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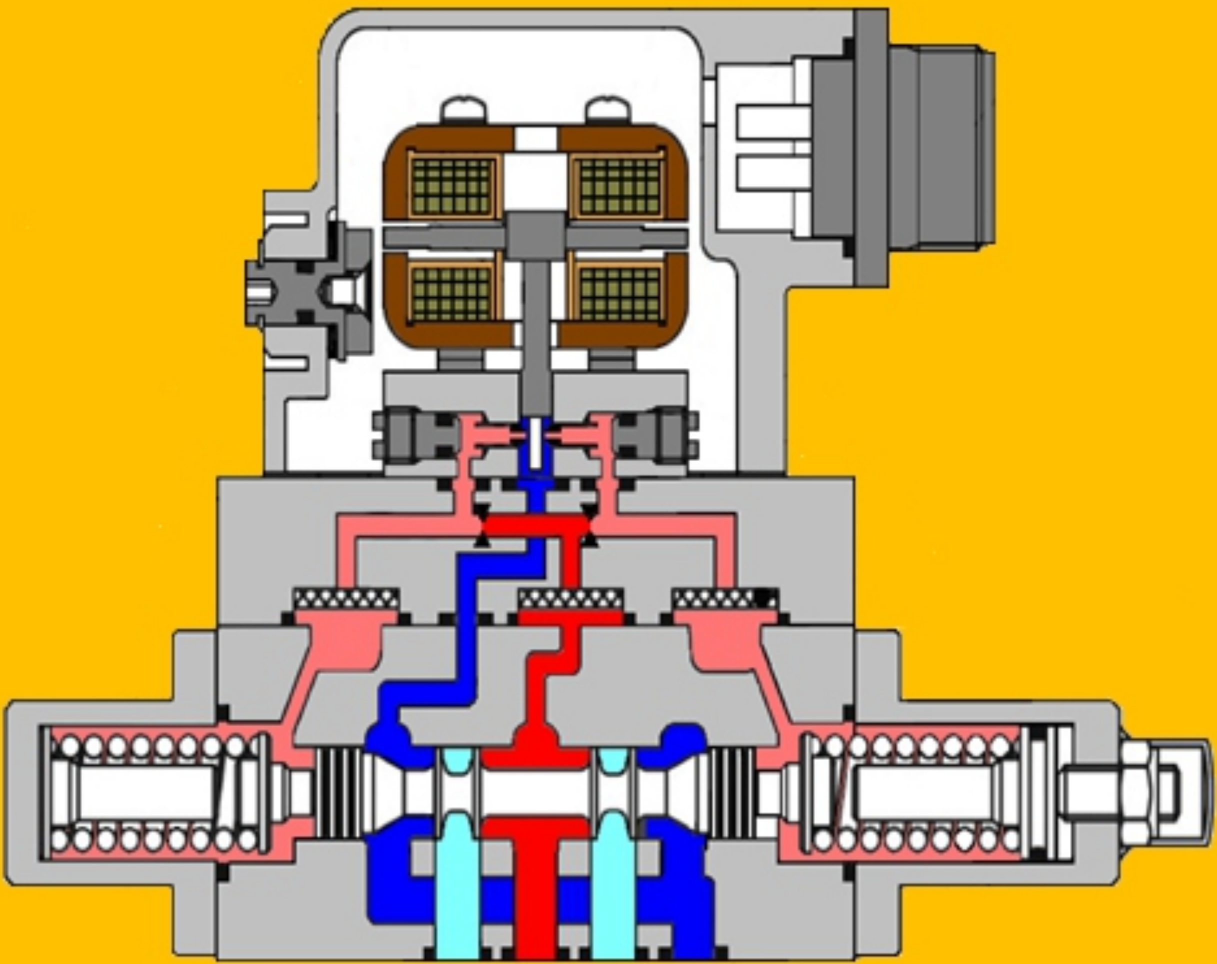

JOSEF CERHA

HYDRAULIC AND PNEUMATIC MECHANISMS I.

LIBEREC 2018

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Faculty of Mechanical Engineering
Department of Manufacturing Systems and Automation

HYDRAULIC AND PNEUMATIC MECHANISMS I

Josef Cerha

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Preface to the third edition

The present textbook “Hydraulic and pneumatic mechanisms I” is intended for students of the 3rd year of the Faculty of Mechanical Engineering, who enrolled in classes of the subject of “Hydraulic and pneumatic drives” and students of the 2nd year, master’s degree in manufacturing systems for the subject of “Dynamics of hydraulic systems” and also students of the 1st year of the master’s degree of the Faculty of Mechatronics, who study the subject of “Hydraulic and pneumatic mechanisms” as well as students of combined study of both faculties. Of course, there are no limits for those who intend to become familiar with this type of mechanisms on their own initiative or an external impulse that is given, for example, by the need for preparing a semester, bachelor’s or master’s thesis. The textbook brings basic knowledge in the field of fluid mechanisms and therefore it is natural that we would search in vain anything completely original in the text. My only task was to make a selection of topics, organize and interpret them. In this context, especially useful have been the books or textbooks of Doc. Prokeš, Prof. Kopáček, Ing. Dráždil and Ing. Zymák and other experts.

