Smart Pneutronic Equipments and Systems for Mechatronic Applications

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Abstract: This paper illustrates the state of the art of pneutronic systems. The article starts from the market analysis in the world. Then two important problems (energy and friction) are analysed and some possible evolution trends are indicated. Some interesting mechatronic applications in industrial and non industrial fields are presented. From the analysis pneutronic systems appears in rapid evolution with good trend for the future.

Keywords: smart pneutronic devices, electro-pneumatic systems, pneumatic components

1. INTRODUCTION

The pneutronic devices are an important sector of the automatic systems and they can be completely considered mechatronic systems, due to a full integration with electronic equipments.

Over the years, pneumatic was developed with following phases of evolution. In fact, the fluidic logic studied and expanded the jets technology, the pneumo-logic elements developed innovative pneumatic components with special characteristics, the microfluidic logic grew up news devices and particular mechatronic applications, useful in fields not exploited before.

The progressive integration with electronic sensors and controls was the main factor on this evolution, that changed pneumatic from a mechanical technique to an hybrid technique. So, nowadays, the term “pneutronic” means a symbiosis between two technologies, pneumatic and electronic.

The use of sensors, of new materials, of proper control techniques allows to obtain better and wider perfomances. In this way, the various applications can be transferred from the traditional manufacturing sectors to innovative ones, such as health, rehabilitation, human aid movement, food, agriculture, transports, etc…, with particular attention to energetic aspects and high efficiency.

A real revolution has then transformed the standard circuits, with valves and actuators, in complex mechatronics systems.
In this paper the required performances and the involved technologies are considered. Energetic problems and their solutions are examined. Then, some examples of pneutronic applications in non conventional fields are considered.

2. REQUIREMENTS FOR PNEUTRONIC SYSTEMS

To satisfy the present demands, the pneutronic systems must have very important characteristics, both in functional performances, reliability and working life.

The main characteristics of a smart pneutronic system are: good accuracy in setting and respecting parameters; high speed and high working frequency; high reliability; long life; energy saving; low cost.

All of these characteristics can be obtained with an effective design and with a careful choice of materials and construction technologies. Some important points to improve pneutronic systems are:

- <u>use of new materials</u> (polymers for valves and cylinders, textile products for actuators, innovative seals).
- <u>use of nanotechnologies</u> (coating technologies, use of nanotubes in carbon and microfibres in polymers).
- <u>integration with smart electronic devices</u> (sensors and controls).
- <u>use of rapid prototyping technologies</u> (construction of integrated elements with complex shapes).
- <u>use of proper CAD/CAE software</u> (design, simulation and project of new components, circuits and systems).
- <u>work in specialized multidisciplinary research groups.</u>

This last point is important to reach the best pneutronic systems applications, with the advice of experts in a special technical field.

3. ENERGY SAVING

The general conditions used as reference for energetic problems are referred to the Protocol of (Kyoto 1997) on climatic changes; increase of energetic cost; competition with

countries having low energetic costs (China, India, etc…).
For what concerns to the electrical energy consumption in industries all over the world, we can think that to generate

compressed air, a percentage higher than 10% is consumed every year, (Save 2000). To produce compressed air 400 TWh are required in the world and 80 TWh are required each year in EU.

As reference, distribution of energy required in European industries for different uses is reported in figure 1, Motor Challenge. The energy for compressed air production is evaluated about 17% of the total energy used.

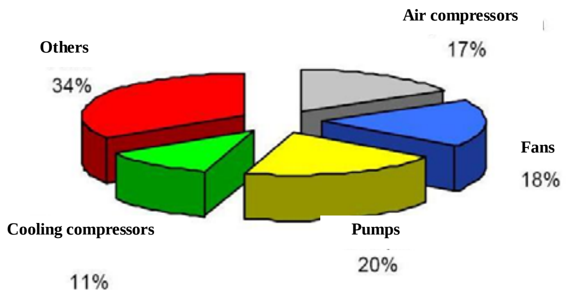


Fig. 1. Distribution of energy in industries.

In Europe the average efficiency of the working systems is about 23-30%, with a maximum value of 80% for a completely electric system; in the pneutronic systems it is less than 20% (BFPA – British Fluid Power Association).

With this efficiency, it is important to find strategies and techniques capable of improving the trend. The European Council has recently underlined to the national governments the goal to reduce, within 2020, gas emissions of about 20%, in comparison with the 1990 levels. This can be obtained increasing efficiency in the energy use of about 20%, with a renewable energy sources production about 20%. So, the production and the use of compressed air in the industrial sector has an important role with great possible benefits, (Save 2000).

