# OPTICALLY POWERED HYDRAULIC PILOT VALVE USING PIEZOELECTRIC MULTILAYER ACTUATOR

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**Abstract**

A normally-closed 2/2 hydraulic pilot valve has been developed for a power- by-light system which is being applied in aerospace fuelling systems and oil-well applications. This system offers unique advantages such as good immunity from electromagnetic interference, intrinsic safety, and low attenuation for long distance.

The valve employs a piezoelectric multilayer bender actuator (Pz29) with an elastomer blocking plate and a nozzle as the valve mechanism. The valve system is operated by 86 mW optical power which is transmitted via a multimode optical fibre (core diameter 62.5 μm) from a laser diode light source. The optical power is converted to electrical power by a photovoltaic cell, to drive the pilot valve, which requires, 8 mW electrical power to operate. The valve output flow-rate of 28 $cm^3/s$ has been achieved at an operating pressure of 1000 kPa, which is adequate for the applications. However, the maximum operating pressure up to 2000 kPa has already been tested. For the valve dynamic response, 18 ms average opening time and 1.5 seconds controllable smooth shut-off time have been observed. There was no valve operation failure during vibration testing up to 196 $m/s^2$. The pilot valve is now used to operate an aircraft refuelling valve system that provides aviation fuel flow-rate up to 680 l/min. It can also be used for other hazardous environments and noisy applications.

**Keywords:** hydraulic pilot valve, piezoelectric actuator, power-by-light system, optical power, flapper valve, fibre optic, hazardous environment

## 1 Introduction

The use of optical fibre linked control-by-light and power-by-light (PBL) systems offers a number of advantages. These can include immunity from electromagnetic interference, low attenuation, intrinsic safety in hazardous environments, small size and light weight. Therefore, a number of these systems have been under development during the past few years for various applications such as aerospace, automobile, chemical and process industries.

In aerospace applications, optical fibre systems are being investigated to replace conventional electrical systems for communication, sensing and control, and are called “fly-by-light” systems. A pneumatic Bimorph valve for proportional control with energy supplied down an optical fibre, and using a hybrid approach, has been demonstrated (Liu, 1987; Liu et al, 1988 and Zhao et al, 1993). For hydraulic applications, an intrinsically safe and optically powered hydraulic pilot valve using a PZT Bimorph actuator has been developed for aircraft refuelling systems (Jackson, 1997a and Lim, 2000). The basic concept and block diagram of the power-by-light hydraulic valve is shown in Fig. 1. The valve employed a triangular shaped Bimorph of PZT-5K as the actuator mechanism, requiring 3.8 milliwatts of electrical power to operate. In the system, 36 milliwatts of optical power from a laser diode was transmitted by an optical fibre to a photovoltaic cell that converted the optical power to a 5.5 volts DC voltage supply. A high efficiency DC-DC converter unit stepped the voltage up to 80 volts DC to drive the actuator in the hydraulic valve. The major advantages of this valve are intrinsic safety and high immunity from electromagnetic interference in the system. However, it can only be operated with pressures up to 410 kPa and with maximum flow rate of 5.4 $cm^3/s$. The valve could not be applied in some aircraft systems and some other applications.

Recently, a power-by-light system for oil-well applications has been proposed. A low-power hydraulic pilot valve is required to control a main valve, called a “sliding sleeve”. However, the PZT Bimorph valve is not appropriate for this application, because it cannot

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cope with the higher operating pressure due to the Bimorph providing only a relatively small actuating force and because it is not sufficiently rigid. The valve installation and operation up to 4 km underground in an oil-well limits operation because of the operating pressure and flow-rate at high temperature (up to 140 °C) and high hydrostatic pressure (40 MPa). Therefore, the valve performance needs to be improved to cope with the higher operating pressure requirement of 1000 kPa and flow rate of over 20 $cm^3$/s.

