Advancing the Capabilities for Miniaturization of Hydraulic and Pneumatic Drives

Introduction

One of the important challenges for market growth of multi-type control systems of industrial manufacturing equipment (machine tools, robots, etc) is the miniaturization of executive power drives. Other areas where miniaturized executive power drives are used include transport vehicles of various types and destinies, energetic objects, medical and public service installations, research laboratory facilities (e.g. fatigue test benches), aerospace vehicles, and military objects and technologies [1]. The ground for development of miniaturization is necessitated by the challenges of decreasing costs of production of such equipment while increasing the products' efficiency, at least owing to the following:

- Maximizing the payload of transport objects and handling machines by minimizing the executive drives in mass-to-dimension rates;
- Enhancing manufacturing output as a result of minimizing the operational area, e.g. decreasing the size of stationary robots and manipulators with the aim of increasing density of their arrangement and the number of concurrent process operations respectively;
- Improving the probability and veracity (i.e. decreasing the vulnerability) of critical data acquisition by miniaturization of special-purpose vehicles (e.g. reconnaissance rovers, aerospace probes, etc.) and increasing the number of vehicles involved simultaneously.

Present-day challenges in miniaturization of executive drives

Current miniaturization processes face several ***developmental and technical challenges*** such as:

- Decreasing of mass-to-dimensions rates vs. keeping high specific power;
- Reduction of transmitted power vs. retaining high fast response;
- Downsizing the electro-mechanical components of the control units of executive drives vs. maintaining invulnerability to harmful environmental stimuli such as heat fluxes, humidity, vibrations, electro-magnetic and radiation fields, liquid and gaseous corrosive chemicals, whose influence becomes more dangerous upon downscaled embodiments.

The ***commercial challenge*** is characterized by the demand of decreasing costs vs. the rising costs of a new generation of manufacturing equipment and instrumentation. The present-day miniaturized drives do possess the mass-to-dimension rates of yesterday's instruments and transducers. As a result, the modern manufacturing equipment and instrumentation must have a higher accuracy rating, which pushes costs upward.

The ***challenge of miniaturizing executive drives*** is followed by the corresponding downsizing of their control units, each with the appropriate feedback loops, communications, power supplying sources, and various auxiliary elements. The miniaturization of the electrical, mechanical, pneumatic and hydraulic embodiments of these components feature their own specific challenges. Those components need to enable the rated operational reliability and accuracy while maintaining high power-to-mass rates in accordance with the designs for:

- Moving mechanical parts within contacting kinematic or power gears of various types; and
- Downsized electric circuitries that are, in most cases, vulnerable to the previously mentioned harmful environmental or man-made stimuli.

By ***miniaturizing mechanical drives***, there is a reduction of absolute values of transmission capacities (kW). The relative value of transmission capacity $\mathbf{N}_r$ (kw./lb, e.g. kw. per lb of drive's weight) depends upon the type of transmission gear, its kinematic scheme, and its strength characteristics. The miniaturization of mechanical drives is usually limited by contradictions between the specification figures and appearance of physical changes, namely:

- Application of open-type contacting micro scaled pairs may entail vulnerability of those mechanical pairs to dust-laden ambient, and to damping action of surface tension along solid-liquid interfaces due to moisture condensation in conditions of alternative temperature drops;
- Small surface roughness for decreasing friction of contacting pairs should predict influence of adhesive forces that hinder from relative motion of said pairs;
- Fine tolerances for sliding joints and for fixed detachable joints will result in commensurability of thermal strain values with values of those fine tolerances that may provoke a casual seizure thereupon;
- Minimizing dimensions of leverages must imply increasing resonance frequencies of linkages that may cause an accidental friction resistance in dry swivel joints;
- High accuracy of dimensions and shape of micro scaled mechanical parts necessitates growing efforts in manufacturing of machining and measuring tools, which must be of higher accuracy grade than said mechanical end products.