The energetic improvement on pneutronic systems can be obtained in various ways:
a) limiting the supply pressure in the chambers of actuators;
b) using a non atmospheric vent pressure;
c) designing cylinders with energy saving;
d) recovering kinetics energy.

In the first case, we consider consolidated techniques for energy saving in the control of actuators movement: the use of 5/2 directional control valves, spool type, with two different supply pressures; the use of pressure reducing valves installed between directional control valve and cylinder; the use of 2/2 directional control valves controlled by end-stroke sensors. All of these solutions are based on limiting the mass of compressed air used, changing the supply pressure in the actuators chambers.

In the second case, we foresee the discharge of valves in an environment with non atmospheric pressure. This kind of solution foresees to discharge the actuators chambers to tanks with reduced pressure (0.2-0.3 MPa) in comparison with the supply one. Then, the air can be used for low pressures loads (for example blower nozzles or drying air devices). Based on Japanese studies, the energy saving on cylinders can be evaluated about 15%, (Mutoh et al., 2008).

The third way uses special designing of actuators with a greater number of chambers, in order to discharge air that is present in the driving chamber of an actuator at the end of the working stroke to many parallel chambers with a lower pressure, always guarantying a proper motor force in the return stroke, (Quaglia et al., 1995).

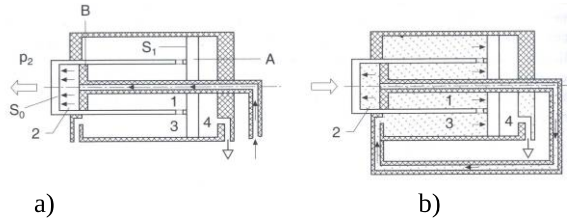


Fig. 2. Energy saving cylinders: a) compact cylinder outstroke; b) compact cylinder instroke.

The last solution sees a conversion of kinetics energy of moving masses of a pneumatic cylinder into a pressure, at each end of the stoke. The goal is to obtain a real pneutronic axis, with valves, sensors and control units integrated in the actuator, that can be programmed in order to switch valves with a energy saving logic in all applications.

To reduce the energetic losses and to increase the system performance, the control strategy shown in Figure 6, can be adopted, (Quaglia et al., 2009).

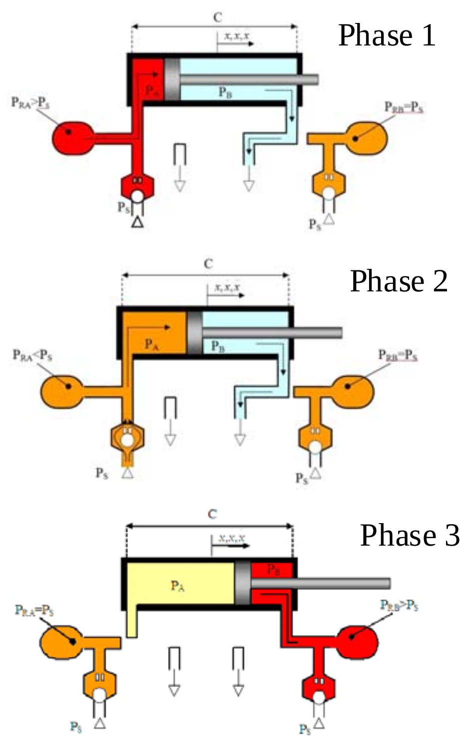


Fig. 3. Recovery kinetics energy.

Each cylinder stroke is developed in three phases (Figure 3).

In the first one (phase 1) the rear chamber A is connected to a tank where pressure P_{RA} is more than supply pressure P_S. this

is due to the energy saving obtained as pressure during the braking back stroke. The frontal chamber B, instead, is connected to atmosphere. Therefore, the actuator piston can be moved on the right quicker than if it were connected to the supply source. In the second phase (phase 2), decreasing the pressure P_{RA}, the rear actuator chamber A is connected to the supply pressure, P_S, while the frontal chamber B is connected to atmosphere.

In the third phase (phase 3), the rear chamber A is isolated, while the frontal chamber B is connected to a tank. In this way, a braking phase of the actuator piston can be obtained, with a contemporary reduction of the pressure in the rear chamber A and an increment of pressure in the frontal chamber B.

The schema of the electropneumatic system is shown in Figure 4.