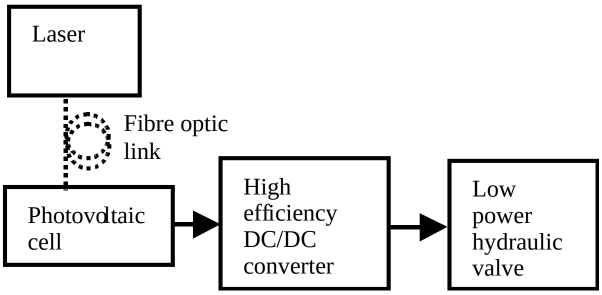


**Fig. 1:** *Optically powered hydraulic valve*

This paper reports on the design, construction and testing of a low-power, 2way-2position (2/2), normally closed (NC) pilot valve which employs the flapper-nozzle mechanism by using a piezoelectric multilayer bender as the valve actuating element. The valve has been tested with Somator31 as the hydraulic fluid at pressures from zero to 1000 kPa.

## 2 Basic Design

A low-power electro-hydraulic valve is necessary due to the limited electrical power which can safely be converted from optical power. In the previous PBL valve developed for aircraft refuelling systems, a piezo-Bimorph was selected for actuating the blocking mechanism of the pilot valve. It offers relatively good power conversion efficiency from electrical-to-mechanical energy, perhaps 15% (Belov et al, 1999). However, it provides very limited actuating force and displacement. To apply a hydraulic system in an oil-well, a higher power needs to be considered due to the higher operating pressure in the system. The PZT multilayer bender has therefore been used to replace the Bimorph actuator. It not only offers much higher blocking forces and better rigidity than the Bimorph but it also provides a good compromise between power consumption and force, compared with other technologies for actuators, such as electromagnetic and electrostatics. In addition, it is not as sensitive to temperature as thermo-mechanical and shape memory alloy devices (Belov et al, 1999).

The valve characteristics and performance depend directly on the valve blocking mechanism and the actuator efficiency. To achieve the optimum performance, five important factors must be considered: power consumption, operating-pressure, fluid flow-rate, static characteristic and dynamic response speed. Power requirements to open and then proportionally control the hydraulic valve have been optimised by varying the orifice exit port diameter at constant operating pressure. The valve opening force is

$$F = A \cdot P \tag{1}$$

related to the cross-section area of the outlet orifice:

The energy loss coefficients, $K_i$, have been used to calculate the pressure loss through a valve using the conventional relationship (Jackson, 1997b).

$$\Delta P = \sum_{i=1}^{i=n} K_i \cdot \left[ \frac{128 \cdot \mu \cdot L \cdot Q}{\pi^2 \cdot d_L^4} \right] \tag{2}$$

Three coefficients have been taken into account (see Fig.2): loss coefficient associated with the enlargement at the valve entrance; friction coefficient associated with the valve enclosure; and discharge coefficient associated with the outlet nozzle (long-hole orifice).

For the valve elements, the nozzle and blocking plate shape and size have been investigated by a valve-test-rig experimental approach that will be reported in the next section.

To investigate a suitable material and type of piezoelectric actuator, important parameters have to be determined. The actuating force of the multilayer bender actuator at the beam end, $F_{bl}$, is the first important parameter because it relates directly to the maximum operating pressure and flow rate of the valve which can be calculated from the expression

$$F_{bl} = C_1 \cdot \frac{T_a^{2.5} \cdot W}{T \cdot L_f} \tag{3}$$

where $C_1 = 7.9$ $Nmm^{-3/2}$ (Ferroperm, 2000).

The displacement at the beam end determines the step-back distance between blocking plate and the tip of the nozzle. This parameter effects the valve output flow rate. The actuator displacement, $S$, is given by the relationship

$$S = C_2 \cdot \frac{L_f^2 \cdot T_a}{T^2} \tag{4}$$

where $C_2 = 1.06$ (Ferroperm, 2000).

The multilayer bender actuator fundamental resonance frequency, $f_{rsn}$ , is defined by the expression,

$$f_{rsn} = C_3 \cdot \frac{T}{L_f^2} \tag{5}$$

where $C_3 = 0.4 \cdot 10^{-6}$ Hzmm (Ferroperm, 2000).

The valve mechanism of the previous Bimorph pilot valve had been optimised. The relationship between the nozzle size, blocking plate diameter, and the step-back distance have to be considered to avoid the instability of the actuator due to the flow forces condition which could lead to actuator failure during high pressure operation (Jackson, 1997b).

## 3 Construction

The valve mechanism has been designed using a minimum number of components to avoid energy loss. A direct actuating blocking mechanism has been employed. The valve blocking mechanism comprises a brass outlet nozzle and an elastomer blocking element which is directly actuated by the PZT multilayer beam as shown in Fig. 2.

