IAES International Journal of Artificial Intelligence (IJ-AI)
Vol. 13, No. 2, June 2024, pp. 1992~2002
ISSN: 2252-8938, DOI: 10.11591/ijai.v13.i2.pp1992-2002

Control system optimisation of biodiesel-based gas turbine for ship propulsion

Affiani Machmudah[1,2], Elmi Abu Bakar[3], Raj Rajendran[4], Wibowo Harso Nugroho[1], Mahmud Iwan Solihin[5], Abdul Ghofur[1]
[1]Research Center for Hydrodynamics Technology, National Research and Innovation Agency (BRIN), Surabaya, Indonesia
[2]Faculty of Advance Technology and Multidisciplinary, Universitas Airlangga, Surabaya, Indonesia
[3]School of Aerospace Engineering, University Science Malaysia, Penang, Malaysia
[4]Department of Automobile Engineering, Faculty of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu District, Tamil Nadu, India
[5]Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur, Malaysia

Article Info

Article history:

Received Jul 6, 2023
Revised Nov 23, 2023
Accepted Jan 6, 2024

Keywords:

Biodiesel
Control system
Gas turbine
Ship propulsion
Whale optimization algorithm

ABSTRACT

Reducing a gas emission of shipping transportations become a main goal of international maritime organization to achieve a clean energy. One of best scenarios to achieve this goal is to shift a fossil fuel to a renewable energy-based fuel of a ship propulsion. This paper studies an optimization of a control system of the renewable-based small gas turbine engine for the ship propulsion. Proposed control system consists of a proportional-integral with engine performance limiters to avoid an engine damage. Proportional-integral gains are tuned by a whale optimization algorithm. A gain scheduling analysis of a step response is performed to obtain a searching area of tuning parameters and values of constant gains. In this step, the gains are modeled as function of plant variables. After the searching area is obtained, the proportional-integral gains are optimized using the whale optimization algorithm while the additional gains are set as constant values. Using this scenario, stable and optimal gains have been successfully achieved. Results show that the proposed method has better performance than that of the previous methods, i.e. gain scheduling and gain scheduling optimized by the whale optimization algorithm. The proposed method has lowest fitness value and does not have an overshoot problem.

Corresponding Author:

Affiani Machmudah
Research Center for Hydrodynamics Technology, National Research and Innovation Agency (BRIN)
St. Hidro Dinamika, Keputih, Sukolilo, Surabaya 60112, Indonesia
Email: affi002@brin.go.id

1. INTRODUCTION

Maritime transportation has significant contributions in global economy through world trade and shipping. The maritime transportation activities also contribute the emissions to environment. It has been predicted that the CO_2 emission from maritime transportation in 2050 will increase by 50-250% compare to 2012. International Maritime Organization (IMO) has created regulations and amendments to reduce this environment issue [1]. Recently, IMO has the new policy to reduce of the SOx emission for the maritime transportation to 0.5 % (5,000 ppm) since 2020 [2].

The main factor which responsible to the dirty environment is the fossil fuel. Shifting to renewable energy-based fuel is the best option toward the clean environment goal [3]. Biodiesel is one of the promising renewable fuels [4]. It is a clean energy which has almost no Sulphur and aromatics [5]. Some Asian countries, which are Indonesia, Malaysia, and Thailand have relatively high resources of plant-based oil so that they can produce quite high amount of the biodiesel fuel. These countries have focused on increasing the use of the biodiesel for the power generation. For example, Indonesia has mandated blended diesel and biodiesel to 30% (B30) since January 2020 [3]. It has been increased from previously B20 mandate. Considerable effort through regulations and amendments have been conducted to achieve more clean energy; however, it is still a challenge to shift the fossil fuel-based engines to the renewable-based engine. Some issues, such as fuel cost and controlling the engine for renewable fuel-based engine need to be solved to completely shift into the renewable fuel-based propulsion systems [6]. Udeh and Udeh [7] has reported that using the blend biodiesel was viable for the gas turbine (GT) engine. Some researchers have also reported the promising of using the biodiesel-based fuel for the GT engine [8], [9].

Control system of aero-derivative engines is an establish research where considerable numbers of research papers have been published; however, mostly they present the control system of fossil-fuel based GT engine. The GT dynamics model as plant in the control system contains many nonlinear equations consisting many parameters which need to be designed and tuned. Using analytical solutions to find the optimum solution will not be effective to solve the GT optimization problem [10]. The meta-heuristic optimization is very promising approach for gain tuning/scheduling controller since it does not rely on the gradient function. Tajalli and Tajalli [11] presented thermodynamics model considering the cooling effect to estimate the design point, the steady state performance, and the transient performance of the two-shaft GT engine. The min-max control approach was utilized as the control system employing the invasive weed optimization (IWO) to optimize controller gains. Wei *et al.* [12] presented model-based method, namely A self-enhancing active transient protection (SeATP), to handle the limit of surge margin and turbine inlet temperature. Montazeri-Gh and Rasti [13] employed the GA to tune the min-max algorithm and model predictive control of the turbofan engine. Pang *et al.* [14] proposed direct thrust control based on an improved model predictive control using a certain strategy that reduced the control sequence dimension. Using this approach, the normal direct thrust control was achieved and the thrust level was also maximized within the engine safe operational range.

