Fuzzy Fan Controller Design and Simulation

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ABSTRACT: A Variable Fill Fluid Coupling (VFFC)provides a way to control an engine fan without the stress that a mechanical gearbox can add, unfortunately VFFCs are very difficult to model mathematically. Because of this, a fuzzy controller for the VFFC is proposed. This controller will be validated and compared to a non-fuzzy solution via a MATLAB simulation. The simulation will allow for an easy comparison of different membership functions and defuzzification methods. The results from these simulations will show that a fuzzy controller can perform equivalently to a non-fuzzy controller. The results also suggest that through more refined tuning, a performance improvement over the non-fuzzy counter-part.

KEY WORDS: Variable Fill Fluid Coupling, Fuzzy Interface System (FIS), Fan Controller, Fuzzy Neural Network

I. INTRODUCTION

The goal of this paper is to design and analyze a fuzzy controller for a variable fill fluid coupling attenuated fan drive. A Variable Fill Fluid Coupling (VFFC) is a viscous torque converter whose output is determined by the volume of oil inside of it. By regulating the ratio of oil in versus oil out, the speed ratio can be controlled. This paper will validate the fuzzy controller through a fuzzy simulation of the fan drive and cooling system. MATLAB will be used to script and run the simulations. The simulation MATLAB code will allow for easy adjustment to various fuzzy properties of the system, including Membership Functions and Defuzzification Methods. The program will simulate a cooling system as shown in figure 1.
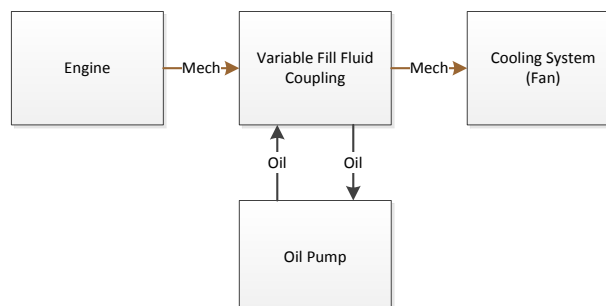

Figure 1 - System Architecture of a cooling system

There is significant research in the field of fuzzy systems and fuzzy controllers. Fuzzy PID controllers have been used to control a variety of systems, from electronic throttles [3] to cold plates [1]. There have also been many advancements to using fuzzy controllers. One significant improvement to fuzzy controllers is to make them a learning controller, through the use of a neural network or other methods [5]. A learning fuzzy controller can modify its fuzzy rule weights and membership functions to optimize the control while it is working. Other research has been done into combining regular fuzzy controllers and learning fuzzy controllers [4]. This has shown to improve performance by leveraging the efficiency of simple fuzzy controllers with the accuracy of learning fuzzy controllers.

This paper is organized into several sections. Section 2 of the paper presents a discussion on why Fuzzy was chosen for this control system and a comparison of fuzzy and non-fuzzy solutions to this problem. Then section 3 of the paper presents the proposed fuzzy inference system. Section 4 presents the simulation methodology. The results of the

simulations are presented after the simulation overview in section 5. The paper ends with a conclusion that sums up the major topics in section 6.

II.   WHY FUZZY?

The fluid mechanics involved in a VFFC make modelling it's mathematically difficult. For a given fluid type, the ratio of input to output rotational speed is dependent on the volume of oil in the coupling, the viscosity (a function of temperature) of the oil in the coupling, and the input speed. Rather than perform the Computational Fluid Dynamics (CFD) to try and identify the performance characteristics of a particular VFFC, a fuzzy control scheme is suggested. A fuzzy oil flow controller will allow for concise control of the cooling system without requiring the specifications for the VFFC.

2.1   Comparison of Fuzzy and Non-Fuzzy

Without a feedback loop on the cooling fan speed, a non-fuzzy system will struggle to determine the optimal amount of oil that should be flowed into the VFFC. Because the cooling system requires engine power to cool, finding the necessary amount of cooling to not over heat the system without overcooling and reducing engine performance is very important. A simple, purely mechanical non-fuzzy controller can be designed to provide sufficient cooling to the system, but to optimize engine performance, a more complicated controller is required. By utilizing fuzzy, a flexible controller that reacts to the current cooling needs of the systems to reduce over cooling can be implemented.

