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A Hybrid Control Strategy for Robust Speed Regulation in Marine Propulsion System

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Abstract

In this paper, a hybrid control scheme is proposed for marine diesel engines. This scheme combines both linear active disturbance rejection control (LADRC) and an adaptive artificial neural network, so-called Online ADALINE. The proposed scheme aimed to improve the performance of marine engines by making the speed control system more stable and firmer against disturbances. To handle the high nonlinearity, disturbance, and complication of operational circumstances in marine engines, the advantages of both LADRC and ADALINE were utilized. To describe the relationship between marine diesel engine speed and fuel injection, a modified mean value engine model (MVEM) was used. Simulation experiments on a 12K98ME marine diesel engine were conducted using MATLAB software depending on its mathematical model to verify the effectiveness of the proposed scheme to control marine

engine speed in various working conditions, such as parameter perturbation, random disturbance and sudden dumping load. The obtained simulation results proved the high effectiveness and distinct performance of the proposed control strategy compared to the conventional linear active disturbance rejection controller.
Keywords: Active disturbance rejection control; Adaptive artificial neural network controller; Hybrid Speed Control; Marine diesel engine.

استراتيجية تحكم هجينة لتنظيم السرعة في نظام الدفع البحري

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الملخص

في هذه الورقة البحثية، تم اقتراح مخطط تحكم هجين لمحركات الديزل البحرية. يجمع هذا المخطط بين كل من التحكم الخطي النشط في رفض الاضطراب (LADRC) وشبكة عصبية اصطناعية تكيفية، تُعرف باسم ADALINE عبر الإنترنت (Online ADALINE).

يهدف المخطط المُقترح إلى تحسين أداء المحركات البحرية من خلال جعل نظام التحكم في السرعة أكثر استقراراً وأكثر مناعة ضد الاضطرابات. للتعامل مع اللاخطية العالية والاضطرابات وتعقيد ظروف التشغيل في المحركات البحرية، تم الاستفادة من مزايا كل

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من LADRC و ADALINE. لوصف العلاقة بين سرعة محرك الديزل البحري وحقن الوقود، تم استخدام نموذج محرك مُعدَّل ذو قيمة متوسطة (MVEM). أُجريت تجارب محاكاة على محرك ديزل بحري من طراز 12K98ME باستخدام برنامج MATLAB ، اعتماداً على نموذجه الرياضي للتحقق من فعالية المخطط المُقترح في التحكم في سرعة المحرك البحري في مختلف ظروف العمل، مثل اضطراب المعاملات، والاضطراب العشوائي، وإزالة الحمل المفاجئ. قد أثبتت نتائج المحاكاة التي تم الحصول عليها الفعالية العالية والأداء المتميز لاستراتيجية التحكم المُقترحة مقارنةً بوحدة التحكم التقليدية LADRCالخطية النشطة في رفض الاضطراب .

الكلمات المفتاحية: التحكم النشط في رفض الاضطراب؛ متحكم شبكة عصبية اصطناعية تكيفية؛ التحكم الهجين في السرعة؛ محرك الديزل البحري .

1. Introduction

There are different transportation methods and shipping is considered to be the most commonly used one because of its low cost, low energy required to ship a huge amount of merchandise in reasonable time, and environmentally friendliness (Di Natale and Carotenuto, 2015). Since marine diesel engines are commonly used for generating energy in ships (Farouk et al., 2012; Tang et al., 2017; Wang et al., 2018a; Yuan et al., 2017), speed control in such engines is considered as an important factor. Engine speed must be carefully regulated in order to avoid any harmful operating conditions due to speed fluctuations (Tang et al., 2017) that negatively affect not only the engine but also the transmission system (Sun et al., 2015). In addition, main marine engine can also be damaged due to continuous over speed (Solutions, 2004). Moreover, once speed is well controlled, the optimal power performance of engine is achieved resulting in less fuel consumption and emission (Di Cairano et al., 2012; Di Cairano et al., 2010). Thus, maintaining optimal and steady speed under various sea conditions and load disturbances is the main purpose of marine engine speed control.