Liu *et al.* [15] enhanced the gain scheduling approach by modifying the scheduling parameters, enabling an aero-engine to attain the desired performance and stability. Pang *et al.* [16] introduced a model predictive control approach based on optimization strategies for the purpose of regulating the aviation engine. A nonlinear state-space was used to build a predictive model, which employs an extended Kalman filter to estimate the present engine operating state. Chen *et al.* [17] devised an innovative adaptive predictive control method using subspace-based improved model predictive control (SIMPC) to provide predictive control across all engine operating points. The results demonstrated that the engine's performance has been enhanced in comparison to the min/max limit controller. Gaudet [18] introduced the GT dynamical model and examined its performance under non-standard conditions. The proposal for gain scheduling control considers engine performance limiters specifically for maritime applications. Machmudah *et al.* [19] introduced a gain-scheduling optimization approach for a thermodynamics-based gas turbine utilizing the whale optimization algorithm (WOA). The suggested approach involved implementing a PI control system with proportional gains, gain scheduling, and a min-max controller. The impact of using bioethanol has also been examined.

To support the goal of the clean energy of the maritime transportation, this research presents the control system optimization of biodiesel based-small GT engine for shipping propulsion. Small/micro-GT has been obtained a great attention because it has very good adaptability to the renewable fuel [20]. Boyce has categorized the small GT for the GT with output in the range 0.5 to 2.5 MW [21]. Barsi *et al.* [22] performed assessment of mini gas turbines application to naval transportation with power output range from 1 MW to 10 MW.

The presented paper is organized as follows: section 2 presents the GT dynamics modeling which involves the steady-state and transient off-design performances. Input and thermodynamics model are described. Proposed control system is described in section 3. Step response analysis and PI control with engine protection limiters are presented. Section 4 presents the results and discussions. Conclusions are presented in section 5.

2. METHODS

Figure 1 shows the step-by-step computation of GT dynamics models and control system optimization. It is started with input and design point modeling and continue with the off-design performance modeling. The steady-state off design performance is conducted to obtain the operating line thermodynamics data. Engine performance limiters are computed to acquire the engine operation area and they are inputted to the control system so that the controller response should be kept within the fuel boundary graph. The off-design transient performance deals with the condition of changing the engine operation to accelerate or decelerate. The step response analysis is necessary to obtain the searching area of controller gains. The PI controller optimized with the WOA incorporating the performance limiter is proposed as the GT control system. There are additional gains which are set as the constant gains.

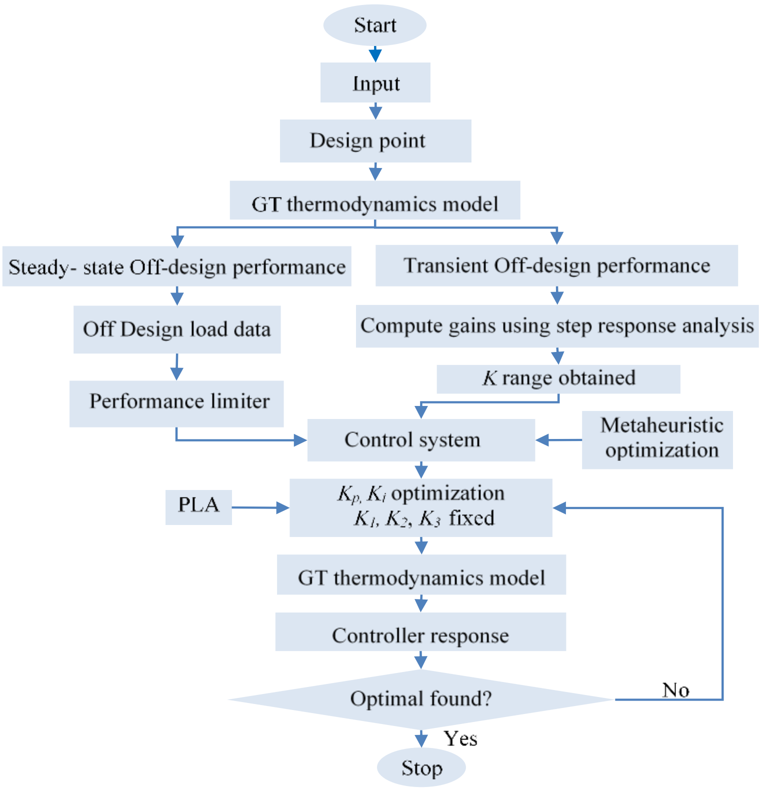


Figure 1. Methodology

2.1. Inputs

Obtaining the design point performance data is necessary for the GT dynamics modeling. There are some design point parameters required as input in the design point performance computation. The design point can be modeled using the standard thermodynamics model of the GT components [23]. The design point performance data will be inputted to the off-design performance modeling. The system under consideration is two-shaft GT with power 1.5 MW. The GT consists of engine components where each engine component is modeled in the form of thermodynamics. Two-shaft GT consist of an inlet, a compressor, a combustor, a gas generator (GG) turbine, a power turbine (PT), and a load. These engine components collaborate each other to create an engine. For two-shaft GT, the design point parameter inputs are indicated in Table 1.

2.2. Off-design performance

The GT is implemented to the marine application where the ship has quite low velocity so that the static and stagnation inlet difference can be simply neglected. The inlet has inputs which are the ambient temperature, the ambient pressure, and the flow velocity. Important characteristic at inlet modeling is pressure loss of the design point as (1) [24],

$$\Delta P_{inlet} = (\Delta P_{inlet})_{des}\left(\frac{\left(\frac{\dot{m}_a\sqrt{T_{oa}R_a}}{P_{oa}}\right)}{\left(\frac{\dot{m}_a\sqrt{T_{oa}R_a}}{P_{oa}}\right)_{des}}\right)^2 \quad (1)$$

where ΔP_{inlet}, $\dot{m}_a$, T_{oa}, P_{oa}, and R_a are loss of pressure, inlet air mass flow, stagnation temperature at inlet intake, stagnation pressure at exit inlet and gas constant for air, respectively.