III.   A VARIABLE FILL FLUID COUPLING FUZZY INFERENCE SYSTEM

The Variable Fill Fluid Coupling fuzzy inference system (FIS) uses two fuzzy input variables which are:
1-   The Engine Speed with three linguistic fuzzy trapezoidal membership functions as shown in figure 2 or Gaussian membership functions as shown in figure 3, and
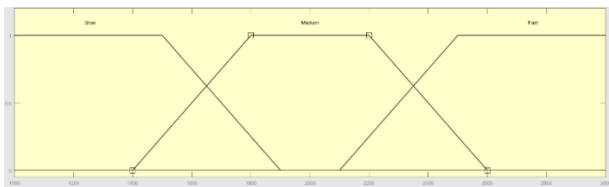

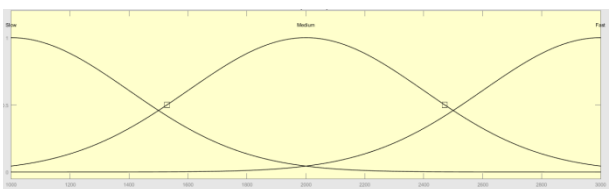Figure 2 - Engine Speed Membership Function – Trapezoid
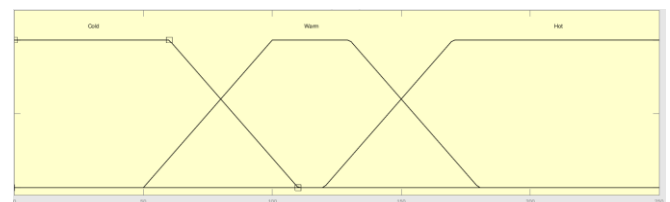

Figure 4 - Coolant Temperature Membership Function – Trapezoid

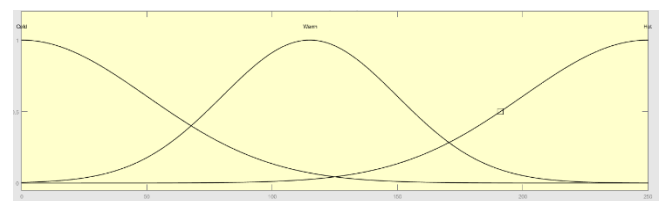Figure 3 - Engine Speed Membership Function – Gaussian

Figure 5 - Coolant Temperature Membership Function – Gaussian

2-   The Coolant Temperature with three fuzzy Trapezoidal Membership Function as shown in figure 4 or Gaussian as shown in figure 5.

The Variable Fill Fluid Coupling fuzzy inference system has two fuzzy output variables as following:
1-   The Oil Flow with three fuzzy Trapezoidal Membership Function as shown in figure 6 or Gaussian as shown in figure 7.
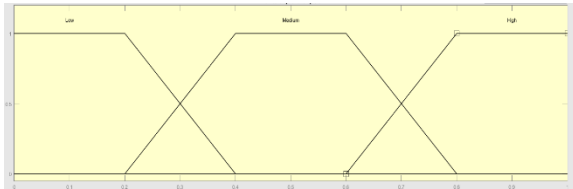
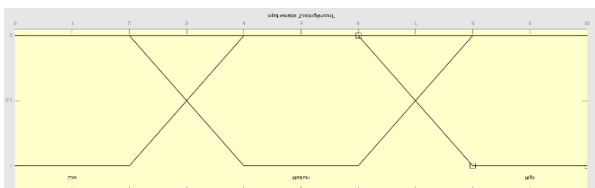Figure 6 - Oil Flow Membership Function – Trapezoid

Figure 6 - Oil Flow Membership Function – Gaussian

2-   The Cooling Amount with three fuzzy Trapezoidal Membership Function as shown in figure 8 or Gaussian as shown in figure 9.
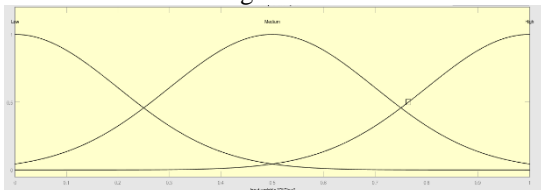