Many different approaches have been introduced for marine main engine speed regulation. These approaches include, proportional-integral-derivative (PID) controller (So et al., 2004), $H\infty$ control

method (Papalambrou and Kyrtatos, 2006), sliding mode control (SMC) (Yuan et al., 2017), fuzzy control (Lynch et al., 2006, 2018) and model predictive control (MPC) (Wang et al., 2018b). However, each of the aforementioned methods has its own defects, in classical PID, parameters have to be readjusted to maintain the calibrated situation under various external conditions the chattering phenomenon in SMC cannot be easily overcome, and the control effects of $H\infty$ and fuzzy methods are limited due to the variation of marine engine operation conditions and MPC is a costly and complicated method.
ADALINE was developed as a combination of LADRC and online self-adaptive discrete time MIMO linear neural network. The contribution of this study is that the proposed hybrid speed control system was applied for the first time, to a 12K98ME type two-stroke marine diesel engine, which was mathematically described using mean value engine model (MVEM). In order to verify the performance of the proposed strategy, it was compared to standard LADRC through simulating different load disturbance conditions that hinder the speed control of diesel engine providing better control performance.
A brief introduction on a mathematical model of a marine diesel engine speed is given in section 3. In section 4, the proposed system design is described and discussed. Section 5 discusses the conducted simulation experiments and shows the obtained results. Conclusions and future work are described in section 6.

2. Literature Review

On high seas, ocean currents are considered as the main cause of load disorder, despite the absence of inappropriate weather conditions. In contrast, when weather is unstable and sea is very turbulent, propeller disk is likely to exit from water and this directly affects propeller torque and generates a sharp sudden changes in engine speed (Oleksiy et al., 2010). In order to effectively deal with load disturbance, active disturbance rejection control (ADRC) was introduced to control marine engine speed (Liu et al., 2019; Xue et al., 2017; Kuang et al., 2019; Li et al., 2019a). Pan et al. (2017) applied a non-linear ADRC to a MAN B&W type diesel engine operating at low-speed levels and mathematically modelled

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the engine by a simple transfer function. Hua et al. (2013), introduced a combined controller to control engine speed in a diesel engine model. Liu and Li (2012) set SCESO along with a model productive control (MPC) to better control under disturbances.

Generally, mean value engine model (MVEM) is considered to be adequate for controller design (Karlsson et al., 1999; Haiyan et al., 2008). However, objectivity may not always be assured in designing a speed controller for piston engines. In case of SMC, acceptable results were obtained when MVEM was tested (Li and Yurkovich, 2001), whereas the results less adequate were obtained for complex engine models. In the works of Xu, (2008) and Assadian et al. (2012), chattering phenomenon was the main obstacle that prevented SMC controller from performing effectively while trying to control the speed of irregular reciprocating engines. Similarly, fluctuation in the speed of these engines makes it difficult for ADRC controllers to reject disturbance and limits its capabilities (Li et al., 2017a)

Despite the distinguished performance provided by the linear active disturbance rejection controller (LADRC) in regards to overcome sudden load disturbances and idle speed control, there is still ambiguity regarding unjustified variations of steady state speed compared to that obtained from conventional (PID) controllers (Kang et al., 2016).

Noise and disturbance in marine engines are quite complicated with varied degrees. In addition, natural speed fluctuations can affect the performance of extended state observer (ESO). In contrast, nonlinear active disturbance rejection control (NLADRC) may not assure desired control performance. Kang et al. (2016) analysed LADRC and NLADRC. Normally, NLADRC outperforms LADRC; however, the performance of NLADRC considerably declines at certain levels of noise and disturbance.

Online system control is achieved via an adaptive control scheme by neural networks, whereas in optimization control approach, a selected performance index is minimized to achieve an optimal control signal. To improve the control of fuel consumption and emission in micro-ignition dual-fuel engines at maximum level, a combination of artificial neural network (ANN) and particle

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swarm optimization (PSO) algorithms was utlized (Ma et al., 2021). Controllable variables were used to traine an RBF neural network prediction model. Moreira et al. (2021) employed neural network computing system to estimate the speed and fuel consumption of a ship engine without the need for information on engine status. Levenberg–Marquardt backpropagation structure was applied to train a neural network assisted by a realistic navigation data set. A combination of ANN and multiple regression (MR) strategies has been proposed by Farag and Ölçer (2020) to estimate ship performance under sea environment conditions. Niu et al. (2017) conducted a assessment on the performance of ANN and support vector machine (SVM) to estimate the responses of a marine diesel engine equipped with a common rail direct injection system (CRDI). For better prediction with a small amount of training data, Taguchi orthogonal array method was employed.