Compressor modeling needs to estimate the compressor exit conditions using the compressor map information. In the case that the compressor map is not available, the compressor map can be estimated using the published compressor map. To digitize the compressor map, the auxiliary coordinates, namely beta lines, are added in the compressor map, as shown in Figure 2. From choke line to surge line, the beta lines are spaced equally with values from 0 to 1. The compressor map is digitized and function (2) is defined. This paper uses Sexton [25] as component map extrapolation based on modified similarity laws of incompressible fluids as (3).

$$PR_{c,map} = fn(\beta_c, \%N_c)\ ;\ \left(\dot{m}_a\sqrt{\theta/\delta}\right)_{map} = fn(\beta_c, \%N_c);\ \eta_{c,isen,map} = fn(\beta_c, \%N_c) \qquad (2)$$

$$\theta = T_o/288.15K\ ;\ ;\ \delta = P_o/101.325kPa\ ;\ \%N_c = \frac{N_{gg}/\sqrt{\theta}}{\left(N_{gg}/\sqrt{\theta}\right)_{des}}$$

Where $PR_{c,map}$, $\eta_{c,isen}$, β_c, N_{gg} are compressor pressure ratio of the map, isentropic efficiency of the map, compressor beta line, and GG spool speed, respectively,

$$\frac{\left(\dot{m}_a\sqrt{\theta}/\delta\right)_b}{\left(\dot{m}_a\sqrt{\theta}/\delta\right)_a} = \left[\frac{\%N_b}{\%N_a}\right]^p;\ \frac{w_b}{w_a} = \left[\frac{\%N_b}{\%N_a}\right]^p;\ \frac{\dot{W}_b}{\dot{W}_a} = \left[\frac{\%N_b}{\%N_a}\right]^r;\ \%N = \frac{N/\sqrt{\theta}}{N_{des}/\sqrt{\theta}} \qquad (3)$$

where N_a, N_b, w_b, w_b, $\dot{W}_a$, and $\dot{W}_b$ are low-speed spool rotational speed, high-spool rotational speed, low-speed spool specific work, high-speed spool specific work, low-speed spool power, and high-spe ed spool power, respectively.

Table 1. Parameters of design point of two-shaft GT

GT components	Parameter	
Inlet	ΔP_{inlet}	Inlet total pressure loss
	$\dot{m}_a$	Inlet air mass flow
Compressor	B_c	Compressor bleed fraction
	PR_c	Compressor pressure ratio
	$\eta_{c,isen}$	Compressor isentropic efficiency
Combustor	η_b	Combustion efficiency
	ΔPR_b	Combustor total pressure loss
	HV	Fuel heating value
	V_b	Combustor volume
Turbine	TIT	GG turbine inlet temperature
	$\eta_{t,\,isen}$	GG turbine isentropic efficiency
	N_{gg}	GG spool speed
	I_{gg}	GG polar moment inertia
Power turbine	$\eta_{pt,\,isen}$	PT isentropic efficiency
	N_{pt}	PT spool speed
	I_{pt}	PT polar moment of inertia
Exhaust	$\Delta PR_{exhaust}$	Exhaust total pressure loss
Shaft	η_{mech}	Mechanical efficiency
Load	η_{gear}	Gear box efficiency

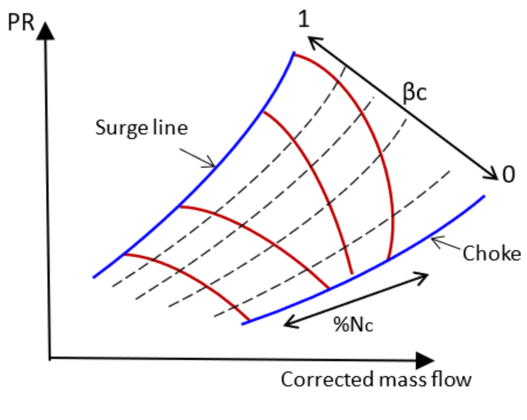


Figure 2. Mapping of β line

Off-design steady-state performances deal with the engine conditions when there is no acceleration and deceleration. Off-design steady-state performances are computed using Newton-Raphson method considering to solve five iteration errors, which are flow compatibility between combustor and GG turbine, work compatibility between compressor and GG turbine, flow compatibility between GG turbine and power turbine, work compatibility between power turbine and load, pressure compatibility of between ambient conditions and exhaust. To accelerate or decelerate the engine, the mismatch conditions between the compressor and gas generator turbine or between the power turbine and the load are necessary in the off-design transient performances. The step-by-step computation of transient off design performance is illustrated in Figure 3. Rate of change of GG spool speed, power turbine spool speed, and pressure can be expressed as (4),

$$\frac{dN_{gg}}{dt} = \frac{(G_t - G_c)}{I_{gg}} \times \left(\frac{60}{2\pi}\right); \frac{dN_{pt}}{dt} = \frac{(G_{pt} - G_{prop})}{I_{pt}} \times \left(\frac{60}{2\pi}\right); \frac{dP_{o2}}{dt} = \left(\dot{m}_{02} + \dot{m}_f - \dot{m}_{03}\right)\frac{(T_{02} \times R_a)}{V_b} \quad (4)$$

where $\dot{m}_f$, $\frac{dN_{gg}}{dt}$, $\frac{dN_{pt}}{dt}$, and $\frac{dP_{o2}}{dt}$ are fuel flow, GG spool sped rate of change, PT spool speed rate of change, and rate of change of P_{o2}, respectively.

