Optimization of PID Governor Coefficient for Turbocharged Diesel Engine

Jagannath Hirkude, Mrinal Manoj Borkar

Abstract**: *The objective of this study is to find optimum governor coefficient for which fluctuation of engine speed is minimum, for given value of engine, turbo-charger, inlet and exhaust manifold characteristics. Current study uses the Wishnegradski Stability Diagram as suggested by V. I. Krutov [1], which graphically represents the dynamic response of governor based on the engine differential equation which is of the third order. For the load type of L = B cos (wt): The objective function is designed to minimize the integral squared error over a time period T, which is taken as 5seconds.***

$$Objective\ Function, A = \sqrt{\int_0^T N_\varepsilon^2 dt}$$

The constraints are formed using Wishnegradski Stability Curves which are mathematically represented as x > 0 and xy – 1 > 0 y > 0, where x, y are non-dimensional parameters depending on engine characteristics and Ne is the error function. From the experimental data obtained by test on a marine turbo-charged, 6 cylinder engine model KTA-1150C-600 of the Kirloskar make, the optimized values of Kp, Ki and Kd were obtained as 798.94, 41.50 and 1137.4 respectively and corresponding objective function is 2.2202e-07 and amplitude of speed fluctuation is 2.6642e-04 rpm.

Keywords **: *About four key words or phrases in alphabetical order, separated by commas.***

I. INTRODUCTION

Diesel Engines have established themselves in all heavy-duty applications due to their high fuel economy, better part load performance and most importantly the reliability. Diesel Engines are extensively used in transportation, electric power generation and earth moving equipment. Better performance and long life of the engine depends on many factors. One of them is controlling of speed fluctuations. Engine does not perform up to the expectations when it's speed goes out of permitted range. Speed fluctuates due to various reasons, like change in ambient conditions, but is mainly attributed to variation in load condition. The consequences of speed fluctuation are increased emission, wear and tear of the engine, vibrations, decreasing fuel economy and engine life [2].

Hence forth, our primary concern is to minimize the speed fluctuations due to varying load conditions, by use of an appropriate governor. The foundation of Automatic Speed Control was laid by James Watt in 1768 to control the rotational speed of a steam engine. Since then, the speed control of Diesel Engine has relied on the conventional mechanical governors but are found to be inefficient in many situations. Some of these are the system complexity due to turbocharger lag, aging factor, dynamic ambient conditions and varying fuel properties etc. With the advent of control engineering, Electronic Governors have shown the ability to control and monitor a number of parameters with better stability and dynamic behaviour, even in a situation where various surrounding conditions are not stable.

In addition, they have an advantage of speed of response, freedom from friction and wear, ease of installation, convenience of adjustment and setting up. For designing an electronic governor, it is a must to simulate it mathematically which in turn, requires an analytical model. Different types of models such as Block Diagram Type, Wholly Dynamic and Quasi-Study Model are available. For our situation, Block Type Modeling is best suited.

II. MATHEMATICAL MODEL

Block Diagram Type of Modeling is a type of wholly dynamic modeling. The model is described in terms of operating parameters, values of which are obtained experimentally from steady state values of the operating parameters of the engine. The components of a turbo-charged engine are shown in the fig. The various parts are considered as individual systems, each having their own inputs and outputs. The engine differential equations have been mentioned below:

A. Differential Equations of the Engine

G Krutov [1] has described the model in terms of operating parameter values which are obtained from steady state values of the operating parameters of the engine. The components of the turbo-charged engine are shown in the figure 1. The various parts are considered as individual systems, each having their own inputs and outputs. Model is derived by applications of laws of inertia, ideal gas equation, conservation of mass and momentum, expansion function of various engine parameters like engine torque, rate of mass of air flow through compressor/turbine, engine, inlet/exhaust manifolds etc., using Taylor Series and taking it's linear approximation. The equations are presented below. Engine – The Prime Mover:

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The final equation for the prime mover as obtained is given below. Reader may refer Krutov[1] for further details on modeling.