Adaptive linear neural network (ADALINE) was used in system identification (Zhang et al., 2016) and system control (Nandana et al., 2015; Penthia et al., 2016; Nguyen et al., 2016; Renan et al., 2009). Online ADALINE controller has the capability of adapting changes and can effectively defusing any disturbances.

3. Marine Diesel Engine Model

Generally, low-speed marine diesel engines are described as large two-cycle diesel engines. The main parts of these engines are turbine, cooler system, compressor, exhaust receivers and cylinder. Designing engine speed control system in real time is difficult due to the complex and non-linear nature of the system. Kang et al. (2016) used mean value engine model demonstrate the relationship between diesel engine speed (the output) and fuel injection (the input) as shown in Fig. 1.

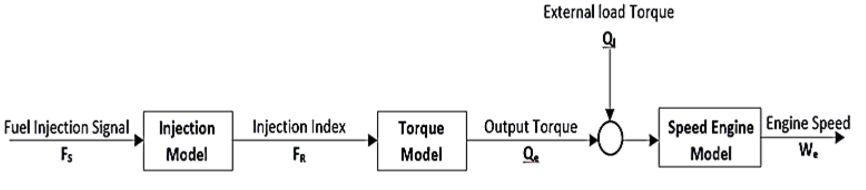

Fig. 1. A Block diagram of principle scheme of marine diesel engine (Kang et al. 2016).

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The following mathematical model represents the acceleration ($\dot{W}_E$) of marine diesel engine that considered and adopted in this study (Tu, 2016; Taskar et al., 2016; Wang et al., 2018c):

$$\dot{W}_E = \frac{30}{\pi} \cdot \frac{Q_E - Q_P + Q_L}{I_{SH}} \, , I_{SH} = I_E + I_P \tag{1}$$

Where:

$$Q_E = \frac{\alpha \, V_D \, P_E}{2\pi} \tag{2}$$

$$Q_P = K_Q D_P^5 \, \rho \, (\frac{W_E}{60})^2 \tag{3}$$

Here, Q_E is the output torque of diesel engine, Q_P is the torque of propeller, and Q_l is the propeller load disturbance which represents the sudden change of propeller torque when the ship adjusts its course while sailing (Xie et al., 2019). Obviously a set of parameters affect the torque absorbed by marine diesel engine propeller. These parameters are listed in Table.1.

TABLE 1. The Value of Parameters

Parameter	Description
W_E	Engine speed
I_P	Rotational inertia of propeller
I_E	Rotational inertia of engine shaft system
K_Q	Torque coefficient
ρ	Sea water density
V_D	Volume of cylinder
α	Number of diesel engines
D_P	Diameter of propeller
$P_E = F_R P_{max}$	Average effective pressure for brake
P_{max}	Engine maximum indicator pressure
F_R	Fuel injection mechanism

The fuel injection mechanism mentioned in Table.1 can be expressed as follows:

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$$\dot{F}_R = \frac{F_S - F_R}{\tau} \tag{4}$$

Where τ is the time constant of fuel injection mechanism and F_S is fuel injection signal (control signal).

4. The Proposed Controller

In this section, the basic structure of the proposed control scheme, called LADRC-ADALINE, of the marine diesel engines is presented. The proposed control strategy is mainly based on a combination of both ADALINE and LADRC to improve the efficiency of conventional ADRC controller.

4.1 LADRC Controller

Several studies have used ADRC strategy to control marine engine speed and the 2nd order ADRC has been chosen for this purpose (Kang et al., 2016; Wang et al., 2018c; Weigang and Hairong, 2015; Zhang et al., 2012). Justification for this choice is that, 2nd order method offers better accuracy in controlling the speed of marine diesel engines in the presence of complicated working conditions.

4.2 Linear Extended State Observer Design

The linear extended state observer (LESO) is an essential component of active disturbance rejection controller structure. It is concerned with observation of diesel engine load disturbance QL and engine acceleration $\dot{W}_E$ in which cannot be measured directly in real-time.

