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Water/Air Performance Analysis of a Fluidic Muscle

Michele Focchi, Emanuele Guglielmino, Claudio Semini, Alberto Parmiggiani, Nikos Tsagarakis,
Bram Vanderborght and Darwin G. Caldwell

Abstract— **This paper deals with a comparative study on using water and air as actuation means for the control of a fluidic muscle (designed for air) and assesses the performance, particularly from a dynamic and energetic point of view. A medium with higher bulk modulus such as oil/water is believed to increase pressure and force bandwidths and reduce sensitivity to load variations, as is the case with conventional hydraulic stiff actuation systems. However in this application the inherent flexibility of the muscle plays a major role. Water has been chosen because of its non-flammability, environmental friendliness and the low solubility of air in it. The operating pressure range of the pneumatic muscle is 0-6 bar (typical range of a pneumatic system) that is well below typical operating pressures of hydraulic systems (typically over 100 bar). At such low pressures the dynamic behaviour of water is less predictable because of the higher likelihood of entrapped air in the water which physically occurs when operating at low pressures. This can majorly affect water bulk modulus and hence its dynamic performance. Therefore, the behaviour of the system in this unconventional pressure range for a liquid must be more thoroughly investigated. Theoretical and experimental analyses on a dedicated test rig have been carried out to assess these assumptions.**

I. INTRODUCTION

Hydraulics is regaining interest in the robotics community with recent applications such as the BigDog [1], Petman [2], Raytheon SARCOS exoskeleton [3], Bleex exoskeleton [4] and HyQ robot [5].

Advantages of hydraulics are that it can transfer a large amount of power with a compact pump working at high pressure, the high power density and a wide range of actuators that can make use of this power. However, hydraulics using oil has some serious disadvantages making indoor applications difficult. Leaks are difficult to avoid. Therefore the first innovative part of the paper is to use water instead of oil as pressure transmitting medium, because it is environmentally friendly, non-flammable, inexpensive, clean, readily available, and easily disposable. A better stability (in terms of flow velocity and efficiency) over a wide range of operating temperatures due to water's higher bulk modulus (nearly 38% greater than that of mineral oil), lower viscosity (less than 1/30 of mineral oil's at 50°C) and higher specific heat capacity are also benefits of using water [6, 26]. All the above mentioned advantages make water hydraulics appealing for high performance actuation techniques in robotics.

Mostly cylinders are used in hydraulics. For pneumatic powered robots also pneumatic artificial muscles (PAMs) are used in different applications such as walking robots (Lucy [7]), mobility enhancement and rehabilitation [9,10], manipulation (like Softarm [8]). An important difference with respect to a classic linear cylinder is that in the PAM position control is carried out by pressure control (generally more efficient) rather than by flow control as in hydraulic cylinders. Furthermore a certain level of misalignment is well tolerated by PAMs. They are very lightweight because their main component is a membrane and they also have a high power-to-weight ratio in the order of magnitude of several kW/kg [11]. PAMs are easily replaceable and can be directly connected to the structure they power without gears and this is beneficial from a control viewpoint as they do not introduce backlash and extra inertia. However inherent pneumatic compliance adversely affects the positional accuracy of the system in position control servos and requires more sophisticated non-linear algorithms such as adaptive control [12] or feedback linearisation techniques [13]. A very serious drawback of PAM is that pneumatic compliance limits the actuation performance in terms of bandwidth [14] and the energy cost to produce the compressed air is much higher compared to compressing a liquid.

This work investigates the benefits of using water instead of air as a working medium with PAM as actuator. The paper is organised as follows: section II describes the test bench and the control system used for the experiments. Section III reports the static experiments aimed at obtaining the force-length relationships (isotonic experiments), Section IV describes the dynamic experiments carried out: a comparison between air and water in terms of bandwidth and stiffness. In Section V pressure and position closed loop experiments are carried out and a brief estimation of the energy consumption using air or water is presented. Experiments on the robustness to load variation in position control are also performed. Section VI addresses the conclusions. Pros and cons of the use of water are discussed.

