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# DYNAMIC RESPONSE STUDY OF HARTNELL GOVERNOR

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**Abstract**
The function of the governor is to minimize the fluctuation in the mean speed, which mainly occurs from load variation. It controls the speed when torque is changing due to load variation. It senses the engine's speed, automatically supplies more fuel when speed decreases, and limits the fuel supply when it increases. This study aims to find the equation of motion of the Hartnell governor for vibrational studies and present the dynamic behavior of the Hartnell governor for different speeds

***Keywords***: Mechanical Governor, Hartnell governor, vibration, natural frequency, dynamic behavior.

## 9. INTRODUCTION

Hartnell governor is a spring-loaded centrifugal governor used to regularize the fuel flow to reduce speed fluctuations. A flywheel which minimizes the variation of speed in one cycle cannot reduce the fluctuations due to variation in load. The average speed of the engine is not under the control of the flywheel in any way. The introduction of governors helps to smooth out the peaks and valleys at the average speed [1]. The governor is responsible for maintaining a constant average speed regardless of the changing demands on the engine over an extended time. The governor readjust the amount of fuel supplied to changes in the vehicle's speed. When the speed is low, the governor increases the fuel supply; when the speed is high, the governor reduces the fuel supply [2].

The governors are mainly classified into two categories, one category consists of inertia governors, and the other category consists of centrifugal governors [1].

In governors characterized by inertia, the controlling force counterbalances the force of inertia. In contrast, in governors characterized by centrifugal motion, the controlling force counterbalances the force of centrifugal motion. The centrifugal governors see a lot of applications and come in various varieties [1].

The working principle of the Hartnell governor is the same as that of other centrifugal governors [1], [3].

- The bell crank lever is pivoted to the frame. It has a fly ball mounted on the vertical arm, and the horizontal arm is connected to the sleeve.
- Fly balls are mounted onto the vertical arm of the bell crank lever.
- Spring is enclosed into the frame. This spring applies a load on the sleeve in the downward direction.
- The sleeve is the main part of the governor that is installed on the spindle.
- The horizontal part of the bell lever is linked to the sleeve using a roller. The movement of the sleeve is used to change the fuel supply.
- The frame holds and safeguard the bell crank levers and springs.

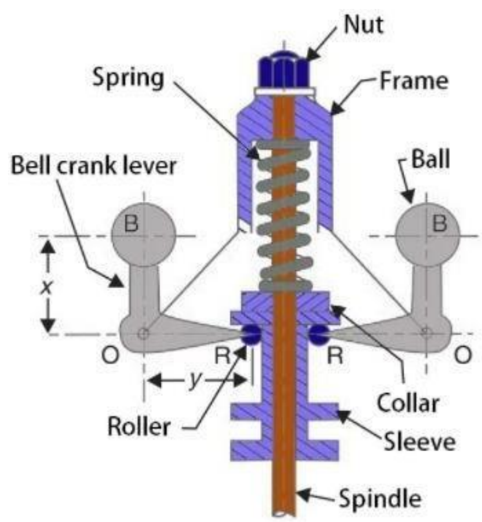


Fig.1. Hartnell governor construction

When the engine load increases, the engine's speed decreases. The decrease in engine speed decreases the rotational speed of the spindle, and as a result, the centrifugal force on the fly balls decreases. The fly balls move inside, and in result the force on the spring decreases; therefore, the length of the spring increases. The sleeve is lowered on the spindle; hence the fuel supply increases, and the engine's speed increases to the mean speed. The same principle is repeated when speed is high, the fly balls move outside due to centrifugal forces, and the sleeve is compressed against the spring, which decreases fuel supply and the engine's speed is reduced [4]. The balls moves away from the spindle axis, the crank levers adjust around pivot point, and the sleeve lifts opposing spring load as the force on the engine reduces. The sleeve's movement is transferred to the engine's throttle, and the fuel supply to the engine is reduced, resulting in a reduction in engine speed. When the engine's load diminishes, the speed drops, the balls move closer to the spindle axis, and the sleeve descends. The sleeve's movement is transferred to the engine's throttle, and the fuel flow to the engine is increased, resulting in increased engine speed. Using a screw cap nut, the spring force may be modified.