In the beginning, equation (1) is derivative as follows

$$\ddot{W}_E = \frac{30\, Q_E}{\pi\, I_{SH}} + \frac{D_P^5 \rho k_Q}{60\pi I_{SH}} W_E \dot{W}_E - \frac{15\alpha V_D P_{max}}{\pi^2 I_{SH}\, \tau}(F_R - F_S) \tag{5}$$

According to (Weigang and Hairong, 2015; Zhang et al., 2012). The fundamental idea lies in defining all terms in Eq. (5) as a generalized disturbance in the system, with exception the input control signal (F_S), as follows:

$$f_S = \frac{30}{\pi} \cdot \frac{Q_E}{I_{SH}} + \frac{D_P^5 \rho k_Q}{60\pi I_{SH}} W_E \dot{W}_E - \frac{15\alpha V_D P_{max}}{\pi^2 I_{SH} \tau} F_R \tag{6}$$

The state matrix is defined according to equation (5) as follows,

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$$x = [x_1, x_2] = [W_E, \dot{W}_E] \tag{7}$$

Where x_1 and x_2 are engine speed and engine acceleration, respectively. Consequently, the 2nd order state space model of marine diesel engine which represents the relation between the speed of a diesel engine and the fuel injection is expressed as follows:

$$\left.\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} [U] + \begin{bmatrix} 0 \\ f_S \end{bmatrix} \\ [y] &= \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{aligned}\right\} \tag{8}$$

$$U = F_S, \quad y = W_E$$

Where: U is state feedback control law, fs is a general disturbance, and b is the corresponding control gain defined as,

$$b = \frac{15}{\pi^2}\left(\frac{\alpha V_D P_{max}}{\tau I_{SH}}\right) \tag{9}$$

The main idea of ADRC control strategy is based on the definition of system disturbance as an extended state. Based on what mentioned above, 2nd order state space model Eq. (8) will be extended to 3rd state space model as follows

$$\left.\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ b \\ 0 \end{bmatrix} [U] + \begin{bmatrix} 0 \\ 0 \\ \dot{f}_S \end{bmatrix} \\ [y] &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \end{aligned}\right\} \tag{10}$$

Where x_3 represents the total disturbance (f_s) to be estimated using a 3rd linear extended state observer (LESO). The dynamics of LESO is expressed as follows

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$$\left.\begin{aligned}\begin{bmatrix}\dot{\hat{x}}_1\\ \dot{\hat{x}}_2\\ \dot{\hat{x}}_3\end{bmatrix} &= \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\end{bmatrix} + \begin{bmatrix}0\\ \hat{b}\\ 0\end{bmatrix}[U] - \begin{bmatrix}\beta_{01}\\ \beta_{02}\\ \beta_{03}\end{bmatrix}(x_1 - \hat{x}_1)\\ [\hat{y}] &= [1 \quad 0 \quad 0]\begin{bmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\end{bmatrix}\end{aligned}\right\} \quad (11)$$

Where $\hat{x}_1$, $\hat{x}_2$and $\hat{x}_3$are the estimations of system states (W_E , $\dot{W}_E$) and total system disturbance (f_s), respectively, $\hat{y}$ is the estimation of system output (engine speed) and U is control input. $\hat{b}$ is the estimation of control gain (b) given by Eq. (9) which typically specifies by the designer.

In this study, Gao method has been adopted to adjust the parameters of LADRC (Gao, 2006). This method is based on the presence of a linear mathematical relationship linking observer bandwidth (ω_o) for LADRC and linear error state feedback (LESF) control bandwidth (ω_c). Furthermore, the latter is related to the required setting time (t^*_s) which is often determined practically by the designer (Chen et al., 2011), based on his full knowledge on the nature of the system.
After the appropriate observer bandwidth (ω_0) and control gain ($\hat{b}$) are selected, the outputs of the extended state observer ($\hat{x}_1$, $\hat{x}_2$ and $\hat{x}_3$) presents an approximation of W_E, $\dot{W}_E$ and generalized disturbance fs, respectively.

Control law for 2nd order LADRC is adopted in this work as

$$U = \frac{U_0 - \hat{Z}_3}{\hat{b}} \quad (12)$$

Where U_0 is linear error state feedback (LESF) control signal. Then, mathematical model represents the acceleration of marine diesel engine Eq. (5) becomes

$$\ddot{W}_E = f_s - \hat{x}_3 + U_0 \quad (13)$$

If $\hat{x}_3 \approx f_s$, the order of basic system is reduced to a 2nd-order integrated system as

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$$\ddot{W}_E \approx U_0 \tag{14}$$

LESF control law is utilized as

$$U_0 = K_P e(t) + K_D \frac{de(t)}{dt} \tag{15}$$

Here, $e(t) = W_d - W_E$ where W_d is the desired speed of marine diesel engine, and K_P and K_D are controller gains to be tuned. In conclusion, after taking disturbances into account, the final speed control law of marine diesel engine can be written as

$$U(t) = (K_P e(t) + K_D \dot{e}(t) - \hat{x}_3)/\hat{b} \tag{16}$$

The structure of the 2nd-order LADRC controller of marine diesel engine is shown in Fig. 2. (Weigang and Hairong, 2015).