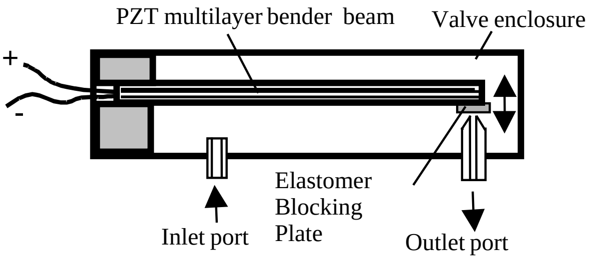


**Fig. 2:** *The PZT multilayer hydraulic valve construction*

The maximum displacement achieved at the tip of the bender beam is 0.5 mm when using a high strain piezo-ceramic material Pz29 (Ferroperm). This material has higher dielectric constant and less hysteresis and creep than the Bimorph ceramic previously used. The actuator was coated with PTFE for fuel and water proofing. A beam of length 50 mm has been used with the beam width being 7.8 mm and the thickness being 1.8 mm (see Fig. 3). In this application, the actuating force at the beam tip is up to 2.6 N. The maximum force obtainable for this type of piezobender beam is 4.0 N with the maximum operating voltage of ±100 $V_{dc}$; its fundamental frequency is 320 Hz, static capacitance 845 nF (at 1 kHz) and Curie temperature 235°C.

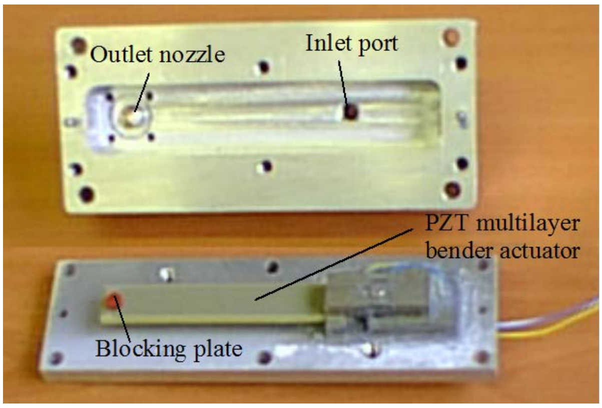


**Fig. 3:** *The valve components*

An outlet nozzle with elastomer blocking plate shape and size has been optimised by the valve-test-rig. The cone shape nozzle with a suitable cone angle $\theta$ of 60° has been investigated and the circular blocking plate diameter of 3 mm offers the shortest step-back distance without instability of the actuator (see Fig. 4).

Various diameters for the outlet nozzle have been tried (between 0.4 mm and 1.4 mm). The 3 mm diameter fluorosilicone blocking element is actuated by the beam tip to control the flow of hydraulic fluid.

The system for the optically powered valve (shown in Fig. 1) has been demonstrated. An optical power at a wavelength of 808 nm was selected.

At this particular wavelength attenuation is low in silica optical fibre and a GaAs based photovoltaic (PV) converter cell provides high optical-to-electrical conversion efficiency of about 35% (Pena et al, 1999). A laser diode with adjustable power output up to a maximum of 1 W at wavelength of 808 nm has been used as the optical source to drive the valve. The output of the laser diode module was connected to a 50 m long 200 µm core diameter silica multimode optical fibre with an FC-connector at one end. The other end of the fibre was connected to the PV converter cell. The output voltage signal of the PV converter (up to 6 $V_{dc}$) was fed to a high efficiency DC-DC converter that stepped up the voltage (up to 80 $V_{dc}$) to drive the valve.

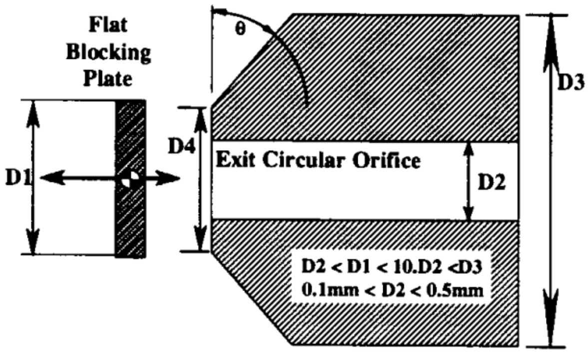


**Fig. 4:** *The Outlet nozzle and the circular blocking plate (Jackson, 1997b)*

The DC-DC converter generates a 30 mW output at 80 $V_{dc}$ from a 4.5 $V_{dc}$ input provided by the photovoltaic converter. The design of the converter circuit is based on an inductor switching power supply which employs a low-cost switching IC chip (Maxim, 1996). This chip has been developed to drive a personal computer TFT screen power supply (similar IC chips are available from other semiconductor manufacturers). The converter block diagram is shown in Fig. 5. The switching circuit operates at frequencies up to 300 kHz. It can provide high converting efficiency up to 90%.

