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What is This?

An innovative pneumatic mini-valve actuated by SMA Ni-Ti wires: design and analysis

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Abstract: This paper presents a proof of concept study on an innovative pneumatic mini-valve. The novelty aspects lie in the creation of an actuation device based on wires formed from the shape memory alloy (SMA) Ni-Ti and in the shape of the body of the valve, with its very limited dimensions being made possible by its construction using mouldable polymeric materials. The proposed device has the following advantages: easy assembly, compactness, silent functioning, bio-compatibility, low power activation, and it is cheap to produce. Extensive static and dynamic characterizations of the valve are performed using a dedicated test rig. Several different valves were measured to ensure measurement reproducibility. The static characteristics of the SMA-based valve are equivalent to those of commercially available valves. A 10 ms activation time and a 90 ms settling time are obtained at a 30 per cent duty cycle and a 1.5 Hz frequency.

Keywords: pneumatics, valves, Ni-Ti wires, shape memory alloy

1 INTRODUCTION

There has been a considerable amount of effort expended on the innovative design of pneumatic systems in recent years. One area of particular interest is the use of shape memory alloys (SMAs) in the actuator devices used in pneumatic systems [1]. There is an extensive literature on this topic. Yokota *et al.* [2] used SMA Ni-Ti wires to develop a small proportional actuator that showed very good static and dynamic performances and a maximum working frequency of 40 Hz. In 1997 the NiTi Alloy Company produced a thin film SMA-based micro-valve for application in the area of fluid flow control [3]. Krulevitch *et al.* [4] designed a valve with a membrane

formed from a Ni-Ti-Cu and silicon composite; the valve is opened by heating the membrane and triggering the shape memory effect. Other reports on the application of SMA wires in pneumatic valves include Ferraresi *et al.* [5] and Maffiodo [6].

The general design of a SMA-controlled valve consists of the following stages:

(a) the choice of the valve structure (spool or poppet type);
(b) the choice of the actuation device;
(c) the selection of the alloy;
(d) the design of the geometry;
(e) the dimensioning;
(f) the static and dynamic characterization.

This paper presents the design and characterization of a prototype 2/2 pneumatic valve that is actuated by means of SMA wires made from Ni-Ti fibres. The design of this prototype requires innovative choices of shape, materials, and opening device. The body has a very compact shape that could only be obtained by using a mouldable polymeric material. The considered pneumatic device is a two-way mono-stable poppet valve [7] with the Ni-Ti wires fixed on the plug and then integrated into the body

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of the valve. The selection of SMA wires as the actuation device instead of SMA springs is due to the higher force exerted by the wires and to their lower mass. A Ni-Ti-NOL alloy was chosen for the wires, and this choice is discussed in detail in section 2.

An important factor in the overall performance of a valve is the suitability of the spring used for the return of the valve: it exerts a pre-stress action on the Ni-Ti wires to guarantee the closed configuration. The resistance of the Ni-Ti alloy ensures that the electrical input is converted into heat and thus the wires contract pulling the plug to open the valve and initiating flow [8]. When the wires cool the reverse operation is performed and the valve again becomes closed.

An appropriate choice of variable is required if valid comparisons are to be made about the behaviour of a value [9]. The International Standard indicates the flow capacity and the main time values as characteristic parameters for the quasi-static analysis and dynamic analysis of a valve, respectively. The static tests performed in this paper have led to the experimental determination of the flow-rate that passes through the valve under various working conditions and allowed the estimation of the load loss and flow behaviour. The performed dynamic tests have allowed evaluation of the activation and deactivation time, the settling time, and the maximum activation frequency.

2 SMA MATERIALS

SMAs undergo a plastic deformation at a relative low temperature and have the unusual property of reverting to their original shape or size when submitted to the appropriate thermal procedure. In other words, the metal 'remembers' its original shape and this property is called the shape memory effect (SME). This effect can be associated with a temperature and stress-dependent phase change between martensite and austenite phases. The low temperature phase (martensite) is relatively soft whereas the high temperature phase (austenite) is relatively hard with a highly ordered crystalline structure.

The shape recovery occurs at the austenite temperature (transformation temperature) T_a. For the case where the alloy is reheated above T_a, the alloy regains its highly ordered crystalline austenite structure and the SMA returns to its original pre-deformation shape in which it was originally formed. The 'training' of the SMA, i.e. the original formation at high temperature, is a very important process.