$$\tau_e \frac{dN_e}{dt} + k_e N_e = R + a_1 P_{in} - b_1 L \qquad (1)$$

$$\tau_e = J_e \left[\frac{\partial T_e}{\partial h}\right]^{-1} \frac{\omega_0}{h_0} \qquad K_e = F_e \left[\frac{\partial T_e}{\partial h}\right]^{-1} \frac{\omega_0}{h_0}$$
$$a_I = \frac{\partial T_e}{\partial p_i}\left[\frac{\partial T_e}{\partial h}\right]^{-1} \frac{n_i}{h_0} \qquad b_I = \frac{\partial T_i}{\partial \emptyset}\left[\frac{\partial T_e}{\partial h}\right]^{-1} \frac{\emptyset_i}{h_0} \qquad (2)$$

$$N_e = \frac{\Delta\omega}{\omega_0} \qquad R = \frac{\Delta h}{h_0} \qquad p_{in} = \frac{\Delta\omega p_i}{h_0} \qquad L = \frac{\theta}{\theta_0} \qquad (3)$$

The Turbocharger:
Using the similar approach as that of the prime-mover equation is obtained as

$$\tau_t \frac{dN_t}{dt} + K_t N_t = P_{ex} + b_2 R - a_2 P_{in} \qquad (4)$$

Where

$$\tau_t = J_t \left[\frac{\partial T_t}{\partial P_e}\right]^{-1} \frac{\omega_{t0}}{Pe_0} \qquad K_t = F_t \left[\frac{\partial T_t}{\partial P_e}\right]^{-1} \frac{\omega_{t0}}{Pe_0}$$
$$b_2 = \frac{\partial T_t}{\partial h}\left[\frac{\partial T_t}{\partial P_e}\right]^{-1} \frac{h_0}{Pe_0} \qquad a_2 = \frac{\partial T_t}{\partial P_i}\left[\frac{\partial T_t}{\partial P_e}\right]^{-1} \frac{Pt_0}{Pe_0} \qquad (5)$$

Intake Manifold:
Following dependence is considered for the derivation

$$mie = f(P_i, \omega);\ mc = f(P_i, \omega_t);\ msa = f(y) \qquad (6)$$

Final equation for the inlet manifold is obtained from above equations

$$\tau_{in} \frac{dP_i}{dt} + K_{in} P_{in} = N_t + b_3 Y_3 - a_3 N_e \qquad (7)$$

Where

$$\tau_{in} = \frac{Vi}{R_2 T_i} \frac{Wt}{m_c} \frac{P_{i0}}{W_{i0}} \qquad K_{in} = F_{in}\left[\frac{\partial mc}{\partial \omega_t}\right]^{-1} \frac{P_{ro}}{\omega t_o} \qquad (8)$$
$$a_3 = \frac{\partial mie}{\partial \omega}\left[\frac{\partial mc}{\partial \omega_t}\right]^{-1} \frac{\omega_t}{\omega_{i0}} \qquad b_3 = \frac{\partial me_o}{\partial y}\left[\frac{\partial mc}{\partial \omega_t}\right]^{-1} \frac{y_t}{\omega_{i0}} \qquad (9)$$

Exhaust Manifold:
Final equation for the exhaust manifold is given by

$$\tau_{ex} \frac{dP_e}{dt} + K_{ex} P_{ex} = N_e + a_4 P_{in} - b_4 R \qquad (10)$$

B. Governor

A Proportional Integral Derivative (PID) control is used to provide the desired engine transient performance and to ensure that actual engine speed corresponds precisely to the desired speed at steady state. The PI Controller Law [3] is expressed as

$$R = K_p N_e + K_i + N_e dt + K_d \frac{dN_e}{dt} \qquad (11)$$

Equation for proportional governor is

$$R = K_p N_e \qquad (12)$$

Where K_p, K_i, K_d are proportional, integral and derivative gains respectively

$$A_3 \frac{d^3Ne}{dt^3} + A_2 \frac{d^2Ne}{dt^2} + A_1 \frac{dNe}{dt} + A_1 Ne = S_2 \frac{d^2L}{dt^2} + S_2 \frac{dL}{dt} \qquad (13)$$

