AIRCRAFT DIESEL ENGINES CONTROLLED BY FUZZY LOGIC

Luca Piancastelli[1], Leonardo Frizziero[1] and Eugenio Pezzuti[2]
[1]Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, Viale Risorgimento, Bologna, Italy
[2]Faculty of Engineering, University of Rome Tor Vergata, via Del Politecnico, Rome, Italy
E-Mail: leonardo.frizziero@unibo.it

ABSTRACT

Normally in diesel and gasoline engines, common rail systems are employed. The key factors for correct engine power management are pressure, precision and velocity. Digital computers and PID control systems characterize current systems. Recovery strategies are used when anomalies occur and engine performance is significantly reduced. So, restoring normal conditions needs technical assistance. For safety reasons this approach cannot be used in aeronautical, naval and energy-supply applications. In some cases it is necessary to utilize all the possible energy from the power unit causing significant life-reduction of the engine. In this case a progressive reduction strategy should be used and injection law should be reduced accordingly. For this purpose injection control based on fuzzy logic is more effective. In this case, traditional PID control systems are substituted by fuzzy logic control. A reference map is introduced in the Full Authority Digital Electronic Control; this map is interpreted by the fuzzy logic control system that adapts the injection law to the current engine situation. This method has been experimented on a common-rail test bed and results are compared with traditional “binary recovery strategy” FADEC.

Keywords: aircraft, engine control, fuzzy logic, diesel propulsion.

INTRODUCTION

Diesel common rail injection systems are conceived for automotive application. In these field emissions is the primary target. A reference map is implemented in the FADEC (Full Authority Digital Electronic Control) to obtain the best emissions to performance compromise. This map is optimized during laboratory and road tests and it is used throughout engine running with the exception of start up. In this case a “cranking” map is adopted. Reliability is a subtask where the engine should be controllable at all times while eliminating risk to driver and passengers [16]. When a minor failure occurs, a suitable “recovery” map is automatically loaded into the FADEC [27] and engine performance is subsequently reduced. For example, if fuel temperature exceeds 110°C, maximum crankshaft angular velocity is reduced to 3000 rpm, and pilot injection is performed only in the case of massive power output reduction. If the air flow meter fails, overall performance is reduced to keep emissions low with limited power reduction. If rail pressure sensor fails the engine is blocked. This recovery system strategy is suitable for applications where the engine can be halted without risk. Aircraft application of common rail systems is conceptually similar but has significant differences. First of all, power output needs to be optimized along with engine efficiency. Power output reduction should be decided by the pilot and it cannot be automatically controlled by the FADEC. In current systems exhaust gas temperature is monitored by an instrument in the cockpit. If maximum allowed temperature is exceeded, the pilot can only reduce power to preserve engine integrity. However, in some flight condition like take-off or steep climb it may be preferable to keep the current power output level while sacrificing the engine. In this case the pilot should hope the engine stay running long enough to get through the critical situation. To overcome this problem this paper proposes fuzzy recovery strategies that anticipate the possible failure and attempts to adapt power output to the current engine condition. This paper is organized as follows: at first a fuzzy control system for common rail application is compared with a traditional PID system. Then the new fuzzy recovery strategy is described. Finally the experimental results are described [1, 2, 3, 4].

Aircraft diesel common rail fadec

The FADEC of a DID (Direct-Injection turbo-Diesel) is composed by sensors ed actuators that are connected to the CPUs.

The sensors are:

- Hall type for RPM of crankshaft.
- Hall type for phase of camshaft.
- Fuel temperature (on the pipe that returns fuel to the tank).
- Coolant temperature.
- Air flow temperature (at the outlet of the air filter).
- Low pressure fuel (at the inlet of the high pressure fuel pump).
- High pressure fuel (installed on the High Pressure Rail).
- Throttle potentiometer.

The actuators are:

- Pressure regulator (installed on the rail).
- Air actuator (for cold start).
- Injectors.

The master CPU collects data from sensors and inputs commands to the actuators. The master CPU also runs self-diagnosis subroutines, tests the sensors and talks with the slave CPU. If the failure of a sensor occurs, the master CPU actuates recovery strategies like sensor software simulation and power reduction. In this situation the FADEC switches from standard (optimum = normal state) to recovery state. In the recovery state engine performance and efficiency may be compromised. In case of in the master CPU failure, the slave CPU automatically switches from idle to active and substitutes the master CPU in engine control [5, 6].

