Full paper

Review on Combustion Control of Marine Engine by Fuzzy Logic Control Concerning the Air to Fuel Ratio
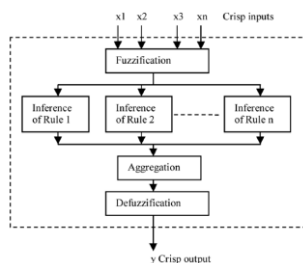
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Graphical abstract

Abstract

This research reviews a close loop control-oriented model, combined with air to fuel ratio, to regulate combustion phasing in a spark- ignition marine engine operation. On the other hand ,Stoichiometric air-to-fuel ratio (λ) control plays a significant role on the three way catalysts in the reduction of exhaust pollutants of the SI marine engine. Air to fuel management for SI marine engines is a major challenge from the control point of view because of the highly nonlinear behavior of this system. For this reason, linear control techniques are unable to provide the required performance, and nonlinear controllers are used instead. Therefore, a fuzzy MIMO Control system is designed for robust control of lambda. As an accurate and control oriented model, an air to fuel ratio model of a Spark Ignition (SI) marine engine is developed to generate simulation data of the engine's subsystems. The Goal of this control is to maintain the A/F ratio at stoichiometry.

Keywords: SI marine engine; air to fuel ratio; fuzzy logic control

■1.0 INTRODUCTION

The emissions from ships engaged in international trade in the seas surrounding ports take a part in the environmental pollution. Exhausts caused by marine engines contains high level of carbon dioxides (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_x), and other of particles due to the heavy fuel oil used for combustion. For example in Europe, It was estimated to have been 2.3 million tonnes of sulfur dioxide and 3.3 million tonnes of nitrogen oxides a year in 2000.[1]

Environment in forms of air pollution due to NO_x, and SO_x, global warming due to CO_2, and water pollution becomes an essential issue on societies' point of view.[2] The governments in industrialized and developing countries consider not only economical issue, but also an environmental issue. The Kyoto Protocol (1997) has been a turning point for the future economic and environmental policies in both industrialized and developing countries.[3]

The impact of environmental sea conditions to the system is significant to be considered by researchers[2 and 3], starting from the phases of ship construction and building to the stage of ship's control system design and implementation. The task becomes crucial for design optimization of the single propulsion system and the whole ship as in the fact that the propulsion system is a key aspect of the global behavior of all the ships.

Ships generally demonstrate the behavior of efficient and safe operation both in steady and transient conditions during sea trials. The quantification of exhaust gases during ship maneuvering has received attention from a few researchers. Jaswar have studied the control surface of Autonomous Underwater Vehicle (AUV) to minimize the effect of fluid dynamic on stability and directional path.[4] Hulda stated that nitrogen oxide levels vary throughout the maneuvering period but at lower levels than at cruising speed. The increase is big enough to suspect a notable impact on air quality in port cities over the short period that manoeuvring at reduced speeds takes place. [5]

Ship propulsion simulation as one of its application, is one of the most useful ways to predict and investigate the dynamic of the ship and the system at the design stage[6, 7 and 8], mainly when it deals with new system configurations. This simulation also reduces the need of conducting costly and time consuming of full scale trial. The simulation has ability to do some experiments which are rather difficult to or even not allowed to conduct using real ships, get practical experiences in the short time which require long term accumulation in real ship, fault recognition and exclusion which cannot be done in real ship. These are advantageous since it is desirable to work with onboard diagnosis and control modeled by an accurate but not complicated propulsion system.[6] This paper reviews combustion control modeling and fuzzy strategy of air to fuel ratio control for SI marine outboard engines.

■2.0 AIR-TO-FUEL MODELING AND CALCULATION

Air-to-fuel (A/F) ratio is the mass ratio of air and fuel trapped within of the cylinder of a motor before combustion starts. When the fuel in the cylinder mixtures with all the current oxygen in the combustion chamber (cylinder), the blend of air and fuel is really a stoichiometric mixture. For gasoline, stoichiometry is achieved once the A/F ratio is 14.6. Any mixture significantly less than 14.6 to 1 is known as rich mixture, any more than 14.6 to 1 is really a lean mixture.