## 10. DESIGN CONSIDERATIONS

**2.1. Sensitiveness.** The governor's sleeve movement must be large to maintain a constant rotational speed, and the accompanying adjustment in equilibrium speed should be as modest as possible. The more sensitive the governor is, the sleeve is adjusted quickly and detect more accurately small changes. A more accurate definition of sensitivity would be the ratio of the difference in equilibrium speed between the highest and lowest speeds to the speed at which the equilibrium is maintained on average. An overly sensitive governor will significantly adjust the amount of fuel supplied whenever there is even a slight variation in the rotational speed. This results in significant shifts in the engine speed, which drives the governor into a state of constant hunting. [2].

Nmax = maximum equilibrium speed
Nmin = minimum equilibrium speed

Sensitiveness = 2(Nmax-Nmin)/(Nmax+Nmin)

**2.2. Stability.** It is possible to determine whether or not a governor is stable by determining whether or not there is only one distance of the balls at which the governor is in equilibrium for each speed that falls within the operating range. If the equilibrium speed were to increase, the governor balls' radius would also need to grow for the governor to remain stable. [5].

**2.3. Isochronism**. Isochronous is the behavior of a governor in which the equilibrium speed remains the same over the whole operating range for a given set of radii of rotation for the balls. A governor based on isochrones theory will have unlimited sensitivity. [6].

**2.4. Governor effort**. The amount of load that a governor can put on the sleeve of the mechanism that regulates the amount of fuel supplied to the engine is referred to as its "effort." The term "effort" refers to the average amount of load applied throughout the specified change in speed. The standard definition of an effort accounts for a one percent chance of speed. [7][8].

### 2.5. Advantages of Hartnell governor

- The Hartnell governor has the following advantages.
- Operational speed is very high
- Compact in size
- Precise regulation
- For required equilibrium speed the compression of spring can be adjusted.

**2.6. Dynamics of Machinery Laboratory's Hartnell Governor Experiment.** The purpose of the work that will be done is to analyze the performance characteristics of a Hartnell governor mechanism available to our undergraduates, postgraduates, and research scholars in the dynamics of machinery laboratory and compare those results with the theoretical one that the manufacturer provided. Researchers, scientists, and design engineers would be able to select the fly ball's precise spring length and mass to execute the specific duty per specific needs based on this study. This paper examines not just the theoretical features of the Hartnell governor but also its practical applications. When beginning the conceptual design stage for their research projects, researchers and scientists may find this study useful as a reference tool to help them carry out their job.

**2.7. Review of centrifugal governor design and analysis.** When there is a change in the amount of work being done by the engine, it is the governor's job to keep the speed constant within a predetermined range. This device is suitable for use in virtually all types of motor vehicles. When the governor is rotated around its axis, our inquiry aims to discover the stress concentration places and the areas most prone to failure and measure the value of these stresses. This investigation is carried performed with the assistance of PRO E. In addition to this, the distance from each component of the SPINDLE is moved away from the base is computed, and graphs are drawn to represent the results. The effect of the "Weight Of the Arms" is the primary focus of our research, and the calculations that are carried out take into account this factor. The weight of the arms acts on the centroid of the arms, and when the governor assembly spins, centrifugal force starts working on the centroid of the arms and tends to bend or deflect the arms; however, this deflection or bending needs to be kept to a minimum. Within the scope of our service, we have performed the Stress study on a specific configuration of the governor. Assembly, after which various materials are offered on a theoretical basis.