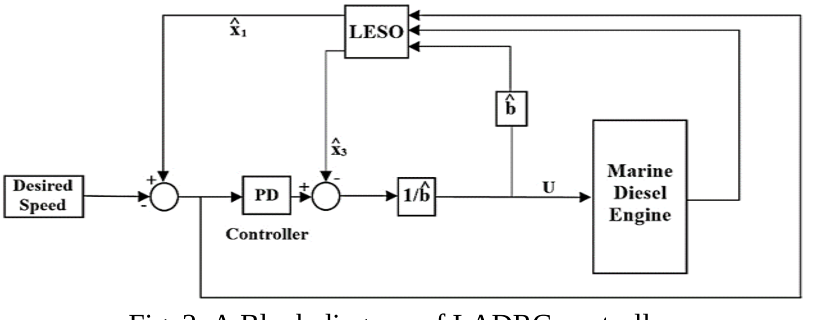

Fig. 2. A Block diagram of LADRC controller.

4.3 The Proposed LADRC-ADALINE Controller

Fig.3. shows the MATLAB/SIMULINK model of marine diesel engine along with proposed LADRC-ADALINE controller.

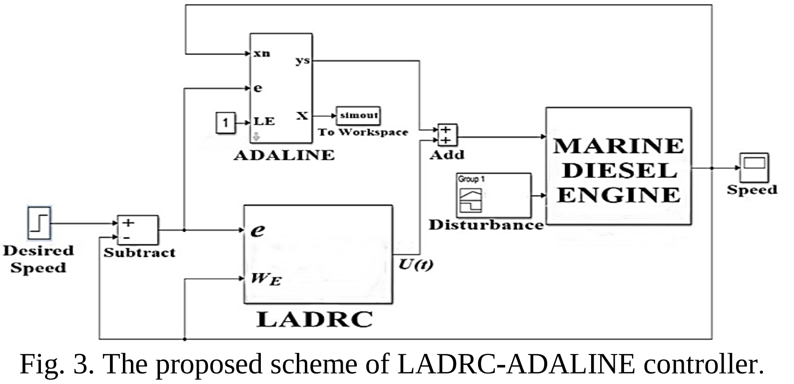

Fig. 3. The proposed scheme of LADRC-ADALINE controller.

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As clearly can be seen in Fig. 3, the general structure of LADRC-ADALINE controller is composed of two controllers which are, ADALINE and LADRC. ADALINE Neural Network inputs are marine motor rotational velocity and the error representing the difference between the desired and actual speed of marine diesel engine while network output is a supplementary signal added to the control signal provided by LADRC controller. ANN library offers an interface to set the parameters of ADALINE network such as the number of input and output neurons, the number of hidden layers, learning rate, sampling time, the number of neurons in each layer and weight limiter. The weights in ADALINE tool are automatically updated to reduce the error between the expected and network outputs. More information about the basic description of ADALINE can be found in (Li et al., 2017a; Callinan, 2003; Campa et al., 2002; Toolbox, 1998). ADALINE parameters are experimentally set as listed in Table 2.

Table 2. The Value of ADALINE Parameters

Parameters	Values
No. of input neurons	2.0
No. of output neurons	1.0
No. of hidden layers	1.0
No. of neurons in hidden layer	3.0
Learning rate	0.8
Stabilizing Factor	2.5
Weight Limiter	$1.0x10^5$
Sample Time	$1.0x10^{-4}$

5. Simulation Results

Similar to two-stroke marine diesel engine 12K98ME type which is utilized in an 8063TEU container ship (Tu, 2016), the same marine diesel engine model was adopted to perform simulations to compare and verify the effectiveness of the proposed control scheme. The main parameters of 12K98ME marine engine are shown in Table 3.