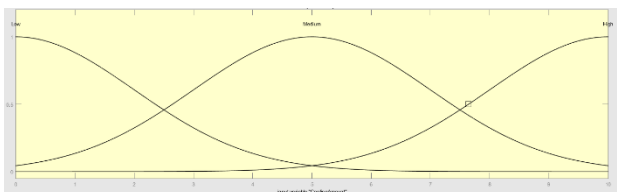Figure 7 - Cooling Amount Membership Function – Trapezoid

Figure 8 - Cooling Amount Membership Function – Gaussian

Figure 10 shows the Fuzzy Rule Surface Plots for the Oil Controller with Trapezoidal MF and Centroid Defuzzification.
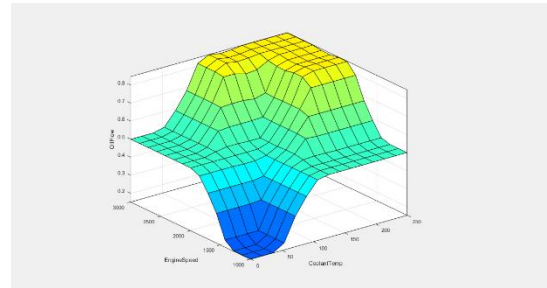

Figure 10 - Oil Controller Rule Surface - Trap MF, Centroid Defuzzification

Figure 11 shows the Cooling System Rule Surface with Trapezoidal MF and Centroid Defuzzification.
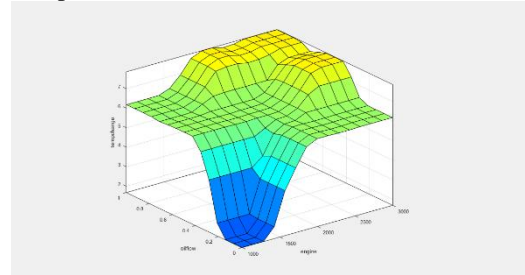

Figure *11* - Cooling System Rule Surface - Trap MF, Centroid Defuzzification

Figure 12 shows the Oil Controller Rule Surface with Gaussian MF and Centroid Defuzzification.
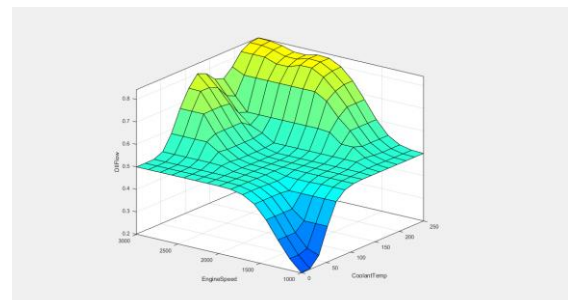

Figure 12 – Oil Controller Rule Surface – Gauss MF, Centroid Defuzzification

Figure 13 shows the Cooling System Rule Surface with Gaussian MF and Centroid Defuzzification. Figure 14 shows the Oil Controller Rule Surface with Trap MF and MoM Defuzzification. Figure 15 shows the Cooling System Rule Surface with Trap MF and MoM Defuzzification.
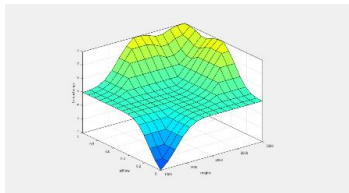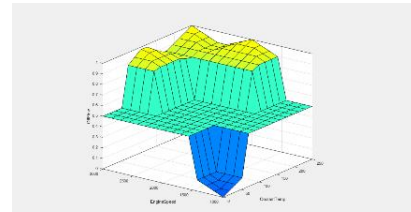
Figure *14*9 – Oil Controller Rule Surface – Trap MF, MoM Defuzzification