In the selection and arrangement of materials I had in mind

- That the hydraulic and pneumatic mechanisms work on the same principle (fluid mechanisms) and thus are interpreted simultaneously, even if they differ significantly in some of their properties. The differences are always pointed out in terms of the characteristics of the elements, significant differences in design, control and application;
- That the designer or engineer, who decides to use a fluid mechanism in the concept of the machine, does not need to construct the elements, but to make a selection of appropriate elements, which are now produced by specialized companies in a wide range, which are assembled in the circuit and meet the requirements not only on function but also on static and dynamic properties of the mechanism.

The first part of the text is devoted to energy transfer in hydraulic and pneumatic mechanisms, basic laws that apply in the transfer of energy and their interpretation referring to the electro-hydraulic analogies. The reader will get acquainted with the basic terms and quantities that make it easier to understand the principle of operation of fluid mechanisms, their parts and some contexts and, last not least, their quantitative and qualitative assessment. A whole series of paragraphs in Chapter 3 can be seen as examples, which make use of knowledge of fluid mechanics and thermomechanics.

Hydraulic mechanisms are discussed in the second part of the textbook. The fourth chapter is devoted to power, control, and other elements: fluids, filtration and filters, connectors, etc. For the above reasons and also because the company literature in this sense is very rich, the interpretation is conceived more or less in an encyclopedic manner, with emphasis placed on the principle of operation, mathematical description, basic (catalogue) data, static characteristics, attractive designs and applications.

The fifth chapter discusses the control of parameters of the power transmitted. The sources of pressure fluids, pressure and flow control or force control or torque control, control of movement frequency, the change in direction of motion and stop of motors with reference to typical designs of circuits with conventional as well as proportional elements linked to control systems.

There also presented the applications of hydraulic mechanisms in the field of manufacturing and processing machinery, and mobile machines.

The above list shows that the range of interest is very broad, but I considered it necessary to take notice of all matters related to the function and design of hydraulic mechanisms to the extent that the reader, after studying the text, acquires the necessary knowledge and enough information for independent work and other possible deeper studying of some specific problems.

For this purpose, a list of literature is enclosed, broken down into book, magazine and corporate literature. The set of books includes titles that are more or less available and many of them inspired me and provided me with not only knowledge, concrete data but also some diagrams and figures. The articles from magazines were used as a basis to illustrate certain specific facts. Corporate documents, very rich, constantly updated and available on the websites of individual manufacturers served as a basis for a wide variety of figures, as the reader will be able to convince himself.

Throughout the text, I tried to apply the terminology and use the schematic symbols set by standards ČSN ISO 5598 "Fluid power systems and components - Vocabulary" and ČSN ISO 1219-1 "Fluid power systems and components - Graphic symbols and circuit diagrams - Part 1: Graphic symbols". However, I must admit that I have not always been able to do so and I have often used the names and terms of the previously applicable standard ČSN 11 9000 "Hydrostatic mechanisms - Terminology". I think that's not such a serious misconduct, but I apologize for that.

The text does not include the modelling of hydraulic mechanisms. I believe, however, that there currently available publications, e.g. [10] [53] [56], [77] and others that are specifically dedicated to this issue.

The following textbooks are devoted to a description of pneumatic elements, their properties, designs, description of their control circuits and examples of applications in manufacturing machines and mobile machines: Cerha, J.: Hydraulic and pneumatic mechanisms II 1st edition. Technical University of Liberec 2008.

My thanks go to prof. RNDr. Ing. Josef Nevrlý, CSc., who carefully read through the textbook in the first and second editions. His comments and observations, that I fully accepted, contributed to the clarity and purity of the text. I also thank to all those whose books, articles and documents I consulted.

In conclusion, I would like to express my pleasure that the textbook "Hydraulic and pneumatic mechanisms I" is already issued in its third edition and I wish all those, who will learn lessons therefrom, success in their studies.

In Liberec, July 2018 Josef Cerha

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HYDRAULIC MECHANISMS

4. ELEMENTS OF HYDRAULIC MECHANISMS

1. INTRODUCTION

The field of fluid mechanisms includes mechanisms that use substances in the liquid state for transferring energy and information. If the energy carrier is fluid, these are the hydraulic mechanisms, if the energy carrier is air, then these are the pneumatic mechanisms. According to the Bernoulli's equation for steady flow and ideal fluid, kinetic, pressure or position energy may be used to transfer energy between input and output transducers. When transducers are designed to use the kinetic energy of flowing fluid (turbines, centrifugal compressors), we speak of the hydrodynamic machines, in which we find the high flow velocities at low pressures.

This textbook deals with the hydrostatic and pneumostatic systems, in which the energy is transmitted through a static pressure and transducers (i.e. hydraulic generators and hydraulic motors) work at high pressures at relatively low flow velocities. For simplicity, the following terms will be used hereinafter:

- Hydraulic mechanisms or shortly hydraulics, or
- Pneumatic mechanisms or shortly pneumatics.

In the interpretation, the fundamentals of hydrodynamics and thermodynamics will serve as a basis [18], [46], [54], [57], [72]. The law will be applied to hydraulic or pneumatic elements (hydraulic pumps, compressors, valves, distributors, cylinders, rotary motors, and accessories - pipelines, filters, tanks, etc.) connected in circuits and systems with regard to their properties.