In SI marine engines, the air-to-fuel ratio is measured by a device known as an oxygen sensor, or sometimes called a lambda sensor. The sensor is located in the exhaust manifold and its main purpose is to determine how far away from stoichiometry the air-fuel mixture is. This unique location of the oxygen sensor is important in reducing the response time from the fuel injector to the sensor, which is a very important time delay that is taken into consideration of A/F ratio feedback control systems.

Air fuel ratio could be the mass ratio of air and fuel trapped within the cylinder before combustion starts. This section consists of four steps as follows: air to fuel modeling, finding the equivalence air to fuel ratio by the stoichiometric A/F ratio, fuel ratio modeling and fuel ratio calculation.

The air-to-fuel mathematically is the mass of the air divided by the mass of the fuel as shown in the equation below.

$$A\!/_F \; ratio = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} \tag{1}$$

where $\dot{m}_{air}$ is the mass of the air and $\dot{m}_{fuel}$ is the mass of the fuel. If the ratio is too much or too low, it could be adjusted by the addition of or reducing the total amount of fuel per engine cycle that's injected to the cylinder. The engine A/F ratio that's modeled in this research could be regulated by both a port and a direct fuel injectors.

Since air-to-fuel ratio could be the ratio of the mass of air to the mass of fuel, then a mathematical calculation of with this ratio is available by dividing the mass of the air by the mass of the fuel. The sum total fuel in the cylinder, $\dot{m}_{fuel}$ could be the fuel flow from the port fuel injector and the direct injector as shown in the equation below.

$$\dot{m}_{fuel} = \dot{m}_{PFI} + \dot{m}_{DI} \tag{2}$$

Finally, the target equivalence ratio is given in the equation below.

$$\lambda_{target} = \frac{\dot{m}_{air}}{14.6 \; \dot{m}_{fuel}} \tag{3}$$

The sum of the fuel that is injected into the cylinder by the port fuel injector and the direct fuel injector is the total fuel, m_{Fuel}. The amount of fuel injected by one injector divided by the sum of the two is the fuel ratio of Port Fuel Injection (PFI) to Direct Injection (DI).

Knowing the equations for the calculation of the air-to-fuel ratio (using the equivalence ratio) and the fuel ratio, the development of the model will be begun. The model will be developed in Matlab Simulink and it included the modeling of the wall wetting dynamics of the port fuel injector, the air movement dynamics, and three appropriately modeled time delays. These full time delays were the full time delay of the fuel injected by the port fuel injector, the time delay of the fuel injected by the direct injector, and the oxygen sensor calculation delay. A delay is also included for the air movement dynamics. [9 and 10]

■3.0 COMBUSTION PROCESS OF SI MARINE ENGINE

In creating a valid engine model of SI marine engines, the idea of the combustion process must certainly be understood. The combustion process is easy and it begins with fuel and air being mixed together in the intake manifold and cylinder. This a/f blend is trapped inside cylinder following the intake valve(s) is closed and then gets compressed. Thereafter, the compressed blend is combusted, usually near the end of the compression stroke, because a power discharge from the spark plug. The flame that's produced close to the spark electrode travels through the unburned a/f mixture and extinguishes when it hits the combustion chamber walls. This combustion process varies from engine cycle-to-cycle and also varies from cylinder-to-cylinder. The particular combustion of the air-fuel mixture begins before the conclusion of the compression stroke, extends through combustion stroke, and ends following the peak cylinder pressure occurs.[11]

The prior explanation of the combustion process could be referred to as the standard combustion phenomenon. An essential abnormal combustion event is called knock and its name arises from the audible noise that resonates from the pre ignition of the air-fuel mixture. When the air-fuel mixture is compressed it causes the pressure and temperature to improve within the cylinder as previously discussed. Unlike normal combustion, the cylinder pressure and temperature can rise so rapidly so it can spontaneously ignite the air-fuel mixture causing high frequency cylinder pressure oscillations. These oscillations cause the metal cylinders to make sharp noises called knock.[12]