II. THE EXPERIMENTAL TEST BENCH

In this work a FESTO fluidic muscle was used (*DMSP 20* with 400 mm resting length and 20 mm diameter at no load [15]). This muscle is specified for use with air only. The pressure range in which it was tested was 0-6 bar which is within the rated pressure of these muscles. This lower

Michele Focchi, Emanuele Guglielmino, Claudio Semini, Bram Vanderborght, Nikos Tsagarakis and Darwin G. Caldwell are with the Advanced Robotics (ADVR) Department of the Italian Institute of Technology, Via Morego 30, 16163 Genoa, Italy. {Michele.Focchi, Emanuele.Guglielmino, Claudio.Semini, Nikos.Tsagarakis, Bram.Vanderborght, Darwin.Caldwell}@iit.it.
Alberto Parmiggiani is with the Robotics, Brain and Cognitive Sciences (RBCS) Department of the Italian Institute of Technology, Via Morego 30, 16163 Genoa, Italy. Alberto.Parmiggiani@iit.it.

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pressure range is limited by the fittings of the muscle (not by the bladder).

It should be remarked that while 0-6 bar is a conventional pneumatic pressure range, conversely typical pressures in hydraulic systems are much higher (over 100 bar) and at such higher pressures the behaviour is more predictable because of the lower likelihood of entrapped air in the liquid [5, 16]. A high pressure helps the free air to pass into solution as stated by Henry's law [25]. Air presence in water majorly affects the dynamic response of hydraulic systems. It is reported that at low pressures (0-10 bar range) a 1% amount of entrapped air can reduce the theoretical bulk modulus of up to the 80% [17]. Hence the dynamic performance of a liquid at lower pressure must be more thoroughly investigated [18].

A testing system, able of generating desired force, displacement and pressure profiles was built. Fig.1 depicts a schematic and Fig. 2 portrays it.

The air supply line is supplied by a compressor controlled by a pressure regulator (SMC ITV2050 range 0-10 bar).

The water supply line is composed of a centrifugal water pump (Pompe Travaini TBH203, 70m head, 8.3 l/min rated flow) driven by an 1.5 kW AC motor with an inverter. A second bleeding circuit has been added to drain back part of the water flow to tank in order to prevent overheating of the water. Due to the volume change of the actuator with length, the measured pressure was not constant. In order to reduce the variation of the pressure, a 1 litre gas accumulator (pre-charged with nitrogen at 2 bar) was connected to the pump upstream the inlet valve.

The pressure control in the muscles is performed using two 2/2-way (Burkert 2835 range 0-8 bar) proportional valves. These valves are suitable both for water and air. One fills the muscle and the other vents to air/bleeds water to tank (quite large, 500 litres, to help keep water at a constant temperature). They have been placed as close as possible to the muscle to reduce dead volumes and are driven by analogue signals generated by two power amplifiers.

A high pressure flexible tubing (3/8") connects the supply source to the filling valve. The variable load is generated by controlling the pressure (range 0-10 bar) in the chambers of a pneumatic cylinder (SMC C95, bore size 80 mm, with 4.2×10^{-3} m^2 active area) via a pressure regulator identical to the previous one. In this way it is possible to obtain up to 4000 N load force. Both chambers can be depressurised to unload the muscle via two 2/2way pneumatic valves driven by digital signals. An air brake enables to block the piston at a desired position to perform isometric tests.

Two pressure sensors (Honeywell MLH series, range 0-10 bar) and two water flow-meters (Remag Vision 2000, range 1-15 l/min) are located on the suction and discharge lines respectively. A Sensirion EM1 gas mass flow meter is located on the air supply line. Contractile force is measured by a load cell (Picotronik ABA series, range 0-5000 N) mounted between the muscle and the rod of the pneumatic cylinder while muscle length is measured via a linear potentiometer (Burster 8710, range 0-0.15 m) connected to an end-cap of the muscle. A percentage of 10% of glycol (antifreeze liquid) was added to the water to provide extra lubrication to prevent damage to mechanical components (due to the poor water lubricating properties) and prevent the generation of algae and bacteria in the water [19, 24].