1.1 Brief historical development of hydraulics and pneumatics

For more than two millennia, mankind uses energy of water and wind in addition to muscle strength. For example, the water wheel is known since the year 200 BC and survived as the drive of water mills or hammer mills until recently and technically developed up to the water turbines. There are mentions that machines driven by air pressure (Archimedes of Syracuse) were developed already in the 3rd century BC. There is a broad description (about 1st century AD) of temple door opening [50], made by the machinist Heron of Alexandria (Fig. 1.1). There was a hollow altar in front of the temple, which was connected

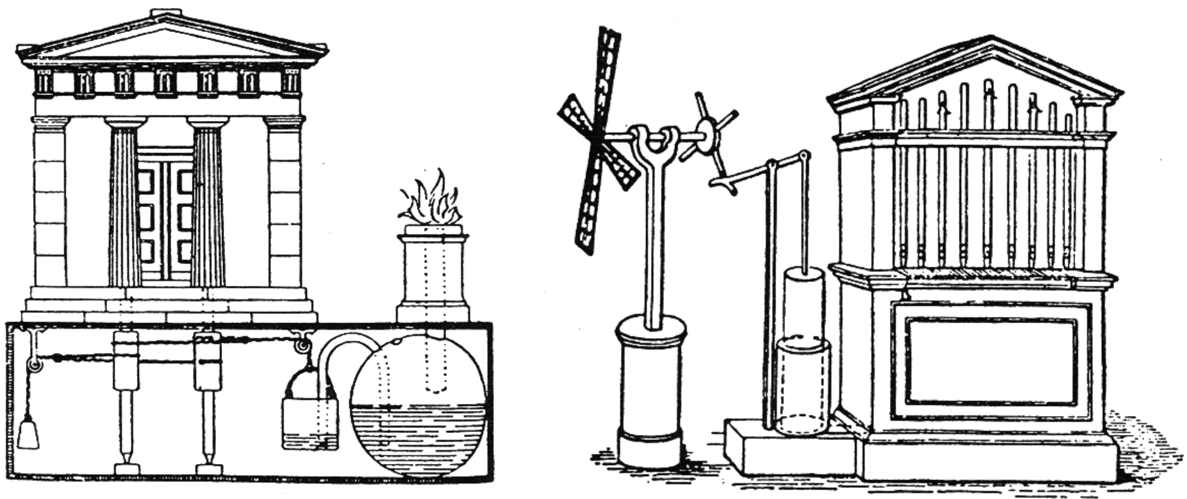


Fig. 1.1. *Use of energy of compressed air* [50]

with a closed underground reservoir with water. Heat of an altar fire warmed air in a tank, which expanded and removed water through a tube into a closed container, the increasing mass of which caused a rope on elongated door shafts to move, thus opening the door. When the altar cooled, air in the tank reduced its volume, creating an underpressure and water was sucked out of the container back to the reservoir. As a result, the weight hanging on the opposite side closed the door. Heron also submitted a proposal for a pneumatic drive of an organ (Fig. 1.1). A windmill was used to drive a piston pump. Air was sucked into a water sealed bell (it was actually the first constant-pressure air receiver) and then flowed into the appropriate organ pipe. Since these early applications, many centuries have passed without any significant application of pneumatics. Not before the 12th century, this technology comes from Persia to the West, where they build windmills.

In the 16th century, a gear pump was invented by Johannes Kepler (1571-1630), which, however, had no use at that time. For the development of hydraulics, work of Blaise Pascal (1623 -1662) was of decisive importance, who explain the principle of the hydraulic press, but industrially applicable press was built by Joseph Bramah (1749-1814) in London in 1795 [13], [49]. The energy carrier was water, the piston in the cylinder was sealed by piston rings. After the invention of a steam engine by James Watt (1736 -1819), the hydrostatics was technically used in England for the transmission and conversion of energy in the form of water pressure distributions (networks). Pressure water was obtained using pumps driven by a steam engine and manufacturing equipment was driven by a piston motor. In the second half of the 19th century, W.G. Armstrong (1810-1900) developed in England many hydrostatic machines and components mainly used in shipbuilding, such as anchor winches and hoists. From that era, application of hydraulics in the construction sector is known - drilling machines in tunnel construction, but also pneumatics - drilling hammers for work in the mines. In 1867, an American entrepreneur, G. Westinghouse, received his patent for a pneumatic brake for rail transport. The central hydraulic networks were also constructed at this time, e.g. the London network supplied energy to about 8,000 hydraulic devices. In the magazine of the Association of German Engineers (VDI), year 1899, several devices working with compressed air are mentioned, e.g. moulding machines, reversing of the points, paint spraying, cannon control, torpedo control, finishing of textiles, pneumatic tube system, etc.

With the development of electric drive in the early 20th century, hydraulics and pneumatics or their central distribution systems lose their previous technical significance because electrical energy allows much simpler transmission. Hand-held rotary pneumatic tools, grinders, drills and screwdrivers, driven by a pneumatic rotary motor, emerged later, which were used in particular where low mass and high speed not achievable by an electric motor were required.