Fuzzy control system vs. PID controller

Fuzzy logic in general

Fuzzy logic differs from conventional logical systems in that it aims at providing a model for approximate rather than precise reasoning.

Fuzzy logic, FL, has the following principal features. (a) The truth-values of FL are fuzzy subsets of the unit interval carrying labels such as true, very true, not very true, false, more or less true, etc.; (b) The truth-values of FL are structured in the sense that they may be generated by a grammar and interpreted by a semantic rule; (c) FL is a local logic in that, in FL, the truth-values as well as the connectives such as and, or, if... then have a variable rather than fixed meaning; and (d) The rules of inference in FL are approximate rather than exact.

The central concept in FL is that of a fuzzy restriction, by which is meant a fuzzy relation which acts as an elastic constraint on the values that may be assigned to a variable. Thus, a fuzzy proposition such as 'Nina is young' translates into a relational assignment equation of the form R (Age (Nina)) = young in which Age (Nina) is a variable, R (Age (Nina)) is a fuzzy restriction on the values of Age (Nina), and young is a fuzzy unary relation which is assigned as a value to R (Age (Nina)) [7, 8].

Moreover, one of the most attractive features of fuzzy set theory is to provide a mathematical setting for the integration of subjective categories represented by membership functions. Indeed, a body of aggregation operations is already available, which may be useful in decision analysis, quantitative psychology and information processing [9].

The experimental test bench

Tests were performed on an originally conceived injection system test bench. This equipment was able to accurately evaluate the entire common rail system composed by the original sensors, FADEC, pumps, rail and injectors (see Figure-1). The high pressure signal was acquired from the sensor on the rail. This signal was elaborated by the control system and regulated the pressure valve on the high pressure pump. This actuator is driven through a PWM (Pulse with Modulation) system at 1 kHz. For this purpose a programmable NI (Nation Instruments) "Field Programmable Gate Arrays" FPGA 7831 R was used. This card is programmable with NI LabView 7.1.

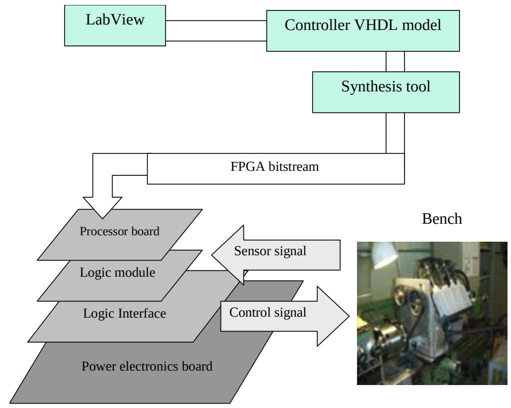

Figure-1. Layout of hardware and software system.

It was then possible to compare a PID (Proportional Integrative Derivative) with a fuzzy system for rail pressure control [10]. Both controllers were implemented on the same card with LabView (see Figure-2).

The PID controller

The input variable "error" is defined as the algebraic difference between the pressure set point and the current pressure value. The pressure range is 50-1350 bar, the PWM output value "Output" is the % of duty cycle. The PID system equation is introduced in formula (1) where g1, g2 and g3 are the proportional, derivative and integrative gain of the system.

$$\text{Output} = g1*\text{error}+g2*\int \text{error}\, dt + g3*\frac{d\,\text{error}}{dt} \qquad (1)$$

The PID control system worked satisfactorily with g1=1, g2=0.015 and g3=0. The PID system was implemented using the control toolbox of Lab View.

The fuzzy controller

The Fuzzy-Logic Toolkit of Lab view 7.1 was then used to implement a rail pressure controller. The inputs are the time derivative of the pressure "dp/dt" and "error". The fuzzy rules have the following form:

RULE i: IF *x* is A AND *y* is B THEN *z* is C with weight (i)

The product operation is used for the AND operator, so that the result of inference for the rule for the inputs x_0 = error and y_0 = dp/dt is:

$$\omega^i \equiv \mu_A(x_0)^i \times \mu_B(y_0)^i \times weight(i) \qquad (2)$$

Where μA(x) and μB(y) are the input membership functions, the weight ranges from 0 to 100%. The "gravity centre" defuzzyfication method was adopted (3):

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

$$out \equiv \frac{\sum_{i=1}^{m} \omega_i \times \mu(\omega_i)}{\sum_{i=1}^{m} \mu(\omega_i)} \quad (3)$$

"m" is the number of output discretization levels ω_i and $\mu(\omega_i)$ are output membership functions.