Then, the new operating conditions can be predicted,

$$N_{gg,new} = N_{gg,old} + \frac{dN_{gg}}{dt}\Delta t \; ; N_{pt,new} = N_{pt,old} + \frac{dN_{pt}}{dt}\Delta t; P_{o2,new} = P_{o2,old} + \frac{dP_{o2}}{dt}\Delta t \quad (5)$$

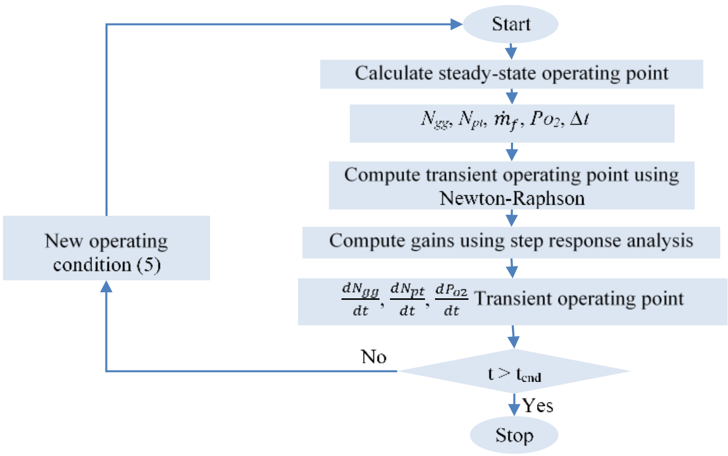


Figure 3. Flow chart of transient off design performance

3. CONTROL SYSTEM OPTIMIZATION

This section presents the proposed control system which consists of the PI control optimized by the WOA considering the engine performance limiter. The step response analysis, which involve gain scheduling to obtain gains range, is presented first. Then, integration of PI control, which is the prime control, engine performance limiters, and meta-heuristic optimization are presented.

3.1. Step response analysis

From thermodynamics analysis, the fuel flow is the control variables; however, for 2-shaft GT the measured variable is the PT speed, N_{PT}. The control system should accommodate the PT speed, the GG speed, and the fuel flow in the control system. Gains Scheduling is performed during the step response analysis. The gains are modeled as function of plant variables as in (7). The calculation of the gains scheduled is performed every step function from idle speed to maximum speed. The step function of the acceleration phase involves the fuel flow step change from the idle speed to the maximum speed. For the deceleration phase, it consists the fuel flow step change from the maximum speed to the idle speed.

After scheduled gains have been obtained, the range of gains K_p and K_i can be detected and these gains are used as the optimization variables as illustrated in Figure 1. For gains K_1, K_2, and K_3, this paper selects the mean value of the gain schedules obtained from the gain scheduling of the step response analysis. K_p and K_i gains are designed as the second-order system as (6) [19],

$$K_p = 2\xi\omega_n \; ; K_i = {\omega_n}^2\tau \quad (6)$$

where τ is time constant obtained as the value when it is achieved 63.2% demand change.

Additional gains, K_1, K_2, and K_3 are defined as plant variables functions as expressed in (7). After the gains have been computed, the area of $[K_{min}, K_{max}]$ can be observed and the value of K_1, K_2, and K_3 in the GT control system are selected as mean of scheduling gains data as in (8). Then, the meta-heuristic optimization is applied to tune PI gains, K_p and K_i, as illustrated in Figure 1.

$$K_1 = \frac{1}{\Delta N_{pt}} \; ; K_2 = \Delta N_{gg} \; ; K_3 = \frac{\Delta \dot{m}_f}{\Delta N_{gg}} \quad (7)$$

Where,

$$\Delta N_{pt} = N_{pt,max} - N_{pt,min}; \Delta N_{gg} = N_{gg,max} - N_{gg,min}; \Delta \dot{m}_f = \dot{m}_{f,max} - \dot{m}_{f,min} K_n = \bar{K} \quad (8)$$

where K_n and $\bar{K}$ are n^{th} additional gain and mean of corresponding additional gains data, respectively.

3.2. PI control with engine performance limiters

Previous section has presented the gains as function of the plant variables. PI gains are the tuned gains while additional gains are selected as constant value based on the step response analysis. The PI control is designed as the prime control. Engine performance limiters should be considered in the control system to make sure the engine operates in the safe operational area. Overall GT control system is illustrated in Figure 4. The engine performance limiter should be kept win over the PI control as the prime control to avoid the engine damage. The low selection is chosen for the engine protection limiters and the high selection is chosen for the engine operation limiters. Engine performance limiter consists of the engine protection limiters and engine operation limiters. Engine protection limiters involve over temperature protection and over speed protection. Engine operation limiters consider minimum spool speed limit, flame out limit, and compressor surge limit.