Utilization of ***miniaturized electrical circuitries*** in control parts of mechatronic units, as well as electro-pneumatic or electro-hydraulic control units, may induce crucial failure modes in the complex interaction of cross-domain signals of MEMS devices [2]. It is because those electrical circuitries undergo unpredictable changes through exposure to heat flux, high frequency vibration, influence of radiation and electro-magnetic fields, corrosive affect of liquid and gaseous chemicals. In spite of the miniaturization of hydraulic and pneumatic drives (mini **H/P-D**) to have a lesser rate of reduction in relative transmission capacity $\mathbf{N}_r$ [3], the present-day engineering of mini **H/P-D** also have the following contradictions between the customized specification figures and the occurrence of obstructive physical events:

- Decreasing of actuating forces in mini drives vs. increasing of relative values of opposite friction forces in hydraulic and pneumatic executive motors;
- Minimizing of flow area and wall thickness of tubes and hoses with compelled keeping of relatively high pressure (especially liquid pressure) must enable appropriate rupture strength of those ducts;
- Decreasing of orifice sizes in hydraulic ducts and of yawns between moving contact pairs provokes occurrence of capillary and silting events that strongly increase flow resistance there through;
- Enabling lubrication for friction pairs in pneumatic drives results in silting of minimized tolerances;
- Use of valve-type distributing and control units with miniaturized moving mechanical parts consequently increases the resonance frequencies of those parts and casual occurrence of self-oscillations;
- Downscaling hydraulic power packs with inevitable increasing circulating factor for working liquids through reservoirs of small volume contributes to overheating of standard oils with sequent changes in viscosity and combined air content, which may result in drift of hydraulic outputs;
- Utilization of the solely scaled down but traditionally designed electro-mechanical leverages in first stage of proportional or servo valves induces vulnerability of said leverages to aforesaid environmental or man-made harmful stimuli.

Innovative approaches

The miniaturization of all the components of executive drives (valves, pumps, leverage, gear pairs, motors, etc.) is an imperative of the industrial development from at least cost-benefit, security and military points of view. Therefore, techniques and designs for miniaturization will be in progressive development under growing requirements of the market. Today's continuing success in the development of miniaturization of executive drives with scaling down modern electro-mechanical, electro-hydraulic and electro-pneumatic components features with keeping reasonable balance between the aforementioned contradictions and customized specification figures of the end products. But the sufficient market growth, thereof, requires the creation of new types of mini executive drives, which must feature with: reduced vulnerability of their control parts to aforesaid stimuli, and with keeping the high value of transmission capacity N_r (kw./lb) of their executive parts. Thus, the said control part should be of hydraulic and/or pneumatic nature with a few, if any, electric elements. And evidently, the high value of transmission capacity shall be kept in the embodiments of a new generation of mini scaled executive pneumatic or, preferably, hydraulic drives. This approach is beneficial for the following reasons:

- Development of MEMS-Micro fluidics will obviously result in the creation of a Microfluidic Platform (**MFP**) where the input signal of any physical, chemical, or biological origin is converted into a hydraulic or pneumatic output signal.
- There has been discovered the possibility for the creation of an Interface Transducer (**IT**) that converts very effectively a weak output hydraulic or pneumatic signal (like a signal from **MFP**) into a relatively powerful hydraulic signal, capable of activating a valve-type hydraulically operated control unit (**CU**) of a mini **H/P-D**.

Such a conversion with simultaneous scaling up of signals are illustrated by **Figure 1**, where **MFP** optionally contains nano and micro scaled components (positions 1, 2, and 3). An **IT** is created on the basis of differently scaled innovative Jet Pneumatic-Hydraulic (**JPHA**) and/or Jet Hydraulic-Hydraulic (**JHHA**) Amplifiers-Converters (positions 4, 5, and 6). And hydraulically operated valve-type **CU** (position 7) is interfaced with **MFP** directly by **JPHA** or **JHHA.** As this interfacing is really possible now, for the first time there appears the opportunity for the creation of such a miniaturized modular assembly that includes all the necessary components to operate mini **H/P-D** by nano/micro scaled signal of various origins. **Figure 2** shows the general layout of such a would-be Microfluidic Modular Assembly (**MiFluMA**), which additionally might have the very important alternative feature of activating mini **H/P-D** directly by **MFP** thru **JPHA** or **JHHA**.

Benefits of the **IT** in the innovative embodiments of **JPHA** or **JHHA** are as follows:

- Does not require moving mechanical parts (positions 4, 5, and 6);
- Reveals high values of pressure $\mathbf{k_p}$ and flow rate $\mathbf{k_q}$ gains;
- Reveals high value of pressure recovery coefficient $\mathbf{k_{pr}}$, see **Table1**.