Rules and membership functions are described in Figures 2, 3, 4 and 5.

TYPING AND ORGANIZATION

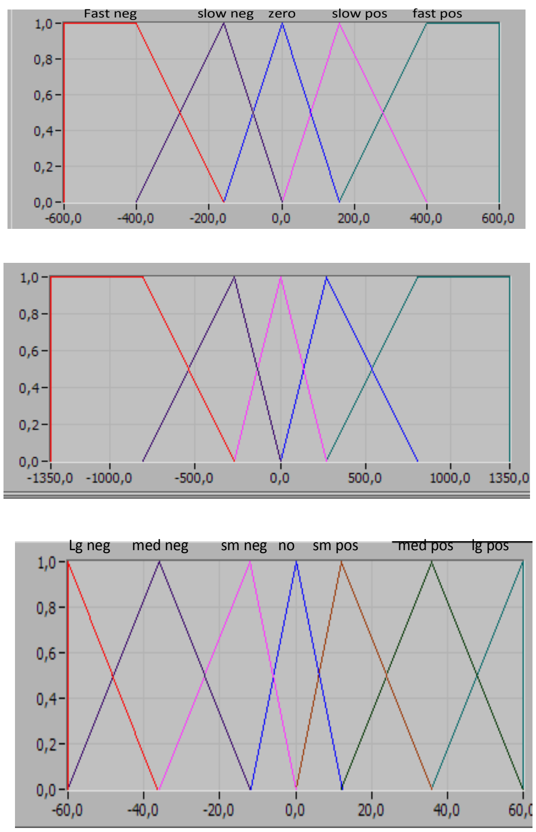

Figure-2, 3, 4. Fuzzy input set and output set.

So it is possible to depict the system in this way (see Figure-6):

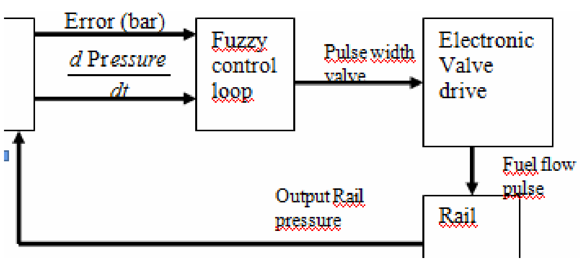

Figure-5. Pressure rail fuzzy control loop.

Experimental tests of the fuzzy controller were not satisfactory. This control system occasionally proved to be unstable or imprecise. In any case it was impossible to obtain a performance improvement over PID [11].

The fuzzy recovery strategy

In airplanes, maximum power should be available in at least some critical conditions, for example during take off or steep climb. In this situation it is better to sacrifice the engine. For this reason the traditional automotive strategy aimed to preserve engine integrity cannot be adopted. Another aspect that should be considered is that flight is mission aimed. The airplane should take-off, land safely and taxi to the desired parking place. The engine must not halt during flight and it must be preserved during flight for maximum power output. In the automotive field a major aim is to avoid catastrophic engine failures that may impair passenger safety and reach the prescribed TBO (Time between Overhaul). The example of the fuel overheating described in the introduction should be dealt with in a very different way. Fuel temperature overheat should be detected well before the maximum value of 110°C is reached. The possible overheat cause should identified and, if possible, a corrective action should be taken. For example fuel overheat can be solved by the fuel cooling system. Speed of the cooling fan can be increased. If this strategy doesn't work, the pilot should be warned, rail pressure can be reduced and fuel injection time can be prolonged accordingly. When the temperature exceeds the maximum value the warning light is activated and the pilot has to reduce power to preserve engine integrity, if possible. These actions can be easily handled by a fuzzy control system. It is well known that fuzzy controller's works better when few variables are controlled at the same time. Optimum control is achieved when one or two inputs control one or two outputs.

If more variables are to be controlled, it is more efficient to implement several fuzzy systems in a serial or parallel arrangement [12, 13].

The fuzzy recovery controllers

Multivariable system control via multiple fuzzy controllers has two main problems due to variable cross correlation. Fortunately, in diesel common rail injection, variables cross correlation is limited [12, 13].

Fuel overheat recovery

If throttle is applied or external temperature increases, fuel temperature increases. The fuel temperature can be controlled through fuel cooling improvement or through rail pressure reduction. The "natural" fuel control model of Figure-6 uses a set point value. However fuel temperature depends on several factors, outside temperature, coolant temperature, rail pressure, amount of fuel in the tanks, heat exchange on tank walls. A correct set point value is difficult to define and it is better to work directly with fuel absolute temperature.