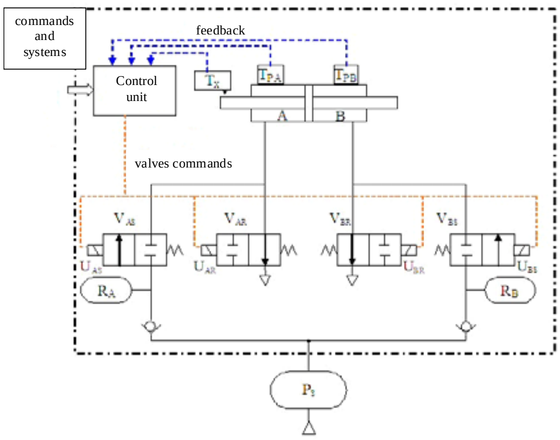


Fig. 4. Recovery kinetics energy.

Here a double acting cylinder and with a crossing doubled rod, is connected to four 2/2 valves. Upstream to V_{AS} and V_{BS} valves, a check valve and a tank are put, respectively R_A and R_B. They are tanks of the pneumatic energy saved during the braking phase.

The energy saving in this case is between 30% and 40%, referred to the working conditions.

4. FRICTION REDUCTION

Friction is a fundamental phenomenon in all mechatronics systems, because it influences the movements. The friction reduction is important to reduce movement resistance forces (energy reduction), to reduce or to eliminate stick-slip phenomena (accurate control of electro-proportional valves; accuracy of target point in continuous positioning systems), to permit low wear and then to guarantee long life.

In pneutronic components, friction is especially due to slippage of sealing elements on a counterface, such as spool and rod in valves, piston and rod in cylinders. Generally to reduce slippage friction on seals a lubricant fluid is used, in general oil or grease, nowadays grease. This is an important point, because the use of grease generates problems of pollution during the working conditions and in the components waste in the end of their life. The European Union requires to reduce grease to protect environment (E.U. Project “Kristal”, www.kristal-project.org).

To improve the seal behaviour it is necessary to optimise the geometry of seals and to use proper materials, looking at working pressure, speed and temperature levels. Some special techniques, using coating or with micro-grove to keep grease (texturing technologies), are adopted.

To optimise seals geometry it is often necessary to use numerical simulations (FEM analysis) and experimental tests carried out on sample of material, on a single seal, on pneutronic components, (Daley et al, 2000; Calvert et al, 2002; Belforte et al, 2006; Cy et al., 2006). In Figure 5 an example of FEM simulation is shown, (Belforte et al. 2006).

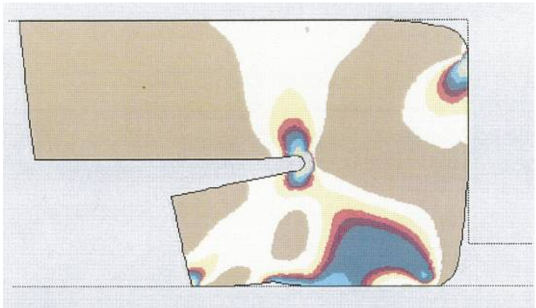


Fig. 5. Numerical technique for a leap seal study.

The numerical models can be validated with tests that often use photoelastic techniques, with seal sections covered by a photoelastic film (Figure 6), (Bignardi et al., 1999).

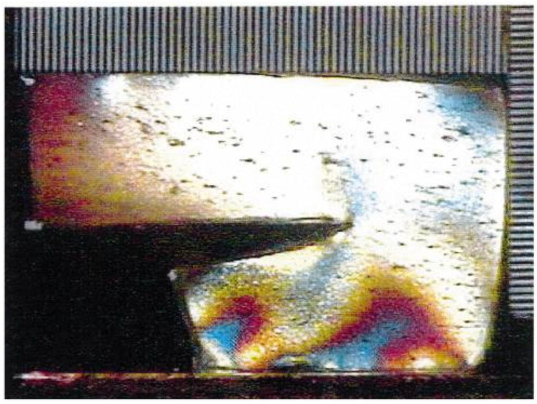


Fig. 6. Experimental photoelastic technique for seal study.

Other experimental activities can be carried out with a local measure of pressure in the contact area between sealing and counterface. In particular, measurements can be performed using pressure sensitive films, to be interposed between the contact surfaces, (Belforte et al., 2009).

Tests can be carried out both on seal rectilinear specimens and on various commercial piston seals. In Figure 7, an actuator with tube of 50 mm in diameter was modified to obtain a window, so that a film sensor sheet could be placed upon the seal.