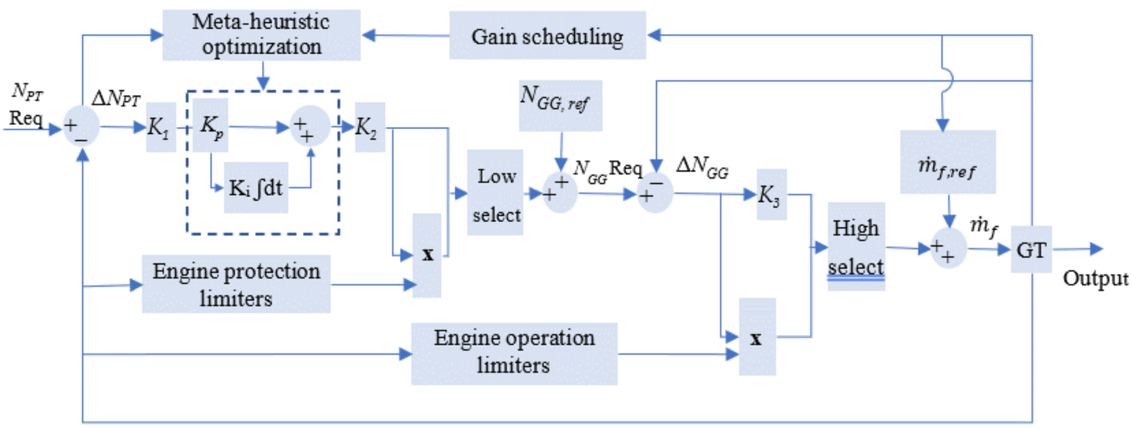


Figure 4. Proposed control system

3.3. WOA

The WOA is a meta-heuristic optimization approach introduced by Mirjalili and Lewis [26]. It draws inspiration from the hunting tactics of humpback whales. The search agents adjust their locations in order to converge towards the optimal search agent, as described by (9) and (10). Humpback whales engage in synchronized swimming around their prey, following a spiral-shaped trajectory as described by (11). During the exploitation phase, the search agent's position is modified based on a search agent that is randomly selected, as described by (12) and (13).

$$\vec{D} = |\vec{C}\,\vec{X}^*(t) - X(t)| \quad (9)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A}.\vec{D} \quad (10)$$

where $t, \vec{C}, \vec{A}, \vec{X}, X^*$, | | and are the current iteration, a coefficient vector, a coefficient vector, the position vector, the current position vector of the best solution, the absolute value, and an element-by-element multiplication, respectively. X^* is updated when there is a better solution.

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A}.\vec{D} & if\ p \le 0.5 \\ \vec{D}'.e^{bt}.cos(2\pi l) + \vec{X}^*(t) & if\ p \ge 0.5 \end{cases} \quad (11)$$

where p is a random number generated in [0. 1].

$$\vec{D} = |C.\vec{X}_{rand} - \vec{X}| \quad (12)$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A}.\vec{D} \quad (13)$$

where $\vec{X}_{rand}$ is a random position vector chosen from the current population.

4. RESULTS AND DISCUSSION

This section presents numerical results of the proposed control system of 1.5 MW GT fueled with biodiesel. The input values of GT dynamics model are the same with [19]. Integral of time multiplied by absolute error (ITAE) is used as the performance index in the PI gains optimization.

4.1. Step response analysis

Figures 5(a) to 5(e) show the step response analysis of the gain scheduled of K_p, K_i, K_1, K_2, and K_3, respectively. From these results, the searching area of K_p and K_i can be selected. The searching area of the metaheuristic optimization can be predicted from the graph and simulation. Through few simulations, it has been detected that the ranges of K_p and K_i for meta-heuristic optimization can be selected in the range [0.1, 27]. These range become the searching area of the optimization variable. The values of K_1, K_2, and K_3, which are selected as mean of the gain schedules data, are 9.6373×10^{-4}, 679.2399, and 1.0303×10^{-5}, respectively.

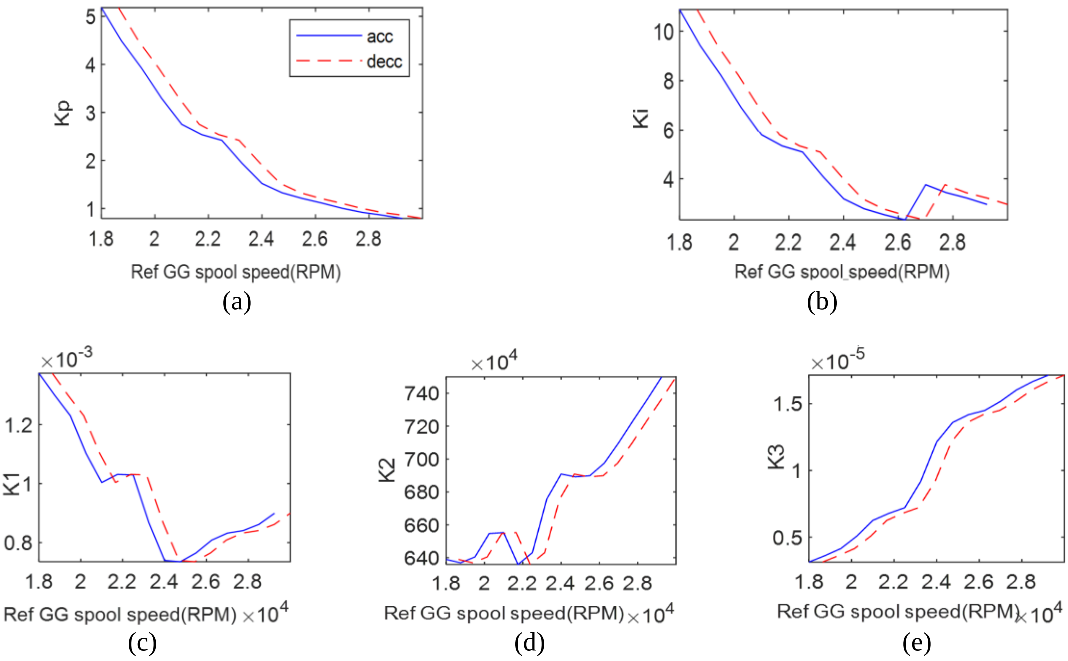


Figure 5. Gains schedules (a) K_p, (b) K_i, (c) K_1, (d) K_2 and (e) K_3

4.2. Optimization results

Figure 6 shows the evolution of the fitness value during 15 generations by the WOA. Figure 7(a) shows the controller response of proposed control system for PLA=25%. The optimal gains by WOA are [K_p, K_i] = [2.0154, 6.8883]. The controller responses of the gain scheduling proposed by Gaudet [18] and the method in [19] using biodiesel fuel of 1.5 MW small GT engine are illustrated in Figures 7(b) and 7(c), respectively. Detail value of the fitness value by these three methods are presented in Table 2. It can be observed that the proposed method has outperformed than that of the other methods where it has the lowest fitness value. The proposed method also does not have overshoot problem as compare with the method in [20]. Using the stopping criteria as in [19], the time to achieve it by the proposed method is also minimum, i.e. t= 1.7 second, as can be seen in Figure 7(a).