ARPN Journal of Engineering and Applied Sciences

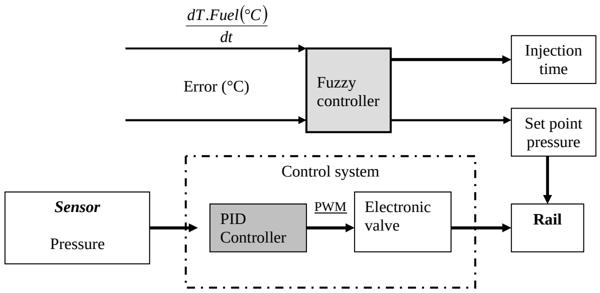

Figure-6. Fuel temperature recovery system with set point.

Single injector recovery

If exhaust gas temperature from a single cylinder is too low, an injector may be defective. In this case it is possible to increase lead angle, to increase fuel injection or increase rail pressure. This latter action compromises high pressure fuel pump life. So three different controllers are to be implemented to work in cascade. At first lead angle is increased. This strategy works if the injector is "lazy". This means that the delay from the electric input and the effective injection opening is longer than usual. If lead angle increase is not sufficient, injection time is increased. If both strategies are ineffective, the rail pressure is increased and injection time of the other cylinders is reduced. Pilot is warned of the latter action [2].

Single cylinder overheating

If exhaust gas temperature from a single cylinder is too high, piston rings may be defective, or the pistons may be overheated for some reason. In this case the fuzzy recovery system may reduce injection time in the defective cylinder. In order to keep the required output power, action should be taken on the other cylinders. This strategy is particularly important to prevent engine failure. In fact, if injection reduction doesn't obtain any positive effect, the single injector is shut off. An increase in rail pressure may partially compensate the malfunction. This recovery strategy is to be performed anyway since engine response in this case is so rapid that human reaction time is comparatively too slow.

Comments on the fuzzy recovery controllers

Fuzzy recovery controllers seem to be precious for modern aircraft diesel engines, where investment on sensors and on logic may be easily justified by the improvement in reliability [13].

CONCLUSIONS

Finally, we can say that the main advantage of the described method is to reduce the difficulties through the good protocol shown, similar to the PDI protocol, providing the relevant variables can be identified. The protocol is consequently developed by a process of integration or accumulation of past experience. Present paper is aimed at the extension of the method to a multi-variable situation.

Some tests were performed by software simulation and experimental simulation on the injection system test bench. The fuzzy controllers implemented were very simple to keep parameters under control. The different strategies introduced in this paper where tested only on a injection system test bench and should be controlled on the real engine and in flight [14, 15].

The prescriptive approach described above is very much an ad hoc implementation. It illustrates what needs to be done to advance beyond a simply descriptive system. What is desired is that such an approach should appear naturally within a suitably improved fuzzy logic theory itself.

REFERENCES

[1] W. Kemmetmüller, F. Fuchshumer and A. Kugi. 2010. Nonlinear pressure control of self-supplied variable displacement axial piston pumps. Control Engineering Practice. 18(1): 84-93.

[2] P. Bidan and S. Boverie. 1995. Nonlinear control of a spark-ignition engine. IEEE Transactions on Control Systems Technology. 3(1): 4-13.

[3] V. K., Jones, B. A., Ault, G. F., Franklin and J. D. Powell. 1995. Identification and air-fuel ratio control of a spark ignition engine. IEEE Transactions on Control Systems Technology. 3(1): 14-21.

[4] A. Amstutz, L. Del Re and R., Ego. 1995. Sensor based robust output control of EGR in diesel engines. IEEE Transactions on Control Systems Technology. 3(1): 39-48.

[5] J. Källström. 2001. Embedded software for new engine controller. Department of Electrical Engineering, Sweden.

[6] S.H. Lee, R.J. Howlett and S.D. Walters. 2007. Intelligent Systems and Signal Processing Laboratories, Engineering Research Centre, University of Brighton, Moulsecoomb, Brighton. Journal of Intelligent and Fuzzy Systems: Applications in Engineering and Technology. 18(1).

[7] R.E. Bellman and L.A. Zadeh. 1977. Local and fuzzy logics in Modern Uses of Multiple-Valued Logic. J. M. Dunn and G. Epstein, (Eds.). Dordrecht, The Netherlands: D. Reidel Publishing Co. pp. 103-165.