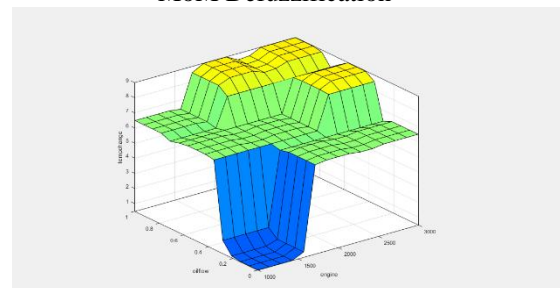Figure *13* – Cooling System Rule Surface – Gauss MF, Centroid Defuzzification

Figure *15* – Cooling System Rule Surfac*e – Trap MF, MoM Defuzzification*

IV.   SIMULATION

MATLAB was used to simulate a fuzzy cooling system for the oil flow controller to interact with. There are four different MATLAB files (.m files) that comprise the simulation code. The MATLAB files are as follows:

- AddEngineHeat.m - This function models heat being added to the system. If desired, the user can tweak the curve used to determine the engine heat. It receives engine speed as an input, and it returns a temperature change.

- CreateCoolingSystemFIS.m - This function creates the Fuzzy Interface System (FIS) that represents the Cooling System. It is a static script that should not be changed by the user. It receives definitions of the engine speed and oil flow linguistic terms, the fuzzy rule set that governs the Cooling System, as well as other fuzzy properties as its input. It returns a Cooling System FIS Object.

- CreateOilCOntrollerFIS.m - This function creates the Fuzzy Interface System (FIS) that represents the Oil Controller. It is a static script that should not be changed by the user. It receives definitions of the engine speed and coolant temperature linguistic terms, the fuzzy rule set that governs the Oil Controller, as well as other fuzzy properties as its input. It returns an Oil Controller FIS Object.

- CrispOilController.m - This code models a non-fuzzy oil controller. It represents a purely mechanical thermostatic oil flow controller. It controls the oil flow linearly per the coolant temperature, between some max and min. If desired, the user can tweak the control curve for the controller. It receives coolant temperature as an input, and it returns an oil flow.

- Wilke_ECE552_Project.m - This is the main code for the simulation. It manages all of the fuzzy properties and calls the CreateCoolingSystemFIS and CreateOilControllerFIS functions to generate FIS's based on those properties. It also includes the main simulation loop that updates the coolant temperature at each time step. The simulation is set up to run through a range of predefined engine speed conditions and return the results as plots. The user can change any of the fuzzy properties, as well as changing the membership function values and types for each of the linguistic variables.

The simulation was split into two main components: the oil flow controller and the cooling system model. The cooling system model is a fuzzy model designed to serve as a simplified representation of a cooling system that the oil flow controller might control. It included a cooling rate, simplified as a temperature drop that was a function of engine speed and oil flow rate. It also had a temperature increase to represent heat going into the coolant as a function of the engine speed. The oil flow controller used the coolant temperature and/or engine speed to control the flow of oil in the simulated cooling system/VFFC.The Fuzzy Rules that were used for the Oil Controller and Cooling System are shown in Table 1 and Table 2, respectively. This simulation was run for different membership functions and defuzzification methods, as well as a range of engine speed profiles.

Table 1 - Oil Controller Fuzzy Rules

IF		THEN
Engine Speed	**Coolant Temp**	**Oil Flow Rate**
Slow	Cold	Low
Slow	Warm	Medium
Slow	Hot	Medium
Medium	Cold	Medium
Medium	Warm	Medium
Medium	Hot	High
Fast	Cold	Medium
Fast	Warm	High
Fast	Hot	High

Table 2 - Cooling System Fuzzy Rules

IF		THEN
Engine Speed	**Oil Flow Rate**	**Oil Flow Rate**
Slow	Low	Low
Slow	Medium	Medium
Slow	High	Medium
Medium	Low	Medium
Medium	Medium	Medium
Medium	High	High
Fast	Low	Medium
Fast	Medium	High
Fast	High	High