The SME was first observed in samples of gold-cadmium alloys and subsequently in copper-zinc alloys. The material of interest in this paper is a Ni-Ti alloy, the so called Ni-Ti-NOL alloy (named after the laboratory in which the discovery was made the US Naval Ordinance Laboratory (NOL)). The great advantages of the Ni-Ti-NOL alloy are its relatively cheap constituent elements and a much larger shape memory strain than normally observed in alloys (8 per cent and in some cases up to 10 per cent). Furthermore, series fabrication is possible using common techniques.

SMA materials have been applied in many fields including medicine, robotics, mechanics, pneumatics, vibration control, aeronautics, etc. Information related to the behaviour of commercial SMA materials can be found in [10–12].

3 LAYOUT OF THE SMA-WIRE-ACTUATED VALVE

The mini-pneumatic valve was initially conceived for application in industrial environments but it is now used in numerous other areas. As a consequence, great attention has been paid to devising a simple assembly process that can be incorporated into low-cost commercial production. The assembly method of the valve presented in this paper takes into account the possibility of using a transfer machine with simple pick-and-place components for its commercial manufacture.

Figure 1 shows a picture of the assembled mini-valve and Fig. 2 is an expanded view; the Ni-Ti wires are clearly visible in both images. The mounted valve has a length of 20 mm and weighs 3 g. The valve components can be seen in Fig. 3; their dimensions can be qualitatively deduced by comparison with the 2 euro cent coin (18 mm in diameter). Seven elements compose the valve; the wires (3) are made from Ni-Ti fibres, while the body of the valve (5) is made from a polymeric material.

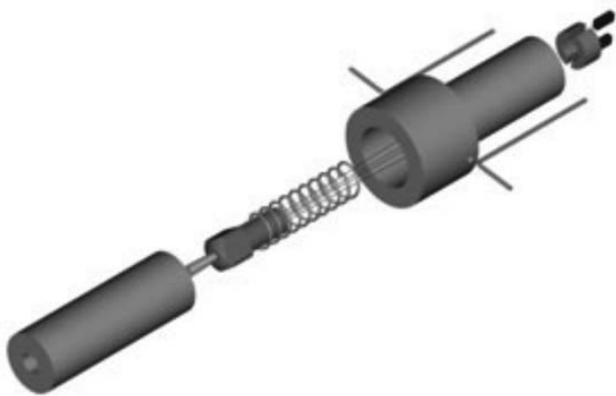**Fig. 1** Picture of the pneumatic mini-valve actuated by the Ni-Ti wires

Fig. 2 Expanded view of the pneumatic mini-valve actuated by the Ni-Ti wires

The time taken to manually assemble the components is about 1 min, with the related steps consisting in the following phases:

(a) with a needle, insert the two Ni-Ti wires first through the plug hole, then through the spring and finally through the valve body;

(b) wind the Ni-Ti wires around the copper wires, and fix the heads of the Ni-Ti wires on the brass plug with the conical pin;

(c) in the final operations, the valve is inserted into the Plexiglass body and the cap is added on the opposite side, with subsequent sealing of points at which air loss could occur.

The wires actuate the poppet of the valve (Fig. 4), by opening it when they are heated and the spring closes the valve when the wires cool.

In this preliminary proof of concept study, the body of the valve has been made from polyamide which is an easily mouldable plastic material. Furthermore, this material is compatible with rapid prototyping systems.

4 FORCES AND VALVE DIMENSIONING

During the on-phase of the valve, the force F that has to be exerted by the Ni-Ti wires to move the plug, has to be larger than the combined spring force and the force due to the air pressure that is trying to keep the plug stationary. Equation (1) allows the calculation of the maximum force F_m exerted by the spring (Δl and k are respectively the extension and the elastic constant of the spring). The calculated values of F_m were between 0.91 and 1.27 N. Equation (2) leads to the force due to the pressure.