Hydraulics received new impetus in 1905, when R. Janney used oil as an energy carrier. Based on the “Waterbury Pump” (Fig. 1.2) modified by H.D. Williams, Janney constructed a hydrostatic transmission (Fig. 1.3). It is the device built on the principle of an axial piston machine with a plate with variable inclination - regulatory. In 1910, a hydraulic regulator was used to regulate a water turbine and in the same year, the Hele - Shaw company put

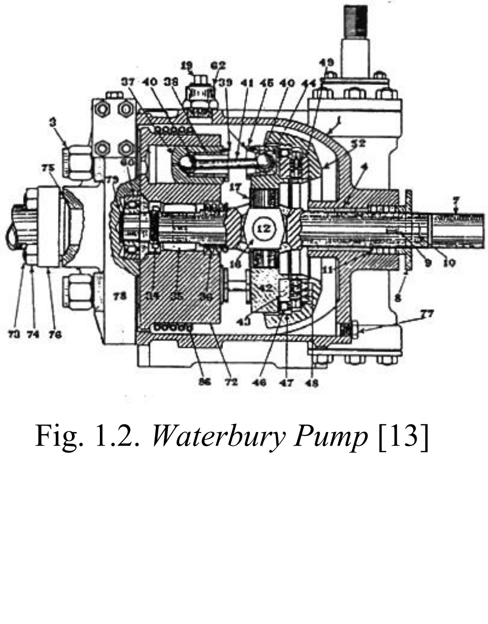


Fig. 1.2. *Waterbury Pump* [13]

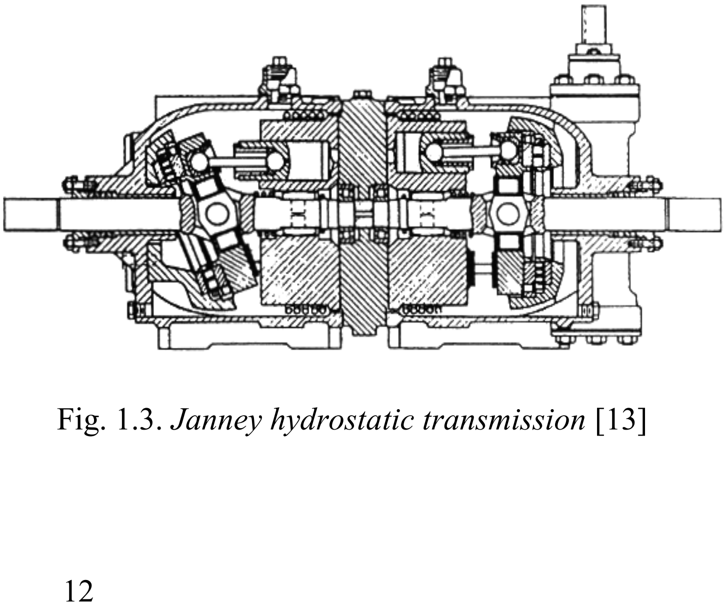


Fig. 1.3. *Janney hydrostatic transmission* [13]

into operation a radial piston machine (Fig. 1.4). The further development of piston-type axial transducers is credited to Hans Thoma. In 1936, Harry Vickers comes up with a design of indirectly controlled pressure valve and in 1950, Jean Marcier builds a hydro-pneumatic accumulator.

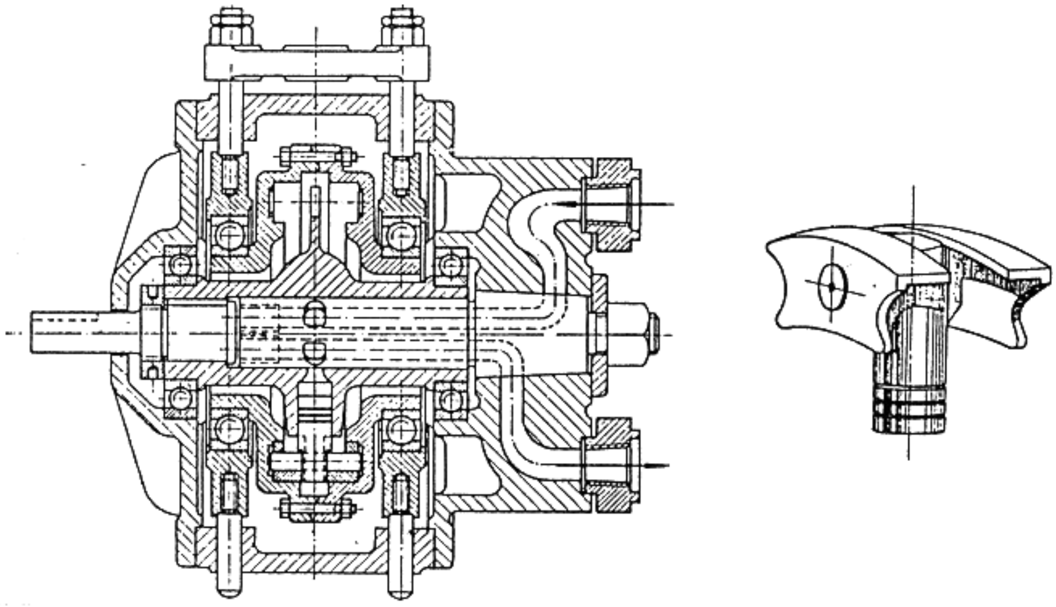


Fig. 1.4. *Helle-Shaw radial pump together with the detail of piston guide in stator path* [62]

Use of pneumatic equipment was initially limited to a few industries, whose special operating conditions required the use of compressed air such as mining, construction (pneumatic hammers and chisels), or in the glass industry, where compressed air was used for bottle-blowing on automatic machines (press-and-blow method), for machine tools (clamping, hydro-pneumatic devices, force control) and the like.