■4.0 FUZZY LOGIC CONTROLLER

Fuzzy logic supply a practicable way to know and manually influence the mapping behavior. Generally speaking, fuzzy logic uses simple rules to explain the device of interest as opposed to analytical equations, which makes it an easy task to implement. Given its advantages such as for example robustness and speed, the fuzzy logic method is one of the finest solutions for system modeling and control. An FIS contains three primary elements, the fuzzification stage, the rule base, and the defuzzification stage. The fuzzification stage is employed to transform the so-called crisp values of the input variables into fuzzy membership values. Then, these membership values are processed within the rule-base using conditional 'if-then' statements. The outputs of principles are summed and defuzzified right into a crisp analogue output value. The results of variations in the parameters of a FIS could be readily understood and this facilitates calibration of the model.[13]

The device inputs, for instance: 'cylinder pressure' and 'air density' are called linguistic variables, whereas 'high' and high' are linguistic values which are characterized by the membership function. After the evaluation of the rules, the defuzzification transforms the fuzzy membership values right into a crisp output value, for instance, the penetration depth.

The complexity of a fuzzy logic system with a fixed input-output structure is set by the how many of membership functions employed for the fuzzification and defuzzification and by the number of inference levels. The block diagram of an over-all fuzzy logic system is shown in Figure 1, where:

$x1, x2, \ldots, xn$ are a symbol of n crisp inputs and y could be the crisp output.[13]
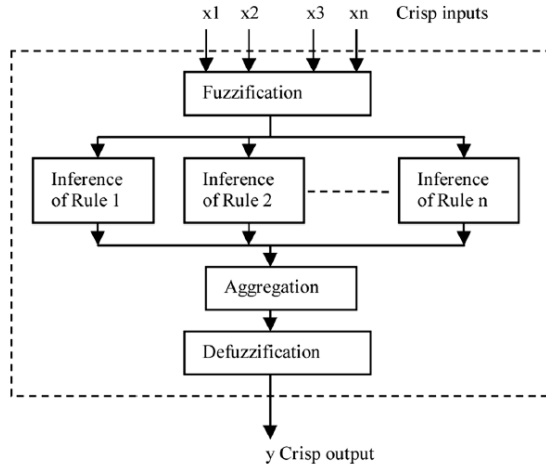

Figure 1 Block diagram of a general fuzzy logic system[13]

The main significant reasons to utilized fuzzy logic technology have the ability to give an approximate recommended solution for unclear and complicated systems to easy understanding and flexible. Fuzzy logic provides a technique which has the capability to model a control for nonlinear plants with a couple of IF-THEN rules, or it could identify the controller actions and describe them by utilizing fuzzy rules. It must be mentioned that application of fuzzy logic is not limited by a system that's hard for modeling, however it can be utilized in solar systems which have complicated mathematical models due to most of the time it could be shortened in design but there's no good quality design just sometimes we could find design with high quality.[5] In this research to be able to solve uncertainty dynamic parameter, adaptive method is applied to the fuzzy MIMO controller.

■5.0　VARIABLE STRUCTURE METHODOLOGY

Centered on variable structure discussion, the control law for a variable level of freedom robot manipulator is written as [14-18]:

$$U = U_{Nonlinear} + U_{dis}$$

Where, the model-based component $U_{Nonlinear}$ is compensated the nominal dynamics of systems. Therefore $U_{Nonlinear}$ can calculate as follows:

$$U_{Nonlinear} = \left[M^{-1}\left(P_m(\theta) + P_{net}(\theta)\right) + \dot{S} \right] M$$

Where

$$M^{-1} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \quad M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

