VOL. 9, NO. 12, DECEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THE COMMON-RAIL FUEL INJECTION TECHNIQUE IN TURBOCHARGED DI-DIESEL-ENGINES FOR AIRCRAFT APPLICTIONS

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ABSTRACT

In the activity of injection mapping optimization, a good degree of knowledge on how a common rail injection works is strictly necessary. This paper is aimed to summarize the basic knowledge about turbocharged Common Rail Direct-injection Diesel engines (CRDID). It is possible to use automotive CRDIDs on aircrafts and helicopter; however their use is very different for the original car installation. For this reason a complete rethinking of the engine and the way the engine control is performed is strictly necessary. For this reason the engine should be reprogrammed for the new application. To perform this activity it is strictly necessary to know how the original automotive application works. This paper is aimed to this objective, in order to point out the differences with the automotive installation and the new optimization functions. The combustion process of turbocharged CRDID, equipped with high pressure common-rail fuel injection systems, with different boost pressures, injection pressures, and fuel quantities are introduced. The influence of the injection and the swirl mode on the ignition delay and the flame propagation is analyzed. The sac hole nozzles with a variable number of holes and different injector types (electromagnetic/piezoelectric) are also briefly described. An experimental analysis of the combustion process is briefly discussed along with spray penetration, dispersing angle, velocity, the distribution/evaporation of the fuel droplets, ignition delay, ignition location, combustion progression. The applied swirl has not an influence on the spray penetration, but it is extremely important for the ignition and the combustion process. On the contrary the swirl itself is reduced by the injected amount of high pressured fuel. The droplet turbulence increases from the center of the combustion chamber of the spray radial rapidly decreases. The difference in the combustion of CRDIDs, traditional diesel engines and spark ignition engine is also briefly discussed. Finally the difference from automotive and aircraft and helicopter CRDIDs, from the combustion tuning point of view is discussed. Optimum combustion (and mapping) is also introduced as basic concepts.

Keywords: aircraft, turbocharged di-diesel-engines.

INTRODUCTION

Common rail injection method has revolutionized the DIDs, in fact the common-rail technology, which applies pressures up to 250 MPa, offers the advantage of an extremely flexible sequential control of the injection process and of very small ignition delay. In order to improve and to optimize the design and the mapping of CRDIDs, it is essential to get a better understanding of the complex processes inside the combustion engine. The common rail technology offers several advantages, compared to other diesel fuel injection systems. It shows high injection pressures independent of the engine speed with acceptable fuel atomization also at the beginning and the end of each injection due to a relatively constant rail pressure. The acceptably flexible and theoretically exact choice of injection begin and injection duration due to electronic control. There also the possibility of a pilot (extremely small) and multiple injections. The reduced need for swirl intensity at low engine speed due to high turbulence energy of the spray is as it will be explained truly a myth along with the reduction of material stress due to a high pressure pump with low torque oscillations and low torque peaks.

The ignition delay, that is very important in low load automotive CRDIDs, is of reduced important for the aircraft and helicopter application.

Spray properties

The sac hole nozzles (Figure-1), obtain an acceptable symmetrical spray, as shown in Figure-2.

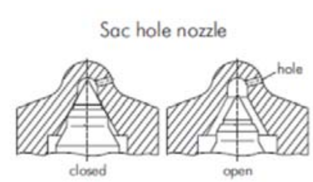

Figure-1. Sac hole nozzle open and closed [1].

This is a main problem of common rail injection system that tend to show random and systematic differences in the spray pattern from nozzle to nozzle, being the random differences due to turbulence and cavitation and systematic one linked to nozzle tolerances, that are extremely critical. Another problem is due to difficulties in controlling needle velocity, especially in the initial opening phase. In fact the solenoid controlled common-rail fuel injector has a slow needle opening velocity, so that the needle remains in a critical partial lift for a relatively long time. This aspect plays an important role for the proportioning of small fuel quantities, as it is needed for the pilot injection. To worsen this fact, the minimum fuel charge injectable depends also on injector temperature (true plays inside injector) and fuel kinematic viscosity. If the injection time is very short, the initial (opening) and final (closing) phases become critical. Since these phases are relatively uncontrolled the injector behavior depends on tiny tolerances and varies from injector to injector even in the same production batch. Even if calibration corrections are introduced, they proved to be unsatisfactory for a proper control of the combustion and its pressure gradients.