**2.8. Hartnell Governor Design and Fabrication.** A governor's job is to maintain the speed of an engine within set limits, and it also increases the sensitivity of an engine whenever there is a difference in load. Our study aims to produce a prototype of a product called "Hartnell Governor." It is a clever piece of equipment used in manufacturing technology. It is not very pricey and can be used in any car. The governors control devices and operate according to the feedback control concept. Their primary purpose is to maintain a constant speed within predetermined parameters regardless of the load the prime mover carries. They are powerless to influence the fluctuation in the cycle's speed. Within the cycle, the flywheel controls the speed at which the cycle rotates. As a result, the governor plays a vital part in controlling the speed. It assures that the speed will be regulated under any

Circumstances to investigate what happens when the mass of the sleeve in the middle of the porter governor is changed.

**2.9. ANSYS design, multi-rigid body dynamic, and modal analysis of the centrifugal governor.** When there are fluctuations in the load, such as when the load on an engine increases, its speed decreases, and as a result, it becomes necessary to increase the supply of working fluid; the function of a governor is to regulate the mean speed of the engine so that it remains constant. This is accomplished by controlling the flow of working fluid. On the other hand, if the engine's load is reduced, then its speed will increase, and as a result, you will need less working fluid. The governor is a device that automatically regulates the flow of working fluid to the engine in response to changing load conditions. It also ensures that the average speed remains within predetermined parameters. And maintains the average speed within a predetermined range by a radial force equal and opposed to it, referred to as the regulating force. It is made up of two balls of the same mass, sometimes called governor balls or fly balls. The engine turns the spindle, which in turn causes the balls to revolve, using bevel gears as the transmission mechanism. Because the top ends of the arms are hinged to the spindle, the balls can ascend higher or descend lower as they circle the vertical axis of the device. The links attach the arms to a sleeve, which is keyed to the spindle. The spindle is the central component. This sleeve rotates around the spindle simultaneously with the spindle itself, but it also can glide up and down the balls. Additionally, the sleeve rises when the spindle speed increases and descends when the speed drops.

In this project, we model centrifugal governor individual parts and assembly of parts of Centrifugal governor using Catia V5 and import into ANSYS WORKBENCH 14.5 for Multi Rigid body dynamic Analysis and Modal Analysis. In this Multibody dynamic analysis, we investigate how the deformation, spring probe, and mode shapes vary depending on the natural frequencies. In modal analysis, velocity is a factor that considers the structure.

**2.10. Hartnell governor's construction and operation.** The Hartnell governor is loaded with a spring. When the spring is first installed, it is done so in a compressed state so that a force can be exerted on the sleeve. It is constructed out of two bell crank levers hinged to the frame. Because it is coupled to the governor spindle, the frame rotates in the same direction. Each bell crank lever has a mass attached to one end and a roller attached to the opposite end. If there is less load on the engine, the speed will go up; the balls will move away from the spindle axis; the bell crank levers will move on the pivot, and the sleeve will be lifted in opposition to the force of the spring. The movement of the sleeve is then transferred to the engine's throttle, which reduces the fuel supplied to the engine and, consequently, a slower engine speed. The speed will also drop if the load being placed on the engine is reduced.

This will result in the balls moving closer to the spindle axis, which will cause the sleeve to slide downward. The movement of the sleeve is transferred to the engine's throttle, which results in an increase in fuel supply to the engine and, consequently, an increase in engine speed. With the use of a screw cap nut, the amount of force generated by the spring can be altered.