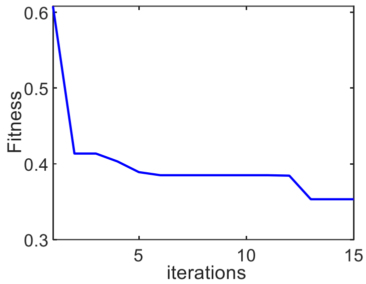
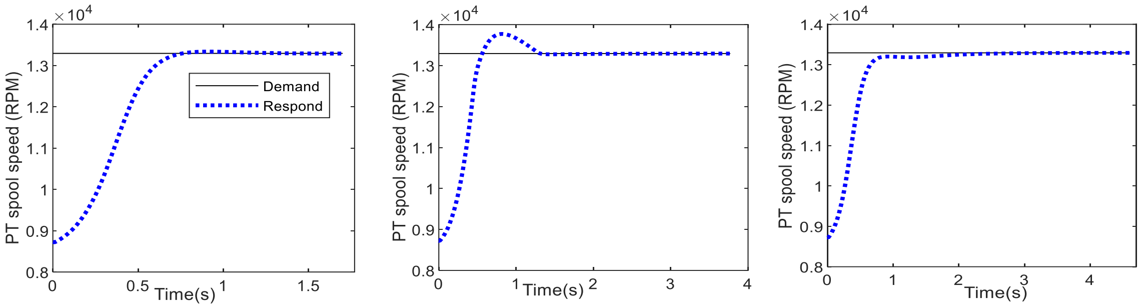


Figure 6. Fitness value by the WOA



(a) (b) (c)

Figure 7. Controller response (a) proposed method, (b) gain scheduling-WOA [20], and (c) gain scheduling [19]

Table 2. Fitness value

	Fitness Value (ITAE)	Best Parameter Value
Proposed method	0.35328	K_p=2.0154; K_i=6.8883
Gain scheduling-WOA [19]	0.5673	a=3.4462
Gain scheduling [18]	0.6659	-

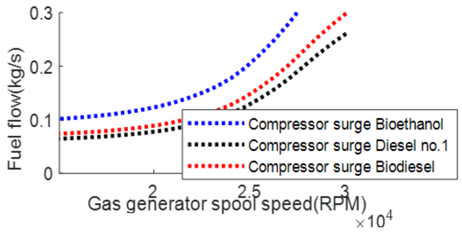
4.3. Comparison with diesel no.1 and bioethanol

Design point comparison of the biodiesel fuel with other fuels, i.e. diesel no.1 and bioethanol, under the same input parameters of gas turbine dynamic model is presented in Table 3. These results agree with the micro-GT results reported in [6], [7] where the lower the heating value, the shaft power is higher but the specific fuel consumption (SFC) is also higher. The low heating value (LHV) of the diesel no.1, the biodiesel, and the bioethanol are 43,100 kJ/kg, 37,600 kJ/kg, 27,200 kJ/kg, respectively.

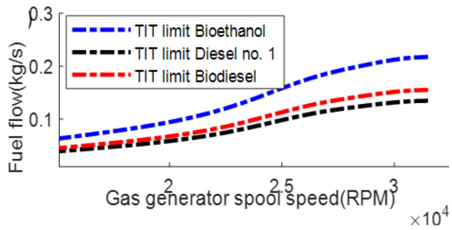
Figures 8(a) to 8(c), provide a detailed comparison of the compressor surge limit, the turbine inlet temperature (TIT) limit, and the steady-state operating line for biodiesel, diesel no.1, and bioethanol, respectively. The limiter graphs delineate the fuel boundary, representing the operational range of the engine. The data indicates that the compressor surge limit, the TIT limit, and the steady-state operating line all exhibit an upward trend when the LHV of the fuel lowers. Therefore, the SFC likewise rises when the fuel's LHV drops. The control system incorporates many limiters to safeguard the engine, including the compressor surge limit, TIT limit, and maximum RPM limit. On the other hand, the engine operation limiters, as shown in Figure 4, consist of the minimum RPM limit and the flameout limit. The fuel boundary graph, which is dependent on the fuel's LHV, must be carefully taken into account while designing the control system for the GT engine. This is necessary to prevent any engine damage that may occur when using renewable-based fuel in the GT engine.

Table 3. Design point comparison between diesel no. 1, bioethanol, and biodiesel

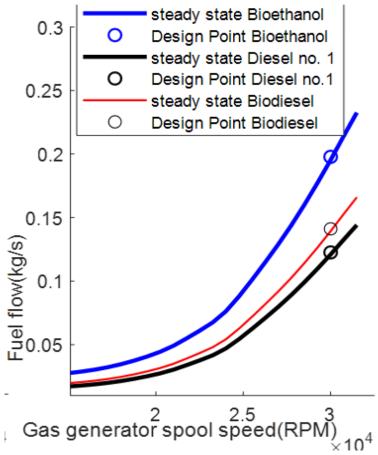
Parameters	Diesel no.1 [20]	Bioethanol [20]	Biodiesel
Shaft power (MW)	1.4994	1.5347	1.5082
Thermal efficiency	0.2839	0.2853	0.2842
Specific fuel consumption (kg/kWh)	0.2942	0.4639	0.3369
Fuel flow (kg/s)	0.1226	0.1978	0.1411



(a)



(b)



(c)