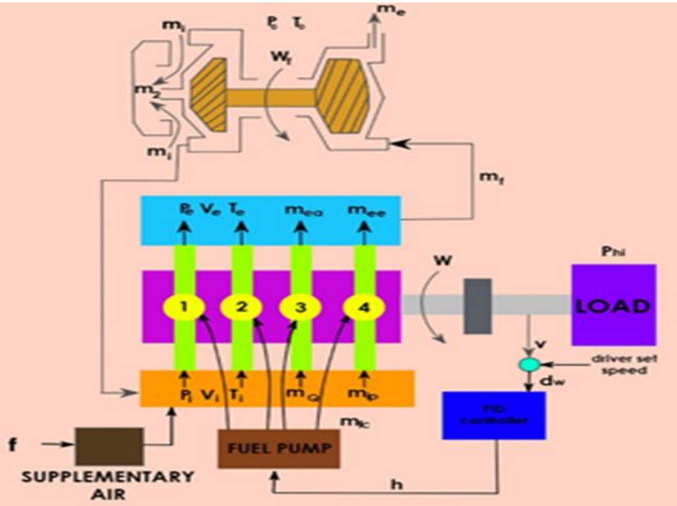

Fig. 1. Layout of the Components

Where

$$A_3 = T_{e2}^{\ 2} - T_R K_d$$
$$A_2 = T_{e1} - T_R K_p - K_R K_d$$
$$A_1 = K_{es} - T_R K_i - K_R K_p$$
$$A_0 = -K_R K_i$$
$$S_2 = -T_L$$
$$S_1 = -K_L$$

Equation (13) is a mathematical representation of the dynamics of an engine, governed by a PID Governor [3]. The coefficients A3, A2, A1, A0, S2 and S1 depend upon engine characteristics, and governor coefficient kp, ki, and kd. Non-Dimensional Form of Engine Differential Equations:

$$W \frac{d^3Ne}{d\tau^3} + X \frac{d^2Ne}{d\tau^2} + y \frac{dNe}{d\tau} + ZNe = \frac{d^2L}{d\tau^2} + S_2 \frac{dL}{d\tau} \qquad (14)$$

Where

$$W = \frac{A_3}{S_1} \frac{S_1^2}{S_2} \qquad X = \frac{A_3}{S_2} \qquad Z = \frac{A_0}{S_1} \frac{S_2}{S_1} \qquad y = \frac{A_1}{S_1}$$

This is non-dimensional form of engine differential equation, which is going to be used in our analysis. Here w, x, y and z are non-dimensional parameters, which depend on engine characteristics and governor coefficients kp, ki and kd. Error Function for sinusoidal load type L = B cos(_t): Equation is a linear differential equation, so if the forcing function which is the load (L) is varying sinusoidally, output (Ne) will also vary in sinusoidal manner, but with different amplitude and phase. The error function is given as

$$N_e = B\sqrt{a^2 + b^2}\,\mathrm{Cos}(\omega t + \theta) \qquad (15)$$

Where

$$\mathrm{Cos}(\emptyset) = \frac{a}{\sqrt{a^2 + b^2}} \qquad (16)$$

The obtained equation gives dimensionless error function (Ne) in terms of dimensionless parameters w, x, y and z, which are also functions of governor parameters kp, ki and kd. Our goal is to optimize the control parameters of the PID Governor by minimizing the speed fluctuations when the engine is subjected to different loads. So, for minimizing the fluctuations, the error function has to be minimized. But minimizing the error function may not assure guarantee minimum of engine speed fluctuations because it will be minimum at a particular instant. So it is better to minimize over a time period, which is objective function here. Objective function is an integral squared error,

$$A = \sqrt{\int_0^T N_e^2 dt} \qquad (17)$$

Where T is the time period of error function Ne and taken as 5 seconds. Simplification gives objective function for load type L = B cos (_t) in case of PID Governor as

$$A = B\sqrt{a^2 + b^2}\sqrt{(2.5 + \sin(2)[5\omega + \theta])/(4\omega) - (\sin[2\emptyset]/(4\omega)} \qquad (18)$$

The next step is to optimize the governor parameters by minimizing the objective function. Optimization has been done for a chosen steady state operating point of the engine system and the constant values of angular frequency of load fluctuations. Hence, for optimization purpose, all the characteristics have been considered as function of governor coefficients only.

III. METHODOLOGY

The objectives of this study are to find governor coefficients for which fluctuations of the speed are minimum, for given values of engine, turbo-charger, inlet and exhaust manifold characteristics and to study the effect of variation of engine and turbocharger characteristics on optimum values of governor coefficients. The pursuance of both these objectives requires minimization of objective functions.