**2.11. Hartnell governor: working, diagram, parts**. One variety of spring-loaded centrifugal governors is known as the Hartnell governor. The Hartnell governor utilizes a spring to exert a downward force on the sleeve of the governor. Adjusting the nut on the frame will compress the spring, resulting in a different amount of downward force. In this particular style of governor, the sleeve is loaded using a spring, as opposed to other styles, such as the porter and propeller governors, which employ a dead weight instead. When using a governor of this kind, the load placed on the spring is altered to adjust the engine's average speed. We can alter the mean speed of the engine because the governor is equipped with a spring; however, in the case of governors loaded with dead weight, it is impossible to adjust the mean speed. When compared to previous governors, this one has a more compact design. Compared to another governor, the flyballs produced by this governor are significantly smaller due to the adjustable spring load. Because it is spring-loaded, it may return to its original place when its speed has been reduced, even without the assistance of gravitational pull. As a consequence of this, it can be mounted in either a vertical or horizontal orientation. The presence of rollers on the surface of the sleeve contributes to a reduction in the amount of resistance caused by friction.

**2.12. Structurer design and Hartnell governor analysis to improve speed sensitivity**. This work will modify the structure design of the Hartnell governor to improve the sensitivity within the alteration speeds by reducing the friction between the sleeve and the spindle. Additionally, this work will analyze the structure of the Hartnell governor after it has been modified. It is possible to change the dimensions of the sleeve without changing the dimensions of the other parts of the governor assembly by introducing ball bearings between the sleeve and the spindle of the governor assembly. This will reduce friction and allow for the dimensions of the sleeve to be changed. When the newly designed governor is rotating at maximum speed about its axis, determining the stress concentration places most prone to failure and measuring the maximum value of these stresses, the goal is to do both of these things simultaneously. The governor's design will be altered in response to the measured values of the stress. The software known as solid works is utilized in the process of carrying out this analysis. The current experiment involves modifying the Hartnell governor to raise the level of sensitivity and lower the friction between the spindle and the sleeve. Ball bearings are inserted in this modification's new location between the spindle and the sleeve. The stress values were measured at various parts of the governor, and the structure of the Governor was modified to lower the amount of stress concentration. This was done to show a graph between the alteration speed and the friction.

Table 2. Summary of Findings

| Author | Method | Results |
|---|---|---|
| Trupti J. Navathale, 2017 [2] | Governor's axial deflection | axial displacement rises with angular velocity. |
| Ramavath Suman, 2019 [5] | Isochronism | It regulates speed under any circumstances |
| Vanga Padmasri, Padmasri, 2018 [1] | ANSYS | Vibration analysis improves accuracy. |
| M.Tech , Shaik Munny, 2020 [8] | Analysis of Hartnell Governor | Governor with bearing reduces friction and change speeds. |

## 3. MATHEMATICAL MODELING

The mathematical equation is derived from studying the Hartnell governor's dynamics. The following assumptions are made while deriving the equation of motion for the Hartnell governor.

- Only the mass of the ball is considered
- The mass deflection is small due to high sensitivity, and the angle is ignored.
- Levers are considered rigid elements

All these assumptions are made to derive the equation for a single degree of governor's freedom.

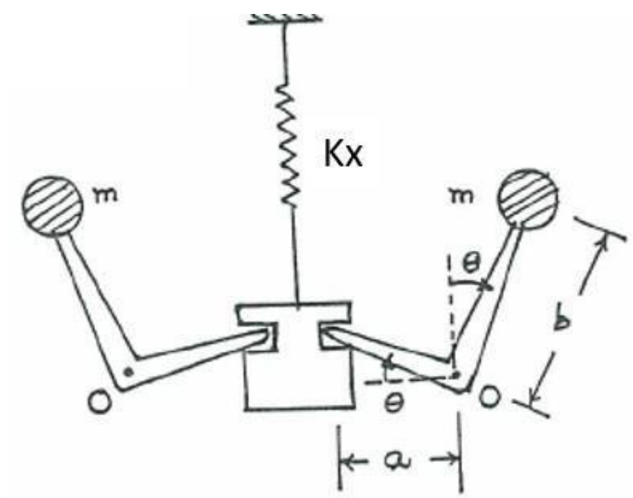


Fig.2. Freebody diagram of Hartnell governor

m = mass of the ball
b = vertical distance between ball and pivot point O.
a = horizontal distance between the pivot point and roller centre
Kx = stiffness of the spring
Considering a small displacement of the ball arm about the vertical position. Equilibrium about point O gives;