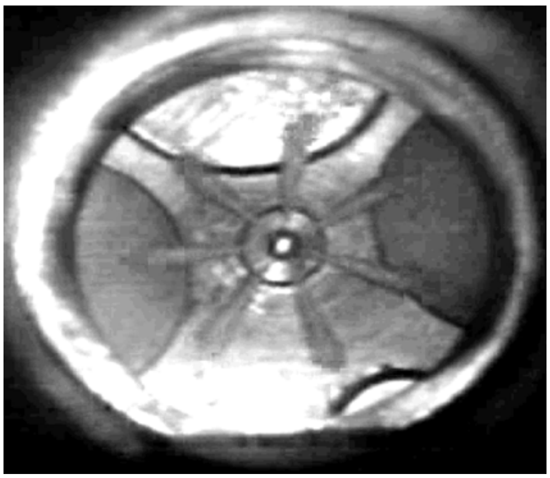

Figure-2. Nearly symmetrical injection pattern: highly symmetrical swirl, injector brand new [1].

An example of injector dynamic: the Caterpillar HEUI (Hydraulic Electronic Unit Injection) [1].

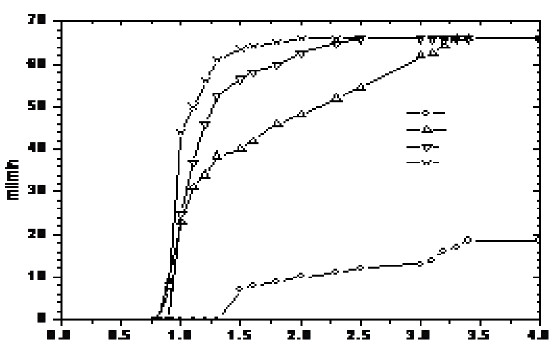

Figure-3. injection quantity under increasing common rail pressure and current pulse (HEUI) [1].

The injection quantity for a single cycle under different common rail pressure and current pulse time are shown in Figure-5. Over a certain value of the rail pressure, under a fixed common rail oil pressure, after the opening phase, the injection quantity increases proportionally with time. Under a fixed pulse width, when the common rail oil pressure rises, the injection quantity increases but not in a proportional way since the opening time varies correspondingly. With a good approximation, it is possible to affirm that three types of common rail injectors have been introduced on the market. The first one constantly improved and still present on the market, is a hydraulically amplified unit with solenoid. Approximately the same unit was developed with a piezoelectric actuation. This later unit has a better dynamic in the opening and closing phase. The third type has not the hydraulic amplifier. The opening dynamic is better, but the electronic control is more critical. Another typical problematic of the common rail injectors is that there is a limit in minimum pulse duration. In the case of the HEUI when the pulse is less than 0.8ms, the injector has not enough time for action so no fuel is injected. If the oil pressure in the common rail is low, the intensifier piston accelerates slowly, so the time of opening becomes very long. The quantity of fuel effectively injected depends on many parameters; a very important one is the fuel. The more viscous the fuel, the less oil is injected in the combustion chamber.

Another important factor is injector permeability. For each engine a special set of nozzles is drilled in the injectors, in automotive common rail injectors it is possible to have 4 to 8 holes with different diameters and different shape. The nozzles are critical, since they affect directly the combustion process. It is also theoretically possible to have different nozzles in the same injector, since swirl is not uniform in the combustion chamber.

The pre-injection(s)

Un to 2,000 rpm the pre-injection can adjust the initial portion of fuel delivery to control the amount of fuel delivered during ignition delay and main injection. It makes the fuel in main injection to burn quickly and stably. This process modifies the heat release characteristics and is beneficial in achieving low emission and noise levels, when temperatures and pressures are sub-optimal.

Under a fixed pulse width, the pre-injection ratio presents decline tendency with the decrease of the common rail pressure. However, the over-low common rail pressure makes pre-injection ratio rising.

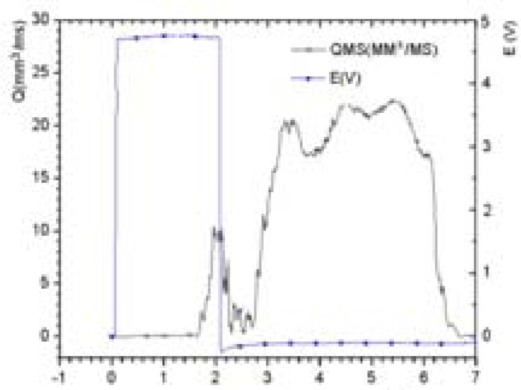

Figure-4. Fuel charge pattern (black) with a 2ms current pulse (blue). Low rail pressure [1].