ENGINE STEADY STATE

The objective functions obtained before represent the quantitative nature of engine speed deviation from its steady state value when the load is changing. These objective functions depend on engine, turbocharger, inlet and exhaust manifold characteristics, governor coefficients and frequency of load fluctuations. Since the characteristics depend upon the choice of the steady state operating point of the system, one such operating point is to be chosen. The steady state operating conditions chosen for optimization are mentioned below in table 1:

Table 1: Steady State Operating Conditions

Paramèter	Value at chosen state
Engine Speed	1200 rpm
Fuel Gallery Pressure	0.26 atm
Inlet Manifold Pressure	1.419 atm
Turbine Speed	34600 rpm
Exhaust Manifold Pressure	1.2771 atm

LOAD SPECIFICATION

$$L = B\cos(\_t) where\ B = 1.0, \_ = .67 * pi$$

CONSTRAINTS OF OPTIMIZATION

From the literature, it can be said that so far nobody used constraints for the optimization process, which lead to unstable governor operation. So, current study uses constraints based on stability criteria. This is obtained from the plot called Wishnegradski diagram [1].

WISHNEGRADSKI DIAGRAM

For the optimization process, there are some constraints, which have to be satisfied for the stability of the governor. Those are obtained by using the Wishnegradski diagram [1]. It is a graphical representation of the stability criterion of an engine transient response, based on the coefficients based on the homogeneous component of an engine system differential equation determines the transient response. Thus, just by analysing the coefficients appearing in the homogeneous component of the engine differential equation, stability of the engine system transient response can be checked. Since we are dealing with only third-order differential equations, only two coefficients are sufficient to know about the transient response of the engine system.

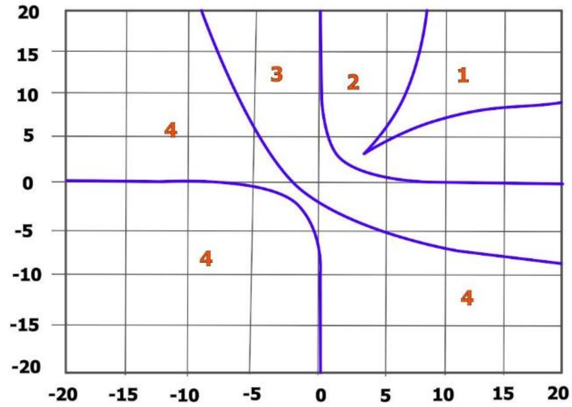

Fig. 2. Wishnegradski Diagram [1]

x and y are non-dimensional parameters which depend on engine, turbo-charger, inlet and exhaust manifold characteristics and the governor coefficients. The non-dimensional parameters x and y are called similarity criterion as their similarity ensures similar transient response. For ensuring the stability of transient response of all the engine systems with the same values of similarity criterion, the following conditions are to be met.

$$X > 0 \qquad (19)$$

$$y > 0$$

(20)

$$Xy - 1 > 0 \qquad (21)$$

If the roots of the characteristic equation

$$P^3 + XP^2 + yP + 1 = 0 \qquad (22)$$

Are all real, the response will be aperiodic and if one root is real and rest two are a pair of complex conjugate, the response will be oscillatory. The condition for all the roots of the characteristic equation to be real is given in terms of the similarity criterion x and y as

$$4(X^3 + y^3) - X^2y^2 - 18xy + 27 < 0 \qquad (23)$$

and for one root real and other two pair of complex conjugate

$$4(X^3 + y^3) - X^2 y^2 - 18\,xy + 27 > 0 \quad (24)$$

From the equations (19), (20) and (21), we can deduce that the curve

$$Xy - 1 = 0 \quad (25)$$

in the first quadrant is the boundary between converging and diverging responses. And from equation (23) and (24), we can deduce that the curve

$$4(X^3 + y^3) - X^2 y^2 - 18\,xy + 27 = 0 \quad (26)$$

is the boundary between aperiodic and oscillatory responses Equation (25) and (26) are plotted in a diagram. These curves divide the whole diagram in four regions as shown in figure. They are region of aperiodic convergence, region of oscillating convergence, region of oscillating divergence and region of aperiodic divergence respectively. This diagram is called Wishnegradski Diagram. We are concerned only with the first two regions ie. Region of aperiodic convergence and region of oscillating convergence [1]. All the programs concerning the mathematical model and the optimization process were written in Mathworks Matlab Software. The results and graphs were generated by Matlab as outputs to the programs for given inputs [4,5].