….. (1)

Equation (1) represents equilibrium about point O

For small values of Ө, sin (Ө) = Ө, cos (Ө)=1. The equation is reduced to the following form in Equation (2)

$$M \cdot b^2 \cdot \ddot{\theta} + k \cdot a^2 \cdot \theta = 0 \quad \text{……………………. (2)}$$

For this, the natural frequency is derived below in Equation (3)

$$w_n := \left(\frac{k \cdot a^2}{M \cdot b^2}\right)^{\frac{1}{2}} \quad \text{…………………………. (3)}$$

**3.1. A general equation for the free and undamped system.** The general equation for the free and undamped system is represented in Equation (4)

$$x(t) := A \cdot \cos\left(w_n \cdot t - \phi\right) \quad \text{…………………. (4)}$$

Where A is the vibration amplitude and Ø is the phase difference. The following formulas are used for calculating the amplitude and phase differences.

$$A = \sqrt{{x_o}^2 + \left(\frac{\dot{x}_o}{w_n}\right)^2} \quad \text{…………………………. (5)}$$

$$\phi = \text{atan}\left(\frac{\dot{x}_o}{x_o \cdot w_n}\right) \quad \text{………………..…… (6)}$$

**3.2. The general equation for the free and damped system.** The general equation for the free and damped system is

$$x(t) = X_o \cdot e^{-\zeta \cdot w_n \cdot t} \cdot \sin\left(w_d \cdot t + \phi\right) \quad \text{……… (7)}$$

$X_0$ is the vibration amplitude, wd is the damped natural frequency, ζ is the damping ratio, and Ø is the phase difference. The following formulas are used for calculating the amplitude and phase differences

$$X_o = \frac{\sqrt{{x_o}^2 \cdot {w_n}^2 + {\dot{x}_o}^2 + 2 \cdot \zeta \cdot w_n \cdot \dot{x}_o \cdot x_o}}{w_d} \quad \text{……..(8)}$$

$$\phi = \text{atan}\left(\frac{x_o \cdot w_d}{\dot{x}_o + \zeta \cdot x_o \cdot w_n}\right) \quad \text{….. (9)}$$

**3.3. The general equation for the forced and un-damped system**. The general equation for the force and un-damped system ignoring the natural response, is

$$x_p(t) = X \cos \omega t \quad \text{………… (10)}$$

Where the value of X can be calculated using the following equations

$$x_p(t) = X \cos \omega t \quad \text{…………….. (11)}$$
$$k - m\omega^2$$

$$X = \frac{F_0}{k - m\omega^2} \cos \omega t \quad \text{……………….. (12)}$$

Equation 11 is for the unit force and equation 12 is for the sinusoidal force.

**3.4. The general equation for the forced and damped system.** The general equation for the force and un-damped system ignoring the natural response is

$$x_p(t) = X \cos(\omega t - \phi) \quad \text{………………… (13)}$$

The value of X and Ø can be calculated using the following equations.

$$X = \frac{F_0}{[(k - m\omega^2)^2 + c^2\omega^2]^{1/2}} \quad \text{…………….. (14)}$$

$$\phi = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right) \quad \text{……………. (15)}$$

C is the damping coefficient, and w is the force frequency.

The force can be calculated using the following formula

$$F_o := M \cdot r \cdot w^2 \quad \text{…………….. (16)}$$

## 4. DYNAMIC RESPONSE

PTC Mathcad Prime 4 is used to plot the dynamic response of the Hartnell governor. The following values are used to calculate different parameters in the governing equations

Gravitation acceleration g=9.8m/s2, spring stiffness Kx=104 N/m, length a=0.12m, length b=0.20m, initial speed w=20 rpm, damping C=5N*s/m, mass of the ball M=2.548kg, central distance r=c=0.16m.