Since pure fluidic amplifiers of previous generations did not possess those operational performances, [4,5,6] there is the need for an innovative technology of origination such Interface Transducers (**IT**). [7] For the creation of a new generation of pure fluidic **JPHA** and **JHHA**, *it has been developed the novel methodology*, based upon the following:

- Method of ***Interface Control of Interacting Flows*** (**ICIF** method) that provides for designing and manufacturing of customized embodiments of **JPHA** where a weak pneumatic signal from **MFP** is being converted into relatively enhanced hydraulic signal. [8]
- Method of ***Attract-to-Merge Control*** (**AMC** method) that enables engineering of customized embodiments of **JHHA** where weak hydraulic and/or auxiliary pneumatic signals from **MFP** are being converted into a relatively enhanced hydraulic signal. [9]

Benefits of application

Today, compact and uniquely powerful actuating hydraulic and pneumatic drive units are traditionally used in main and redundant trains of critical objects where hazardous environmental or man-made stimuli are of concern for operational reliability and safety. These objects are used in industries such as energetics, transportation, military, and utility. Therefore, the anticipated applications of **MiFluMA** should be as follows:

- Industrial robots. Fire robots. Mine clearing and reconnaissance robots. Robots for handling poisoning and radioactive materials;

- Rock-cutting equipment, operating in a dusty and explosion hazard ambient;
- Coal-plough machines, utilized in an enclosed, explosion hazard ambient;
- Casting, milling, forging and pressing equipment, operating in specific industrial conditions of high temperature, contaminated air, and vibrations under loading;
- Gearboxes of large dimension metalworking tools, where it seems to be economically reasonable to feed the power input of **JPHA** and **JHHA** from the oil lubricating systems;
- Automated hydraulic drives for the wheel or track trailers and other ground vehicles;
- Hydraulic steering or other control drives of the live or unmanned air, ground and marine vehicles, where it is economically advantageous to feed the power input of **JPHA** and **JHHA** from the vehicular flow-through fuel system;
- Automated distributing devices for liquid products in petrochemical and food industries;
- Liquid loading level regulators for gas, oil, pharmaceutical and chemical industries;
- Programmed loading test benches for fatigue trials onto the carrying structures of aircrafts or other critical objects.

This new technology will be of interest and need to industrial, transport, energetics, medical, utility, aviation, space, security and defense. As the concept expands to all levels of controls, there will be a possible market to retro fits of legacy equipment, which will be driven by environmental, health, security and safety issues. All areas of hydraulic and pneumatic drives will benefit from this new development.

Further explanation

As stated earlier, for the purpose of creation of new generation of pure fluidic **JPHA** and **JHHA** amplifiers-converters there have been developed the innovative **ICIF** and **AMC** methods, see attached **Flow chart**.

Operational schematic of **AMC** method is shown at **FIG.3**. The high-speed, high impulse planar liquid jet flow **Ji** streams out of supply channel **1** between two hydrophilic plane solid surfaces **2**, **3** and runs along straight trajectory **4** of its free path thru pneumatic control area, keeping its two opposite side free surfaces uninterrupted and bringing nearly in full its initial impacting impulse into hydraulic intake and distributing area. The low impulse liquid control flow **Jc** is being directed, optionally in the form of separate drops **5**, **6**, downstream over the curved shape solid surface **7** (namely over its free part **7p**) to the point **Attr** of contact with side free surface of flow **Ji**. Point **Attr** lies on the line **Asl** that separates pneumatic control area from hydraulic intake and distributing area. After said contact happened, flow **Jc** continues to go downstream over surface **7** under occurrence of Coanda effect. In the result of influence of surface tension forces, flow **Ji** is being attracted to a drop-shaped flow **Jc** and both flows start to run as an integral stream of cocurrent flows due to liquid flow continuity. Thus, flow **Ji** starts to go along curved deflected trajectory **8** under influence of multi-layer Coanda effect over submerged portion **7s** of curved shape solid surface **7**. So, flow **Ji** vectors its high impacting impulse to the place of making useful work, e.g. activating a valve-type hydraulically operated control unit (**CU**) of mini **H/P-D**, see **FIG. 1** and **2** in Part 1 of this article. Optionally, non-pressurized drop-type or short-length liquid control flow **Jc** may be narrower than distance between plane solid surfaces **2** and **3**. In this case the stability and correct vectoring of free flow **Jc** is being enabled by guide facility, e.g. by reference slot **9**, see Section **A-A**, option **a)** at **FIG.3**. Otherwise, flow **Jc** may run in contact with solid surfaces **2** and **3**, having one free surface, as shown in Section **A-A**, option **b)** at **FIG.3**. Line **Sh** separates free part **7p** from submerged part **7s** of surface **7**, where those parts may differ in hydrophilic rates for enabling easier motion of flow **Jc** over surface **7p**. Downstream motion of flow **Jc** is being accomplished under influence of either gravitation or slight pushing action of additional gaseous flow **Agf**, or both. The stability of flow **Ji** is being kept by soakage zones **Sz** that exist along its lines of gas-liquid-solid interfaces due to preliminary appropriate designed selection of hydrophilic solid surfaces **2** and **3**, see Section **B-B** at **FIG.3**. Moving flow **Ji** back to its straight trajectory **4** should be fulfilled in the result of breaking down the multilayer Coanda effect, which may be done either by termination of flow **Jc** or by rated blowing in the auxiliary gas flow **Agf**, or by both.