V.   SIMULATION RESULTS

The four different configurations that were simulated and compared were:
1.   Crisp Controller
2.   Fuzzy Controller, Trapezoid Membership Functions, Centroid Defuzzification Method
3.   Fuzzy Controller, Gaussian Membership Functions, Centroid Defuzzification Method
4.   Fuzzy Controller, Trapezoid Membership Functions, Mean of Maximum (MoM) Defuzzification Method
Due to the linear nature of the Crisp Controller, the oil flow rate over time had a much smoother curve compared to the fuzzy methods as shown in figures 16, 17, 18, 19, 26, 27, 28 and 29. The fuzzy controllers were much more jagged because of the system switching between the different rules as the coolant temperature and engine speed changed. The Crisp Controller only used coolant temperature as its input, and did not react to changes in engine speed. Because of this, the Fuzzy Controllers performed better on the high and variable engine speed configurations as shown in figures 20, 21, 22 and 23. Although this performance gain was marginal, it could be increased through better tuning of the Fuzzy Rules and Membership Functions. The Crisp Controller has similar or better performance during the lower engine speed profiles as shown in figure 28.
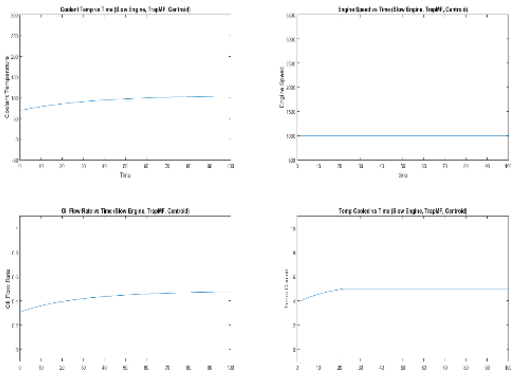
Figure 16 - Slow Engine Curve, Trapezoid MF, Centroid Defuzzification
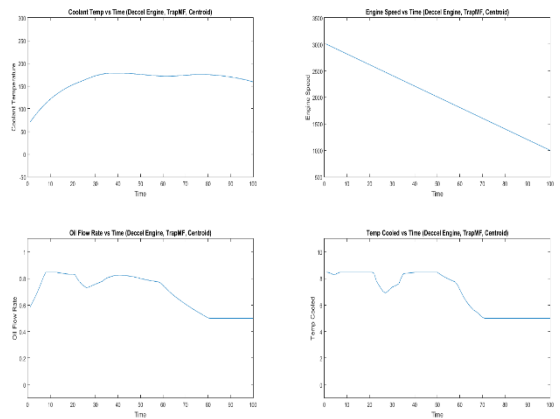

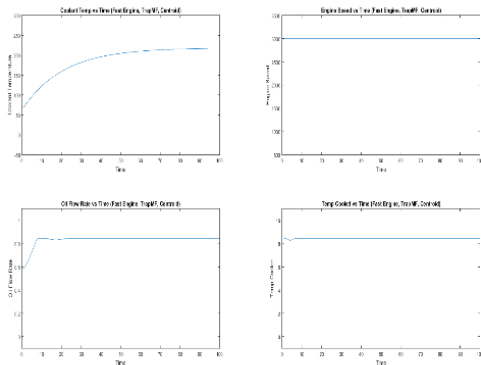Figure 19 - Deceleration Engine Curve, Trapezoid MF, Centroid Defuzzification

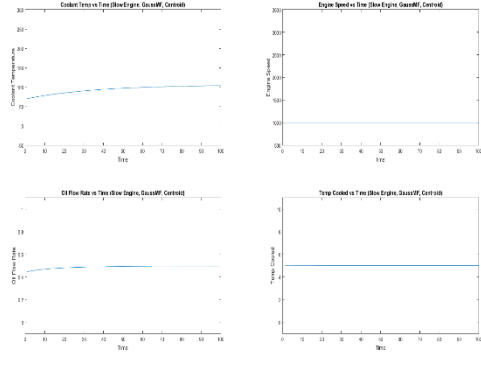Figure *17*- Fast Engine Curve, Trapezoid MF, Centroid Defuzzification

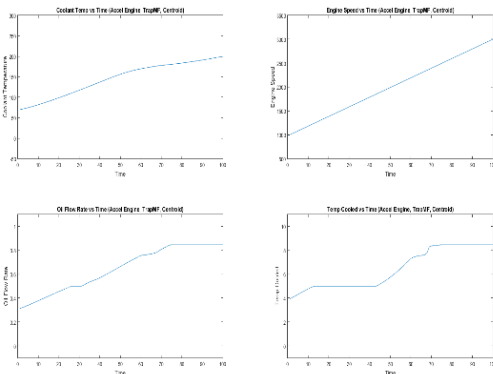Figure *20* - Slow Engine Curve, Gaussian MF, Centroid Defuzzification

