An efficient high-repetition-rate fast-pulsed gas valve[a)]

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In this work we present an alternate concept of a fast-pulsed valve which is convenient for molecular-beam spectroscopy and gas puffing in plasma assemblies. The valve operates at repetition rates up to 100 Hz with repetitive high-intensity 100-μs FWHM pulses. Its efficient closed magnetic circuit with low power consumption permits a high-repetition-rate operation. The very light mass-spring assembly allows for rather narrow repetitive pulses. The valve has a small size and is self-sealed for use with corrosive gases. A fast PVDF pyroelectric detector was used for diagnosis.

INTRODUCTION

Pulsed valves to admit small quantities of gas in short pulses into a vacuum chamber have been used since the early 1960s. Initially, molecular-beam spectroscopy was the main application. An opening time of about 1 ms was reached using an electromechanical concept.[1,2] This small opening time simplified the apparatus needed in continuum-beam experiments, allowing for larger instantaneous intensity without overloading the vacuum pumps. Narrower pulses were needed to achieve good resolution in time-of-flight experiments. Pulses of the order of tens of microseconds were obtained. In 1978, a 10-μs FWHM valve was developed using the concept of repulsion of two conductors with current following in opposit directions.[3] In 1979, this type of pulsed valve was improved to operate at 10-Hz repetition rate and 50-μs FWHM pulse width.[4] Other valves of electromechanical type were described with modifications to operate at this range of opening times and higher repetition rates.[5-7] A new concept of pulsed valve using a piezoelectric element as piston driver[8] operated at high frequencies; however, it lacked the characteristics to produce high-intensity molecular beams. We described previously a 80-μs FWHM valve of high beam intensity, but with a low repetition rate.[9]

In this work we present the concept of a pulsed valve with short pulses, high repetition rates, and high intensity, which are characteristics suitable to use in molecular-beam spectroscopy and flow control. An efficient magnetic circuit and light moving parts are used to obtain good performance. It has been operated with 100 μs pulses up to 100 Hz and gas flow limited by a 1-mm-diam orifice and up to 20-bar back pressure. In Sec. I we present its description and principle of operation. In Sec. II we describe the experimental aparatus, including the pyroelectric detector. In Sec. III its performance is presented.

I. DESCRIPTION AND PRINCIPLE OF OPERATION

The design and construction of this pulsed valve obeyed the same criteria used in satellite micropropulsion control valves optimization, with power consumption and mass minimized. A schematic diagram is presented in Fig. 1, consisting of the following: 1: body of 430 stainless steel; 2: coil; 3: 304 stainless-steel magnetic isolator; 4: piston of 430 stainless steel; 5: flat spring; 6: spring spacers; 7: Teflon seal; and 8: metallic seat flange. It has been designed to operate at high repetition rates with the development of spring and piston fixation. The use with corrosive medium has been considered so that anti-corrosive materials are used and the coil is isolated.

The valve has normally closed operation because of flat spring force. A small gap exists between the piston and the valve body. When the coil is energized, the magnetic flux is forced to pass through the piston in a closed magnetic circuit as shown by dashed line in Fig. 1. The valve opens by magnetic force action over the piston. When the current in the coil stops, the valve closes by spring action. Narrow pulses can be obtained by a coil of low inductance and a fast mass-