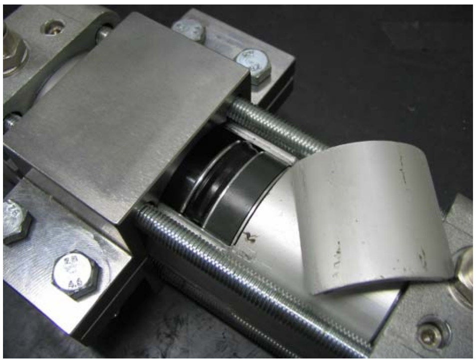


Fig. 7. Pressure sensitive film on commercial piston seals.

With reference to tests on rectilinear specimen (seal segment) the test set-up also allows the optical visualization of seals cross section in order to evaluate seal deformation and seal extrusion, (Raparelli et al., 1997).

The measure of friction forces in various working conditions (pressure, velocity, lubricant conditions, etc…) is possible by means of proper modular experimental set up in which actual working conditions can be reproduced. Tests are allowed on single seals or complete cylinder.

In Figure 8 an electrocylinder drives at constant velocity the rod of a cylinder under test; the friction force due to relative motion is discharged on the cylinder tube and rear end supported by an air bearing pad and measured by a load cell.

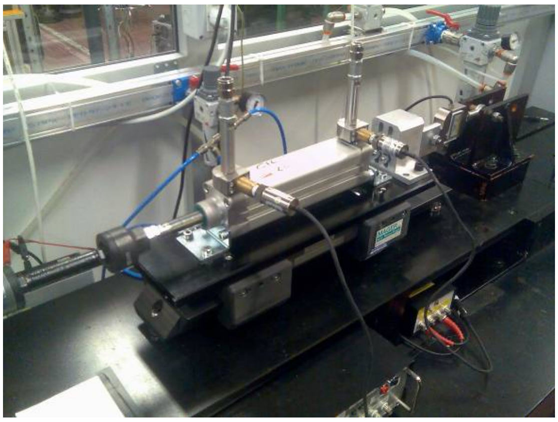


Fig. 8. Friction force measurements – configuration for whole commercial cylinders.

According to different test benches, the speed can be regarded in the range: 0-0.3 ; 0-0.6 ; 0-5.0 m/s.
For low speed experimental set up with electric motors or hydraulic drives can be used, while for high speed only electric linear motors have to be used.

Life and reliability are very important, in particular in mechatronic systems, where parameters of mechanical and pneumatic devices are compared to those of electronic ones. So, it is important to set proper life test methods and wear mechanism measurement. An example of experimental test bench for wear detection is shown in Figure 9.

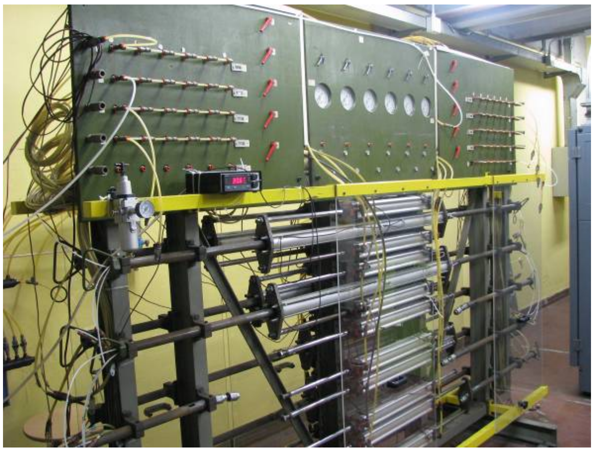


Fig. 9. Test bench for accelerated tests on pneumatic piston seals.

5. MECHATRONIC APPLICATIONS

Nowadays, pneutronic systems are used in various industrial and non industrial fields. The integration between compressed air technology and electric/electronic devices allows both to improve actual systems and to open new borderline for innovative applications.

Thanks to the miniaturisation and to the use of very efficient materials, useful for eletromechanic actuations, microelectrovalves are available with working frequencies up to 500 Hz. The electronic control of pressure is nowadays a standard application and it allows optimum force controls useful for smart grippers. Pneumatic sensors suitable for the presence of objects or with tactile characteristics give new possibility of use, for example in case of high temperature applications (engines, chemical plants, etc…).

Pneutronic is now gone out from the traditional applications of pnematics and is directed towards themes considered very important from the EU, such as health, food, transports.

Here as follows, some various applications in industrial and non industrial sectors will be examined:

- production systems;
- textile industry;
- health and well-being;
- food;
- agriculture;
- transport.

a. *Applications to production systems: pneumatic pads and bearings.*

An interesting application of pneutronic devices to the production systems is the construction and the use of pneumatic pads and pneutronic rotating bearings using compressed air. The use of a gas as a lubrificant means allows to obtain very efficient supports, with very low friction, capable of working without stick and slip effect and with very high velocities. These characteristics are absolutely important for measurement equipments, for testing machines, for assembly devices, for precision robots, for various kinds of electrospindles and microrotors, etc...

