evaluate the characteristics and performance of the test equipment used in accordance with the working principle of the centrifugal governor.

In this study, 4 experiments were carried out on load variants which produced the following data:

1. First attempt

The results of experiment 1 that we present notable 1 below:

Table 1. Experiment 1 Results

Round	Experiment 1					
	No Load		Load 1		Load 2	
	rpm	mm	Rpm	Mm	Rpm	mm
800	802,1	120	651,3	60	159,9	15
900	898,9	140	764,3	90	230,3	25
1000	1027,3	160	822,9	105	282	30
1100	1130,2	170	952,4	160	398,5	40
1200	1189,7	180	1052,4	175	527,3	55

The results of testing the governor test equipment with various loads (no load, load 1 of 300 grams, and load 2 of 800 grams) show a consistent working pattern in accordance with the working principle of the centrifugal governor. The rotation (rpm) and sleeve rise (mm) data indicate that the rotation value required to lift the sleeve to a certain height is inversely proportional to the value of the load used.

In no-load conditions, the rotational value required to produce a sleeve increase of 25 – 30 mm is in the range of 720 - 810 rpm as seen in Figure 2. Meanwhile, with load 1 (300 grams), the rotational value for the same increase decreases significantly, which is in the range of 540 – 630 rpm, and even with load 2 (800 grams), the rotational value can be much lower, which is around 180–225 rpm to produce an equivalent sleeve increase. This phenomenon indicates that the heavier the load used, the smaller the rotational value required to produce a certain displacement on the sleeve.

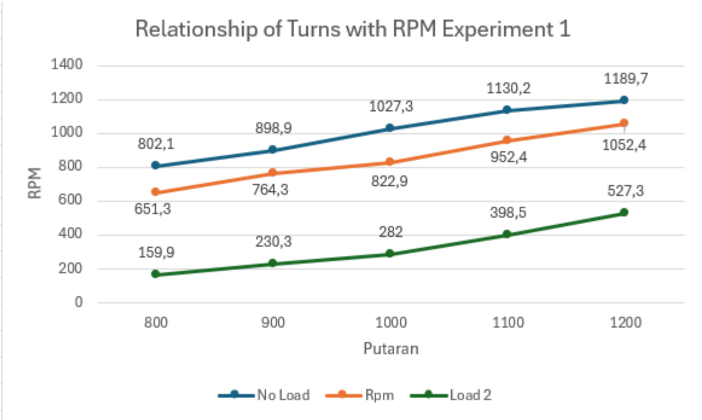

Figure 2. Relationship between Rotation and RPM Rotation Experiment 1

The increase in the rotational value also has a linear impact on the increase in sleeve height. Under all load conditions, it can be seen that the higher the dimmer rotational value, the RPM rotation also increases. Under no-load conditions, the RPM value increases from 802.1 rpm to 1189.7 rpm as the dimmer increases. Meanwhile, with load 1 (300 grams), the RPM value is in the range of 651.3 rpm to 1052.4 rpm, and at load 2 (800 grams), the RPM value is much lower, only 159.9 rpm to 527.3 rpm. This shows that the load effect makes the system more sensitive, namely it can achieve higher displacement with lower rotational values compared to the no-load system Figure 3.

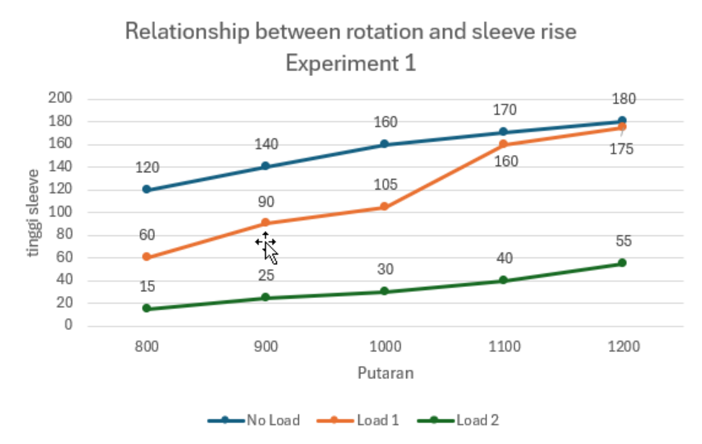

Figure 3. Relationship between Rotation and Sleeve Increase Experiment 1

2. Second Attempt

The results of experiment 2 are presented in table 2 below:

Table 2. Experiment 2 Results

Round	Experiment 2					
	No Load		Load 1		Load 2	
	rpm	mm	Rpm	Mm	Rpm	mm
800	821,9	125	547,2	55	163,1	15
900	911,4	140	670,4	85	222,9	30
1000	1008,7	160	806,9	100	271,4	35
1100	1121,8	175	921,8	150	413,1	45
1200	1231,6	180	1026,4	170	562,4	60

In this experiment, it can be seen that the rotational speed required to lift the sleeve to a certain height is inversely proportional to the load value used. When the load used is smaller (without load), a relatively higher rotational speed is required to produce a significant sleeve rise (Figure 4). For example, for a sleeve rise of 30–35 mm, the rotational speed required is in the range of 890–1190 rpm. However, with the addition of a load of 300 grams, the rotational speed to produce the same rise can decrease to 650–1050 rpm, while for a larger load, namely 800 grams, the rotational speed required can even decrease to 160–530 rpm. This phenomenon explains that the governor system with a heavier load can react more sensitively and quickly, even with a lower rotational speed value.

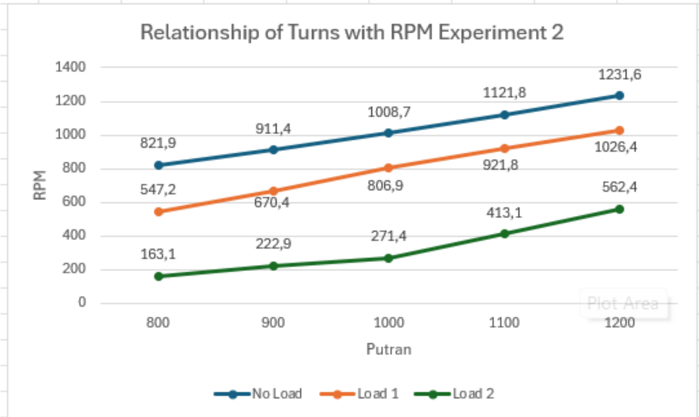

Figure 4. Relationship between Rotation and RPM Rotation Experiment 2

Furthermore, the pattern of sleeve height increase also shows that with increasing rpm, the sleeve height also continues to increase, both under unloaded and loaded conditions (Figure 5). The highest rpm value used in this experiment (1231.6 rpm) resulted in the largest sleeve increase value for the heaviest load (800 grams), namely in the range of 163.1–562.4 rpm. This indicates that the rpm value is indeed a key parameter that controls the height of the sleeve movement according to the work requirements of the governor system.

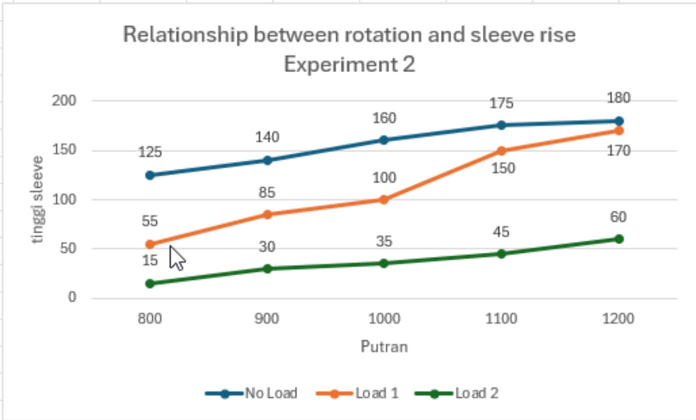

Figure 5. Relationship between Rotation and Sleeve Increase Experiment 2

In terms of operating characteristics, this pattern can be explained in terms of centrifugal force and gravitational force. In a governor system, the ball or mass used as a load provides a gravitational force that counteracts the centrifugal force from the shaft rotation. With a heavier load, the resulting gravitational force is also higher, but this also makes the system more responsive. It can be seen that at the heaviest load (800 grams), the sleeve rise can reach 60 mm with only the fifth dimmer rotation (562.4 rpm), while at no-load conditions, the sleeve rise is much greater, namely up to 180 mm with the same dimmer rotation (1231.6 rpm). Load 1 (300 grams) is in between the two with a maximum sleeve rise of 170 mm at 1026.4 rpm.