$$F_m = k \times \Delta l \tag{1}$$

$$F_p = P \times A_{pl} \tag{2}$$
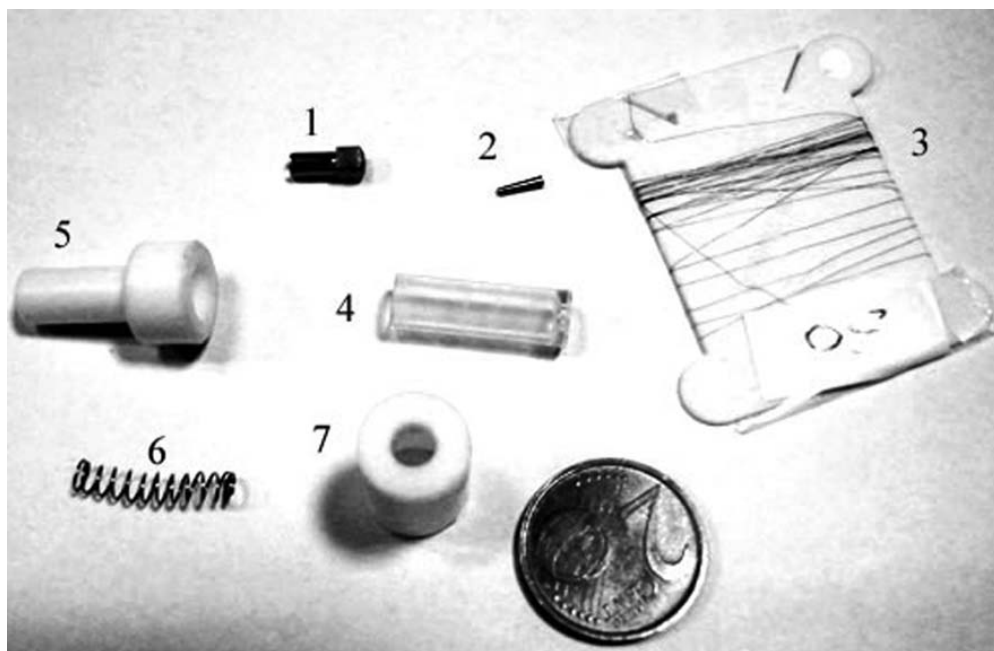
$$F = k \times \Delta l + P \times A_{pl} \tag{3}$$

Fig. 3 Components of the valve: 1 brass shutter; 2 conical steel plug; 3 Flexinol wire $\Phi 50\,\mu m$; 4 valve body in Plexiglass with flow exit orifice; 5 internal valve body; 6 spring; 7 stopper with a hole $\Phi 4\,mm$ for air entry
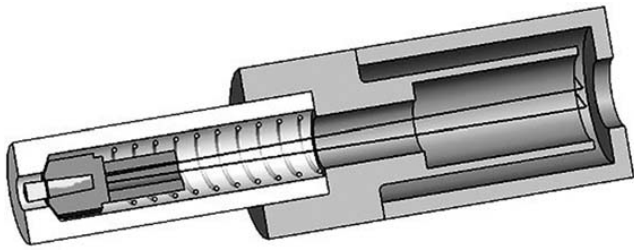
Fig. 4 Section of the mini-valve actuated by wires

where F_p is the product of the pressure P on the plug area A_{pl}.

In equation (3), the plug area A_{pl} and the spring stretch are fixed, the maximum force that the wires can tolerate is known, hence, the elastic coefficient k is chosen to be as low as possible to obtain a wide pressure range. A return spring (a passive mechanical component) keeps the wires correctly stretched and the plug in the closed position by exerting the necessary force and also allows valve opening after the activation of the Ni-Ti due to its compliance. The values of the parameters used for the prototype valve were: $k = 0.62 \times 10^3 \, \text{N/m}$, $A_{ott} = 9 \, \text{mm}^2$, and $\Delta l = 2 \, \text{mm}$.

The stretching properties of four types of spring were tested. In these tests the internal diameter and the length had to remain unchanged since they are fixed by the internal size of the Plexiglass housing and the housing of the closing-pin, respectively. Once a good compromise between the spring stability and the linearity of the force–length ratio is obtained it is possible to avoid lateral bending of the spring: after the valve activation, the Ni-Ti wires contract and move the plug. Although the use of the spring is essential for the return to the starting condition of the Ni-Ti wires, this could be a source of undesired phenomena: as a matter of fact some tests, with a work frequency higher than 1 Hz, have shown noteworthy lateral bending of the spring and this undesired behaviour is emphasized by an increasing differential pressure.