In translation systems used in fast machines, a proper solution foresees the use of linear electrical motors and air bearings without friction, connected to the moveble parts of the system.

Air bearing can be used without any preload or preloaded, in order to maximise the stiffness of the air bearing and help maintain constant air gap. High stiffness is required in precision machinery in which an accurate position of moving parts is necessary to guarantee the final processing requirements. In Figure 10 four possible solutions are shown:

a) weight preload pad;
b) opposing air bearing preload;
c) vacuum preload;
d) magnetic preload.

Except for the first solution, the other ones are all capable of guarantying a stable connection without any detachment between fixed structure and mobile part, as it is necessary for non horizontal applications or in presence of dynamic forces due to accelerations.

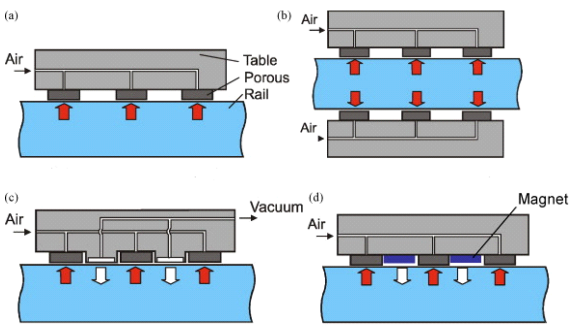


Fig. 10. Preloading air bearings.

In Figure 11 an industrial linear translation unit, composed by electrical linear motor and magnetic preloaded air pads, is shown, that can be used for high speed electronic testing devices (http://www.mager-ab.com/).

Fig. 11 Industrial linear translation unit, composed by electrical linear motor and magnetic preloaded air pads.

In Figure 12 an active pneutronic pad is shown. Here the pad can change its shape using piezoelectric actuators, that are activated measuring the distance between the pad and a mobile plate and using a capacitive sensor, (Farid 2009).

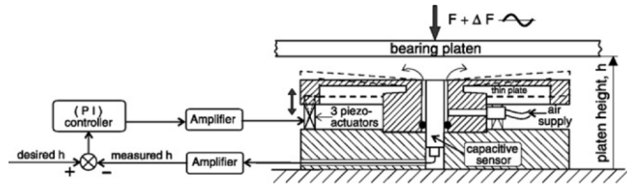


Fig. 12. Piezo-active air pad.

In static conditions, the piezoelectric actuators modify the air clearance shape and the consequent load capacity. As a result it is possible to increase the pad stiffness respect to the passive pad.

Different solutions may be adopted for supply compressed air system: annular orifice, orifice with feed pocket, supply line with woven wire clothes, metal powders sintered pad. The use of circumferential and/or radial groove can improve the behaviour. Certainly, the design and the study of these components require proper simulation software and experimental validation tests.

Air pad is an example of precision mechanics. In fact, it is necessary to study devices in which the reference dimension is of the order of magnitude of one micron, with gap height about 5-10 microns. Pressure distribution in this gap is the basis of any calculus, (Renn et al., 2002; Belforte et al., 2007; Colombo et al., 2009). In particular the pressure distribution close to supply hole is important, (Belforte et al., 2007; Colombo et al., 2009).

In the fields of rotors, the rotations speed can be different, in comparison with the application and the rotors dimensions.
In any case, for rotors with high velocity of rotation it is necessary to use smart mechatronic devices with electrical motors and air bearings. There are various applications with different fields of rotor angular speed: electro-spindle for mechanical operations (up to 100.000 rpm, Figure 13), drill for electronic cards (up to 200.000 rpm), rotor for textile production (up to 150.000 rpm), rotor for micro-generation of energy (up to 500.000 rpm).

Fig. 13. Electro-spindle.

Development of high spped rotors require accurate theoretical models and numerical simulation, supported by epxerimental tests validation, (Belforte et al., 2006; Belforte et al., 2008).

b. *Textile industry*

The textile industry is an important user of compressed air (air spinning, air texturization , etc…). The sector of air spinning is very important for its high capacity of production. A fundamental factor is the consume of compressed air, for its high cost of production. Here, the pneutronic system used is quite complex, having a main nozzle and some relay nozzles, with an eletropneumatic circuit based on electrovalves with low response time (Figure 14).