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ARPN Journal of Engineering and Applied Sciences

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Effect of pressure on injection rate

Figures 4 and 5 shows the injection rate shape of HEUI [2] under various common rail pressures when the ECU gives a 2ms control pulse. It can be seen that the injection quantity and injection rate increase with the increase of the common rail pressure. What it is truly important, however, is the repeatability of the injection. Injection, injection pattern and fuel charge are not equal even with the same engine parameters. These inequalities or tolerances tend to be reduced by rail pressure that is beneficial to the injector.

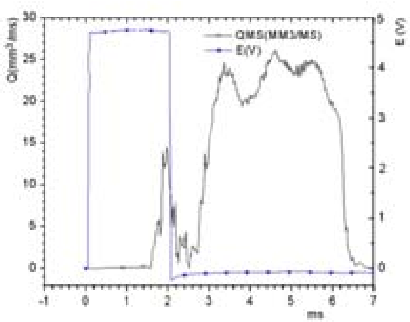

Figure-5. Fuel charge pattern (black) with a 2ms current pulse (blue). High rail pressure [2].

Since the common rail is essentially a Boolean device. Injection duration and injection quantity increase significantly with the extension of pulse width, but the injection rate keeps invariant mainly on the whole. Injection rate is affected by common rail pressure; injection duration is affected by the pulse width.

Experimental method to obtain the graphs of Figures 4 and 5

In order to map correctly a CRDID it is necessary to calibrate each injector. In fact the very small tolerances have a relatively large influence on injector behavior. Each injector is then tested by the manufacturer and often also by the user, to extract the data necessary to calculate the right timing in the ECU. A simple method to obtain reliable results is the long tube method [2].

This method is used to measure the injection characteristics of the injector. A long tube mechanism is attached to injector fuel outlet for realizing this method, and a high-precision pressure sensor is used to measure the fuel pressure in the long tube. The injection rate and injection quantity per-cycle can be calculated according to pressure wave theory. In practical treatment, formulas (1) to (4) are applied for calculation.

$$K = \sqrt{1 + \frac{2E}{E_0}\left(\frac{D^2 + {d_L}^2}{D^2 - {d_L}^2} + \mu\right)} \quad (1)$$

$$a = K \cdot \frac{2L}{t_w} \quad (2)$$

$$q' = 10^{12} \cdot \frac{F_L}{a\rho}(p - p_0), \quad mm^3/ms \quad (3)$$

$$q = \int_{t_1}^{t_2} q'dt \quad (4)$$

K——	modifying coefficient of sound velocity;	F_L——	area of tube's internal cross section, m^2;
E——	flexibility modulus of diesel oil, Pa;	ρ——	density of diesel oil, kg/m^2;
tw——	time interval between pressure waves in long tube, s;	p——	injection instantaneous pressure at the measurement point, MPa;
L——	external diameter of long tube, m;	p_0——	stable pressure in long tube before injection, MPa;
d_L——	internal diameter of long tube, m;	E_0——	flexibility modulus of tube material, Pa;
μ——	Poisson ratio of tube material;	t——	injection duration, ms;
a——	sound velocity at measurement point, m/s;	t_1——	injection start time, ms;
L——	length of long tube, m;	t_2——	injection end time, ms;

This method uses a standard automotive fuel at a standard temperature. All the corrections that are then made to take into account of injector temperatures and plays, fuel temperature, fuel kinematic viscosity, electrical actuator temperature are then applied "automatically" by correction maps. Usually these correction maps are supplied in the SW inside the "drivers" that pilot the injectors. The way this correction maps are implemented is a well kept secret, however it is possible to implement "personalized" correction map or to rewrite the drivers. This activity is complicated by the fact that injectors are continuously upgraded to improve performance, to correct defects and to reduce costs.