ICIF method is represented by **FIG.4**. Moreover, **FIG.4** illustrates capability of combining in one embodiment of **IT** both of those innovative control techniques with applying alternatively **ICIF** and **AMC** methods with the aim of corresponding alternative controlling **CU** by hydraulic and/or pneumatic outputs of **MFP** see **figures 1** and **2** in Part 1 of this paper. Well, high-speed, high-impulse planar liquid jet flow **Ji** runs out of supply channel in solid **1** and goes downstream along pneumatic control area into pressurized submerged hydraulic intake and distributing area thru narrow flow passing channel **Ch** between solids **7** and **8** that separate the said pneumatic and hydraulic areas. Pneumatic and/or hydraulic control channels **16** and **17** are outlined between solids **4&8p** and **5&7p** respectively. Pneumatic control area is divided by flow **Ji** into two isolated pneumatic control cavities **L** and **R**. Each of said cavities services as pneumonic two-port with input throttle at the entrance thereinto and output throttle, which represents the variable gap between an inner side solid surface of channel **Ch** and an adjacent side free surface of flow **Ji**, see Section **B-B** at **FIG.3**. If there is no any pneumatic (**Pctrl**) or hydraulic (**Hctrl**) control signals, the flow **Ji** goes straightly and shares evenly its impacting impulse over splitter **6** through hydraulic output channels **9** and **10**. Hydraulic reactive thrust and free flow vent channels **11** and **12** are arranged spatially in such a manner as to form the reactive thrust flows from the extra amount of liquid that cannot pass thru channels **9**, **10** and must be evacuated. These reactive liquid flows apply additional thrust impulse upon the entrance openings **En** of hydraulic outputs **9** and **10**. Since high-speed flow **Ji** entrains gas through cavities **L** and **R**, making them under-pressurized, some liquid tries to enter the said cavities, streaming up from pressurized hydraulic area, but locking whirls **13** of liquid-gas mixture prevent this up streaming, isolating reliably under-pressurized pneumatic control area from pressurized hydraulic intake area. Such isolation may be done by stable meniscus **M** of gas-liquid interface, if impacting influence of entrained gas fails to destroy the said interface, i.e. when speed of flow **Ji** is low enough.

Assume there is necessary to deflect flow **Ji** at full angle $\gamma = \gamma_{max}$ to the right, where the most part **14** of flow **Ji** is vectored onto entrance **En** of output **9** and the rest part **15** of this flow will impact slightly the inverse output **10**. Let it be decided to utilize **ICIF** method thereupon. In this case pneumatic control signal **Pctrl** must be applied into the left control channel **16** with cavity **L** closed, with no any control signal in the inverse channel **17**, and with cavity **R** open to ambient gas. Moving flow **Ji** back in initial position ($\gamma = 0$) is being accomplished by deleting signal **Pctrl** and opening cavity **L**, as far as cavity **R** and channel **17** to ambient gas. Optionally flow **Ji** may be deflected at angle $\gamma = \gamma_{max}$ to the left by simultaneous closing cavity **L** and channels **16**, **17** and opening cavity **R** to ambient gas, since an entraining influence of flow **Ji** under-pressurizes cavity **L** and bigger pressure of flow in cavity **R** interacts with right side gas-to-liquid interface of liquid flow **Ji**.