The results of this experiment demonstrate that the governor system can be calibrated to meet the engine's operating requirements. Under higher loads, the operating speed can be reduced to achieve the desired sleeve height. This provides a baseline for developing governor systems that require low operating speeds but high mechanical response, such as those used in engines with specific speed control requirements.

3. Third Attempt

The results of experiment 3 can be seen in Table 3 below this:

Table 3. Experiment 3 Results

Round	Experiment 3					
	No Load		Load 1		Load 2	
	rpm	mm	Rpm	Mm	Rpm	mm
800	813,7	120	565,3	60	178,4	15
900	924,6	145	678,7	85	235,6	25
1000	1006,4	160	831,9	100	299,7	30
1100	1095,8	170	939,7	155	403,4	40
1200	1222,9	180	1032,2	170	551,3	55

In this experiment, the no-load condition shows that the rotational speed required to produce a sleeve elevation of 30–40 mm is in the range of 911 to 1008 rpm. With the application of a load of 300 grams, the required speed range decreases to 670 to 807 rpm, while at a load of 800 grams, the range is lower, namely 222 to 413 rpm Figure 6. These data show an inverse relationship between the magnitude of the load and the rotational speed required to achieve a certain sleeve elevation. The greater the applied load, the smaller the speed value required to move the sleeve.

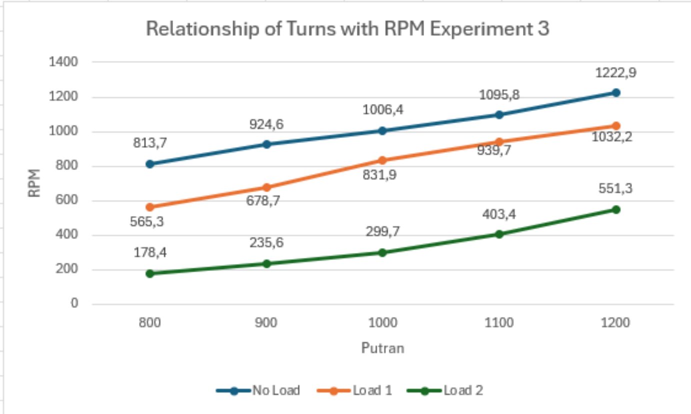

Figure 6. Relationship between Rotation and RPM Rotation Experiment 3

Increasing the dimmer speed consistently resulted in an increase in sleeve height across all load conditions. At maximum rotational speed, the sleeve height was recorded at 195 mm for no-load conditions, 185 mm for a 300-gram load, and 75 mm for an 800-gram load (Figure 7). These results indicate that the governor system with a larger load exhibits a more efficient mechanical response to centrifugal forces, allowing significant sleeve movement even at lower speeds. This characteristic makes the system more stable in maintaining the engine's rotational speed under changing operational load conditions.

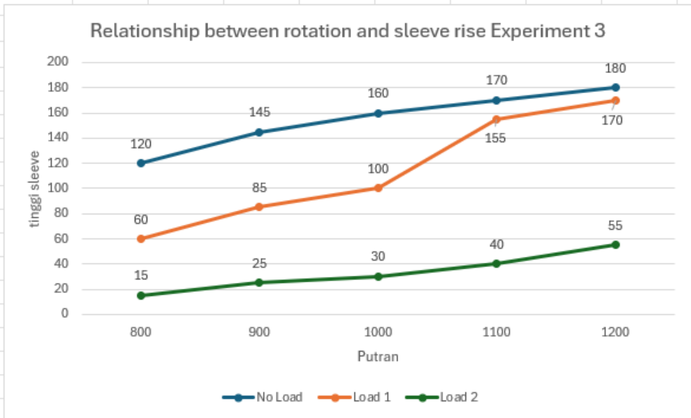

Figure 7. Relationship between Rotation and Sleeve Increase Experiment 3

4. Fourth Attempt

The results of experiment 4 are presented in table 4 below:

Table 4. Results of Experiment 4

Round	Experiment 4					
	No Load		Load 1		Load 2	
	rpm	mm	Rpm	Mm	Rpm	mm
800	795,3	120	542,1	55	151,2	15
900	925,1	140	662,7	85	229,5	25
1000	1010,2	160	804,7	100	261	35
1100	1126,5	170	930,2	160	393,1	45
1200	1254	180	1013,8	170	535,7	55

In this experiment, the no-load condition shows that the rotational speed required to produce a sleeve rise of 30–40 mm is in the range of 902 to 1015 rpm. With the application of a load of 300 grams, the required speed range decreases to 675 to 812 rpm, while at a load of 800 grams, the range is lower, namely 218 to 405 rpm Figure 8. These data show an inverse relationship between the magnitude of the load and the rotational speed required to achieve a certain sleeve elevation. The greater the applied load, the smaller the speed value required to move the sleeve to reach the same height.

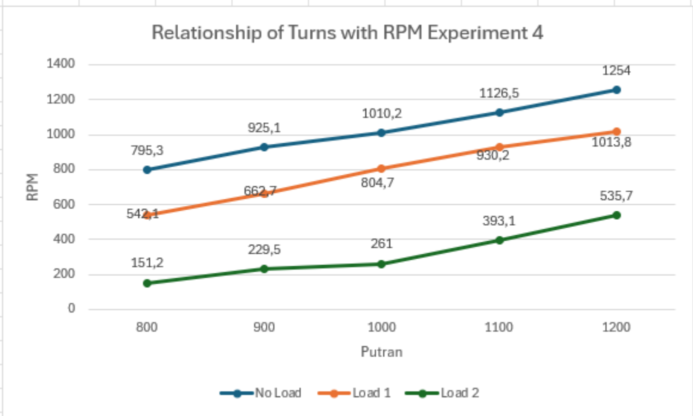

Figure 8. Relationship between Rotation and RPM Rotation Experiment 4

The results of experiment 4 further emphasize the working principle of the centrifugal governor system, namely the close relationship between the rotational speed (RPM), load, and the height of the sleeve rise. In general, the higher the rotational speed, the greater the sleeve rise that occurs. This pattern is consistent across all load variations. Under no-load conditions, the maximum sleeve rise was recorded at 190 mm at 1205 rpm. With a load of 300 grams, the maximum rise decreased to 180 mm at 995 rpm, while with a load of 800 grams, the maximum rise only reached 75 mm at 395 rpm. This data can be seen in Figure 8, which illustrates the relationship between dimmer rotation and sleeve rise height.

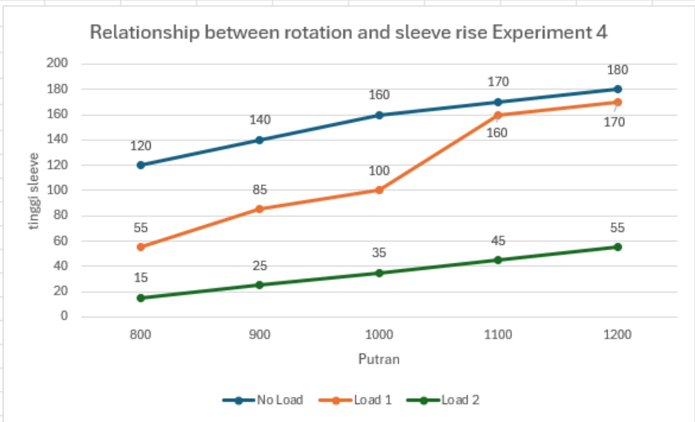

Figure 9. Relationship between Rotation and Sleeve Increase Experiment 4

Furthermore, the load's influence on the system is also significant. Higher loads tend to decrease the required rpm to raise the sleeve to a given height. For example, to achieve a sleeve height of 35–45 mm, a speed of 996–1085 rpm is required without load, 805–930 rpm for a 300-gram load, and only about 261–393 rpm for an 800-gram load. This phenomenon indicates that the governor system becomes more sensitive to changes in rotational speed when given a heavier load. This is also evident in Figure 9, which illustrates the relationship between dimmer speed and the required RPM under each load condition.

Overall, the sleeve increase characteristic versus dimmer rotation shows a linear trend, especially under no-load and 300-gram load conditions. Meanwhile, even though the 800-gram load shows a decrease in the required rotation value, the pattern trend remains. This indicates that the governor has response characteristics that can be calibrated according to operational needs, both to maintain engine speed stability and increase system sensitivity to load changes.