Autoignition

The autoignition point is the crank position when the apparent heat release shows a minimum. In this point (Point of Start of Combustion PSOC) the energy release due to combustion exothermic reactions begins to exceed the energy losses due to the fuel evaporation. This first stage of combustion is spectrally characterised by a weak flame emission, mainly in the near ultraviolet range, attributed to natural chemiluminescence. Chemiluminescence is linked to the emission of OH, CH and HCO, due to exothermic chemical reactions occurring during thermal decomposition of the hydrocarbon molecules preceding true ignition. This is the concept of "flameless" or low temperature ignition at low thermal loads that is the problem in diesel-ignited dual fuel l (GAS + Diesel) engines. OH distribution at selected crank angle for the FIAT 1900 jtd is shown in Figure-6 [The OH (high intense energetic chemical activity) is found in a region with a large amount vaporized fuel mixed with the air entrapped into the spray around the jet. Then it proceeded toward the injector nozzle area.

Generally this location is placed near exhaust valves, where the temperature is higher. Then the OH evolves following the fuel jet traces.

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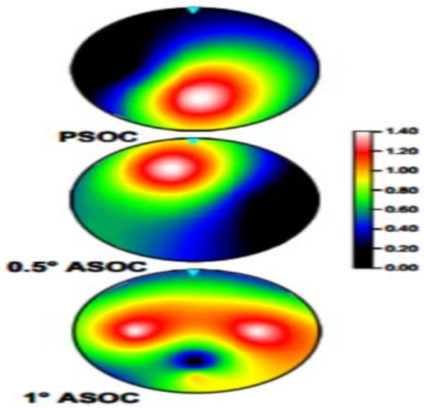

Figure-6. OH emissions PSOC for FIAT 1900 jtd at 1000rpm and 57bar peak combustion pressure [3].

COMBUSTION

In the UV flames emission sequence of Figure-7 in the same very low load condition of Figure-6. As it can be seen the combustion begins asymmetrically. The jet proceeds straight and radially inside the combustion chamber, slowing down toward the "cool" cylinder/head/piston wall. Given the high swirl ratio the combustion is not symmetrical along the jet axis. And the jet burns more quickly in the surface that is more exposed to oxygen reach air. It is to be said that the combustion in CRDIDs is completely different than in spark ignition engines. In this engine the flame "bowl" is full of hot burnt gas, while the front surface is burning toward the fresh, oxygen rich air. Meantime pressures and temperature grows. The race is won if the front burning surface reaches all the air before detonation. By the way detonation is a severe phenomenon. Figure-8 shows the effect of a little interpretation error on the lambda output during tuning. So in spark ignition engine the combustion works by volumes of burnt and hot gases that expand inside the cylinder.

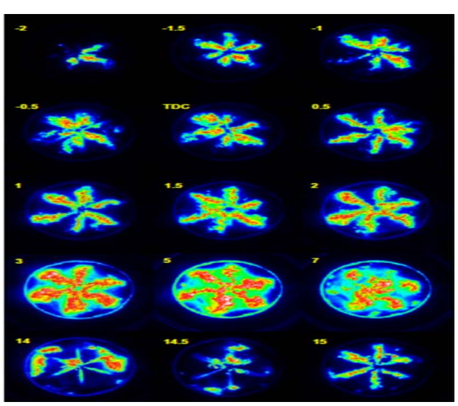

Figure-7. UV flame emission sequence [3].

The CRDIDs have relatively cold sprays that burn on the surface into a hot environment. This concept is to be held in consideration when piston and head temperature simulation in to be performed. CRDIDs have very short ignition delay that may be as low as 0.1 CAD.

Figure-8. A piston heavily damaged by improper timing advance.

Starting

The initiation of diesel fuel combustion is dependent on the temperature pressure, fuel properties and fuel injection characteristics. During cranking, air temperature in cylinder is lower than those during any other modes of engine operation. The low compression temperature and pressure are caused partially by the low ambient temperature, and more importantly by the excessive heat losses an blow by losses at low cranking speeds. Consequently, low compression temperature and pressures result in reduced starting ability of diesel engines.

The effect of cranking speed on compression pressure and temperature is very important especially at low cranking speed below 200 rpm. In modern automotive CRDIs glow plugs can reach temperatures up to 1050°C, within a few tenth of second. Their strategical position near the injectors and the lowest common rail pressure possible make it possible to have very short cranking time. However, since chemical reaction is influenced by temperature, the battery is the weak point of the system along with high lubricant viscosity. Very cold starting below -35°C may require battery, fuel and oil pre-heating. In this condition an oil heater may be used to warm-up the entire engine compartment. The starting with the propeller is particularly heavy for the battery, since the propeller inertia requires more energy for crankshaft acceleration.