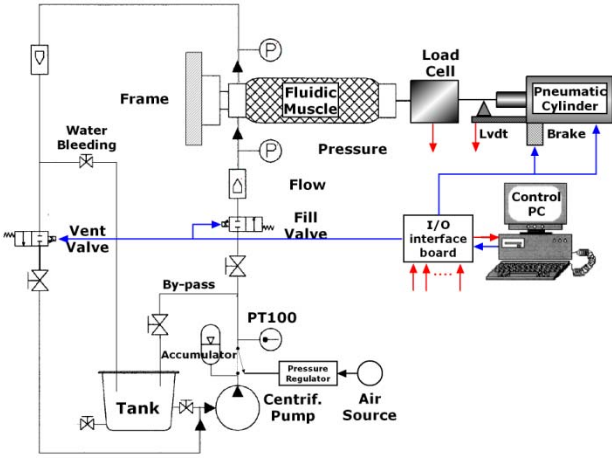
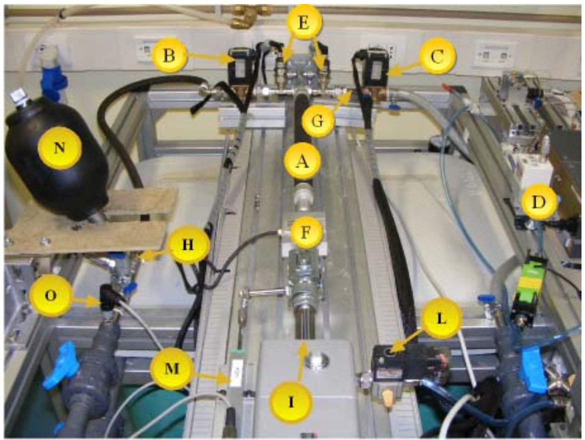


Fig. 1. Test bench schematic.



(A) Muscle, (B) Delivery Valve, (C) Discharge valve, (D)Pneumatic pressure regulator (for air tests), (E) Muscle Pressure transducers, (F) Load cell, (G) Flow Meter, (H) Supply pressure transducer, (I) Pneumatic Cylinder (load), (L) Air Brake valve (load), (M) Lvdt, (N) Accumulator, (O) Temperature transducer

Fig. 2. Picture of the test bench.

The acquisition system is composed of a PC104 motherboard with an 800 MHz Celeron processor equipped with a Sensorray 526 data acquisition board. Custom-made signal conditioning boards provide the proper amplification and filtering of the sensors signals in order to maximise their performance. Sampling rate was set to 1 kHz.

The system can perform a variety of tests, namely constant pressure tests, isometric tests, isotonic tests and free contraction tests.

Preliminary numerical simulations showed that the accumulator can deliver up to 0.5 l at 6 bar that is the water volume needed to fully fill the muscle and the connecting pipes to/from valves. As a result the pressure variation in normal operating conditions was limited to less than 0.1 bar.

This paper is not addressing the control of either drives *per se*. A control loop is required as the system inherently works in closed loop. Furthermore, it has to ensure a fair comparison between the two systems. This is not trivial since they exhibit quite different control characteristics.

A cascade control system (Fig. 3) having an inner pressure loop (controlled by a P regulator) and an outer position loop (controlled by a PI regulator) was designed and implemented. The output of the position regulator is the pressure setpoint that is fed to the pressure regulator.

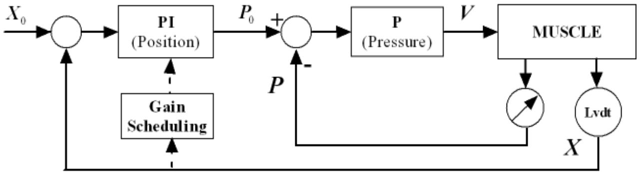


Fig.3. Control system block diagram.

From the physical structure of the muscle at low contractions a pressure variation leads to a high force variation. This means that a small positioning error creates a force change that needs a high pressure variation to be compensated. Therefore a position PI regulator tuned at high contraction can lead to oscillations at low contraction and conversely. Hence a gain scheduling algorithm was designed and implemented; the controller gains were scheduled according to the system operating point obtained linearising the system around several points. Firstly the PI position controller was tuned to have good performance at high contraction. Then an adaptive integral term was added that, in the range of 0% to 15% contraction, increases from 20% to 100% of its nominal value.

III. PRELIMINARY STATIC TESTS

Static experiments (with air and water) aimed at obtaining the force-contraction relationships (isotonic experiments) were carried out to mainly assess the reliability of the test-bench and for the identification of the parameters of a mathematical model not presented in this work. Experimental results are presented in Fig. 4 where the points represent data samples. A 3D surface of the force-contraction-pressure relationship together with the surface that represents the error with the FESTO datasheet data [15] (not represented here) are also shown. The error is higher at low pressures. However it has an average of 120 N which is negligible.