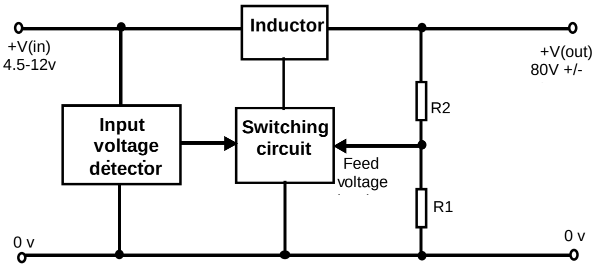


**Fig. 5:** *High efficiency DC-DC converter block diagram*

In the block diagram, the input voltage is monitored by the voltage level detector circuit which is used to switch on the switching circuit when the input voltage is higher than 4.5 $V_{dc}$. The switching circuit controls the switching frequency and current for the inductor. The resisters, $R_1$ and $R_2$ are used for providing the feedback output voltage to the switching circuit. They are also used to discharge the capacitance of the piezoelectric actuator when the input voltage is cut off. Therefore, the total resistance of both resisters is used to determine the valve closing time for smooth shut-off. All components highlighted in Fig.1 have been selected and designed to operate between –55 °C and +160 °C. This paper focuses on room temperature tests that have been carried out prior to thermal profile tests.

## 4 Blocking Plate and Nozzle Optimisation

Due to the limitation of actuating force to open the blocking plate, the valve-test-rig was used to investigate the suitable shape of the blocking plate and the outlet nozzle, as shown in Fig. 6. The effect of changing cone angle θ between zero and 60°, on the hydraulic flow-rate is shown in Fig. 7. The test was done with a 0.45 mm diameter nozzle, at a fixed distance of 0.35 mm from the 2.0 mm diameter blocking plate, at 410 kPa. From the results, it can be seen that flow-rate increases considerably with increase in angle between 0° and 45°. Above 45°, the curve levels out towards the maximum angle of 60° used in this test.

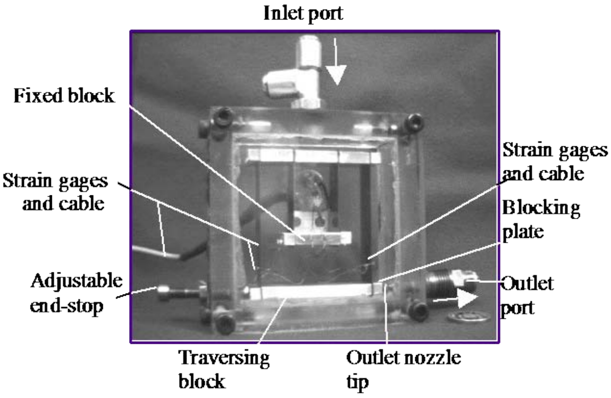


**Fig. 6:** *The Valve-test-Rig (Jackson, 1997b)*

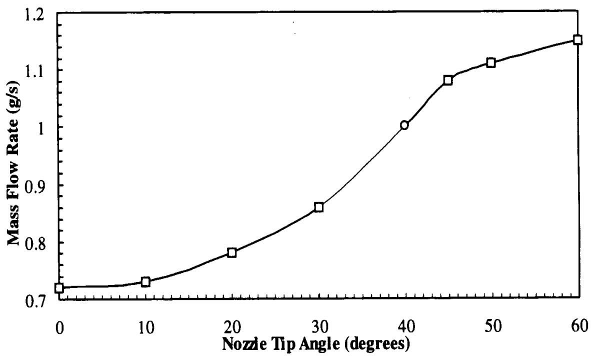


**Fig. 7:** *Nozzle external cone angle against flow rate for 0.45mm nozzle diameter (Jackson, 1997b)*

As the nozzle tip angle is increased the exit flow volume gets larger, and so the mass flow rate increases. No great advantage for increasing the angle beyond 60° could be gained in terms of greater flow-rate or better stability from any instability of the beam that might occur due to flow forces. Thus, the nozzle cone angle 60° was selected because it gives a good compromise between flow-rate and wear on the external tip angle. Moreover, the 60° cone angle nozzle is practical in term of manufacturing capabilities.