A simple solution to get the variable structural condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = K(\vec{x}, t) \cdot \text{sgn}(s)$$

where the switching function sgn(S) is defined as

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases}$$

and the $K(\vec{x}, t)$ is the positive constant.
The Lyapunov formulation can be written as follows,

$$V = \frac{1}{2} S^T . M . S$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T . \dot{M} . S + S^T M \dot{S} \tag{4}$$

the dynamic equation of IC engine can be written based on the structure variable surface as

$$M\dot{S} = -VS + M\dot{S} + P_m(\theta) + P_{net}(\theta) \tag{5}$$

it is assumed that

$$S^T \left(\dot{M} - 2P_m(\theta) + P_{net}(\theta) \right) S = 0 \tag{5.1}$$

by substituting (5) in (4)

$$\begin{aligned} \dot{V} &= \frac{1}{2} S^T \dot{M} S - S^T P_m(\theta) + P_{net}(\theta) S \\ &\quad + S^T \left(M\dot{S} + P_m(\theta) + P_{net}(\theta) S \right) \\ &= S^T \left(M\dot{S} + P_m(\theta) + P_{net}(\theta) S \right) \end{aligned} \tag{6}$$

suppose the control input is written as follows

$$\begin{aligned} \widehat{U} &= \widehat{U_{Nonlinear}} + \widehat{U_{dis}} \\ &= \left[\widehat{M^{-1}}\left(P_m(\theta) + P_{net}(\theta) \right) + \dot{S} \right] \widehat{M} \\ &\quad + K . sgn(S) + P_m(\theta) + P_{net}(\theta) S \end{aligned} \tag{7}$$

by replacing the equation (7) in (6)

$$\begin{aligned} \dot{V} &= S^T (M\dot{S} + P_m(\theta) + P_{net}(\theta) - \widehat{M}\dot{S} - \widehat{P_m(\theta) + P_{net}}(\theta) S \\ &\quad - K sgn(S) \\ &= S^T \left(\widetilde{M}\dot{S} + \widetilde{P_m(\theta) + P_{net}}(\theta) S \\ &\quad - K sgn(S) \right) \end{aligned}$$

It is obvious that

$$\left| \widetilde{M}\dot{S} + \widetilde{P_m(\theta) + P_{net}}(\theta) S \right| \leq \left| \widetilde{M}\dot{S} \right| + \left| \widetilde{P_m(\theta) + P_{net}}(\theta) S \right|$$

The Lemma equation in the IC marine engine system can be written as follows

$$K_u = \left[\left| \widetilde{M}\dot{S} \right| + \left| P_m(\theta) + P_{net}(\theta) S \right| + \eta \right]_i, i = 1,2,3,4, \ldots$$

The equation (5.1) can be written as

$$K_u \geq \left| \left[\widetilde{M}\dot{S} + P_m(\theta) + P_{net}(\theta) S + \right]_i \right| + \eta_i$$

Therefore, it can be shown that

$$\dot{V} \leq -\sum_{i=1}^{n} \eta_i |S_i| \tag{8}$$

Consequently the Equation 8 guarantees the stability of the Lyapunov equation. Variable structure controller (VSC) and developed fuzzy logic controller will be tested to sinus response trajectory. The simulation will be deployed and implemented in Matlab/Simulink software. Fuel ratio trajectory, disturbance rejection and error are evaluated in these controllers. The analysis results revealed these systems are evaluated by band limited white noise having a predescribed 40% of relative to the input signal amplitude. This kind of noise is deployed to exterior annoyance in constant and hybrid systems.[19-20]

■6.0 CONCLUSION

The major objective is to plan a MIMO fuzzy methodology which deployed to the interior combustion engine with simple to design and apply. SI engine uses nonlinear dynamic and uncertain parameters accordingly; subsequent purposes pursuit in the explained research: To expand a chattering in a place pure variable structure controller versus ambiguity, to plan and apply a Lyapunov MIMO fuzzy structure variable controller to answer the equal problems with least rule base and lastly to expand a place fuzzy structure controller to answer the annoyance refusal and decrease the calculation load.

Refer to the study, a MIMO fuzzy controller design and application to SI engine has been developed to plan and design of lofty performance nonlinear controller in the attendance of uncertainties, exterior annoyances and Lyapunov based. Due to the positive points in the variable structure controller, fuzzy inference system and adaptive fuzzy back stepping methodology, it can be concluded that the variation laws is obtained in the Lyapunov sense.

Acknowledgement

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