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An investigation into the use of the piezo-fluidic combined units as fuel injectors for natural gas engines

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ABSTRACT

A novel piezo-fluidic gaseous fuel injector system designed for natural gas engines is described in this paper. The system consists mainly of no-moving-part fluidic devices and piezo electro-fluidic interfaces. The steady state and dynamic characteristics of the system were tested on a laboratory experimental rig. The results show that the system can handle the large gas volume flow rate required by natural gas engines and is capable of operating via pulse width modulation. A few typical commercial solenoid type gas injectors were also tested and the results were compared with those from the piezo-fluidic injector system. It was found that the piezo-fluidic gaseous fuel injector system has faster switching responses and smaller injection cycle-to-cycle variations.

INTRODUCTION

Natural gas consists primarily of methane. As an alternative automotive fuel, natural gas can produce significantly less harmful emissions. However, to meet the increasingly stringent vehicle emission legislation, the fuel metering system of natural gas engines must be capable of accurate control and have a fast switching response, especially when stoichiometric air/fuel ratio combustion strategy incorporated with a three-way catalyst exhaust system is employed [1].

Gaseous fuel injection, combined with a sophisticated engine management system, is able to provide good air/fuel ratio control [2]. However, since natural gas has a much lower energy density and less lubrication than conventional liquid fuels, the gaseous fuel injectors must, therefore, be capable of handling the large gas volume flow rate. Thus, for conventional solenoid type gas injectors, not only will the components be larger, with higher pintle lift than liquid fuel injectors to achieve a larger orifice for the

large gas volume flow rate, but they also have to work in an environment with poor lubrication.

In order to partially overcome the low energy density drawback, a conventional solution for solenoid type gas injectors is to use a high injection pressure (over 700 kPa) which is obtained directly from natural gas onboard storage tank. As a consequence, when tank pressure drops lower than injection pressure, the tank must be refuelled. This leaves a part of onboard fuel unused. If the onboard natural gas is stored as compressed natural gas (CNG), this part of unused natural gas may not affect vehicle travel range obviously since the storage pressure is up to 20 MPa. However, if adsorbed natural gas (ANG) is utilised, the high injection pressure will certainly seriously limit vehicle travel range since the storage pressure is only up to 3.5 MPa [3].

It is to meet these difficulties that the development of a novel fluidic gaseous fuel injector system based on the use of mono-stable fluidic devices has been undertaken. This system has the potential of providing a very accurate and fast response gas control as well as being able to handle large gas volume flow rates. Also, this system can be arranged as a multi-point gas injection system and be operated with pulse width modulation mode [4,5].

One of the important features of the fluidic device is the amplification characteristic (ratio of the operating pressure to the control pressure). It offers the possibility of using a very low energy consumption, and very fast response piezo unit to control the fluidic device to inject gaseous fuel into the engine manifold. In this paper this piezo-fluidic gaseous fuel injector system is proposed and evaluated. Both steady state flow rates and dynamic switching properties of the system were tested on a laboratory experimental rig. The test results were compared with those from typical commercial gas injectors. It was found that the piezo-fluidic gaseous fuel injector system has faster switching responses and smaller injection cycle to cycle variations.

PIEZO-FLUIDIC GASEOUS FUEL INJECTOR SYSTEM

MONO-STABLE FLUIDIC DEVICES - The fluidic device which is being used in the piezo-fluidic gaseous fuel injector system is a mono-stable fluidic amplification device based on the wall re-attachment Coanda effect as shown in Figure 1. It has two control ports, namely the positive control port and the vacuum control port. These are located on each side of the input jet nozzle. The output flow channel which connects with the positive control port is called the stable side output. The one which connects with the vacuum control port is called the unstable side output.

Figure 1 Mono-stable fluidic device

If the pressure in the two control ports is atmospheric, and the pressure of the gas stream entering the input nozzle is higher, the jet flow issuing from the input nozzle will attach to the stable side output. This is because the geometry design is such that this bias exists. When a gas flow at a sufficiently high pressure is initiated in the positive control port through an electro-fluidic interface, the jet flow will switch to the unstable side output and remain there. When this control flow is removed, the jet flow will shift back to re-attach to the stable side output. This switching control method is called the "positive control" method.