The optimum blocking plate was investigated by an experimental test that employed various plate diameters from 2 mm to 10 mm with different sizes of nozzle diameters between 0.25 mm and 0.50 mm. The step-back distance was slowly reduced until the instability of the beam due to the flow forces occurred. The instability of the actuator characteristic curves of various nozzle and blocking plate sizes were plotted, as shown in Fig. 8.

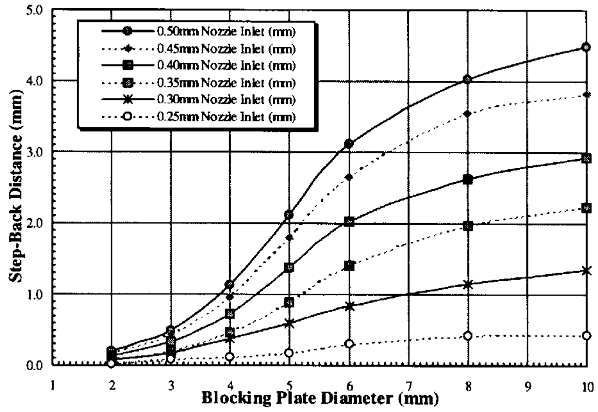


**Fig. 8:** *Characteristic curves of various blocking plate sizes (Jackson, 1997b)*

For the bender actuator giving a displacement of 0.5 mm, the blocking plate diameter should not exceed 3 mm, and this sized plate can be used with a nozzle up to 0.5 mm diameter. It is suggested that the minimum diameter of the blocking plate should not be less than four times the nozzle inlet diameter, due to the limitation of alignment of the blocking plate on the nozzle tip.

## 5 PBL Pilot Valve Experimental Setup

In the experiment, a pneumatic-to-hydraulic converter system was used to supply the constant hydraulic pressure for testing the PZT valves. This system employed a pressure tank to store hydraulic fluid and the top part of the tank was connected to pneumatic pressure which could be adjusted between 0-1000 kPa by a pressure regulator. The hydraulic pressure was utilized from the bottom of the tank at the same pressure as the applied pneumatic pressure. The hydraulic output was fed into the PZT valve, as shown in Fig. 9. The maximum flow rate was up to 60 ml/s at 600 kPa pressure.

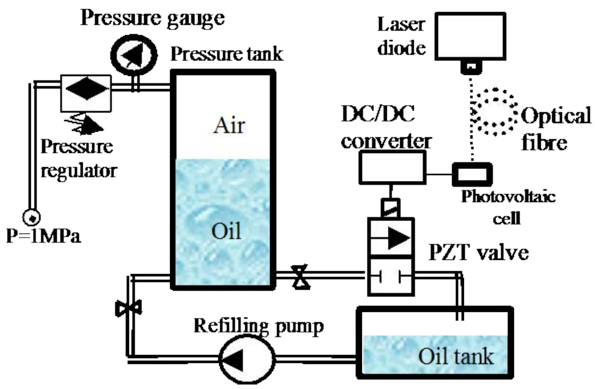


**Fig. 9:** *Hydraulic system experimental setup*

A laser diode with a peak wavelength of 808 nm generate optical power output which could be adjusted from 0-1 W was used. The optical power was transmitted via multimode optical fibre (62.5 / 125 µm) to a AlGaAs/GaAs photovoltaic cell which converted optical power to electrical power. The electrical output from the photovoltaic cell, 4-6 $V_{dc}$ was stepped up to 80 $V_{dc}$ by the DC/DC converter. The 80 $V_{dc}$ regulated voltage was used to drive the PZT valves in the experiments.

## 6 Experimental Results

In the experiment the laser power was adjusted from zero to 200 mW, and the voltage output from the PV converter and the voltage output from the DC-DC converter were monitored by digital voltmeters. The output from the PV converter was proportional to the optical power input, and the maximum voltage was 6.5 V at approximately 110 mW of optical power output.