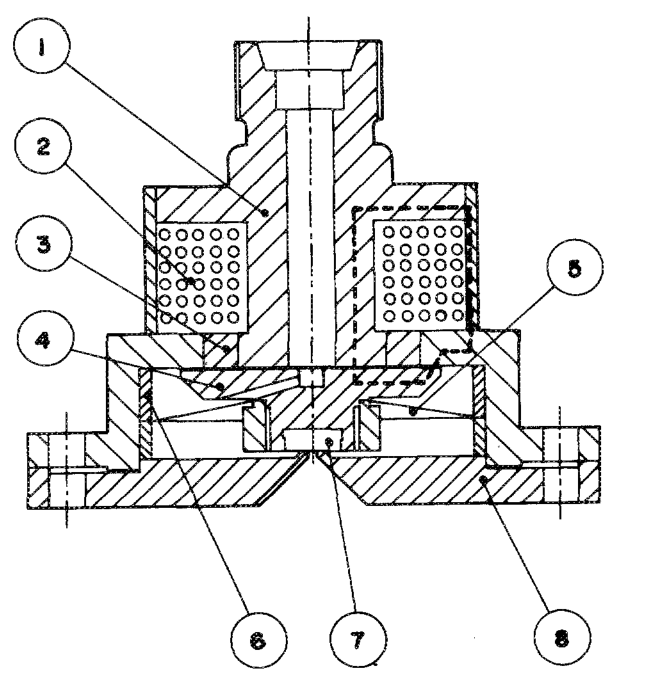

FIG. 1. Schematic valve set. 1: body; 2: coil; 3: magnetic isolator; 4: piston; 5: flat spring; 6: spring spacers; 7: Teflon seal; 8: valve seat. The dashed line is the magnetic flux path.

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spring system response. Some details of design are presented in the sequel.

A. Magnetic circuit

The main advantage of using a closed magnetic circuit is its high efficiency which allows low-voltage and low-peak-current operation. This characteristic permits high repetition rates with low power consumption. The magnetic force over the piston is

$$F_m = B^2 S / 2\mu_0, \tag{1}$$

where B is the magnetic induction, S is the piston-body contact area, and μ_0 is the gap magnetic permeability. The force is larger for larger B and S, but on the other hand, S must be smaller to minimize the piston mass. The optimization condition obtained is that the inner coil diameter is a half of piston diameter.[10] The maximum B is limited by the magnetic material saturation. The selected material is ANSI 430 stainless steel because of its relatively high magnetic permeability and 1.4-T saturation B. Other materials with higher magnetic permeability give more efficient magnetic circuit, but ANSI 430 has been chosen because of its resistance to corrosion.

B. Mass spring system

A fast response mass-spring system is one of low mass and high elastic constant. The piston mass was minimized as considered before and an elastic constant of the order of 100 N/mm has been evaluated to give response time of the order of a few hundreds of microseconds. Helical springs within this order of elastic constant are very hard and too large, and so we have chosen a flat Belleville spring as the best one. The deflection-load formula of this flat spring is[11]

$$F = \frac{Ex}{(1-\sigma^2)Ma^2}\left(\frac{x^2}{2}t + t^3\right), \tag{2}$$

where F is the force, x is the deflection, t is the spring thickness, E is the Young's modulus of the spring material, σ is the Poisson ratio, $M = 0.77$ in this case, and a is the spring outer radius. This nonlinear deflection-load behavior is another advantageous characteristic because if we operate the spring in a high-force-gradient region we obtain higher acceleration in a small displacement than with a linear one.

The valve operates with the spring in a preloaded condition and a piston travel in the order of 0.1 mm is sufficient for gas flow through a 1-mm-diam orifice. For smaller orifices smaller travels are needed and narrower pulses are possible.

II. TEST APARATUS

A simple capacitor discharge circuit is used to energize the coil. The coil inductance and the capacitor give the current pulse width. The current pulse is not a sine-wave semicycle because the coil inductance is current and piston position dependent. The capacitor discharge is controlled by a SCR gated by a pulse generator with frequency adjustment. The capacitor is charged by a 0–150-V power supply through a 4.7-Ω resistor. The capacitance of the capacitor and the number of coil turns has been varied to obtain a current pulse width sufficiently small to assure that the gas pulse width is limited only by the mass-spring system. This has been obtained with a 1.5-μF capacitor, a 300-turn coil, and 130-V power supply. This condition has been used to carry out the performance test.