In order for the system to work the Ni-Ti wires must overcome the maximum force obtained using equation (3). In this equation, the only changing parameter in the valve configuration is the pressure which increases as a function of the diameter and characterizes therefore the limit condition, since it is associated with the maximal air pressure resulting when the wires start yielding.

The chosen configuration of the wires consisted of two segments with 100 mm length. The Ni-Ti wires show a self-contraction of 8 per cent per cycle during the first 100 cycles; in fact a tested four-wire version

of the proposed valve with shorter wire lengths (36 mm) was tested and displayed unsatisfactory behaviour created by these displacements.

5 EXPERIMENTAL ANALYSIS

A dedicated test rig was built to study the static and dynamic behaviours of the valve in order to identify the important parameters and input–output variables of the prototype device. The flowrate through the valve under different working conditions, the load loss, and the flow behaviour were experimentally determined using static tests. The shifting time, the maximum activation frequency, and the extent to which the step response speed and changes in the activation frequency of the device could be controlled were established by means of the dynamic tests.

5.1 The pneumatic test rig

The test rig (Figs 5 and 6) was designed so as to create a common measurement interface for the considered parameters. It consists of four main parts.

1. The electrical feed circuit: a PWM system [13] with variables programmable through a microchip supplies the SMA wires with a constant current-step (I_{const}) at a frequency $f = 1/(T_{on} + T_{off})$ and with a duty cycle that is changeable for a fixed number of cycles.
2. The fluid control system: compressed air is generated and the input pressure P_1 of the dry and filtered air is regulated.
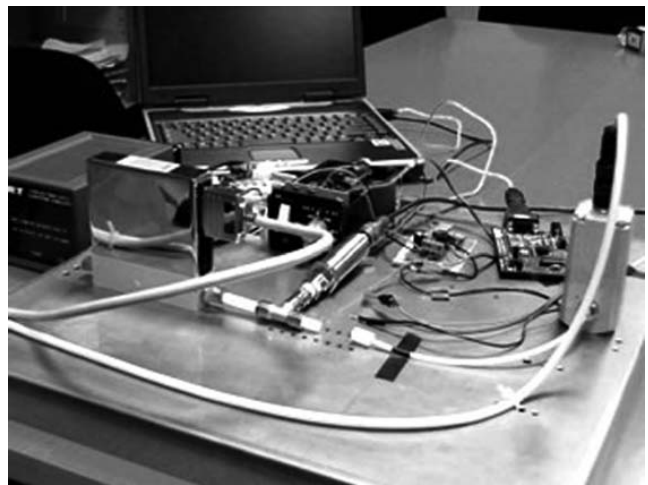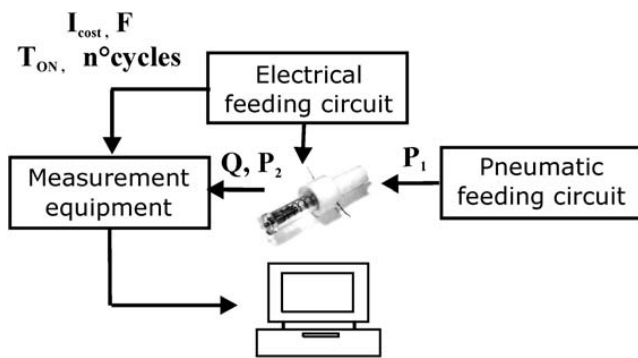

Fig. 5 A picture of the test rig

Fig. 6 Test rig: architecture

3. The measurement equipment: pressure P_2 and flow Q at the output of the valve are measured by a pressure transducer and a mass flowmeter, respectively.
4. Data acquisition: performed by means of a PC and dedicated software.

Since the air used in the tests to determine the static and dynamic characteristics of the valve needs to have known properties and also to avoid damage to the instruments, the test rig uses compressed air that is generated from a dedicated setup. The ambient air was filtered and compressed by a volumetric compressor (maximum pressure $P_{max} = 0.8$ MPa, power $W = 1.5$ kW), and then dehumidified as required by international standards, then a group formed by a filter and a pressure regulator (FR) was used to further filter the air (a 20 μm filter) and reduce the pressure. A maximum pressure of 0.6 MPa was used in the experiments.