Alternatively, the electro-fluidic interface can be used to close off the vacuum control port. Because of the jet flow entrainment, a "vacuum" is created in the vacuum control port. This too, will cause the jet flow to switch to the unstable side output from the stable side output till the vacuum control port is re-opened to atmospheric. This switching method is called the "vacuum control" method.

Opening the electro-fluidic interface and applying a sufficient high pressure to the positive control port will result in a rapid switching of the jet flow. Conversely, when the electro-fluidic interface is closed, that is to cut off the high pressure from the positive control port, the pressure in the port will take some time to decay. The switching from the unstable side output to the stable side output, therefore, will be relatively slow by positive control.

While by vacuum control, the switching of the jet flow from the stable side output to the unstable side output is relatively slow, since it will take some time for the vacuum to be established. Conversely, when the vacuum control port is opened suddenly, the jet flow will switch from the unstable side output to the stable side output rapidly. This is because the necessary pressure change in the vacuum control port is relatively small and the switching is helped by the bias design.

The overall view is that, to switch the jet flow from the stable side output to the unstable side output, the fast method is the positive control method. Conversely, to switch the jet flow from the unstable side output to the stable side output, the fast method is the vacuum control method. However, there is an advantage in using the vacuum control method because the amplification is higher. Hence, the power requirement for the electro-fluidic controlling interface with the vacuum control method is lower.

The speed of switching the jet flow from the stable side output to the unstable side output by vacuum control can be greatly improved by connecting the stable side vent to the positive control port as illustrated in Figure 2. This will create a pressure slightly above the atmospheric in the positive control port when the jet flow attaches to the stable

Figure 2 Improvement on the mono-stable fluidic device

side output. This, in itself, will not be high enough to cause the jet flow to be switched. However, it is a help when the vacuum control port is closed. This improvement has been experimentally proved in the previous research [5] and was adopted in this work.

PIEZO ELECTRO-FLUIDIC INTERFACE - The fluidic device needs an electro-fluidic interface to switch the jet flow to the opposite side output. Therefore, the total switching response of the fluidic injector is largely affected by the interface response. In the previous research [5] which was focused on the concept of the fluidic gaseous fuel injector system, a conventional central fuel injector (CFI) used for Ford engines was selected. The fluidic gas injector system driven by this CFI interface has shown its faster response and higher injection stability over the tested commercial gas injectors. However, the gas injection problems associated with the solenoid were still not solved properly.

Piezo-electrical material can produce an almost instantaneous deformation when an electric field is applied. This physical effect has been known for a long time, but it is rarely used for engine fuel injection systems. The major reason is that the deformation is much too small and the required driving voltage is much too high.

There are two basic methods to increase the deformation. One is to stack the multi-layer piezo materials together to generate an accumulated deformation. This requires a high strength electric field and incurs high manufacturing costs. Therefore, it is inefficient to use it in an engine fuel injector.

The second solution is to bond two-layer piezo-electrical material together by polarising in the opposite direction to generate a large bending deformation. This principle is well known in bimetallic strips. The piezo bending strip based on this principle can generate a relatively large deformation at a much lower driving voltage with a low manufacturing cost, but exerts a little force. Also, the strip bending response time is proportional to its geometric size and much slower than the multi-layer piezo stack. Therefore, if the piezo bending strip is used as a fast responding gas flow switching valve, it must be made small, work with a relatively low operating pressure and control a very small gas flow. Hence, it cannot be used as the gas injector directly. However, the small gas flow controlled by the piezo bending strip can be used as the control flow of the fluidic device. The large jet flow of the fluidic device can then be controlled by this small flow and switched between the two outputs.

Figure 3 shows a schematic set-up of the piezo-fluidic combined unit where a piezo bending strip is used as the controlling interface and fitted on the vacuum control port. When the piezo strip is energised, it will bend off the fluidic device, and let the vacuum control port open. The jet flow will then switch to the stable side output from the unstable side output. When the piezo strip is de-energised, it will

bend to the fluidic device and close the control port. The jet flow will then switch back to the unstable side output.