During World War II, the development and deployment accelerated in particular in the area of hydraulic mechanisms, which were applied, for example, in heavy weapon systems for automatic fire control for very short response times to the input signals, in aeronautical engineering for the favourable power to mass ratio, thus enabling to increase the speed and range of aircraft (see Fig. 1.5). Fuel systems of diesel and jet engines are the special area.

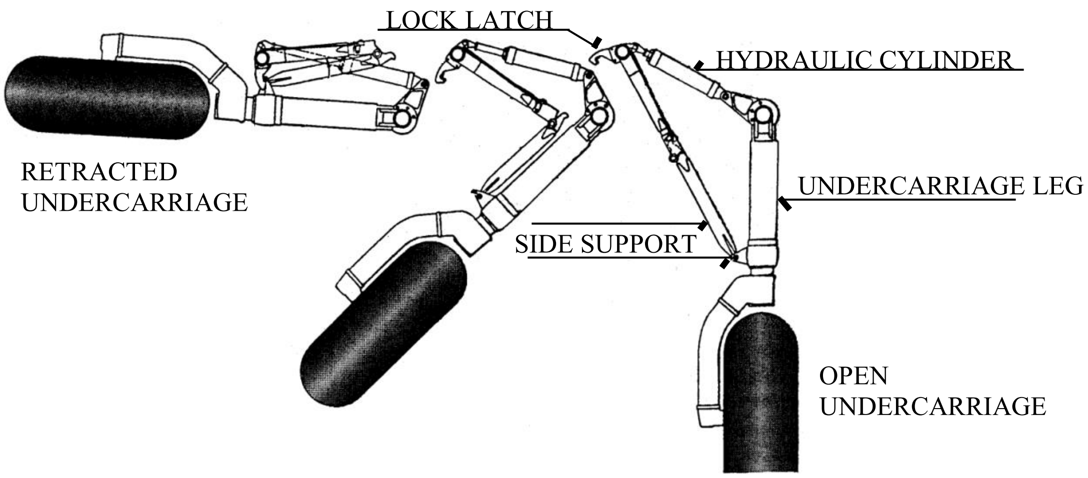


Fig. 1.5. *Hydraulically controlled undercarriage of the LIBERATOR aircraft*

After the war, there was a significant application of hydraulic and pneumatic mechanisms in the field of automation of manufacturing and processing machines and in the field of drives of mobile and other machines, in particular after proceeding to standardization and typing of elements (cylinders - diameters, strokes, valves - inner diameters and connecting dimensions, etc.), i.e roughly in the 1950s. Independent assembly industries have gradually developed from hydraulics and pneumatics. Fundamental theoretical works were created [3]; national (currently in the Czech Republic - the Czech Mechanical Engineering Society, expert section "Hydraulics and Pneumatics") and multinational expert societies (CETOP - Comité Européen des Transmissions Oléohydrauliques et Pneumatiques - European Association of National Associations) were established. Manufacturers of the elements began profiling themselves, bringing them to high technical perfection in recent decades. An example might be a compact hydraulic axle (Fig. 1.6) formed by an axial piston pump (1) with an inclined block and mechanical-hydraulic regulation (3) of the geometric volume, two axial piston rotary hydraulic motors (2) also having am inclined block but with a constant geometric volume, reducers and flanges for fixing the wheels of the vehicle.

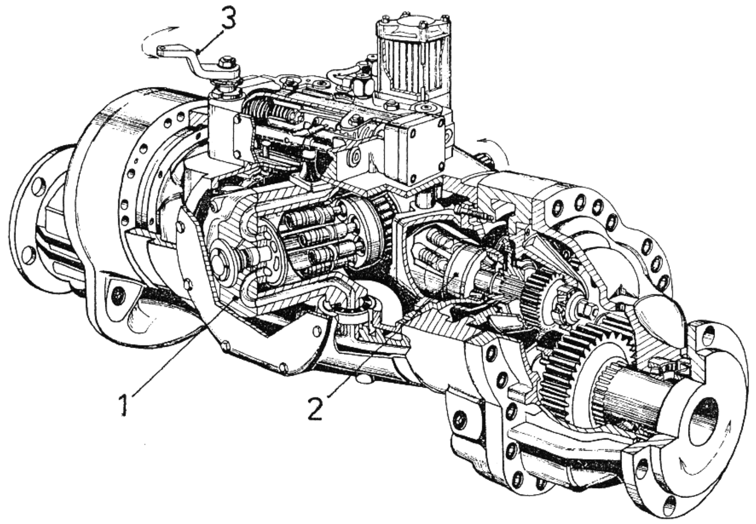
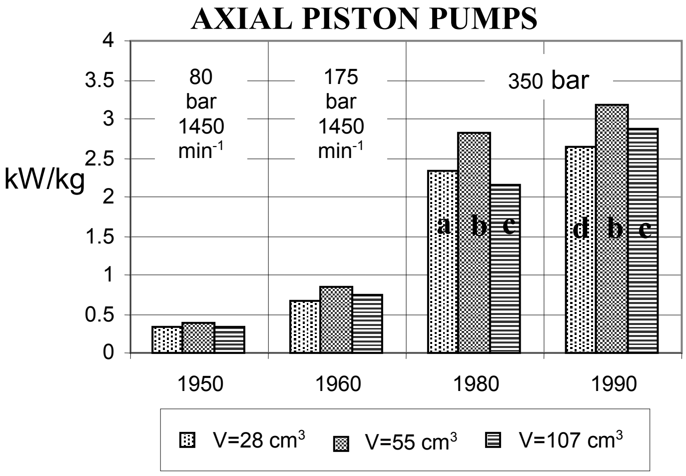