5.2 The static tests

Figure 7 is a schematic diagram of the experimental setup used for the static and dynamic tests. Electrical signals from the PWM circuit are used to control the valve and an almost constant pressure is preserved during the test, by means of the proportional pressure regulator R set at a desired pressure value (the pressure lightly decreases as the valve is opened by the plug). The input pressure P_1 is measured using the internal transducer of the proportional electro-valve in the test rig. This choice introduces a small error into the pressure measurement. However, this is considered acceptable at this step of the research, since the goal is to simply provide a proof of concept. The output pressure P_2 is measured by the pressure transducer T connected crosswise to the air flow.
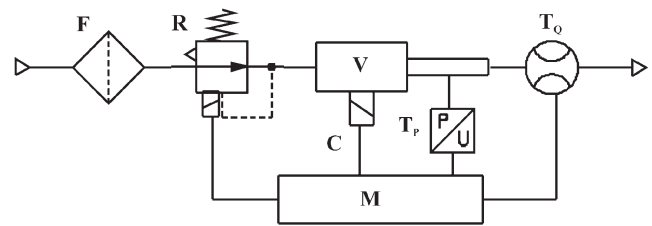

Fig. 7 The experimental setup for the static and dynamic tests (R is the proportional pressure regulator, T the pressure transducers, V the valve, F the mass flowmeter, and M the data acquisition system)

The linking pipes are ISO pressure tubes (Φ 6 mm) that comply with the ISO standards (ISO 6358) for an easy intra pipe connection without pressure loss and for standard conditions of the internal roughness.

The flow rate Q is measured by the mass flowmeter (F). At $T_1 = 293$ K (ambient temperature), the signal C, the output pressure P_2, the feeding pressure P_1, and the flowrate Q are recorded by the data acquisition system M (Fig. 7). Static tests can provide the effective flowrate Q passing through the valve as a function of the fixed upstream pressure P_1 and a measured downstream pressure P_2.

From tests using Φ 50 μm Ni-Ti wires, it became clear that the maximum input pressure was $P_1 = 0.2$ MPa (absolute and with open output) and the maximum flowrate was less than 0.41 l (ANR)/s. The comparison of results obtained in tests in calm air with those obtained using compressed air showed the follow intuitive effects:

(a) the use of compressed air increases the force required to open the plug;
(b) the recovery time of the Ni-Ti wires is reduced (due to cooling by the compressed air);
(c) a part of the energy supplied during the transition between austenite and martensite phases is lost (because the cooling effect created by the compressed air also occurs during the activation phase).

At an absolute pressure of P_1 higher than 0.06 MPa, the tests revealed that the energy supplied by the $I_{const} = 240$ mA current flowing for 200 s is not able to activate the wires. Tests to identify the activation current limits were therefore performed. For an activation current $I = 240$ mA with an input pressure P_1 of 0.2 MPa the valve remained closed, since the NiTi wires cooled down instantaneously. When the activation current was increased to 900 mA (maintaining a fixed pressure), the valve quickly opened (in about 0.05 s), but the wires became burnt after 0.5 s, even though they were constantly cooled

by the flow of compressed air. In a further test using an activation current of 500 mA the valve worked correctly and the wires were not damaged. This value was chosen as the activation current.

To find the flowrate using quasi-static tests, the valve was kept open until a steady state flow was reached and a 30 s recording time was used. At first, the activation current was fixed at 500 mA at an input P_1 of 0.12 MPa, then the signal from the mass flowmeter was recorded and then the input pressure was changed until the differential pressure limit was reached.

The data collected through a set of static tests, repeated on ten different examples of the valve, allowed the calculation of the flow capacity, evaluated as K_V using the protocol in EN 60534-2-3. The value of this parameter is taken to be a valid basis on which to compare the prototype with commercial valves. The calculation of K_V according to CEI-EN 60534-2-3 requires the application of a procedure (implemented in an Excel sheet) with different steps. The main expression used for the estimation of the flow capacity is

$$K_V = \frac{Q}{N_9 P_1 \{1 - [(\Delta P / P_1)/3F_\gamma x_T]\} F_p} \sqrt{\frac{M T_1 Z}{\Delta P / P_1}} \qquad (4)$$

where Q is the flow through the valve, T_1 is the absolute temperature of the test, P_1 is the absolute input pressure, ΔP is the pressure drop across the valve, M is the molecular mass of the air, and N_9, F_γ, x_T, F_p, and Z are parameters defined by the standard, whose values can be found in Table 2 of the standard.