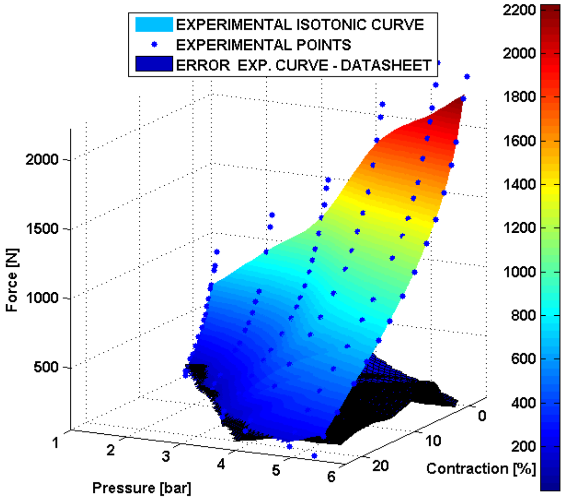


Fig. 4. Experimentally measured isotonic relationship and error with the datasheet curves.

IV. COMPARISON BETWEEN WATER AND AIR

Static tests showed no difference between air and water because they represent only the steady-state behaviour of the muscle without considering if the muscle pressure is generated by water or air. The differences are indeed present in the stiffness and dynamics as subsequently described.

A. Stiffness

Bulk modulus is the parameter that gives a measure of the stiffness of a fluid. The compressibility of hydraulic fluids is the predominant factor in the determination of the hydraulic resonant frequency in fluid power systems. Under high pressures and in response to fast variations, the fluid behaves like a hydraulic spring and limits the response of the system. Hence water in the muscle can be regarded as a spring. Bulk modulus B (from now on defined as B_{air} for air and B_{water} for water) is defined as the reciprocal of the rate of change in volume $V/\Delta V$ due to a change in pressure ΔP [20]:

$$B = \frac{pressure \quad change}{Volumetric \quad Strain} = -V\frac{\Delta P}{\Delta V} \tag{1}$$

As pressure and volume are proportional to force and length, muscle stiffness K can be related to bulk modulus:

$$\Delta V = -A\Delta x = \frac{V\Delta P}{B_{water}} \Rightarrow \Delta x = \frac{V\Delta F}{A^2 B_{water}} \Rightarrow K_{water} = \frac{\Delta F}{\Delta x} = \frac{A^2 B_{water}}{V} \tag{2}$$

where x is the muscle length and A the cross section. This equation states that for water (under the assumption that there are no bubbles entrapped in the liquid) bulk modulus is independent from pressure, hence stiffness only depends on the muscle volume (as in a hydraulic cylinder) and increases with muscle length (because volume becomes smaller). However, differently from a classical cylinder where there exists an algebraic relationship between pressure and force, in the muscle this relationship is non-linear and pressure-dependent:

$$\Delta V = -A\Delta x = \frac{V\Delta P}{B_{air}} \Rightarrow \Delta x = \frac{Vf(p)\Delta F}{AB_{air}} \Rightarrow K_{air} = \frac{\Delta F}{\Delta x} = \frac{Af(p)B_{air}}{V} \tag{3}$$

Therefore in a water-actuated muscle the stiffness increases linearly with contraction and non-linearly with pressure.

The behaviour is different in case of air: air bulk modulus is not constant with pressure. In particular in case of an isothermal process (as this one can be considered) it can be shown that [20]:

$$B_{air} = P \tag{4}$$

Therefore in the case of air an additional non-linearity is present due to the bulk modulus variation with pressure on top of the non-linearity due to the muscle length changing. An elongation leads to a smaller volume configuration hence to an increase in pressure and hence to a higher stiffness.

$$K_{air} = \frac{\Delta F}{\Delta x} = \frac{Af(p)B(p)}{V} \tag{5}$$

These results were experimentally confirmed. Experiments to assess stiffness have been carried out firstly with water and then with air. In both cases the muscle was pressurised at a set pressure, the inlet valve closed and the output valve removed in order not to have any leakage to atmosphere and the connection plunged (it should be noted that for the tests with water a bleeding is necessary to remove entrapped air).

Initially the muscle was left free to contract up to its maximum value (around 25%), then the load force was steadily increased regulating the pressure in the loading cylinder. Forces and corresponding contractions were recorded. The stiffness was computed by numerically differentiating the force with respect to the muscle length. Since signals were noisy the derivative was performed using values coming from a 60 sample averaging process.