Fig. 1.6. *LINDE compact hydraulic axle* [64]



a) n = 3000/ min, b) n = 2500/ min, c) n = 2000/ min, d) n = 3150/ min

Fig. 1.7. *Development of specific power in axial piston pumps*

A view of the technical development of basic hydraulic components - transducers is shown in the following figure. Fig. 1.7 shows increasing of the power to mass ratio of axial piston pumps. However, relative power is primarily influenced by the speed and level of the working pressure, but also improved efficiency. Axial piston units (transducers) now achieve overall efficiency of about (92-94)% over a wide working range. Both the development in the construction, rolling bearings and materials used, and the development in the foundry industry, in finishing technologies or even in the manufacture have contributed to this result.

Hydraulic monitoring mechanisms (vehicle power steering systems, forming rests, etc.) were improved, and last but not least, considerable effort has been devoted to the development and manufacture of electro-hydraulic position and speed servomechanisms that at the time of variable-speed DC motors with a Ward-Leonard's device were the only appropriate drive, e.g., for machine tools. Due consideration was also given to the linkage of hydraulic and pneumatic mechanisms to electrical, and later electronic or NC systems. At a time when prevailed especially the so-called "switching technology", distributors were an essential part of fluid circuits, whose resistance, flow rates and working pressures influenced the level of their transmitted power and efficiency of the circuit. An idea of the enormous increase in the power transmitted by the distributors, reduction in their mass and increased working pressure, which took place in the late 19th and early 20th century, is shown in Fig. 1.8. In particular, improved casting technology of distributor bodies, design measures to reduce hydrodynamic and radial forces acting on the slide valve and development of electromagnets contributed to this increase in power. Since the pneumatic mechanisms work with significantly lower pressure than hydraulic mechanisms, the problems associated with permeability of distributors were and are subject to a permanent solution in the area of both design, and materials and manufacturing technology, which can currently be considered large-scale series production.

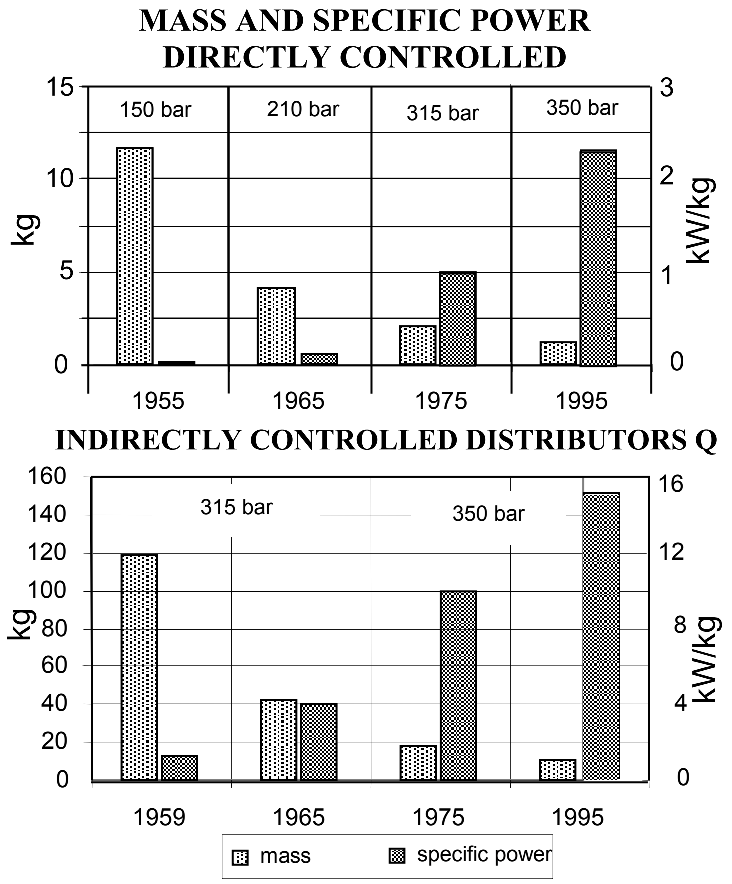


Fig. 1.8. *Development of specific power, mass and pressure in hydraulic distributors*
(Fig. 1.7 and 1.8 were prepared according to [80])

Roughly from the mid-1980s, we can see that the innovation of hydraulics and pneumatics involves mainly technology transfer from other fields - particularly concerning the application of electronics or microelectronics and sensor technology. However, essential is that the view of the concept of elements and the configuration of fluid mechanisms changes generally from conventional to mechatronic. The comparison of significant differences in these two approaches to solving technical problems is briefly shown in the Table 1.1 [12].