Moreover, the conductance of the valve can be approximately estimated, by using equation (5), where Q_N^* is the sonic flow at absolute input pressure P_1 and $K_T = \sqrt{293/T_1}$ is the temperature factor

$$C = \frac{Q_N^*}{P_1 K_T} \qquad (5)$$

The value of the conductance C obtained by the estimation is C = 2 (l(ANR)/s)/MPa.

The factors that influence the functioning of a generic valve have to be considered in the flow capacity calculations using equations that express the relationship between flowrate, flow coefficients, related installation factors, and pertinent service conditions for the valves [1].

The flow rate Q, as represented in Fig. 8, is a function of the input pressure P_1, (the output pressure P_2 is fixed at 0.1 MPa): the flow rate Q
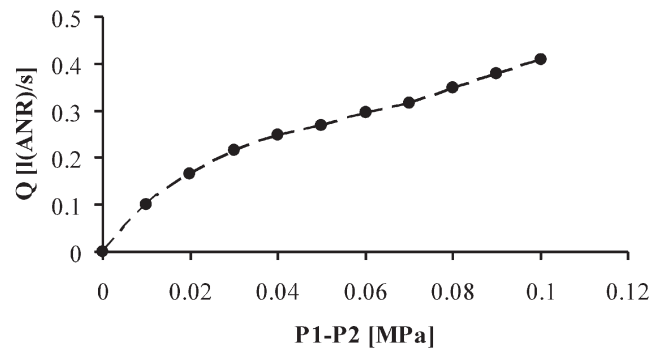

Fig. 8 The P–Q curve of the valve with pressure P_2 equal to 0.1 MPa, where Q is the flowrate, P_1 is the inlet pressure, and P_2 is the outlet pressure

increases in a progressive manner until the pressure P_1 reaches 0.16 MPa, corresponding to the critical ratio condition between P_1 and P_2. Exceeding this pressure value means a sonic flow and the flowrate becomes a linear function of $(P_1 - P_2)$.

Table 1 compares the prototype 2/2 mini-valve actuated by Ni-Ti wires with the same type of valve actuated by a solenoid (K_V calculated at a differential pressure of 0.1 MPa). It is clear that the flow coefficient results are better for the prototype valve.

5.3 Dynamic tests

Tests were performed to investigate the dynamic behaviour of the prototype valve since the dynamic response of the valves is important in many industrial applications.

Table 1 Technical data of a commercial solenoid meso-valve 2/2 and the experimental data of the SMA valve

	SMA	Solenoid
Medium	Air	Air
Function	2/2 NC	2/2 NC
Operation	Direct acting	Direct acting
Φ (mm)	2.0	1.6
K_v (l(ANR)/s)	1.35	1.2

Table 2 Dynamic characteristics of the mini-valve during the test with an input pressure P_1 of 0.12 MPa for 100 cycles

Input parameters		Dynamic response of the valve	
I_{const}	500 mA	t_s	90 ms
T_{on}	200 ms	t_1	15 ms
T_{off}	450 ms		
DC	30%		
f	1.5 Hz		

5.3.1 Step response tests

To identify meaningful step response times dynamic tests were performed that followed the procedures in ISO 12238 and used a current $I_{const} = 500\,\text{mA}$, an input pressure $P_1 = 0.12\,\text{MPa}$, and a step signal $T_{on} = 200\,\text{ms}$. Figure 9 shows the response of the valve to changes in the current step signal.

The shifting time (or activation time) is the time between the application of the electrical signal and the time at which 10 per cent of the output pressure is reached, whereas the deactivation time is the time between the application of the electrical signal and the time at which 90 per cent of the output pressure is reached.

The obtained activation time is 15 ms, which is comparable to the value for a generic commercial mini electro-valve. This parameter could be further improved by the use of more efficient wires. It proved impossible to obtain a meaningful deactivation time and this is probably a result of the complex behaviour exhibited by the SMA wires on cooling [14].