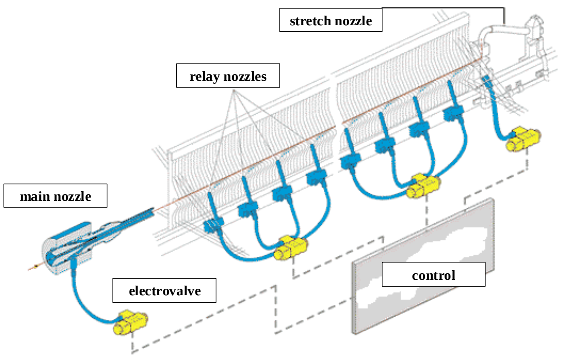


Fig. 14. Air jets looms.

The system efficiency is based on an accurate dimensioning of pneutronic components and on a proper smart control system, (Belforte et al., 2009; Belforte et al., 2011).

In Figure 15 the sketch of an efficient main nozzle is shown. The compressed air is supplied through a conical annular nozzle and the weft yarn is introduced through the control orifice.

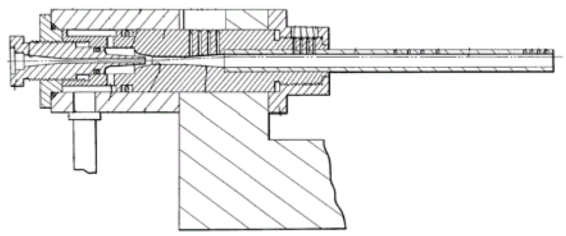


Fig. 15. Main nozzle in an air jet loom.

Standard loom consumption, in normal operative conditions, can reach and get over 900 dm^3/min (ANR). With an optimisation of pneumatic components (main nozzle and relay nozzles) and a proper electronic control of electrovalves, Belforte et al., (2009), Belforte et al., (2011), an economical saving (more than 25%) can be obtained. With a number of 100 weaving machines, the economical saving is 1350 dm3/h (ANR). On the basis of 4000 working hours in a year, the economic benefit is 81.000 euro.

c. *Health and well-being*

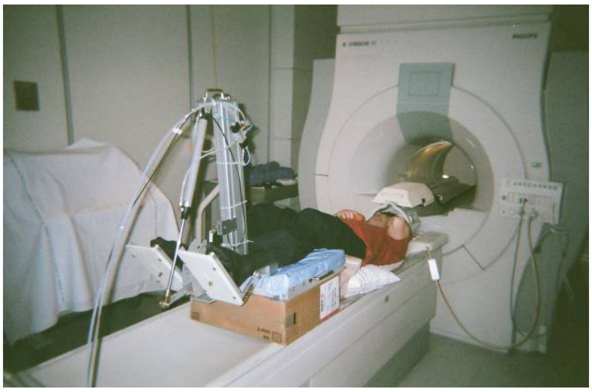
During the second half of the last century, a large body of basic research addressed the biomechanics of the musculoskeletal system. A number of reasons have motivated interest in this area. The increasing number of the elderly, for instance, has made it necessary to deal with problems such as hip and knee osteoarthritis. For younger people, on the other hand, research has focused chiefly on patellofemoral problems following cruciate ligament rupture.

Work on biomechanics and rehabilitation techniques thus influences the independence and the quality of life of individuals living with chronic conditions, (Wang et al., 2009; Ghafari et al., 2009; Lunenburger et al., 2007).

Design and development of powered exoskeletons for locomotor rehabilitation therapy is a topical research issue worldwide. Basically, an exoskeleton is a kind of pneutronic or electronic man-machine system designed as an external structure whose joints must correspond with those of the human body. Research in these devices thrived at the end of the 20th century, when researchers in the United States, Japan, Germany, and other countries introduced many innovations in the man–machine concept. Exoskeleton type systems then developed rapidly. Robot neuro-rehabilitation has actually had a great impact on motor learning, due to its high measurement reliability and high intensity training protocols, Dollar et al., (2008). Robots are also used to assist in repetitive movement therapies following neurologic injury. Electric actuation is easily controllable, but can in general produce rigid movements. Pneumatic actuation can ensure that movements are executed safely, due to its inherent ability to adapt to patient response. It is thus minimally invasive and readily accepted by the user (Daniel et al., 2005; Raparelli et al., 2004).

In Figure 16 two propotypes of pneutronic devices useful for motor learning and for robotized neurorehabilitation are shown, (Belforte et al., 2011).

In Figure 17 another example of mechatronic pneumatic active orthosis for lower limbs movements is shown, that was developed at University of L'Aquila (Italy), (Raparelli et al., 2000).



a)

b)

Fig. 16. a) MR-compatible interface for motor learning exercises and fMRI analysis; b) Active exoskeleton.