Table 1.1 *Conventional and mechatronic approach to solving technical tasks*

CONVENTIONAL APPROACH	MECHATRONIC APPROACH
Complex components and therefore often complex mechanical system	Autonomous elements, conversion of the mechanical functions in the field of software
Accuracy is achieved by close tolerances	Accuracy is achieved by measuring and feedback
“Hard” configuration	“Flexible” and thus lighter design
Communication - problems with wiring	Communication - the use of fieldbus systems
Driven (controlled) motion	Software-controlled motion
Unmeasured quantities are cannot be affected	Calculation and regulation of unmeasured quantities
Simple control of limit values	Control in the form of fault diagnostics

1.2. Brief overview of the current state

Currently, it can be concluded that all the above approaches are reflected in the design of individual elements or compact group of elements - blocks to a greater or lesser extent in both hydraulics and pneumatics. Therefore, fluid mechanisms have more extensive functional possibilities. They are more complex, have higher power but are also more economical and easier to use. Proportional technology and regulation hydraulic generators (hydraulic pumps) with integrated control electronics in hydraulics and pneumatic distributor (valve) islands with individual or integrated electrical connections are not the only example. Complex assemblies (modules) - subsystems are created, which are assembled, tested, adjusted and distributed by manufacturer. This concept brings savings in assembly of machines, their installation, diagnostics and maintenance.

Therefore, fluid mechanisms gained an important impetus for further development. They have become important assembly fields and are an integral part of machinery manufacture. They are used mainly in drives, in control of machines, both stationary and mobile, in clamping and gripping mechanisms and the handling technology and, to a lesser extent, in other fields.

Each application has its specific features that are reflected in the design of elements, the materials used for their components, seals, protection against ambient influences, and the like. Thus, we can see today that the fluid mechanisms are divided (even from a commercial viewpoint) to:

1. Mechanisms of stationary machines and equipment, i.e. the so-called “industrial hydraulics and pneumatics”; typical is the operation in a closed, regularly repeating cycle.
2. Mechanisms of mobile machines and equipment, i.e. the-so called “mobile hydraulics and pneumatics”; they may not differ in its composition from the previous mechanisms, but do not work in regular cycles. This also includes hydrostatic transmissions used mainly in travel drive of mobile machines.
3. Hydraulic and pneumatic servomechanisms; i.e. mechanisms with at least one external feedback (position, velocity or force or moment). They are usually part of both stationary and mobile machines.

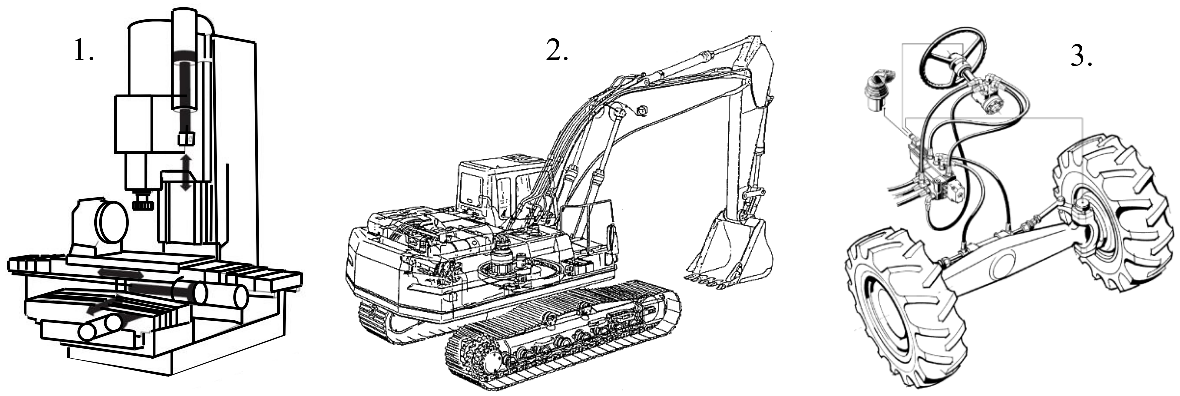


Fig. 1.9. *Industrial and mobile hydraulics and pneumatics, servomechanisms*

1.3. Properties of hydraulic and pneumatic mechanisms

First, we notice common properties resulting mainly from the principle of their operation and during the transfer of pressure energy in comparison with electrical and rigid mechanisms and then specific properties.