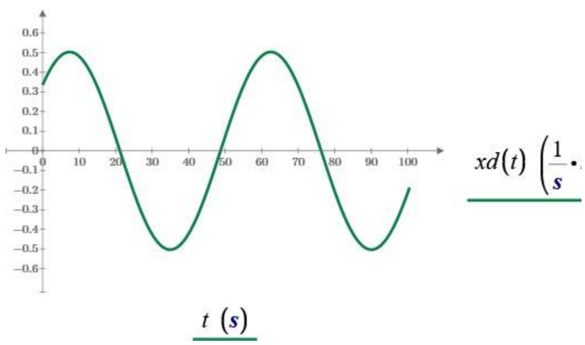


Fig.3. Displacement vs time (un-damped, free)

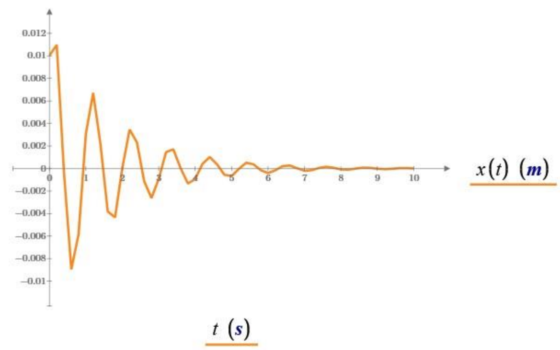


Fig.6. Displacement vs time (damped, free)

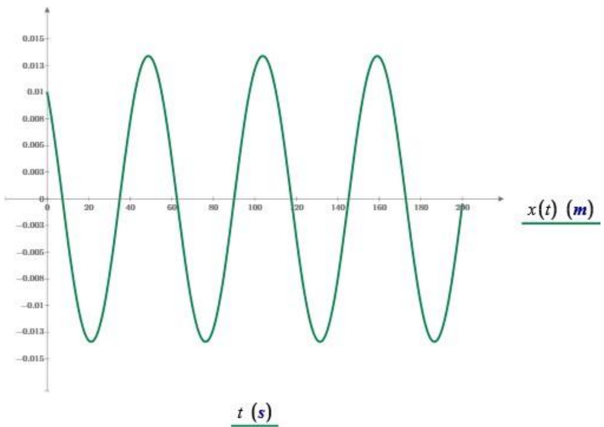


Fig.4. Velocity vs time (un-damped, free)

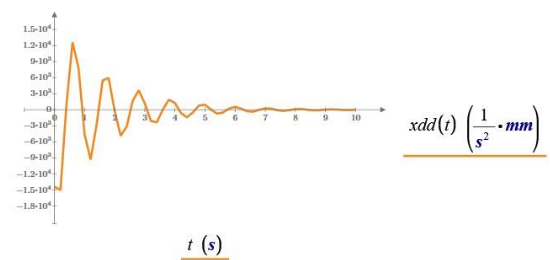


Fig.7. Velocity vs time (damped, free)

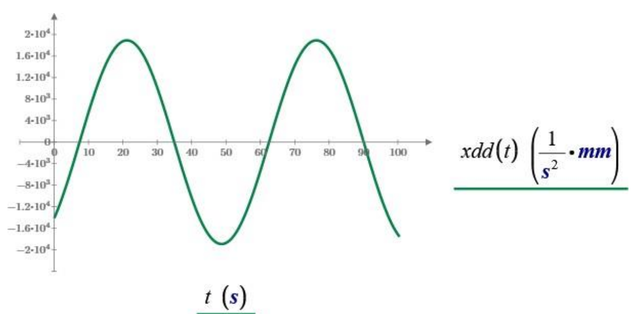


Fig.5. Acceleration vs time (un-damped, free)