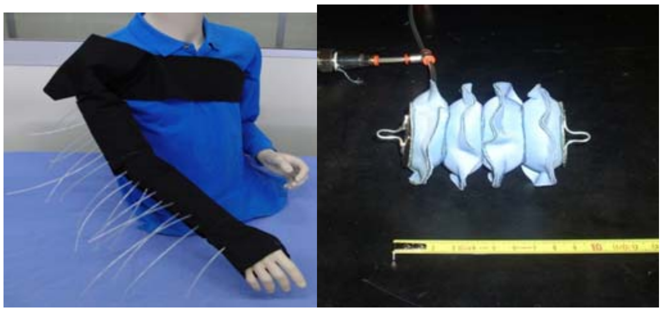
Fig. 17. University of L'Aquila (Italy) orthosis.

Wearability is an important problem in the exoskeletons. From this concept, it is possible to define the idea of active suit, where the movement of a limb or some special rehabilitation therapies can be carried out by a proper integration of actuators in the suit. In this case, a wearable clothes also becomes an actuation system. This concept is defined in Figure 18, where example of active suits with pneumatic muscles (for aid movement of the arm) is shown, (Noritzugu et al., 2005), www.kobalab.com.

Fig. 18. An example of active suits.

Studying this experience, since 2006, in the Department of Mechanics – Politecnico di Torino, an innovative textile reasearch was going on with the purpose to realise an active suit suitable for massage and for arm movement.

In Figure 19 two propotypes are shown. The first one (Figure 19a) is a prototype of a sleeve for upper limbs massage, used to relax the body and for aesthetic purposes. It is made of 21 pneumatic chambers for the whole arm and a glove for the hand. A PLC (Programmable Logic Controller) is set to control the electro-pneumatic circuit. In Figure 19b the prototype of an innovative textile pneumatic muscle, useful for the arm aid movement, is shown.



a) b)

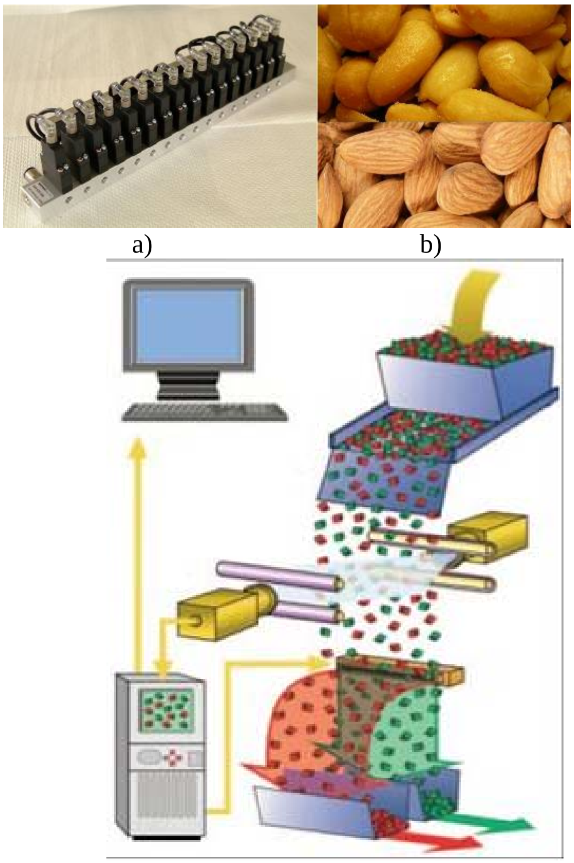
Fig. 19. a) Active suits for massage; b) pneumatic muscle.

d. Food production

Some examples of pneutronic systems applied to foodstuff production, based on microeletrovalves, are referred to the sweet sector and to the selection of non packed products. In these fields, characteristics such as low volume, high working frequency and high reliability are very important. Electrovalves for high frequency, up to 500 Hz, are used, (www.matrix.to.it). The case of Figure 20 is referred to an application where the electrovalves control some jets nozzles, that spray foodstuff materials as decorations on various products, in order to improve their aspect.

Fig. 20. Decorations on foodstuff products (Matrix – Italy).