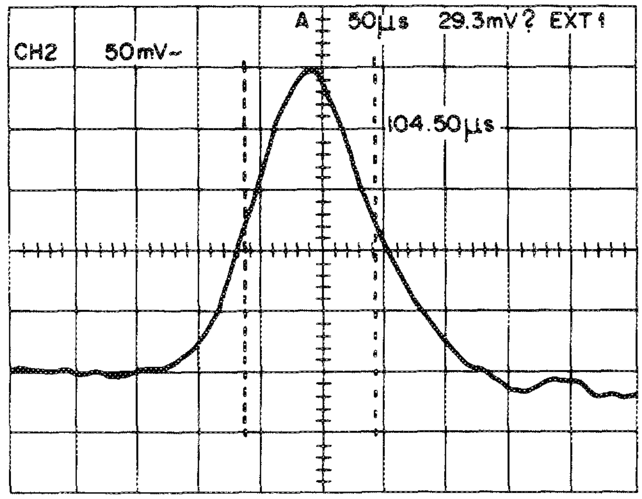

FIG. 2. Typical valve pulse.

The valve and the detector were placed into a vacuum chamber. The distance between the detector and the valve orifice was about 2 cm. The detector was a pyroelectric one made out of PVDF organic film with thickness of 28 μm, diameter of 3 mm, and aluminized surfaces. The back surface was mounted in a very efficient heat sink, allowing for a fast thermal response. The amplifier input impedance was 100 kΩ to extend the flat frequency response up to 1 MHz so that the observed pulse width was not limited by the detector-amplifier response. The detector signal was observed in a Tectronics 150-MHz digital oscilloscope.

Nitrogen gas was used to pressurize the valve, and pressures from 1 to 20 bars were used in the performance test.

III. PERFORMANCE TEST

Figure 2 shows a 128-pulse average with a typical 104.5-μs FWHM width. The current pulse width (not shown) was 90 μs to obtain these gas pulses, and current pulses of less than 50 μs were tested without any change in the width of the gas pulse, showing that the valve mass-spring system limited the response. For current pulses larger than 120 μs, the gas pulse follows the current pulse.

We considered 100 μs FWHM the minimum characteristic pulse width because the observed one is convoluted with the time-of-flight distribution due to the spread in molecular speeds.

To obtain Fig. 3 we used the oscilloscope's envelop function, and a 256-pulse envelope was made. In the figure, there is a 6% pulse amplitude variation. The base-line variation indicates that the electrical noise is the main source of amplitude variation. This indicates a very good pulse reproducibility and the high performance of the valve.

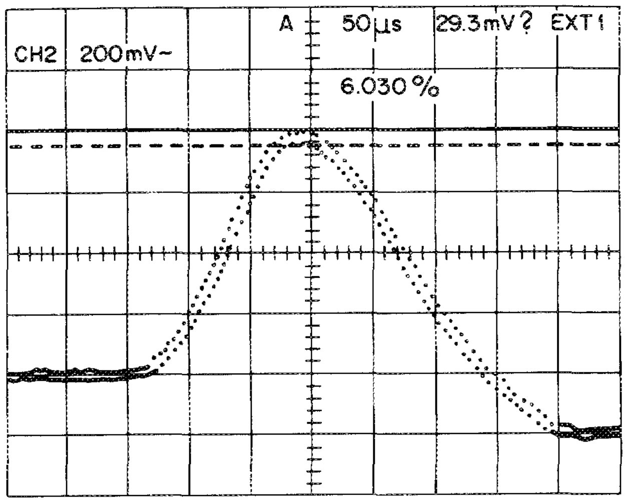

FIG. 3. Envelope of 256 pulses.