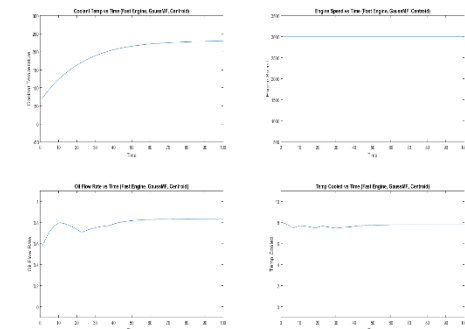Figure *18* - Acceleration Engine Curve, Trapezoid MF, Centroid Defuzzification

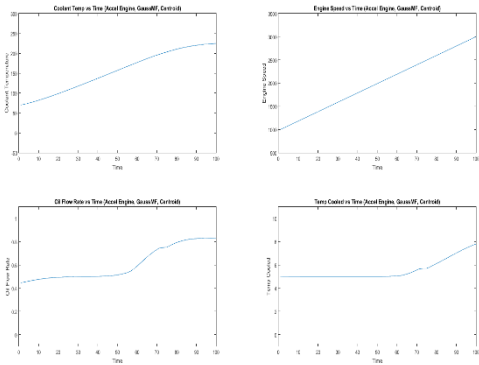Figure *21* - Fast Engine Curve, Gaussian MF, Centroid Defuzzification

Figure *22* - Acceleration Engine Curve, Gaussian MF, Centroid Defuzzification
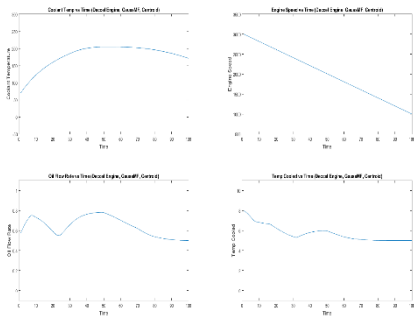

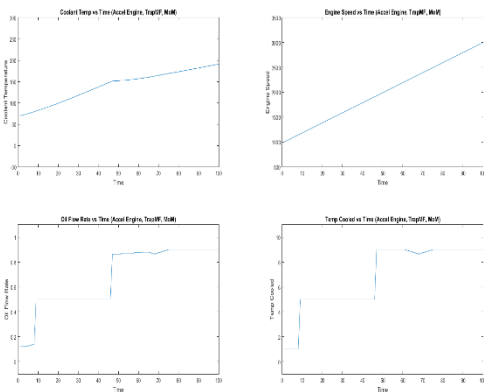Figure *23* - Deceleration Engine Curve, Gaussian MF, Centroid Defuzzification

Figure *24* - Acceleration Engine Curve, Trapezoid MF, MoM Defuzzification
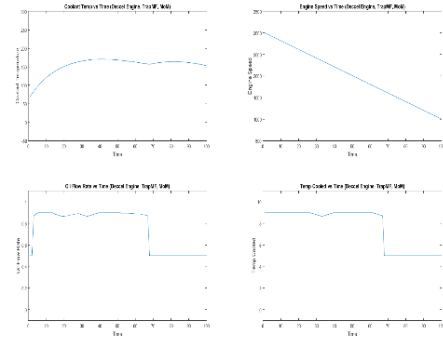

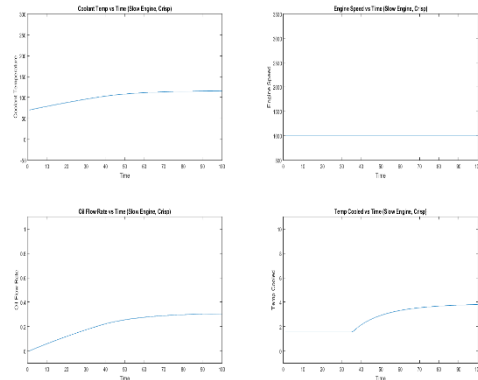Figure *25* - Deceleration Engine Curve, Trapezoid MF, MoM Defuzzification