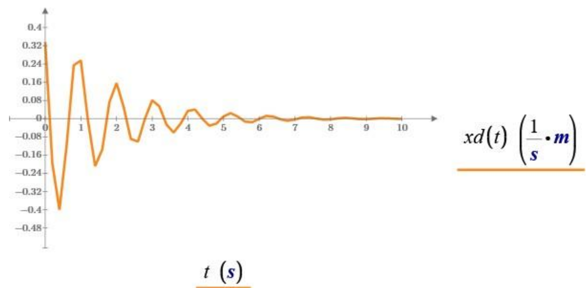


Fig.8. Acceleration vs time (damped, free)

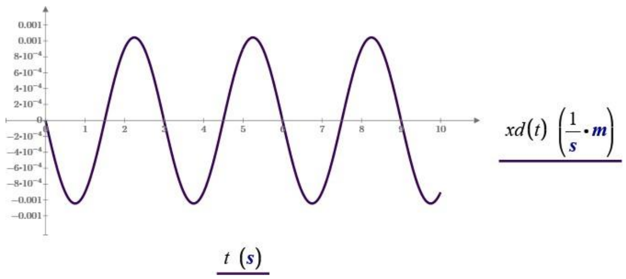


Fig.9. Displacement vs time (un-damped, forced)

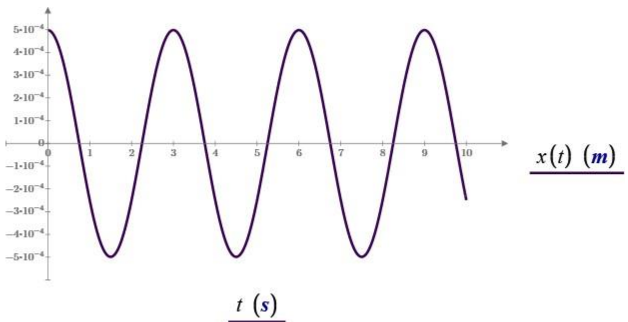


Fig.10. Velocity vs time (undamped, forced)

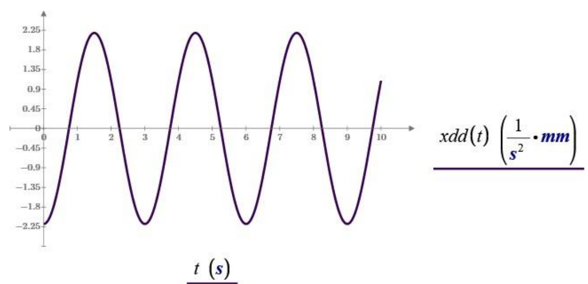


Fig.11. Acceleration vs time (undamped, forced)

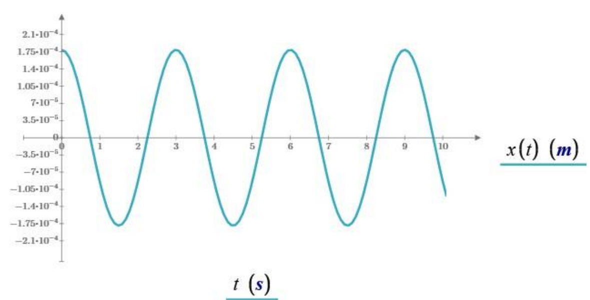


Fig.12. Displacement vs time (damped, force)

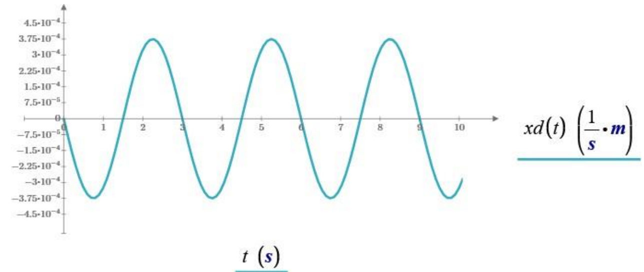


Fig.13. Velocity vs time (damped, force)