The output voltage from the DC-DC converter increased sharply when the input voltage was over 4.5 V and it saturated at 80 V above approximately 100 mW of optical power output, as shown in Fig. 10.

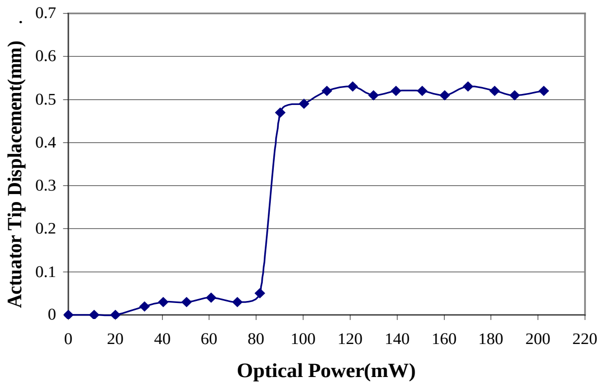


**Fig. 10:** *Voltage outputs from photovoltaic and DC-DC converter versus launched optical power*

The converter efficiency has been tested with the PZT multilayer actuator load. The converter started working when the input voltage reached 4.5 $V_{dc}$ and it provided conversion efficiency up to 55% at 80 $V_{dc}$ output regulated voltage.

The displacement of the actuator tip (without load) was monitored as the optical power was increased from zero to 200 mW (Fig.11).

The valve has been tested to obtain its characteristics with a light hydraulic fluid (Somentor31) at pressures between zero and 1000 kPa (hysteresis does not matter in this application). The outlet nozzle diameter was varied from 0.4 mm to 1.4 mm and the PZT driving voltage varied up to 80 $V_{dc}$. The relationships between applied pressure and flow-rate for different nozzle sizes are shown in Fig. 12. The maximum flow-rate has been achieved with 86 mW optical power supplied to the PV converter. With small nozzle sizes the step-back distance between the blocking plate and nozzle tip is adequate, while for large nozzle sizes this distance is inadequate and consequently instability of the beam due to flow forces occurs. Consequently, the result is non-monotonic characteristics (as shown in Fig. 12).

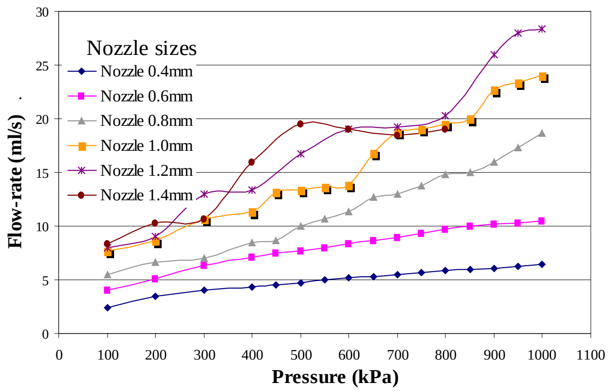


**Fig. 11:** *Multilayer actuator displacement versus launched optical power*

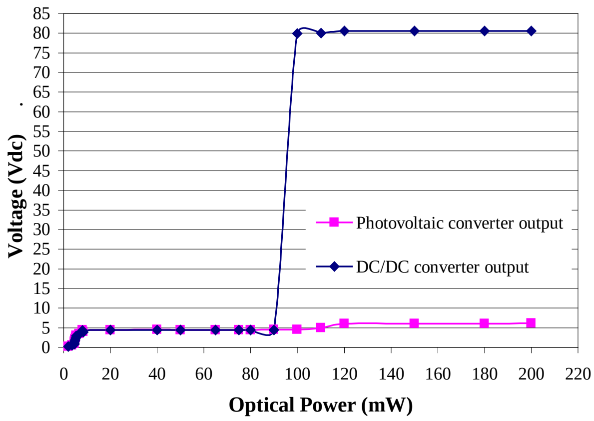


**Fig. 12:** *PZT multilayer valve test results*

The valve opening time was measured using an 80 $V_{dc}$ output from a DC power supply, which was connected directly to drive the valve. Average opening time was 18 ms (Fig. 13) and the valve closing time was approximately 1.5 seconds at 1000 kPa.