Figure 3 Piezo-fluidic combined unit

The potential advantages of the piezo-fluidic combined unit in comparison with the previous solenoid controlled fluidic unit [5] are lower energy requirement, lower wear and faster switching response. Unlike a solenoid interface which is controlled by electric current, the piezo bending strip exhibits an electric capacitor behaviour and is driven by electric voltage due to its two-layer construction. Therefore, no further energy input is required after the bending work has been done. The piezo bending strip unit being used in this project can be driven by 24 V. Its energy consumption is only about 0.001 W. In contrast, the solenoid fuel injector needs current to hold it open. Its energy consumption is over 100 W. Since the switching action of the piezo-fluidic combined unit is achieved by simply bending the piezo strip, and the fluidic device itself is a no-moving-part unit, there is no direct contact movement within the piezo-fluidic combined unit, therefore the wear can be expected to be reduced to an extremely low level. The fast switching response of the piezo bending strip unit will be discussed in later experiments.

PIEZO-FLUIDIC GAS INJECTOR SYSTEM - In the piezo-fluidic gas injector system, the piezo-fluidic combined unit is arranged to be "submerged" in an encapsulated gas reservoir as shown in Figure 4. A conventional three-stage pressure regulator is used to reduce the gas pressure from 20 MPa CNG storage pressure to atmospheric. It is by connecting the output from the regulator to the reservoir that the "submerged" pressure of atmospheric can be maintained.

Figure 4 A schematic set-up of the piezo-fluidic gaseous fuel injector system

A low pressure gas pump is connected to the gas reservoir and supplies a gas flow to the input nozzle of the fluidic device. When the piezo unit closes off the vacuum control port, the jet flow will attach to the unstable side output and be returned to the reservoir. In this state, the system is switched off. When the piezo unit is energised, the vacuum control port is opened. The jet flow will then switch to the stable side output and so provide fuel to the engine inlet manifold. In this state, the system is switched on.

The requirement of the pump is a drawback of the system due to its extra power consumption. However, since the current research is in the early stage to investigate the feasibility of using the piezo-fluidic combined unit as a gas injector, the optimisation of the pump requirement is, therefore, left for future research.

A diaphragm type isolating nozzle is used to connect the stable side output of the fluidic device to the engine inlet manifold. The nozzle only contains a free moving diaphragm as illustrated in Figure 5. At the bottom of the diaphragm, around the outlet, is the gas pressure. At the top side, a hole is opened to the atmosphere. Therefore, when the jet flow is switched to the stable side output, the gas pressure becomes higher than atmospheric. The diaphragm opens and the gas is injected into the engine manifold. When the jet flow is switched off, the gas pressure drops to atmospheric. The diaphragm closes. The vacuum in the manifold, then, cannot suck the gas from the fluidic injector.

Figure 5 Diaphragm type isolating nozzle

EXPERIMENTAL STUDY

The experimental work was focused on the dynamic switching characteristics of the piezo electro-fluidic interface, steady state flow delivery and the dynamic switching response of the piezo-fluidic gas injector system. Several commercial solenoid type gas injectors were also tested and the results were compared with those from the piezo-fluidic gas injector system.

DYNAMIC TEST OF THE PIEZO ELECTRO-FLUIDIC INTERFACE - The dynamic switching

Figure 6 Dynamic test rig for the piezo-fluidic interface

response of the piezo electro-fluidic interface plays an important part of the total switching response of the piezo-fluidic gas injector system. It was measured by a fast responding Entran pressure transducer (type EPI-M4) on the laboratory test rig as shown in Figure 6.

A PC based data acquisition system was used to collect the test results and analyse the switching responses and the cycle-to-cycle switching variations. The software used in the PC was written in "LabVIEW", a language developed by National Instrument. An Amplicon data acquisition (DAQ) board was chosen for its high frequency and low cost. Advanced linking driver software had to be developed in order to operate the Amplicon DAQ board in the LabVIEW language satisfactorily.