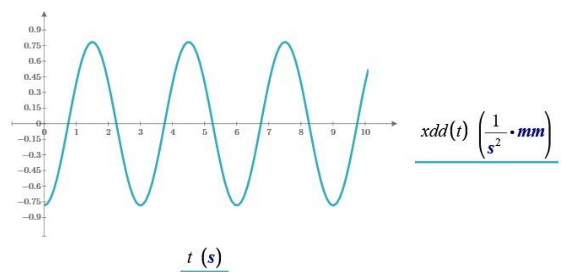


Fig.14. Acceleration vs time (damped, force)

## 5. RESULTS

The dynamic response or behavior of Hartnell behavior for a different situation is shown in the previous section by taking some parameters constant. This section explains the graphs presented in section 4.

**5.1 Un-damped and free vibration.** First, the natural frequency is calculated using equation 3. The natural frequency of Hartnell governor for the given data is 37.58 rad/s. Figure 3 shows the displacement vs time graph where the maximum amplitude is 0.013m. Figure 4 shows the velocity vs time graph, and figure 5 shows the Acceleration vs time graph. The amplitude is different for each graph, but the frequency is the same. Another difference is phase difference. The difference between the respective graphs is 90 degrees.

### 5.2. Damped and free vibration.

Figure 6 shows the displacement vs time graph for the damped and free system. The amplitude reduces over time because of damping. The damping causes the loss of energy and vibrations to vanish over time. Figure 7 shows the velocity vs time graph, and figure 8 shows the acceleration vs time graph. There is a phase difference in each graph from the other, but the damping behavior is almost the same.

### 5.3. Un-damped and forced vibration.

Figure 9 shows the displacement vs time graph for the un-damped and forced system. The force is applied in repetitive sinusoidal form. The natural response is ignored because it dries out quickly, and the response under force is shown. Figure 10 and figure 11 shows the velocity and acceleration graphs for time. The amplitude for these graphs is different, but the frequency is the same as that of applied forces.

### 5.4. Damped and forced vibration.

Figure 12 shows the displacement vs time graph for the damped and forced system. The vibrations do not die over time because of the constantly applied force. The damping changes the phase of the vibration, and this is how the response of the system lags the applied force and resonance is prevented. Figure 13 shows the velocity vs time graph, and figure 13 shows the acceleration vs time graph. There is a phase difference in each graph from the other, but the damping behavior is almost the same.

## 6. CONCLUSION

The main aim of this study was to present the mathematical model and behaviour of the Hartnell governor. The study is based on assumptions, and calculations are done using a single degree of freedom approach. The mathematical models are presented for four different scenarios, and then these mathematical models are presented on graphs for each case. This calculation can be used if any manipulation is required in the governor for different inputs and loading conditions.

The natural frequency of the Hartnell governor depends upon the stiffness, dimensions of the lever arm and mass of the ball. If the natural frequency lies in the range of operational forces, then the natural frequency of the Hartnell governor can be changed by changing these parameters. Suppose the range of the forces is large, and it is impossible to change the natural frequency. In that case, suitable damping should be added to the Hartnell governor, which is always tricky because of the sensitivity of the governor. Damping decreases the sensitivity of the governor. Therefore, an optimum solution should be found for scenarios where both phenomena should be interconnected, and suitable damping is used.

## 7. RECOMMENDATIONS

This study details the single degree of freedom where the weights and stiffness of different parts are ignored. Multi-degree studies will give a detailed picture of the dynamic response of the Hartnell governor. The effects in 3 dimensions and inherent damping and stiffness's of the part will affect the dynamic response. Such detailed studies can be carried out using FEM (finite element method). Dynamic mode analysis gives the natural frequencies range and directions in different possible directions. The response spectrum density analysis shall be used to find the system's response under the applied loads and damping. This will ensure that the governor is stable and strong in different forces.

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