IV. RESULTS

For the optimization purpose and model validation, the values of characteristic coefficients are to be evaluated, which will determine the values of w, x, y and z appearing in the objective function of both the cases. These characteristic coefficients represent the engine, turbo-charger, inlet and exhaust manifold characteristics in the objective functions are tabulated in Table 2 and Table 3.

Table 2: Values of Engine and Turbocharger Characteristic Coefficients

τ_e (Sec)	K_e	a_1	b_1	τ_t	K_t	a_2	b_2
30.87	37.75	24.67	5.4e - 4	1.55	54.53	5.34	0.05

Table 3: Values of inlet and exhaust manifold characteristics

τ_{in}	K_{in}	a_3	b_3	τ_{ex}	K_{ex}	a_4	b_4
0.28	5.13	0.87	0.00	0.05	3.28	1.6	0.96

The resulting graph for the speed fluctuations is given in figure 3. Optimization of the control parameters of the PID Governor at minimal speed fluctuations is carried out at different loading conditions. From the experimental data obtained by test on a marine turbo-charged, 6-cylinder engine model KTA-1150C-600 of the Kirloskar make, the optimized values of Kp, Ki and Kd were obtained as 798.94, 41.50 and 1137.4 respectively and corresponding objective function is 2.2202e-07 and amplitude of speed fluctuation is 2.6642e-04 rpm.

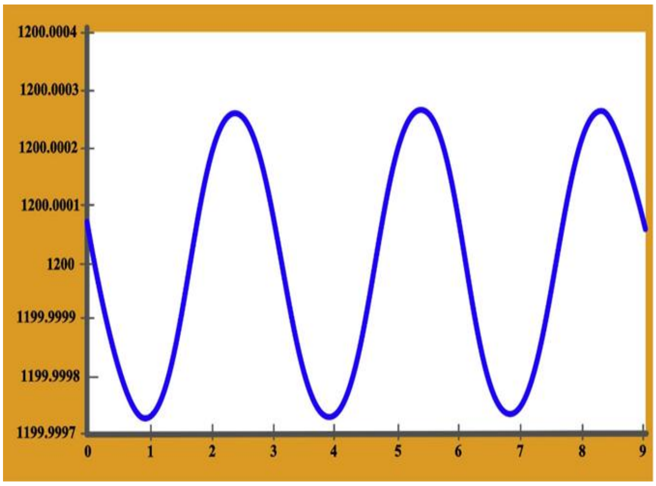

Fig 3. Resulting Graph of Speed Fluctuations

V. CONCLUSION

The optimum governor coefficients for which fluctuation of engine speed is minimum, for given value of engine, turbocharger, inlet and exhaust manifold characteristics were calculated satisfactorily. The optimized values of PID governor coefficients were found to be 798.94, 41.50 and 1137.4 which gave minimum amplitude of speed fluctuation as 2.6642e-04 rpm.

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Dr. Jagannath Hirkude has a Bachelor's degree in Mechanical Engineering and Master's Degree (MTech) in Energy Systems Engineering from IIT Bombay. He has PhD in Mechanical Engineering in the area of Thermal Engineering from University of Pune. He is presently working as Associate Professor in Mechanical Engineering Department at Goa College of Engineering, Goa. He has published more than 30 papers in different International conferences and Journals. His published work is published in reputed referred Elsevier Journals like Applied Energy, Fuel, Fuel Processing Technology, Energy, Energy Procedia etc.

Ms. Mrinal Manoj Borkar has a scholarly academic track record with a Bachelor's degree in Mechanical Engineering (2019) from Goa University. Her final year research based project was on 'Design and Analysis of Automobile Chassis (Formula Style Race Car)'.She has been a member of the Society of Automotive Engineers (SAE), India. She is currently gaining her work experience in area of composite materials in the Aerospace & Defense Division of Kineco Kaman Composite Structures India Pvt. Ltd. at Goa and aspires to pursue her higher studies and work in the field of Materials Engineering in an esteemed University and reputed organization. She is a Wildlife Enthusiast with commendable linguistic proficiency, having authored a few popular articles in Nature and Environment magazines.