Figure 7 to Figure 9 show the measured pressure trace of the piezo bending strip unit and the response results from 500 consecutive cycles. The supply pressure at the inlet of the piezo unit was 550 kPa at which the piezo unit can switch enough gas flow to control the fluidic device. It can

Figure 7 Measured output pressure of the piezo unit

Figure 8 Switching-on response time of the piezo unit from 500 cycles

Figure 9 Switching-off response time of the piezo unit from 500 cycles

be seen that the average response time of switching-on t_{on} is 0.31 ms with a standard deviation (SD) of 0.016, and switching-off t_{off} is 0.72 ms with a SD of 0.018

Figure 10 shows the switching-on and -off responses of the piezo unit under varying supply pressure. It can be seen that the switching-on response delay is very consistent while switching-off response delay increases slightly as supply pressure increases. The slight increase of the switching-off may be due to the high restriction at the outlet of the piezo unit to obtain a clear pressure trace. Therefore, it is reasonable to predict that both switching-on and -off of the piezo unit will be more or less independent of its supply pressure when outlet is opened to ambient.

Figure 10 Switching response times of the piezo unit

Figure 11 Switching standard deviations of the piezo unit

Figure 11 shows the switching-on and -off switching stability of the piezo unit under varying supply pressure. It can be seen that the standard deviations of both switching

on and -off of the piezo unit are fairly consistent as supply pressure increases.

In comparison, Figure 12 and Figure 13 show the switching-on and -off responses of the previously used CFI solenoid interface. The average response time of switching-on is 1.08 ms with SD of 0.017 and switching-off is 0.93 ms with a SD of 0.015. The supply pressure to the solenoid was 100 kPa which was the optimal operation pressure as the electro-fluidic interface. The previous experimental results [5] showed that both switching-on and -off response times of the CFI solenoid interface were not affected by the control pressure.

Comparing the switching response times of the piezo unit at 550 kPa supply pressure with those of the solenoid, the switching-on response of the piezo unit is over 70% faster and the switching-off is about 23% faster.

Figure 12 Switching-on response time of the CFI solenoid unit from 500 cycles

Figure 13 Switching-off response time of the CFI solenoid unit from 500 cycles

STEADY STATE TEST OF THE PIEZO-FLUIDIC INJECTOR SYSTEM - The gas flow handling capability of the piezo-fluidic gas injector system was estimated by the steady state flow test operating on air. Figure 14 shows a

Figure 14 Steady state test rig of the piezo-fluidic gaseous fuel injector system

Figure 15 Steady state flow rate of the piezo-fluidic gas injector system

schematic set-up of the laboratory test rig. The piezo interface was energised during the test. The jet flow attached to the stable side output and was routed to a gas flow meter through the isolating nozzle.

Figure 15 shows the measured steady state flow rate under varying supply pressure of the system. It can be seen that the steady state flow rate of the piezo-fluidic gas injector system is linearly proportional to the system supply pressure. At 150 kPa supply pressure, the gas flow rate of

Figure 16 Dynamic flow delivery of Servojet injectors and the piezo-fluidic (P-F) gas injector system

the system is about 100 SLM (standard litre per minute). This flow rate is equivalent to the fuel requirement of a 2-litre natural gas engine.

Figure 16 shows the comparison of the results between commercial Servojet solenoid gas injectors and the dynamic flow delivery of the fluidic device. The Servojet data were provided by the manufacturer. The dynamic flow delivery of the piezo-fluidic gas injector system was calculated from

Figure 17 Dynamic test rig of the piezo-fluidic gas injector system

the measured steady flow rate at 150 kPa supply pressure because the dynamic gas flow rate cannot be measured by the current test facility in the laboratory

Three Servojet units were used, namely SP014, SP021 and SP051. The supply pressure for these injectors was 700 kPa. It can be seen that the dynamic flow delivery of the piezo-fluidic gas injector system at the supply pressure of 150 kPa is same as the SP051 which is the smallest Servojet unit. In order to achieve the flow delivery of the SP014, which is approximately twice that of the SP051, two fluidic devices can be stacked together to give the required flow delivery for such larger engine applications. The advantages of the stacked arrangement are the flexibility of adapting the fluidic unit for various engine sizes and the avoidance of a slow response time.