The settling time t_s (the time after which the step response remains within a tolerance band of 2 per cent of the final value) is about 90 ms and corresponds approximately to the contraction time of the Ni-Ti wires: varying the current amplitude, the T_{on} should not be slower than 100 ms with a 20 per cent margin of safety for the change of phase.

This response results in an overshooting of the pressure at the opening of the plug. A possible explanation of this phenomenon is as follows: at the activation of the valve the wire contraction, due to the high temperature, causes a large movement of the poppet, afterwards the flux of compressed air reduces the temperature of the wire with a conse-
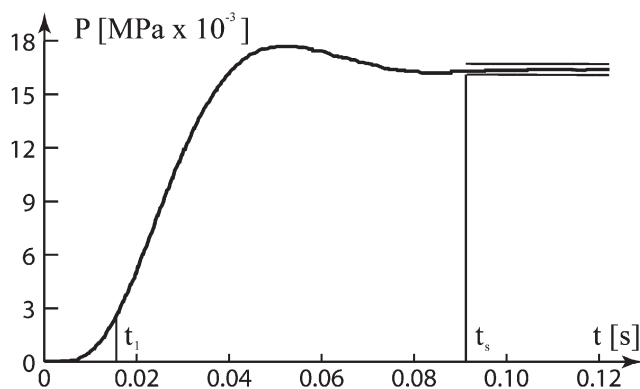
quent reduction of the contraction resulting in a decrease in the pressure.

5.3.2 Dynamic response tests

The dynamic response behaviour of the valve was studied using tests based on on-off cycles with prefixed frequency values (Fig. 10).

Parameter values of $I_{const} = 500\,\text{mA}$ and $T_{on} = 200\,\text{ms}$ were used to analyse the dynamic behaviour of the valve, and these values were guided by the tests reported in section 5.3.1: initially T_{off} was set at 800 ms with a 1 Hz frequency, because a slow return of the plug was expected. Then, T_{off} was adjusted to 450 ms, and the working frequency to 1.5 Hz and the duty cycle (DC) to almost 30 per cent. The number of cycles was limited to 100 since there is a consensus in the literature that after this point there is a significant degradation in the SME in SMAs [8, 10, 14].

The input pressure P_1 was set at 0.12 bar using a digital regulator. Sometimes, the opening of the plug was not completed; in fact its step showed smaller amplitudes, especially in the first ten cycles, before settling to the correct value.

The results obtained in these experiments are shown in Fig. 11. The following points emerge from an analysis of this figure.

1. The activation phase (the opening of the plug) is repeatable and substantially constant, in fact the main times are easily extracted; the activation time t_1 and the settling time t_s are the same as those extracted with the response tests.
2. The return of the wires is not repeatable and not linear in the first 100 cycles. This is due to the complex behaviour exhibited by the SMA on cooling.

Fig. 9 Pressure response to current step signal with: $I_{const} = 500\,\text{mA}$, $T_{on} = 0.2\,\text{s}$, and $P_1 = 0.02\,\text{MPa}$. t_1 is the activation time (shifting time) and t_S is the settling time
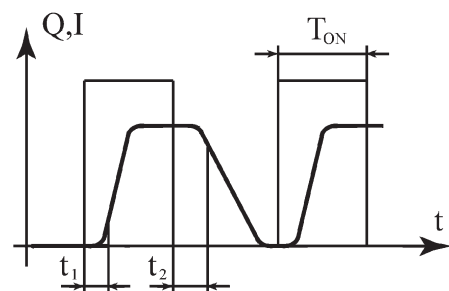
Fig. 10 Main signal time of current I and flow Q, where T_{on} is the electrical activation time, t_1 is the activation time (shifting time), and t_2 is the deactivation time
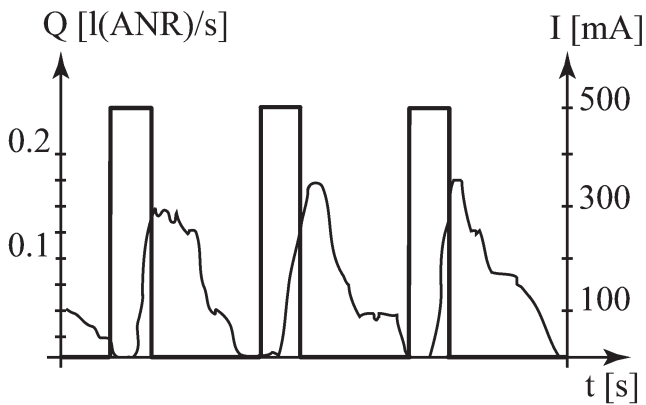
Fig. 11 On-off cycles: the current signal ($I_{const} = 500$ mA, $T_{on} = 200$ ms, and $T_{off} = 450$ ms) and the flow signal