Figure 8. Comparison of Biodiesel, diesel No.1 and bioethanol; (a) compressor surge limit, (b) TIT limit, and (c) steady-state operating line

5. CONCLUSION

The proposed control system of small GT engine for ship propulsion fueled with the biodiesel has been presented. The control system consisted of the PI controller with additional gains considering the engine performance limiter. The PI gains were tuned with the WOA. Engine performance limiters were kept win over the PI control to avoid the engine damage. To avoid trial and error, the searching area of the optimization was selected based on the result of the step respond analysis which consisted gain scheduling. It has been observed that the WOA had success to find the fixed gain of PI controller that was stable and optimal. Similar with the micro-GT results previously reported, for the small GT, the lower LHV exhibits the higher SFC. The power output and SFC of the biodiesel fuel is higher than that of the diesel no.1 while as compare to the bioethanol, the power output and SFC of the biodiesel fuel is lower than that of the bioethanol fuel. Designing the optimal acceleration/deceleration schedule of the renewable-based small/micro-GT engine can be considered as future research to improve the renewable-based GT engine performance.

ACKNOWLEDGEMENTS

Author thanks to Universitas Airlangga, Badan Riset dan Inovasi Nasional (BRIN), Universiti Sains Malaysia, SRM Institute of Science and Technology, and UCSI University for supporting this collaborative research. This research was funded by SATU JRS Scheme (1003/UN3/2022), Universitas Airlangga.

REFERENCES

[1] H. Xing, C. Stuart, S. Spence, and H. Chen, “Alternative fuel options for low carbon maritime transportation: Pathways to 2050,” *Journal of Cleaner Production*, vol. 297, May 2021, doi: 10.1016/j.jclepro.2021.126651.
[2] C. Ji and M. M. El-Halwagi, “A data-driven study of IMO compliant fuel emissions with consideration of black carbon aerosols,” *Ocean Engineering*, vol. 218, Dec. 2020, doi: 10.1016/j.oceaneng.2020.108241.
[3] A. Syafiuddin, J. H. Chong, A. Yuniarto, and T. Hadibarata, “The current scenario and challenges of biodiesel production in Asian countries: A review,” *Bioresource Technology Reports*, vol. 12, Dec. 2020, doi: 10.1016/j.biteb.2020.100608.
[4] S. Dey, N. M. Reang, P. K. Das, and M. Deb, “A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel,” *Journal of Cleaner Production*, vol. 286, Mar. 2021, doi: 10.1016/j.jclepro.2020.124981.
[5] O. Ogunkunle and N. A. Ahmed, “A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines,” *Energy Reports*, vol. 5, pp. 1560–1579, Nov. 2019, doi: 10.1016/j.egyr.2019.10.028.

[6] H. Montazerinejad and U. Eicker, "Recent development of heat and power generation using renewable fuels: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 165, Sep. 2022, doi: 10.1016/j.rser.2022.112578.
[7] G. T. Udeh and P. O. Udeh, "Comparative thermo-economic analysis of multi-fuel fired gas turbine power plant," *Renewable Energy*, vol. 133, pp. 295–306, Apr. 2019, doi: 10.1016/j.renene.2018.10.036.
[8] D. Rochelle and H. Najafi, "A review of the effect of biodiesel on gas turbine emissions and performance," *Renewable and Sustainable Energy Reviews*, vol. 105, pp. 129–137, May 2019, doi: 10.1016/j.rser.2019.01.056.
[9] Z. Liu, T. Lian, W. Li, C. Cao, H. Xiong, and Y. Li, "Mini review of current combustion research progress of biodiesel and model compounds for gas turbine application," *Energy & Fuels*, vol. 35, no. 17, pp. 13569–13584, Sep. 2021, doi: 10.1021/acs.energyfuels.1c01895.
[10] S. Jafari and T. Nikolaidis, "Meta-heuristic global optimization algorithms for aircraft engines modelling and controller design; A review, research challenges, and exploring the future," *Progress in Aerospace Sciences*, vol. 104, pp. 40–53, Jan. 2019, doi: 10.1016/j.paerosci.2018.11.003.
[11] S. M. Tajalli and A. Tajalli, "Thermodynamic simulation of two-shaft gas turbine to study invasive weeds optimization and Min-Max controller strategies considering air-cooled blades," *Journal of Mechanical Science and Technology*, vol. 33, no. 2, pp. 931–938, Feb. 2019, doi: 10.1007/s12206-019-0150-3.
[12] Z. Wei, S. Zhang, S. Jafari, and T. Nikolaidis, "Self-enhancing model-based control for active transient protection and thrust response improvement of gas turbine aero-engines," *Energy*, vol. 242, Mar. 2022, doi: 10.1016/j.energy.2021.123030.
[13] M. Montazeri-Gh and A. Rasti, "Comparison of model predictive controller and optimized min-max algorithm for turbofan engine fuel control," *Journal of Mechanical Science and Technology*, vol. 33, no. 11, pp. 5483–5498, Nov. 2019, doi: 10.1007/s12206-019-0847-3.
[14] S. Pang, S. Jafari, T. Nikolaidis, and Q. Li, "Reduced-dimensional MPC controller for direct thrust control," *Chinese Journal of Aeronautics*, vol. 35, no. 4, pp. 66–81, Apr. 2022, doi: 10.1016/j.cja.2021.08.024.
[15] J. Liu, Y. Ma, L. Zhu, H. Zhao, H. Liu, and D. Yu, "Improved gain scheduling control and its application to aero-engine LPV synthesis," *Energies*, vol. 13, no. 22, Nov. 2020, doi: 10.3390/en13225967.
[16] S. Pang, Q. Li, and B. Ni, "Improved nonlinear MPC for aircraft gas turbine engine based on semi-alternative optimization strategy," *Aerospace Science and Technology*, vol. 118, Nov. 2021, doi: 10.1016/j.ast.2021.106983.
[17] Q. Chen, H. Sheng, and T. Zhang, "A novel direct performance adaptive control of aero-engine using subspace-based improved model predictive control," *Aerospace Science and Technology*, vol. 128, p. 07760, Sep. 2022, doi: 10.1016/j.ast.2022.107760.
[18] S. R. Gaudet, "Development of a dynamic modeling and control system design methodology for gas turbines," Thesis, Carleton University Ottawa, Ontario, Canada, 2007.
[19] A. Machmudah *et al.*, "Design optimization of a gas turbine engine for marine applications: Off-design performance and control system considerations," *Entropy*, vol. 24, no. 12, Nov. 2022, doi: 10.3390/e24121729.
[20] I. I. Enagi, K. A. Al-attab, Z. A. Zainal, and Y. H. Teoh, "Palm biodiesel spray and combustion characteristics in a new micro gas turbine combustion chamber design," *Energy*, vol. 254, Sep. 2022, doi: 10.1016/j.energy.2022.124335.
[21] M. P. Boyce, *Gas turbine engineering handbook*. Elsevier, 2012. doi: 10.1016/C2009-0-64242-2.
[22] D. Barsi, M. Luzzi, F. Satta, and P. Zunino, "On the possible introduction of mini gas turbine cycles onboard ships for heat and power generation," *Energies*, vol. 14, no. 3, Jan. 2021, doi: 10.3390/en14030568.
[23] A. Machmudah and T. A. Lemma, "Design-point performance adaptation of small gas turbine using particle swarm optimization," in *Advances in Manufacturing Engineering*, 2020, pp. 411–423. doi: 10.1007/978-981-15-5753-8_38.
[24] G. Gmbh, "GasTurb 14: User's manual," 2023. www.gasturb.com (accessed Jul. 26, 2023).
[25] W. R. Sexton, "A method to control turbofan engine starting by varying compressor surge valve bleed," Thesis Virginia Tech, 2001.
[26] S. Mirjalili and A. Lewis, "The whale optimization algorithm," *Advances in Engineering Software*, vol. 95, pp. 51–67, May 2016, doi: 10.1016/j.advengsoft.2016.01.008.