The advantages can include:

1) possibility of continuous and step control of the parameters of transferred energy, i.e. flow and pressure, thus control of velocity or motion frequency, force or torque at the output member of the mechanism in a wide range at an appropriate power to mass ratio, with good dynamics, especially when compared to systems where energy transfer by rigid mechanisms predominates,
2) easy overload protection, possibility of stopping or reversing the motion of the motor at full load by simple means,
3) easy connection to the control systems, whether PLC or PC, including the use of modern means of communication, makes these mechanisms suitable for machine automation,
4) easy implementation of linear motions by simple and reliable motors - hydraulic cylinders, without the inclusion of other members of transformation,
5) possibility of integrating the control elements in blocks, on the board, in the islands with a common connection to a fluid channel and with a separate or common connection of communications channels,
6) possibility of easy distribution of pressure energy even to less accessible points of machinery and equipment, to differently oriented motors, to nodes of machines that move with each other, even to a relatively large distance,

the disadvantages include:

7) losses at output power, partly due to dissipation of pressure energy in the fluid flow through a pipeline (tubes, hoses, shaped pieces and changing cross-sectional areas of flow), which are dependent on the flow rate, viscosity of fluid or flow contraction, and partly due to volumetric losses that are given by the size of the functional clearances or any leaks, viscosity, and size of the pressure drop; volumetric losses can be significantly affected by the manufacturing accuracy and the technical and material level of seals,
8) sensitivity to impurities is the fact, closely related with the preceding paragraph, that requires filtration of liquids or air conditioning,

9) fluid compressibility is reflected in stiffness and hence operation of mechanisms in static and time-variable phenomena, in motion synchronization of two or more motors variously loaded, is reflected in position accuracy, etc.; for pneumatics, this phenomenon is intensive and cannot be solved in a conventional manner,

the advantages of hydraulic mechanisms compared to pneumatic mechanisms can include:

10) significantly greater stiffness and efficiency,
11) possibility of achieving very low velocities and smooth operation due to good lubrication and therefore low passive resistances,
12) removal of heat flowing through fluid; especially in transmission of high powers, a cooler is required to be included in the circuit,

the disadvantages of hydraulic mechanisms compared to pneumatic mechanisms include:

13) need for an independent source of pressure fluid,
14) achieving high velocities of motion of the motor is difficult, filling the working chambers is associated with large pressure drops, see point 7,
15) significant change in viscosity with temperature is mainly reflected in internal volumetric losses, which is indicated by a change in motion frequency, efficiency and accuracy, see point 7,
16) need for recirculation of fluid,
17) hydraulic mechanisms use mostly mineral oils as energy carriers, less synthetic oils and emulsions or non-flammable liquids, most often substances that may adversely affect the environment in case of leaks in circuits,

the advantages of pneumatic mechanisms compared to hydraulic mechanisms can include:

18) possibility of supply from the central air distribution system and that there is no need for a return line; the central distribution system must be well designed in terms of the cross-sectional area of flow of lines and reliably sealed so as not to be loaded with too large losses,
19) very fast response to an input signal; possibility of achieving very high motion frequencies of the motor, which is related to the viscosity properties of air, which permit a high flow rate in lines with acceptable pressure drop, see point 7,
20) possibility of operating in explosive atmospheres, moisture, the environment with an ignition hazard, etc.,

the disadvantages of pneumatic mechanisms compared to hydraulic mechanisms include:

21) in terms of energy, operation is relatively expensive,
22) low stiffness, see point 9,
23) difficult to maintain a uniform motion of the output member of the mechanism, especially at low velocities, which is the result of a low stiffness and variable passive resistance.

1.4. Technical parameters

Technical parameters of hydraulic and pneumatic mechanisms significantly affect their use and application possibilities. The basic parameters of power transmission through fluid are: pressure p and flow rate Q, which together with the size of area S of linear and geometric volume V of a rotary motor determine the force $F = p.S$, moment of force $M = p.V/2\pi$, velocity $v = Q/S$, angular velocity $\omega = Q/(V/2\pi)$, or speed $n = Q/V$ and power $P = F.v = M.$

$\omega = p.Q$. Given the significant difference in the compressibility of oil and air, which is reflected in the magnitude of stored energy and the associated changes in volume at a given pressure drop, the working pressures in the pneumatics are significantly lower.

Hydraulic mechanisms today work with the pressures ranging up to 35 to 45 MPa and the flow rates from several dm^3min^{-1} to several thousand dm^3min^{-1}. On the other hand, pneumatic mechanisms generally work with a pressure of 0.63 MPa and a flow rate of intake air in an order of magnitude from 10 to 1.10^3 dm^3min^{-1}. Based on the foregoing and the manufactured sizes of the motors, it is possible to determine the output parameters of hydraulic and pneumatic mechanisms - Table 1.2 [42].

Table 1.2. *Parameters of hydraulic and pneumatic mechanisms*

PARAMETER	HYDRAULIC MECHANISM	PNEUMATIC MECHANISM
	SIZE	
force [N]	10 to 10^6	1 to 10^5
torque [N.m]	1 to 10^6	0.1 to 10^2
power [kW]	0.1 to 10^3	0.01 to 10
velocity [$m.s^{-1}$]	0.01 to 0.5	0.01 to 5
speed [min^{-1}]	5 to 10^4	10^2 to 10^5

The application areas of hydraulics include: construction machinery and construction industry; machine tools; road, municipal and rail vehicles; transport machinery and equipment; plastic and rubber processing machinery; agricultural and forestry machinery; metallurgical manufacturing machines, and metal forming machines. Pneumatics shall be applied: in particular in automation of manufacturing, assembly and handling processes, especially in mechanical engineering; electrotechnical, chemical and metallurgical industries; in textile and paper industries; for printing and packaging machines, and in transportation and construction industries.

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