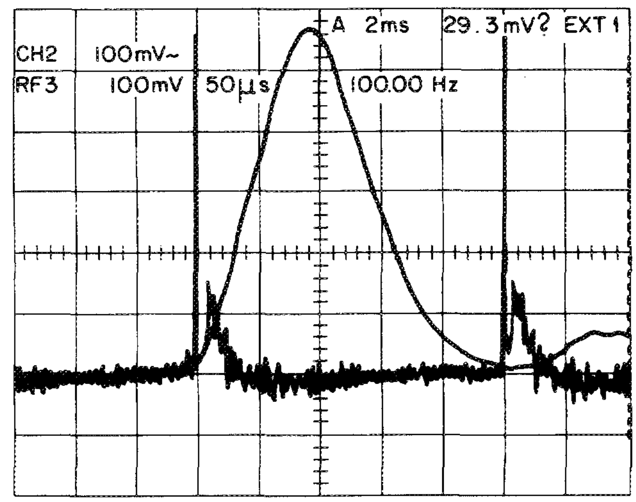

FIG. 5. Pulses in 100-Hz repetition rate operation.

The results of the test with different pressures are shown in Fig. 4. Two 128-pulse averages, for 1- and 20-bar back pressures, are shown. The gain of the oscilloscope was adjusted to normalize the pulse amplitude for better comparison. The 1-bar pulse initiates slightly before and turns to close slightly after the 20-bar one, indicating the influence of a small additional force against the piston due to pressure. This influence is small and the pulses have essentially the same FWHM width.

Figure 5 is a demonstration of valve operation at 100-Hz repetition rate. In a 2-ms scale, two successive pulses are shown, and in a 50-μs scale a 256-pulse average of the valve operating at this frequency is shown. The higher amplitude noise after each pulse is due to the valve opening acoustical noise propagated to the detector through the structure of the vacuum chamber. The 100-Hz frequency was limited by our power supply and the capacitor-charging cycle. In principle, higher frequencies are possible for the valve moving parts.

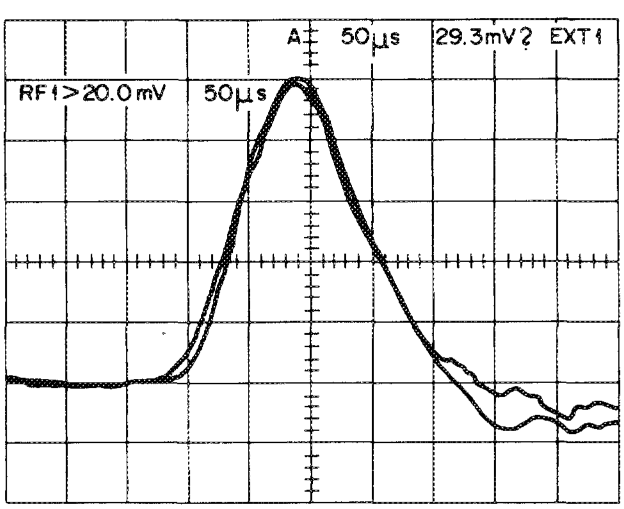

FIG. 4. Pulses with 1- and 20-bar back pressure.

IV. DISCUSSION

The pulsed valve demonstrated here presents good characteristics for use in pulsed molecular-beam experiments. The very good pulse reproducibility is advantageous due to the low error generated in pulse-to-pulse measurements on a molecular beam. With the high repetition rate it is possible to average several pulses in a short time giving a small signal-to-noise ratio and a more dynamical experiment. The gas flow limited only by the expansion orifice is of great interest because high intensity molecular beams are possible to generate. The narrower pulse width of 100 μs is limited by the mechanical moving parts of the valve, and it is convenient for most experiments in molecular-beam spectroscopy. For experiments where narrower pulses are needed, it is possible to impose a limitation on the piston travel to reduce the pulse width, but with lower beam intensity. Also, it is possible to reduce the piston mass in a new design with smaller valve inner diameter, and it is possible to increase the spring force. With these modifications we estimate that 40–50-μs FWHM pulse width is possible.

This valve is also suitable for use in other applications where the above described characteristics are needed, with the additional advantage of easily extending the pulse width from the 100-μs minimun, up to continuous operation. Gas puffing in plasma assemblies is a very possible application.

[a] The value was manufactured by COPESP–Coordination for Special Programs-S.P., Brazil.

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