High pressure system control

In CRDID ECUs it is strictly necessary to have a feedback controller for the rail pressure that achieves tracking of a reference pressure signal. The latter is generated on-line by an outer loop control algorithm so to optimize fuel injection and obtain proper fuel combustion for the current engine operating point.

From [4] the specifications for the rail pressure controller are:

- steady state rail pressure error lower than 30 bar;
- settling time lower than 150 ms;
- undershoot/overshot lower than 50 bar, for a ramp of rail pressure reference

With a rate 800 bar/s, at 1000 rpm of the high pressure pump, with a 15 mm3/stroke fuel injection, typical of a small CRDID.

The most critical aspect to be taken into account is the varying time delay between the flow rate valve control command and the fuel flow from the HP pump to the rail. This delay is due to HP pump cycles and is roughly in inverse proportion to engine speed. The control is particularly critical during cranking and at engine speed < 1700rpm. This aspect is not so important for aircraft/helicopter application. For these engines the propeller/fan high inertia induces a "lazy" behavior of the engine that easies the control at low rpm, by slowing down the whole process.

The high pressure pump (HPP)

The HPP consists of three equally phased, identical hydraulic rams mounted the same shaft that is mechanically connected to the crankshaft. Maximum rpm of automotive engines is in the 3500 up to 6000 range, while the pump should not exceed 2700 rpm. HPP efficiency reduces the fuel flow qI [mm3/s] to the rams, i.e. $qI = \eta(p, n)qM$ where the efficiency $\eta(p, n)$ depends on the rail pressure p and the pump speed n asdepicted in Figure-9.

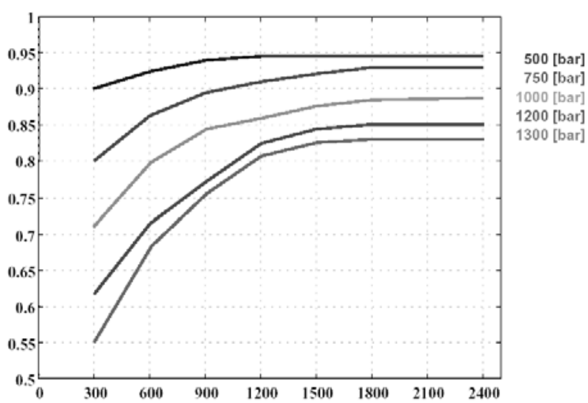

Figure-9. HPP efficiency η (p, n); x axys [rpm], y axis efficiency [4].

The partial closure of the flow-rate regulation valve produces the cavitation at the HPP intake. For small effective area of the flow-rate valve, the pressure reduction in the ram during the intake phase causes fuel vaporization with an output fuel charge volume is lower than the HPP geometric displacement. This fact means that in the first part of the compression phase the increase of pressure inside the cylinder causes fuel condensation only and the ram does not deliver any fuel to the rail. In fact, the flow to the rail starts when the fuel is completely in the liquid state. From this time on, pressure increase in the ram produces the opening of outlet valve and the exit of the compressed fuel to the rail. Since the geometrical intake duration is 180° and the three rams are mounted with a relative phase of 120° then the intake phases of the rams partially overlap. Intake overlapping results in different supplying fuel flow to the rams. All these phenomena are particularly important at starting, at very low loads or at very high fuel temperature. In fact $\eta(p, n)$ depends on the fuel temperature with an approximately proportional way. Temperature increases the cavitation phenomenon making this compensation not linear at low loads. This becomes critical when the pilot requires power after a descent, for example when the helicopter slows down to land. In this case the fuel may be very hot, the rpm are high but the load is extremely load, a sudden increase of blade pitch, induces and high load that requires more fuel to the injectors. Since fuel temperature depends on cooling and on the amount of fuel in the tank, a vertical landing with nearly empty tanks may mean high fuel temperatures and high cavitation. Standard automotive rail pressure ECU control may became insufficient in this condition with a temporary drop in rail pressure.