[8] L.A. Zadeh, Fuzzy Sets, Fuzzy Logic and Fuzzy Systems. 1996. Selected Papers of Lotfi A. Zadeh, G. J. Klir and B. Yuan, (Eds.). Advances in Fuzzy Systems -- Applications and Theory. Vol. 6, River Edge, NJ: World Scientific.

[9] D. Dubois and H. Prade. 1979. Decision making under fuzziness, in M.M. Gupta, R.K. Ragade, and R.R. Yager (Editors). Advances in fuzzy set theory and applications. North Holland, Amsterdam, Netherlands.

[10]J. Pereira. 1994. A comparison of PID and Fuzzy Control of a model car: Electrical and Computer Engineering, University of South Carolina, Fuzzy Systems, 1994. IEEE World Congress on Computational Intelligence. Proceedings of the 3rd IEEE Conference on, 26-29 June.

[11]H. Holzmann, C. Halfmann and R. Isermann. 1997. Representation of 3-D Mappings for Automotive Control Applications using Neural Networks and Fuzzy Logic. IEEE Conference on Control Applications Proceedings. pp. 229-234.

[12]A. Bastian. 1994. Modeling Fuel Injection Control Maps Using Fuzzy Logic. Laboratory for International Fuzzy Engineering Research (LIFE), Siber Hegner Bldg. 4F1, 89-1 Yamashita-cho, Naka-ku, Yokohama, 231 Japan.

[13]M. Abate and N. Dolsi. 1990. Use fuzzy logic for engine idle speed control. SAE 900594. pp. 873-880.

[14]E.H. Mamdani. 1976. Application of Fuzzy Logic to approximate reasoning using linguistic synthesis. Department of Electrical and Electronic Engineering, Queen Mary College, University of London, London, U.K.

[15]E.H. MAMDANI. 1974. Application of Fuzzy Algorithms for the Control of a Dynamic Plant. Proc. IEE. 121: 1585-1588.

[16]A. Donnarumma. 1986. Disegno di macchine, Utet.

[17]L. Piancastelli, L. Frizziero, G. Zanuccoli, N.E. Daidzic and I. Rocchi. 2013. A comparison between CFRP and 2195-FSW for aircraft structural designs. International Journal of Heat and Technology. 31(1): 17-24.

[18]L. Piancastelli, L. Frizziero, N.E. Daidzic and I. Rocchi. 2013. Analysis of automotive diesel conversions with KERS for future aerospace applications. International Journal of Heat and Technology. 31(1).

[19]L. Piancastelli, L. Frizziero and I. Rocchi. 2012. An innovative method to speed up the finite element analysis of critical engine components. International Journal of Heat and Technology. 30(2): 127-132.

[20]L. Piancastelli, L. Frizziero, S. Marcoppido and E. Pezzuti. 2012. Methodology to evaluate aircraft piston engine durability. International Journal of Heat and Technology. 30(1): 89-92.

[21]L. Piancastelli, L. Frizziero and I. Rocchi. 2012. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology. 30(2): 121-126.

[22]L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. Fuzzy control system for aircraft diesel engines. International Journal of Heat and Technology. 30(1): 131-135.

[23]L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma and E. Pezzuti. 2011. Fuzzy control system for recovering direction after spinning. International Journal of Heat and Technology. 29(2): 87-93.

[24]L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma and E. Pezzuti. 2011. Active antiskid system for handling improvement in motorbikes controlled by fuzzy logic. International Journal of Heat and Technology. 29(2): 95-101.

[25]L. Piancastelli, L. Frizziero, E. Morganti and E. Pezzuti 2012. Method for evaluating the durability of aircraft piston engines. The Walailak Journal of Science and Technology, Institute of Research and Development, Walailak University, Thasala, Nakhon Si Thammarat 80161, Thailand. ISSN: 1686-3933. 9(4): 425-431.

[26]L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. Embodiment of an innovative system design in a sportscar factory. Pushpa Publishing House, Far East. Journal of Electronics and Communications, Allahabad, India. ISSN: 0973-7006. 9(2): 69-98.

[27]L. Piancastelli, L. Frizziero, E. Morganti and A. Canaparo. 2012. The Electronic Stability Program controlled by a Fuzzy Algorithm tuned for tyre burst issues. Pushpa Publishing House, Far East. Journal of Electronics and Communications, Allahabad, India. ISSN: 0973-7006. 9(1): 49-68.