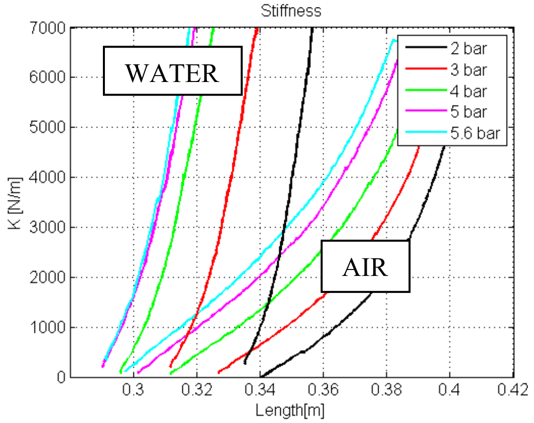


Fig. 5. Stiffness vs. length of the water- and air -supplied muscle with length and pressure.

As Fig.5 shows stiffness increases both with pressure and length (i.e. decreases with contraction) and in the case of water it is almost an order of magnitude higher than for air.

B. Bandwidth

The bandwidth is directly related to the concept of stiffness in this application. In order to measure it, tests were made in isometric conditions. Before undertaking the experimental work, a lumped parameter model of the system was developed to theoretically assess the difference in bandwidth between water and air supplied muscle. The electrical equivalent of the system is depicted in Fig. 6. All resistive pressure losses due to valves and fittings were modelled as an equivalent linear resistor R, the flow-pressure governing equations were linearised and the capacitive effect of the volume of the connecting hoses was negligible.

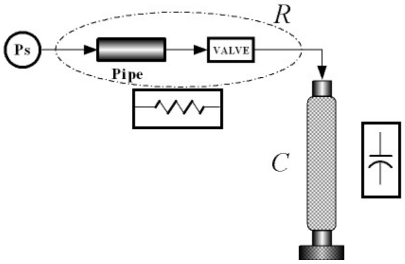


Fig. 6. Pneumatic/hydraulic circuit and its electrical equivalent.

The muscle was represented with a capacitance C. The linearised relation leads to [23]:

$$P_s - P = RC\frac{dP}{dt} \tag{6}$$

where P_s is the supply pressure and P is the actual muscle pressure. Hence in a linearised context the dynamics of the system are first order with $\omega_c = 1/RC$ being the cut-off frequency. Treating air as a perfect gas the capacitance for air can be obtained with the gas law [21]. At a temperature of 25°C (298 K) and at a volume of 0.4 l (max contraction 20%) yields:

$$C_{air} = \frac{V}{R_{air}T} = \frac{0.0004}{287*298} = 4*10^{-9}\,kg/Pa \tag{7}$$

where R_{air} is the gas constant divided by the air molar mass R_{air} =287 J/kg*K. Water hydraulic capacitance can be easily obtained by differentiating (1) with respect to time and changing the sign:

$$\frac{dP}{dt} = -\frac{B}{V}\frac{dV}{dt} \Rightarrow \dot{m} = \rho\frac{V}{B_{water}}\frac{dP}{dt} \Rightarrow \tag{8}$$

$$C_{water} = \rho\frac{V}{B} = \frac{1000*0.0004}{2.15*10^{9}} = 1.86*10^{-10}\,kg/Pa$$

where ρ is the water density and B_{water} the water bulk modulus at room temperature B_{water}=2.15*10^{9}Pa.

The main resistive pressure losses are the ones in the valves. To calculate them, firstly the relationship between flow and pressure was measured and linearised at 3 bar, obtaining 5.13 l/min/bar for water and 304 normal l/min/bar for air. As the air flow-meter gives a measurement at standard ISO conditions (P_0=1bar, T_0=293.15 K, ISO 6358) the value must be pressure and temperature compensated as per ISO 5167-1 standard [22]

$$Q_{out} = Q_{std}\frac{P_{std}}{P_{out}}\frac{T_{out}}{T_{std}} \qquad \rho_{out} = P_{out}/R\,T_{out} \tag{9}$$

where R=8.314 J/(K*mol) is the gas constant. From the measured flow and pressure drop the value of the resistance is calculated. The time constant (and so bandwidth) have been derived according to the values of resistance and capacity. Table I summarises the results:

TABLE I
MODEL PARAMETER AT MAXIMUM CONTRACTION

	WATER	AIR
Resistance [Pa*s/kg]	800000	1938580
Capacitance [kg/Pa]	3.72 *10^{-10}	4*10^{-9}
Time constant [s]	0.00015	0.009
Bandwidth [Hz]	1070	17

From table I it can be seen that water bandwidth is more than two orders of magnitude higher than that of air. In case of water the theoretical value of the bulk modulus is representative of a condition without entrained air. This is physically not realistic. In practice in the experiments a certain amount of air is always entrained and it affects strongly the bulk modulus. A small free air percentage can produce a large reduction of the bulk modulus. Therefore in the experiments it is expected to find a significantly lower bandwidth for water (but still higher than air) than the above-mentioned value.