BIOGRAPHIES OF AUTHORS

Affiani Machmudah received the Ph.D. and M.Sc. degrees of Mechanical Engineering from Universiti Teknologi PETRONAS, Malaysia in 2018 and 2011, respectively. She also received her B.Sc. of Aeronautics Engineering from Bandung Institute of Technology, Indonesia in 2005. She is currently a Researcher at Research Center for Hydrodynamics Technology, National Research and Innovation Agency (BRIN), Indonesia. Previously, she was a lecturer in Faculty of Advanced Technology and Multidiscipline, Universitas Airlangga. Her research includes engineering optimization, control system, motion planning, and mathematical modeling. She can be contacted at email: affi002@brin.go.id.

Elmi Abu Bakar Elmi Abu Bakar is an Associate Professor in Aeronautics Engineering, University Science Malaysia, USM. He is also serving as deputy dean of research in USM. He received all his higher educations from Japan (Dip. Eng Mechanical at Kisarazu, Bachelor Engineering Mechanical at Iwate, Master Engineering Production System at Toyohashi and PhD certificates in Electronics and Information at Toyohashi, Japan). His research interests include Control System and Robotic, Machine Vision (Image based Measurement), Abnormal detection using Signal Processing Methods, Shape Classification and Analysis, CAD, Tool & Die Quality Inspection and Computer Aided Inspection. He can be contacted at email: meelmi@usm.my.

Raj Rajendran received the Ph.D. degree in Mechanical Engineering from Anna University India in 2008. He is head and Professor in Department of Automobile Engineering, SRM Institute of Science and Technology, India. His research interests are material and surface engineering, machine learning, electric vehicle, and self-driving car. He can be contacted at email: rajendrr@srmist.edu.in.

Wibowo Harso Nugroho (Ir in Naval Architecture, MSc in Engineering Mathematics and PhD in Mechanical Engineering) works as Researcher at BRIN (National Research and Innovation Agency) of Hydrodynamic Technology Research Centre. He has main research interests in marine structure dynamics with various applications on field of engineering ranging from dynamic loads prediction on surface and underwater vehicles, damage detection of smart structures/ instrumented /controlled structures, structural health monitoring, ship structural vibration, and design of tsunami / seismic buoys and the ocean bottom unit (OBU). He can be contacted at email: wibo001@brin.go.id.

Mahmud Iwan Solihin Mahmud Iwan Solihin is an Associate Professor at the Department of Mechatronics Engineering. He was a Research Assistant for an eScienceFund project under the Ministry of Science Technology & Innovation (MOSTI), Malaysia. His current research interests include machine learning and data-drive modeling in various fields, including agriculture, water resource management, the IoT, control systems, robotics, and sensor networks, toward sustainable engineering development in the future. He is also a Professional Member of the Institution of Engineers of Indonesia and recognized by the ASEAN Federation of Engineering Organizations (AFEO) and APEC Engineer. He can be contacted at email: mahmudis@ucsiuniversity.edu.my.

Abdul Ghofur received his B.Sc. in Marine Technology from Institute Technology Sepuluh Nopember and M.Sc. in Marine Technology from The University of Newcastle upon Tyne in 1990 and 1995, respectively. He is currently a Researcher at Research Center for Hydrodynamics Technology, National Research and Innovation Agency (BRIN), Indonesia. His research includes ship design, mooring design and analysis, and offshore structure analysis. He can be contacted at email: abdg001@brin.go.id.