Figure 21 shows an application where actuation speed and low time control are the fundamental characteristics. The selection of foodstuff products, where it is important to chose in completely safety the proper product, rejecting all not conform to the requirements, is considered. The selection can be easily done for little foodstuffs products (rice's grain or dried fruit, small or medium size). The products fall down vertically, passing in front of a camera and of a nozzle. When camera sets non conforming the product, a pneumatic jet, controlled by a microelectrovalve, expels the discard.



a) b)

c)

Fig. 21. Selection of foodstuff products (Matrix – Italy):
In the figure21: a) is a set of electrovalves; b) food products; c) sketch of pneutronic system.

e. Agriculture

Agriculture is one of the fields where types of robot being developed for specific purposes is growing quickly. The greenhouse in particular is a special type of ecosystem, where pneutronic systems may be used successfully.

Pesticide application in particular is an operation where eco-compatible automation is a pressing need because of the environmental and human health concerns that it raises, (Nuyttens et al., 2004). Generally, in fact, pesticides are applied in greenhouses using simple handwand sprayers, where as much as 80% of the pesticide can be wasted, (Piccarolo, 2008).

Fig. 22. Robot for spraying pesticides in a defined volume.

When low-volume, highly atomized spray equipment is used, on the other hand, spray droplets can evaporate, leaving the active principle of the pesticide suspended in the air. This technique if efficient, but a serious hazard for greenhouse workers and the environment.

The diffusion of greenhouses mobile robot and of new automatic spraying techniques lead to design of automatic systems, capable of various operations, such as: moving on crops; making treatment with very fine droplets fog in a defined flexible chamber; recovering pesticide after treatment; saving both environment and health operator.

In Figure 22 the prototype of the robot useful for spraying pesticides in a defined volume is shown. In this case, pneutronic equipments were used because it was necessary to operate in hazardous enviroments, with high humidity level. Compressed air was used to produce spraying jets, to move nozzles, to open or close a textile cover useful to limit pesticides in a defined volume, (Belforte et al., 2009), Belforte et al., (doi). Experimental tests showed that such pneutronic systems are able to reduce significantly enviroment pollution.

f. Transports

The transport field is over and over in wide expansion. In the railways field, the more innovative aspect is the development of a wide rail high speed train network.

In the field of high speed train, a very important aspect is the braking system, that represents an example of a very complex mechatronic system. For its development, many numerical simulations of the high speed train pneumatic system are required, in order to design special electropneumatic components, different from standard ones and that require proper theoretical models, (Belforte et al., 2008).

In Figure 23 a theoretical model of a particular pneumatic valve in AMESIM code is shown, www.lmsintl.com/LMS-Imagine-Lab-AMESim

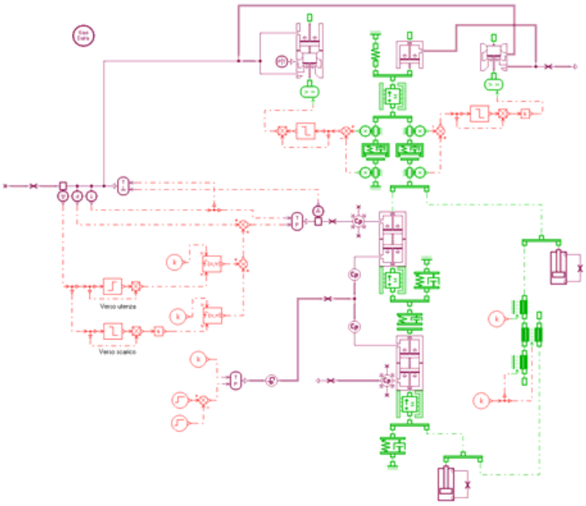


Fig. 23. Amesim simulation of relay valve.

It is also fundamental the use of test benches, capable to reproduce all of the various working conditions of a high speed train during the braking phase.

In Figure 24, the photo a) and the schema b) of an experimental test bench is shown: it allows to measure the functionament and the behaviour of an electropneumatic system, integrated with high speed train braking devices. The system was developed in the frame of the European Project MODBRAKE, www.modbrake.com .

The test bench, that is a mechatronic system too, can be divided into four parts: the control system, the electronic devices, the pneumatic devices, the simultators of brake cylinder.

Fig. 24. Test bench for braking systems applied in high speed trains.

7. CONCLUSIONS

The pneutronic systems need the use of pneumatic and electropneumatic components, with high efficiency and realiability. The energy saving is a very important aim. Friction is a fundamental phenomenon to control. The integration between pneumatic actuation and electronic sensors allows to create mechatronics systems with high efficiency. The possible applications of pneutronic systems spread out to various fields, industrial and not. Pneutronics is nowadays in evolution with good perspectives for the future.

ACKNOWLEDGEMENTS

In this paper figures and photographs without reference are referred to equipments and prototypes developed in the Department of Mechanics – Politecnico di Torino.

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