Since some components have non-linear dynamics it is not possible to assess the bandwidth open-loop by simply supplying a chirp signal voltage to the valve solenoids and measure force and pressure, because in non-linear systems bandwidth changes with input signal amplitude. A closed loop pressure control is necessary. The pressure sinusoidal reference amplitude is set between 2 bar and 4 bar with a frequency between 0.5 Hz and 16 Hz. The choice of using 2 bar as the lower value for pressure was to prevent the muscle to deflate during venting and to work at a higher value than the threshold pressure. During each test the brake is kept active to maintain the muscle at a fixed contraction. Each test was repeated for 0%, 5%, 10%, 15% and 20% contraction for both air and water. An FFT analysis was then carried out and two empirical transfer functions calculated to estimate the bandwidth for both pressure and force at different contraction levels. The results are summarised in Fig. 7 and Fig. 8. The bandwidth decreases with contraction because the volume increases and as expected water pressure bandwidth is always higher than air bandwidth. For 20% contraction the result (7.5 Hz) is not far from the theoretical value (17 Hz) for air while (as expected) there is a big difference for water. A reason can be due to the fact that the measured bulk modulus is different from the theoretical one because of the presence of a certain amount of undissolved air that is difficult to estimate. A limit to the bandwidth is given also by the valve dynamics that is the most critical limiting factor. Some dynamic tests on only the valve have been carried out. Since the measurement of the spool position was not available, the valve opening time has been roughly estimated by measuring the pressure dynamics with closed ports. An estimate of around 22ms has been obtained. Furthermore structural modes of the supporting structure become important at higher frequencies since the dynamics of the light metallic frame is excited. Finally muscle and pipe wall compliance also contribute to further reduce the bandwidth. It should be eventually noted as stated in the introduction, bandwidth can be further improved by reducing dead volumes as is done in pneumatics.

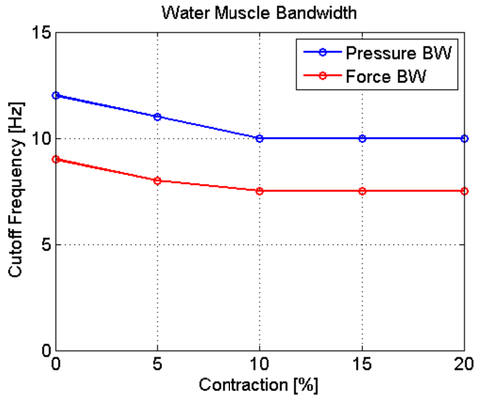


Fig. 7. Water bandwidth for different contractions.

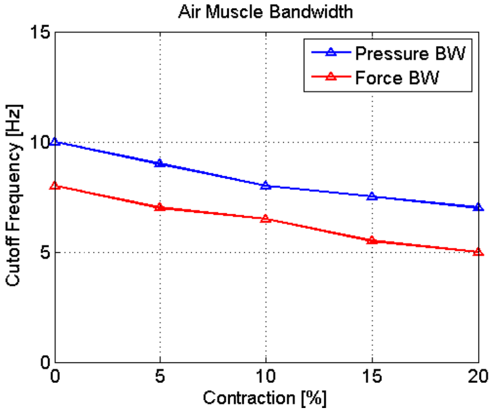


Fig. 8. Air bandwidth for different contractions.

V. PRESSURE AND POSITION CLOSED LOOP EXPERIMENTS

Pressure and position control closed loop tests have been performed with trapezoidal reference signals. The tests have been performed for both air and water using the parameters of the control system listed in Table II. Results are shown in Fig. 9 for pressure and Fig. 10 for position.