Injectors

In multi-jet engines, each injection phase is composed by a sequence of up to 5 distinct injections. However, in most of the aircraft engine operating conditions only one injection is used. From the HPP point of view, if its speed is equal to crankshaft rpm the frequency of injection sequences is equal to the numbr of cylinder multiplied by the engine speed. The ECU defines the amount of fuel to be injected and, consequently, the durations $ET = (\tau 1, \tau 2, \ldots .\tau N)$ [s] and phases $(\theta 1, \theta 2 \ldots .\ \theta N)$ [CA] of each fuel injection, depending on the engine mapping. The amount of fuel that flows from the common rail to each injector is the sum of three different flows: the flow that enters the combustion chamber *Qinj*, a flow necessary to "keep the injector open" *Qserv*, and a leakage flow *Qleak*. In most of the injectors, the latter two returns back the tank. While the leakage flow-rate *Qleak* is continuous, the flow-rate *Qinj* and *Qserv* are not zero only when the injector is open. Since the common rail control model is zero-dimensional (Boolean) the additional flow taken into account in the injection time $\tau 2$ which is the time of energization of the injector electrical control system? In fact the ECU outputs the opening boolean (ON/OFF) signal to an electronic control system that gives the current shape to open the injector and to keep it open for the time required. As it can be seen in Figures 3, 4 and 5, the amount of fuel injected is not directly proportional to this time. In the ECU used for engine development and for racing, a software model of the injector is implemented, in ultra-cheap automotive unit this behavior is compensated by (a) correction map(s).

Common rail dynamic behavior

The dynamics of the rail pressure is obtained by considering the balance between the HPP inlet flow and injectors' outlet flows. Under the assumption of non deformable rail, the fuel volume is constant, while the capacity depends on the pressure and temperature of the fuel in the rail according the Bulk module, which takes

VOL. 9, NO. 12, DECEMBER 2014 ISSN 1819-6608
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into account fuel compressibility. The derivative of the rail pressure $p^i(t)$ is given by:

$$p^I(t) = \frac{K_{Bulk}}{V_{rail}}(q_{HPP}(t) - q_{INJ}(t)) \tag{5}$$

Figure-10 shows the evolution of the common rail pressure, along with the pulsating fuel flows of the HPP pump and the injectors for a 4 cylinder in line CRDID. The pressure is typical of very low load that is the worst condition for a CRDID ECU. As it can be seen the rail pressure is far from constant: when the injector opens the pressure drops.

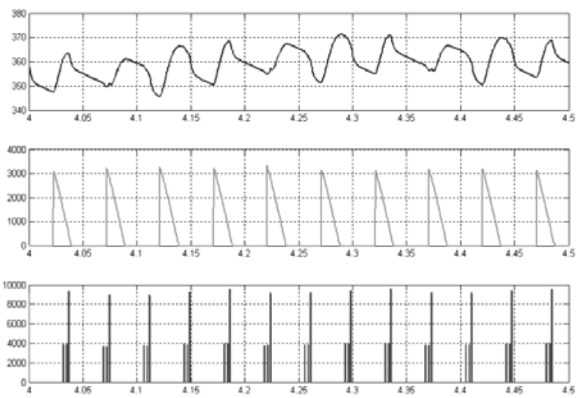

Figure-10. Common rail pressure [bar], HPP flow [mm^3/s], injector flow [mm^3/s] vs time [s] [4].

This problem can be reduced by increasing the volume of the rail. This solution is unfeasible for automotive application since the volume of the rail directly affects the time to start the engine. Automotive conversions may use larger rails. However this choice should be carefully studied and experimented, since vibrations in piping and pressure resonant condition may arise. In this case the rail system may fail. This is not so uncommon. The presence of damping material on piping is common also in production cars.

CONCLUSIONS

CRDIDs are brilliant systems with remarkable performance. However these systems are very complex and their correct dynamics should be understood before trying to adapt them to aircraft applications. CR main issues are introduced in this paper; problems and solution are discussed for the most common CR system available in the automotive field. The necessity of understanding the HW is fundamental to operate on SW input during engine tuning.

In automotive to aircraft CRDIDs conversions the original ECU is substituted by a more reliable FADEC. This unit should be programmed and integrated with a different set of sensors. In order to obtain acceptable understanding a comprehension of the differences between aircraft/helicopter CRDIDs and automotive ones is strictly necessary.

In this paper the CRDIDs are briefly introduced and the more important differences are discussed, along with optimization problems.

Even without any changes in engine geometry, it then possible to obtain a reliable and powerful unit for aircraft or helicopter application.

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