DYNAMIC TEST OF THE PIEZO-FLUIDIC GAS INJECTOR SYSTEM - In order to evaluate the dynamic switching characteristics of the piezo-fluidic gas injector system and to compare them with those from commercial gas injectors, a laboratory dynamic test rig was built as shown in Figure 17.

Two Entran pressure transducers were used in the rig. One was fitted on the stable side output of the fluidic device to detect the response of the piezo-fluidic combined unit to

the driving signal. The other one was fitted downstream of the isolating nozzle to monitor the response of the whole piezo-fluidic gas injector system.

A vacuum chamber equipped with a relieving valve and driven by a vacuum pump was used in the test rig to simulate the engine inlet manifold. Different manifold conditions were obtained by adjusting the relieving valve. The output of the piezo-fluidic injector system was delivered to the vacuum chamber by connecting the outlet of the isolating nozzle to the vacuum chamber.

Figure 18 shows the pressure traces from the two transducers with the vacuum chamber at atmospheric pressure. The supply pressure of the system was 150 kPa. The control pressure to the piezo interface was 550 kPa.

Figure 19 and Figure 20 show the switching response results of the piezo-fluidic combined unit measured by the pressure transducer (1) from 500 consecutive cycles. It can be seen that the average response time of switching-on is 1.15 ms with a SD of 0.059. The average response time of switching-off is 0.98 ms with a SD of 0.038.

Figure 21 and Figure 22 show the switching response of the whole piezo-fluidic gas injector system to the driving signal measured by pressure transducer (2). The average response time of switching-on is 1.46 ms with a SD of 0.055. The average response time of switching-off is 1.31

Figure 18 Measured pressure traces of the piezo-fluidic gas injector system at 150 kPa supply pressure and 550 kPa control pressure

Figure 19 Switching-on response time of the piezo-fluidic combined unit from 500 cycles

Figure 21 Switching-on response time of the piezo-fluidic gas injector system from 500 cycles

Figure 20 Switching-off response time of the piezo-fluidic combined unit from 500 cycles

Figure 22 Switching-off response time of the piezo-fluidic gas injector system from 500 cycles

ms with a SD of 0.068

Deducting the response times of the piezo-fluidic combined unit from those of the system, the net response times of the isolating nozzle can be obtained as 0.32 ms of switching-on and 0.33 ms of switching-off

Figure 23 and Figure 24 show the piezo-fluidic gas injector system switching response times and injection cycle-to-cycle variations under varying supply pressure. The control pressure to the piezo interface was 550 kPa, and the pressure of the vacuum chamber was atmospheric. It can be seen that both switching-on and -off response times are fairly stable as the system supply pressure increases. This feature permits the gas flow rate through the piezo-fluidic gas injector system also to be adjusted by varying the supply pressure of the system

Figure 23 Switching response times of the piezo-fluidic gas injector system at varying supply pressure

Figure 24 Standard deviations of the piezo-fluidic gas injector system at varying supply pressure

Figure 25 shows the system switching response times under different vacuum chamber pressures (absolute pressure). It can be seen, when the chamber pressure drops to vacuum, both switching-on and -off switching response times of the system will slightly increase. This is because when the pressure in the chamber drops to vacuum, the pressure of the gas surrounding the outlet of the isolating nozzle has to take some time to build up to overcome the force acting on the diaphragm due to the suction of vacuum. However, since the size of the outlet hole is small, the suction force is limited. Therefore, as vacuum increases, the system switching response delay will not increase very much

Figure 25 Switching response times of the piezo-fluidic gas injector system at varying outlet pressure

Figure 26 shows the switching stability of the system under varying chamber pressure. It can be seen that the system switching stability is slightly increased when the pressure of the chamber drops to vacuum. This, too, is due to the contribution of the suction force acting on the diaphragm

Figure 26 Standard deviations of the piezo-fluidic gas injector system at varying outlet pressure

DYNAMIC TEST OF THE COMMERCIAL GAS INJECTORS - The commercial gas injectors available for comparison tests were three Servojet gas injectors and one Bosch gas injector. Since no dynamic characteristics were available for these proprietary injectors, it was decided to carry out similar tests on the laboratory test rig so that their switching performances could be compared with those from the piezo-fluidic gas injection system.