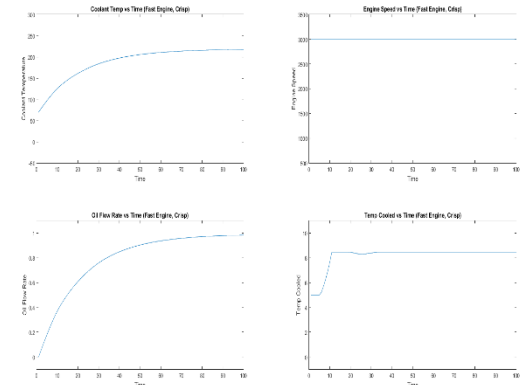Figure *26* - Slow Engine Curve, Crisp Controller

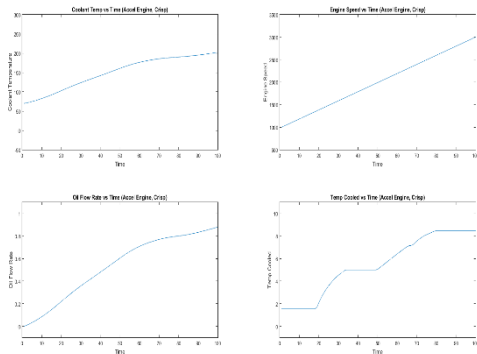Figure*27* - Fast Engine Curve, Crisp Controller

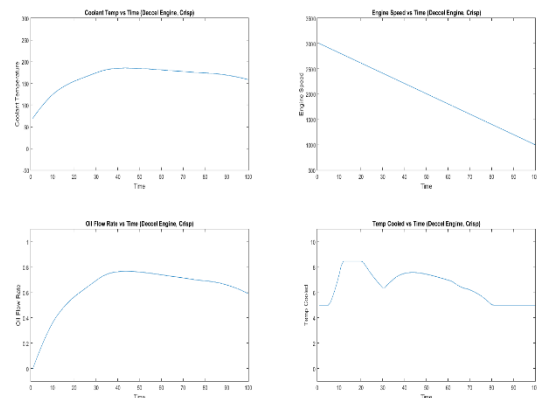Figure *28* - Acceleration Engine Curve, Crisp Controller

Figure 29 - Deceleration Engine Curve, Crisp Controller

The Gaussian Fuzzy Controller had much smoother transitions through the Fuzzy Rules compared to the Trapezoid Fuzzy Controller as shown in figures 20 and 21. A side effect of this smoothness was a performance loss when compared to the Trapezoid Fuzzy Controller in most conditions. This smoothness is due to the shape of a Gaussian Membership Functions compared to that of a Trapezoid Membership Function.

The MoM Fuzzy Controller had a noticeably more jagged response than the Centroid Fuzzy Controllers as shown in figures 24 and 25. Depending on the engine speed, this had different impacts on the performance of the MoM Fuzzy Controller. For a constant engine speed, the MoM Fuzzy Controller performs similarly to the Centroid Fuzzy Controller. It sees a performance advantage on the acceleration and deceleration engine profiles. This is because the MoM Defuzzification Method causes the controller to react slower to rule changes, but in a more drastic way, so the controller will provide more cooling for longer than the other Centroid Fuzzy Controller.

VI.   CONCLUSION

The objective of this paper was to design an engine fan controller for the prescribed system architecture, and compare the performance of a non-fuzzy and fuzzy controller. We also wanted to compare the effects that changing the different fuzzy properties have on the response of the controller. This was carried out through the use of a MATLAB simulation. The simulation had two components, the oil flow controller and the fuzzy cooling system. A crisp and a fuzzy controller were simulated, as well many simulations with various fuzzy properties. Although the results of the simulations did not show a significant performance improvement for the fuzzy controller, they did make it evident that the additional flexibility of a fuzzy solution could provide an improvement. The fuzzy controller could be refined and improved via additional iterations of the simulations or by implementing a learning method, such as a Fuzzy Neural Network, into the controller that can tune it as it runs for optimal efficiency.

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