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Table 3. The Specification Parameters MAN B&W of 12K98ME

Parameters	Values
Amount of cylinders, α	**12**
Single cylinder volume,Vd	**1.81 m^3**
Maximum mean indicator pressure, P*max*	**19.55x10^3 *Pa***
Moment of inertia of the spindle, *Ie*	**5.53 x 10^3 kgm^2**
Moment of inertia of the propeller, *Ip*	**4.13 x 10^3 kgm^2**
Maximum speed, w_e.*max*	**104 r/min**
Propeller diameter, D*p*	**8.80m**
Torque coefficient, *Kq*	**0.04**
Time constant of fuel injection mechanism, τ	**0.10 s**
Density of sea water, *ρ*	**1027.0 g/m^3**

Based on (Gao, 2006) tuning principles and in order to meet the requirements of control performance as settling time, which is desired to be 2 s, the parameter values of LADRC were tuned to be as follows

LESO: $\omega_o = 8\,\omega_c$, $\beta_{o1} = 3\omega_o$, $\beta_{o2} = 3\omega_o^2$, $\beta_{o3} = \omega_o^3$

LESF (CL): $\omega_c = \frac{10}{t_s^*}$, $K_d = \omega_c^2$, $K_p = 2\omega_c$

It is clear that in LADRC law, ω_c is the only parameter that needs to be adjusted.

In order to verify the efficiency and effectiveness of the proposed design, conventional LADRC controller is compared with the proposed controller in the next section under random disturbance load, sudden dumping load and system parameter uncertainty.

5.1 System Performance Analysis with Random Disturbance Load.

According to maximum continue rating (MCR) working condition, the rated speed provided by 12K98ME diesel engine is 104 *r / min*, and the value of the maximum load under MCR is equal to 6.29x10^6 *Nm* (Xie et al., 2019). The change of wave shape randomly and continuously changes propeller load during the sailing (Taskar et al., 2016). To represent this fluctuation, an external load estimated at

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$5x10^6$ *Nm* is added to diesel engine model in Eq. (5). Simulation results of the proposed LADRC-ADALINE and LADRC with random disturbances are shown in Fig. 4.

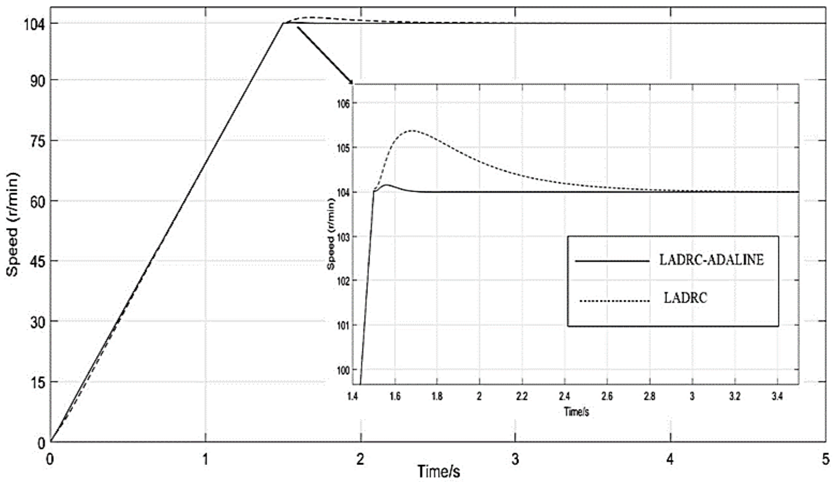

Fig. 4. Comparison of speed tracking performance with random disturbances.

In Fig. 4, it can be seen clearly that the proposed control strategy (LADRC-ADALINE) had better tracking accuracy than traditional LADRC strategy where LADRC-ADALINE controller managed to reach the target speed in the presence of random disturbances and provided preferable control performance compared to LADRC.
To learn more about the performance of LADRC-ADALINE control method, a comparison of performance indicators for the proposed and conventional LADRC controllers was made using well-known performance indices including integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE). The performance indices of LADRC-ADALINE and LADRC with random disturbances are listed in Table 4.

Table 4. Performance Indices of LADRC-ADALINE and LADRC with Random Disturbances.

Controllers	ISE	IAE	ITAE
LADR-ADALINE	0.01236	0.05962	0.0327
LADRC	0.6963	1.06	1.542

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5.2 System Performance Analysis with Sudden Dumping Load

The sudden demise of external load on engine happens when the propeller leaves sea surface. This often happens when the ship sails in inclement weather (Xie et al., 2019). Unless engine speed control system can quickly absorb this sudden load change, any delay may lead to severe consequences for the safety and cargo of ship. Therefore, it is necessary to verify the efficiency of the proposed control strategy under these conditions by setting external load value to zero at a specific time maintaining maximum continue rating (MCR) working condition.