TABLE II
POSITION AND PRESSURE REGULATOR GAINS

	Water	Air	Trapez. reference signal
Position PI (500N load)	P=500; I=5	P=300; I=2	Range: 7.5%-12.5% contr. Frequency: 0.5 Hz
Pressure P (contraction 10%)	P=10	P=5	Range: 1.4-3.6 bar Frequency: 1 Hz

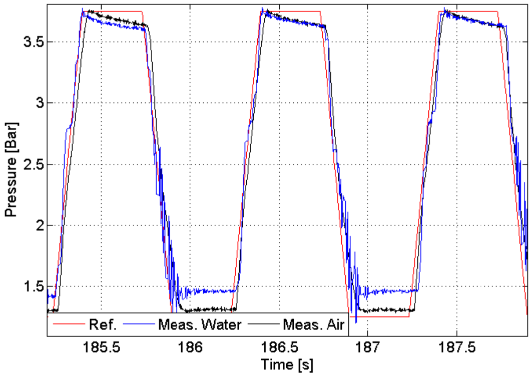


Fig. 9. Response of water and air muscle to a trapezoidal pressure reference.

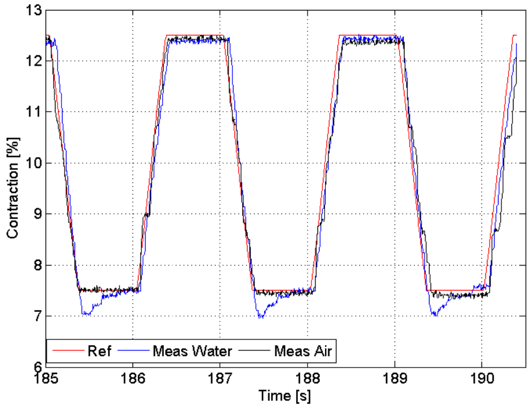


Fig. 10. Response of water and air muscle to a trapezoidal position reference.

In the position response with water the undershoot is caused by oscillations (they are present also in the pressure response) that are postulated to be due to the high water stiffness at lower contractions. Indeed, as there is a load applied, lower contractions correspond to lower pressures. In future a derivative term in the controller will be implemented to add more damping to the water supplied system.

An advantage of using water stems from the energy saving. As water is almost non-compressible a significantly lower (two orders of magnitude) compression work is required to generate set pressures. If we define efficiency as:

$$\eta = \int_{t_0}^{t_0+nT} |Fv|\,dt \Big/ \int_{t_0}^{t_0+nT} |PQ|\,dt \qquad (10)$$

An integral of the force-velocity product over the time interval of Fig. 10 reveals a similar mechanical energy production of 93 J for water and 65 J for air. Measurements revealed that average mass flow is only three times higher for water than for air. This means a lower volumetric water flow since density is more than two order of magnitude higher (at 5 bar). Therefore power consumption is significantly lower for water leading to a higher efficiency.

A. Robustness

To assess the improved rejection of water to load disturbances steady positioning tests were performed. A constant contraction set-point was given while a 1 Hz sinusoidal load disturbance (170 N to 600 N) was applied. The experiments were repeated for three values of contraction (5%, 10% and 15%). The RMS of the error was calculated over 10 cycles (Table III).

TABLE III
RMS OF THE POSITIONING ERROR

Contraction	5%	10%	15%
RMS Air [mm]	1.6	1.8	1.5
RMS Water [mm]	0.06	0.07	0.0001

The results show a better noise rejection of the water to load disturbances. To obtain errors comparable to air, further tests have been done with a higher amplitude load disturbance (170-1000 N) and (170-1450 N) obtaining RMS errors of 0.4 mm and 0.7 mm respectively.

VI. CONCLUSIONS AND FUTURE WORK

The purpose of this work was to investigate the feasibility of using water to actuate a pneumatic FESTO muscle instead of air. First experiments to estimate the stiffness of the two means have been carried out showing that water stiffness is higher and that varies linearly with pressure while air stiffness varies non-linearly. Then theoretical analysis has been carried out to assess if pressure and force bandwidth could be increased by the use of water. Experiments have validated these assumptions. Closed loop positioning experiments showed that a water powered muscle is more reactive to load variation and therefore positioning accuracy is improved. On the other hand dynamic positioning experiments showed worse control performance due to the more underdamped characteristics of water. Finally the mass flow with water is reduced (at the same supply pressure), with benefit in terms of energy efficiency. On the other hand from an implementation viewpoint the use of water requires addressing problems of corrosion, algae, poor lubrication and filtering. A con of using water is the weight increase. Future works will investigate more sophisticated control algorithms loops and antagonistic configurations.

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