4.2 Discussion

4.2.1 Relationship between Rotation and Sleeve Increase

Across all the experiments (1 through 4), the most consistent pattern observed was that the higher the input shaft rotation (RPM), the greater the sleeve lift. This principle aligns with the working mechanism of a centrifugal governor, where the centrifugal force generated by rotation causes the flyball to move away from the central shaft, thus lifting the sleeve upward.

The data shows that across all load variations (no load, 300 grams, and 800 grams), increasing the rotation speed directly increases the sleeve rise height. For example, in Experiment 4 (Figure 8), the maximum sleeve rise was recorded at 190 mm at 1205 rpm with no load, 180 mm at 995 rpm with a 300-gram load, and 75 mm at 395 rpm with an 800-gram load. A similar trend was also seen in Experiments 1 to 3, which showed consistent sleeve rise with each increase in the dimmer rotation level.

4.2.2 Effect of Load on Governor Sensitivity

The results of Experiments 2 through 4 demonstrate the significant effect of load size on the rotational speed required to reach a given sleeve height. The greater the load, the lower the rotational speed required to lift the sleeve to the same height. This phenomenon occurs because the greater gravitational force on a heavy load can be quickly offset by centrifugal force at lower speeds.

In Experiment 4, to achieve a sleeve height of 35 – 45 mm, the required rotational value is:

No burden	:902 – 1015 rpm
300-gram load	:675 – 812 rpm
800-gram load	:218 – 405 rpm

These findings support the results of Experiment 3, where a 30–40 mm sleeve increase required:

No burden	:911 – 1008 rpm
300-gram load	:670 – 807 rpm
800-gram load	:222 – 413 rpm

This confirms that the governor system with a larger load shows a faster response to changes in shaft speed, even at lower rotational values.

4.3.3 System Linearity Characteristics

From the graph of the relationship between dimmer rotation and sleeve increase (Figure 9) and the relationship between dimmer rotation and RPM (Figure 8), it can be seen that at light loads (no load and 300-gram load), the sleeve increase against rotation shows a linear trend. Each increase in the dimmer level results in a relatively uniform sleeve increase.

However, at heavy loads (800 grams), although the sleeve rise pattern remained consistent, a deviation from linearity was observed. This was due to greater mechanical resistance and inertial effects, resulting in a sleeve rise at higher dimmer levels that was not as large as expected.

These characteristics demonstrate that the centrifugal governor system has good adaptability to load variations, maintaining engine stability despite changing operating conditions. The system maintains rotational stability by dynamically adjusting the sleeve position to the resulting centrifugal force.

4.3.4 Validation with Previous Research

The results of this study are in line with the basic theory of the centrifugal governor system which states that centrifugal force increases with increasing shaft rotation speed, and will cause movement of control elements such as the sleeve (Rao, 2004). Adding a load to the system results in increased sensitivity, where the minimum rotation value to lift the sleeve becomes lower. This supports the findings of Giri (2007), which states that additional loads can accelerate the response of the governor system to changes in rotational speed, making it more sensitive and efficient in maintaining system stability.

Furthermore, a study by Setiawan and Mulyadi (2019) showed that the governor system experienced a shift in its operating point when subjected to load variations, as reflected in the change in the RPM required to reach equilibrium. These results were reinforced by experiments, particularly with an 800-gram load, in which the system was able to lift the sleeve at a significantly lower RPM than under no-load conditions. The alignment of these experimental results with theoretical and previous studies provides strong validation of the data's reliability and interpretation.

5. CONCLUSION

Based on the experimental results, it can be concluded that the centrifugal governor system shows a clear correlation between the shaft rotational speed and the sleeve lift height. Increasing the rotational speed produces a greater centrifugal force, thus causing the sleeve to move to a higher position. Increasing the load on the system has been shown to increase the sensitivity of the governor, indicated by a decrease in the minimum rotational speed required to lift the sleeve. The characteristics of the relationship between rotational speed and sleeve lift tend to be linear at light loads, and remain stable at higher loads. These findings are consistent with the basic theory of centrifugal governors and validated through previous studies, so they can be used as a basis for automatic and adaptive engine speed control to changes in load conditions.

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