The simulation results of LADRC-ADALINE and LADRC controllers in the presence of sudden dumping load are illustrated in Fig. 5.

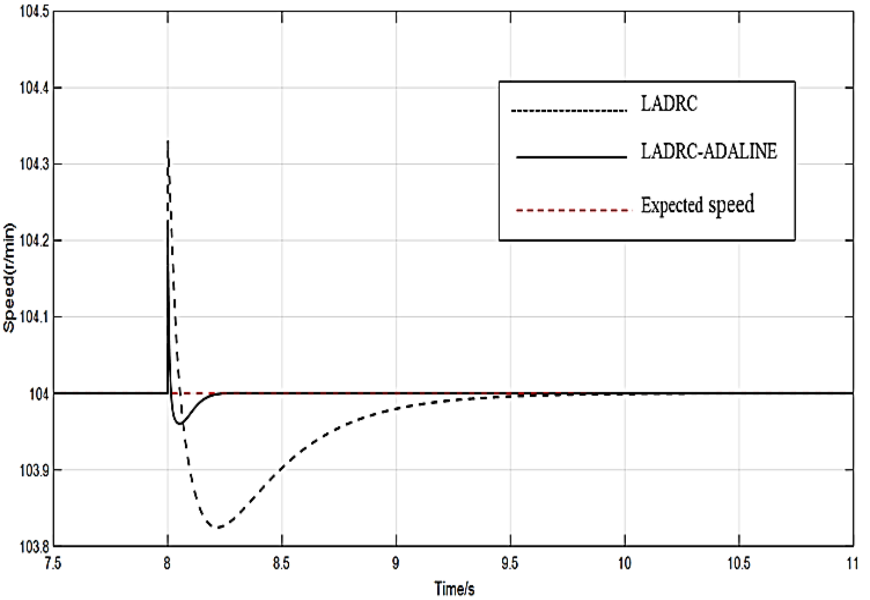

Fig. 5. Simulation results with sudden dumping load.

It is noticeable from Fig. 5 that, when a sudden demise of external load occurred, LADRC-ADALINE controller took only 0.2 *s* to return engine speed to nominal value which was faster than the performance of conventional LADRC controller. For further clarification, the calculation of stability time and maximum speed of both techniques are listed in Table 5.

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Table 5. Maximum speed and stability time results with sudden dumping load condition.

Method	Maximum speed (r/min)	Stability time (s)
LADR-ADALINE	104.22	0.2
LADRC	104.33	2.3

Table 5 shows that, in the presence of a sudden damping load, the maximum speed of diesel engine and stability time with LADRC-ADALINE controller were lower than that obtained with LADRC controller.

5.3 Performance Analysis with System Parameter Perturbation

In this section, the robustness of LADRC-ADALINE controller is investigated compared to system parameter perturbation. This is because ADRC control strategy mainly depends on measurements and observation. Therefore, the variation of rotational inertia moment (I_{SH}) in marine diesel engine systems includes the rotational inertia of propeller and the rotational inertia of diesel engine shaft system is considered as a parameter perturbation.
The uncertainty of system parameters is simulated by assuming that there was an inequality between the torque of propeller (Q_P) and the output torque of diesel engine (Qe). This condition is not fulfilled without specifying the interval time of perturbation (Xie et al., 2019). For this purpose, sudden demise of the external load should be occurs synchronizing with the interval time of perturbation. Therefore, when sudden damping load occurs, rotational inertia moment (I_{SH}) is changed by ± 50% to show the effect of parameter perturbation on speed control system. Figs. 6 and 7 illustrate the performance of control inputs in both LADRC-ADALINE controller and conventional LADRC control strategy when inertia moment is changed. In addition, maximum speed and stability time are calculated and listed in Tables 6 and 7.