Figure 27 and Figure 28 show the switching-on and -off responses of these solenoid gas injectors under varying supply pressure. It is known that the operating pressures of these injectors are over 700 kPa on gas engines. However, the maximum pressure used in the test was 350 kPa due to limited peak pressure availability in the laboratory. It can be seen that the switching-on response time increases as the supply pressure increases for all four injectors. As

mentioned earlier, the switching-on response time achieved by the piezo-fluidic injection system at the required injection pressure of 150 kPa is in the region of 1.46 ms. Therefore, it is reasonable to predict that the fluidic injector has a faster switching-on speed than these commercial gas injectors, when equivalent quantities of gaseous fuel are injected.

For the switching-off response the Bosch unit showed the best response time (1.4 ms) among all the commercial units. However, the switching-off response time achieved by the piezo-fluidic injector at 150 kPa injection pressure is 1.3 ms. It should be noted that the Bosch gas injector used here is a relatively small unit designed for gas engines possibly below 2 litres capacity. Therefore, it has the advantage of a light armature and a small passage area resulting in a faster response than the Servojet injectors.

Figure 27 Switching-on response times of the commercial gas injectors

Figure 29 Switching-on standard deviations of the commercial gas injectors

Figure 28 Switching-off response times of the commercial gas injectors

Figure 30 Switching-off standard deviations of the commercial gas injectors

Figure 29 and Figure 30 show the injection stability of these solenoid injectors. It can be seen that the Bosch unit showed extremely consistent cycle-to-cycle variations with a SD of 0.02 for both switching-on and -off delays. This is largely due to its compactness and light weight design. In comparison, the switching cycle-to-cycle variations of the piezo-fluidic injection system are capable of switching-on with a SD of 0.055 and switching-off with a SD of 0.068.

FUTURE WORK

The research reported in this paper has proved the possibility of using the piezo-fluidic combined unit as a gaseous fuel injector for natural gas engines. Future work will concentrate on the evaluation of the piezo-fluidic gaseous fuel injection system on a research natural gas engine, and the optimisation of the circulation pump.

CONCLUSIONS

(1) A novel piezo-fluidic gaseous fuel injection system was proposed. The system consists mainly of the no-moving-part fluidic device and the bending strip type piezo-electro-fluidic interface. The operating principle of the system was described and verified by experiments on a laboratory test rig.

(2) The volume flow rate of the system at 150 kPa supply pressure is equivalent to the Servojet SP-051 unit. Higher flow rates can be obtained by stacking the multi-layer fluidic injector.

(3) The vacuum control method of the mono-stable fluidic device is ideal for gaseous fuel injection due to the higher amplification. The switching properties can be improved by connecting the positive control port to the stable side vent.

(4) The piezo electro-fluidic interface was tested and compared with the CFI solenoid interface. It was found that the piezo unit has faster switching response speeds and much lower energy consumption.

(5) The switching responses of the system at the supply pressure of 150 kPa are 1.46 ms of switching-on with a SD of 0.055, and 1.31 ms of switching-off with a SD of 0.068.

(6) Inlet manifold vacuum will slightly increase the system switching response delay, but decrease injection cycle to cycle variations.

(7) Three Servojet and one Bosch commercial solenoid gas injectors were tested. It was found that the piezo-fluidic gas injector system at 550 kPa control pressure and 150 kPa supply pressure has faster switching responses than all four commercial units at their normal operation pressure (over 700 kPa). Also, the switching cycle to cycle variations of the system are smaller than all Servojet units. However, the Bosch unit showed a slightly better cycle to cycle switching repeatability than the piezo-fluidic gas injection system.

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