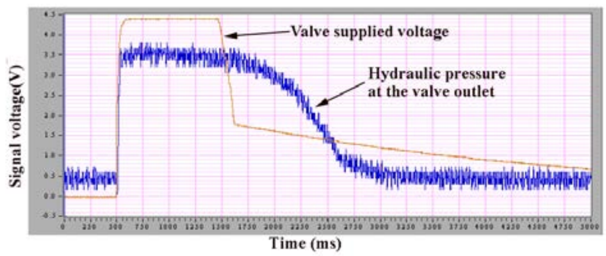


**Fig. 13:** *Valve dynamic response*

It is expected that for a higher operating pressure, the opening time will increase and the closing time will decrease. The valve closing time is determined by the feedback resistance chain $R_1$ and $R_2$ (see Fig. 5). A higher valve shut-off speed could be obtained by reducing the resistance values.

## 7 Discussion and Conclusions

An optically-powered hydraulic valve system has been developed and demonstrated. The major optical power loss in the system is caused by optical fibre attenuation, connector loss, the photovoltaic converter loss and losses through the DC/DC converter. Thus, the total power conversion efficiency of the system is approximately 12 %, which could be improved by using a high efficiency piezoelectric transformer (Philips, 1997).

The pilot valve can be operated by a 86 mW optical signal (measured at the fibre end) at an operating hydraulic pressure up to 1000 kPa. At this pressure, the valve can provide maximum flow-rate up to 28 ml/s by employing a 1.2 mm outlet nozzle. To achieve a higher operating pressure, smaller sizes of outlet nozzle need to be employed.

It is expected that the 1.4 mm nozzle will provide higher flow rate at 1000 kPa. However, the instability of the actuator due to the flow forces occurred at the operating pressure from 550 kPa due to the limitation of step-back distance provided by the actuator. The valve response time is 18 ms for valve opening and 1.5 seconds for smooth shut-off closing time to prevent high pressure surge which may cause components damage in the hydraulic system. The valve response speed is adequate to replace the conventional sliding sleeve mechanism (a minute response time) in an oil-well system. To improve the dynamic response of the valve, the actuator beam optimisation method used in the previous Bimorph valve design could be applied in the new actuator design (Jackson, 1997b). It should be possible to have an opening time of 10 ms and a closing time of less than 1 second. The higher pressure test, up to 2000 Mpa, has been demonstrated by using a 1.0 mm diameter outlet nozzle, with no instability of the beam due to the flow forces effect observed.

The valve developed is suitable for use in oil-well applications and aircraft refuelling systems. Currently the pilot valve has been tested with an in-flight refuelling servo-valve system that controls the aviation fuel flow-rate up to 680 l/min, at a pressure of approximately 420 kPa. In a vibration test, the piezoelectric pilot valve worked satisfactorily up to figure vibrations of 20 $m/s^2$, which is much higher than that for conventional electromagnetic pilot valves.

In addition, the piezoelectric pilot valve could be applied for in-flight aerospace systems (for example as a pilot valve within hydraulic landing gear and with flight-control surfaces) and other hazardous environment applications, such as petrochemical industries. It has a number of significant advantages, including low power requirements and intrinsically safe operation, when compared to low power electromagnetic valves.

## Nomenclature

| | | |
|---|---|---|
| $A$ | cross-section area of the outlet nozzle | [$m^2$] |
| $C_1$ | the Pz29 blocking force constant | [$N/mm^{1.5}$] |
| $C_2$ | the Pz29 strain constant | [-] |
| $C_3$ | the Pz29 fundamental frequency constant | [Hz mm] |
| $d_L$ | the inlet pipe diameter | [$m^2$] |
| $F$ | the valve opening force | [N] |
| $F_{bl}$ | the actuator blocking force | [N] |
| $f_{rsn}$ | the actuator fundamental resonance frequency | [Hz] |
| $K_i$ | the individual energy loss coefficient | [-] |
| $L$ | length of the conduit passage | [m] |
| $L_f$ | free length of the actuator | [mm] |
| $P$ | hydraulic pressure | [Pa] |
| $Q$ | the volumetric flow rate | [$m^3$] |
| $S$ | displacement of the actuator beam tip | [mm] |
| $T$ | total thickness of the actuator | [mm] |
| $T_a$ | active thickness of the actuator | [mm] |
| $\mu$ | kinematic viscosity of the working fluid | [$m^2/s$] |
| $W$ | the actuator beam width | [mm] |

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