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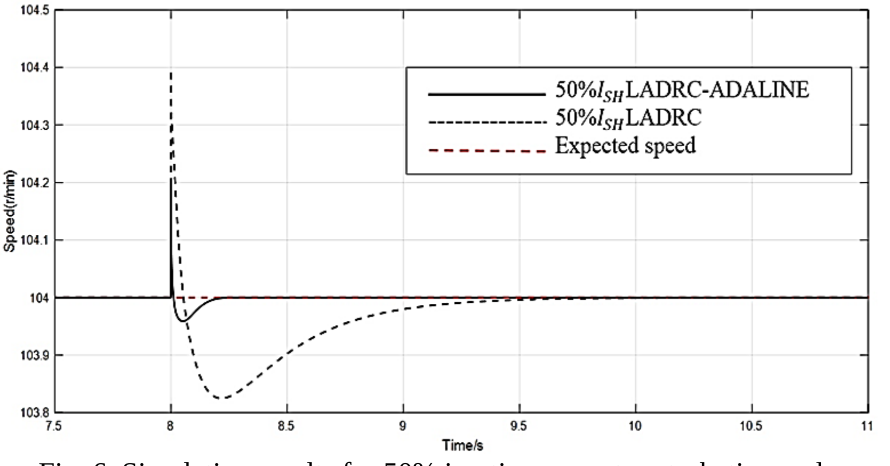

Fig. 6. Simulation results for 50% inertia moment perturbation and sudden dumping load.

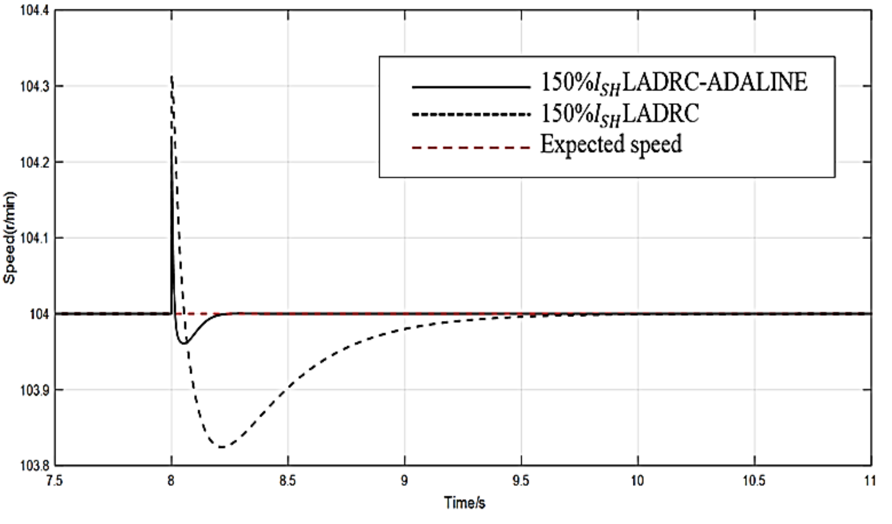

Fig. 7. Simulation results for 150% inertia moment perturbation and sudden dumping load.

Table 6. Maximum speed and stability time results with 50% I_{SH} perturbation and sudden dumping load conditions.

Method	Maximum speed (r/min)	Stability time (s)
LADR-ADALINE	104.22	0.2
LADRC	104.33	2.3

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Table 7. Maximum speed and stability time results with 150% I_{SH} perturbation and sudden dumping load conditions.

Method	Maximum speed (r/min)	Stability time (s)
LADR-ADALINE	104.23	0.19
LADRC	104.314	1.9

The simulation results showed that simultaneous appearance of inertia moment perturbation and a sudden dumping load disturbance caused increased maximum speed. However, it was clear that the reaction of the proposed control method to overcome these disturbances was faster than that of conventional LADRC controller, where LADRC-ADALINE controller was able to more effectively return engine speed to steady state compared to LADRC. This was confirmed by calculations results presented in Tables 5 and 6 where it can be observed that the proposed LADRC-ADALINE control strategy had a superior disturbance rejection capability than conventional LADRC method in the presence of inertia moment perturbation.

6. Conclusion

In order to deal with marine diesel engine speed problems under load disturbances and unpredictable uncertainty, an adaptive ANN control approach was presented. The proposed control strategy relied mainly on the combination of both adaptive linear neural network and LADCR and was referred as LADRC-ADALINE. The performance and efficiency of the proposed controller was tested in the presence of a set of disturbances which usually affect marine diesel engine speed control, namely random disturbance load, sudden discharge load disturbance and parameter disturbance. Simulation experiments were conducted using a large low-speed two-stroke marine engine 12K98ME. The obtained results showed that, the proposed controller proved to be advantageous over standard LADRC control method regarding tracking accuracy, disturbance rejection, and robustness. In practice, the proposed control strategy greatly improved the performance of conventional LADRC controller, especially under external disturbance conditions and the results were very promising. This paved the way for the

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proposed control strategy to be applied in the field of marine diesel engine speed control in real time.

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