Table 2 summarizes the values of the main times for the experiments performed at an on-off cycle frequency of 1.5 Hz, shown in Fig. 11.

These tests were performed at two different loads: a pure thermal one and a mechanical one. The former is due to the combined effect of the spring force and the pressure created by the input air flow, the latter to the martensite to austenite phase changes and *vice versa*.

If the SMA is subjected to a group of thermo-mechanical cycles, many properties are influenced. From a metallurgical viewpoint, fatigue degrades the material resulting in softening and a more elastic behaviour is noted when the valve is dismantled and reassembled. Wires that have experienced almost 100 cycles tend to display micro-cracks and therefore these wires are prone to breaking very easily [**9**]. This effect is proportional to the amount of supplied energy, and these phenomena increase with an increase in the T_{on} and I_{const} values. The detailed study of this fatigue problem is a topic that should be the subject of future work.

6 CONCLUSIONS

It has been experimentally verified that the prototype valve has an activation time of 15 ms with a 1.5 Hz frequency at a 30 per cent DC. The required current for the activation of the Ni-Ti wires was almost 500 mA for 200 ms.

The key external parameters that influence the cycle life are: time, temperature, stresses and application type, deformations, and the number of cycles. The key biasing internal parameters are: the alloy composition, the thermal treatment, and the mechanical treatment. The complex thermo-mechanical behaviour of SMAs means that it did not prove possible to obtain a simple relationship between the temperature and the displacement or between the temperature and the applied forces. The maximum SME was obtained and then the stresses and limit deformations were selected as a function of the number of working cycles. Stoeckel [**15**] presents useful data to describe the fatigue of SMAs: this data is used with an appropriate safety margin for the Ni-Ti wires used in the proposed valve. The wires become unusable after 100 cycles and need to be changed.

Future work in this area will concentrate on improving the operational life of the valve so that it reaches the levels displayed by commercial electro-valves (at least 20 000–40 000 cycles reaching up to 100 000 000 + cycles). Possible variations in the valve design to achieve this goal are: the choice of SMA wires with a larger cross-section, the use of a higher number of wires to open the plug (in this way the wires can work far from their limits), the selection of a more efficient SMA (even if this means a costs increase), and the forced cooling of the wires.

Other areas worthy of further investigation include: the complete and rigorous characterization of the valve; and the isolation of the optimal valve configuration (a normally open valve or a valve with multiple outputs can be easily realized). A pressure P_0 applied to the internal surface of the plug could, for example, replace the spring force. This would favour the miniaturization of the valve. In this case the plug must be redesigned to minimize inlet pressure effects. The absence of the spring would improve the manual assembly process.

This valve could also be used as passive component without electrical activation of the wires to realize a safety valve that triggers when a specified air flow temperature is reached. The extension of this concept to a 3/2 bistable valve would be of particular interest in this safety-related scenario.

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APPENDIX

Notation

A_{pl}	plug area
C	conductance
f	frequency of the actuation of the valve
F	force exerted by the NiTi wires to move the plug
F_m	force exerted by the spring
F_p	pressure force on the plug
k	elastic constant of the spring
K_T	temperature factor
K_V	coefficient for the flow capacity
I_{const}	amplitude of the step-current
M	air molecular mass
$N_9, F_\gamma, x_T,$	parameters of the EN 60534-2-3
F_p, Z	standard used to evaluate K_v
P	pressure acting on the plug
P_1	absolute input pressure
P_2	absolute output pressure
Q	flowrate
Q_N^*	sonic flowrate
t_1	activation time
t_2	deactivation time
t_s	settling time
T_1	absolute ambient temperature
Δl	maximum extension of the spring
ΔP	difference in pressure on the valve