Now assume that for deflection of flow **Ji** at full angle $\gamma = \gamma_{max}$ to the right it is reasonable to use a weak hydraulic signal from **MFP**. It seems evident to utilize **AMC** method. In this case hydraulic control signal **Hctrl** must be applied into control channel **17** in the form of continuous pressurized or short-length nearly non-pressurized control liquid flow **Jc** with keeping cavity **R** open into ambient gas. This flow **Jc** goes over part **7p** of solid surface **7** and than runs downstream over submerged part **7s** of solid surface **7** under influence of Coanda effect. Once flow **Jc** contacts with flow **Ji** in point **Attr**, it attracts flow **Ji** to run together along trajectory that repeats the shape of solid surface **7s**. So that both said flows run cocurrently in one common stream due to flow continuity and in arrangement of multilayer Coanda effect. If control flow **Jc** is continuous, the angular deflected position of flow **Ji** will be maintained until flow **Jc** has been terminated. **FIG.4** reveals also the procedure of forming the short-length pulse control flow in the result of pulse-width sharing of a continuous control flow **Jc** by an auxiliary pneumatic signal **Adg** in an optional mode of periodical insertion gaseous bulb-type cavities **Ct** inward an enclosed and initially continuous control liquid flow thereof. Application of control flow **Jc** in said short-length format enables controlling the angular deflection of flow **Ji** in pulse-width mode of hydraulic output signal, where the length and running speed of each portion of short-length flow **Jc** predicts time of existence of hydraulic output signal from **JHHA** embodiment of **AMC** method.

Figures 3 and 4 demonstrate that the embodiments of **AMC** and **ICIF** methods are appropriate for flow-through circuitries, pertaining to traditional embodiments of valve-type control units of mini hydraulic/pneumatic drives. Nevertheless, there is also the possibility to maintain the servo control principle while using static hydraulic circuitries designed on the basis of Pascal's law. **Figure 5** shows the optional schematic of such a static amplifier-converter of a weak pneumatic and/or hydraulic signal from **MFP** into mechanical working stroke. Use of miniaturized mechanical flexible elements (mini-bellows, mini-membranes, etc.) and today's knowledge in capillary micro fluidics provide the capabilities to create such static amplifier-converters. As illustrated in **Figure 5,** a weak pneumatic or hydraulic signal impacts on entrance **En** of the volute duct, which results in the elastic working stroke of flexible mini-bellows. The properly rated relationship of the mini-bellows diameter to the diameter of the volute duct predicts the customized figures of a working stroke and thrust force of the mini-bellows that can then be applied to a valve-type **CU** of a mini **H/P-D**.

Additional benefits of application

The advantages demonstrated by the initial micro/meso scaled prototyping described over pure fluid amplifiers of previous generations are revealed in **Table 1** of Part 1 of this paper. Interfacing of existing **MFP** with today's **CU** can occur without aforementioned constraints. Furthermore, customized meso scaled embodiments of **JPHA** and **JHHA** may be used for actuating mini **H/P-D** directly, without any intermediate **Control Unit**, thereby enhancing the value of transmission capacity $\mathbf{N}_r$. Also, micro scaled **JPHA** and **JHHA** can be used in node points of micro fluidic chips, partially avoiding hydro mechanical and aeromechanical challenges. The scaling down of these components would then provide the opportunity for fundamental and systematic efforts in the scaling down of the production systems, i.e. manufacturing equipment and measurement instrumentation.

Since typical embodiments of innovative **ICIF** and **AMC** methods do not contain moving mechanical parts and electronic components in the process of amplifying and conversion thereof, those amplifiers are not vulnerable to the above-mentioned environmental or man-made stimuli. With the appropriate selection of solid, liquid, and gas materials, **JPHA** and **JHHA** may be used in fire and explosion hazardous ambient, and in presence of aggressive liquid and gaseous chemicals.

Figures 3 and 4 illustrate the enticing possibility to apply micro/meso scaled embodiments of **JPHA** and **JHHA** with already existing micro fluidic integrated or modular platforms (**MFP**) for controlling power Hydraulic/Pneumatic Drives, which may even be in mini/macro scale. Initial prototyping of this technology demonstrates the potential, in a very real way, for the creation of Microfluidic Modular Assemblies (**MiFluMA**), using the existing nano/micro scaled **MFP** and micro/meso scaled hydraulically operated valve-type Control Units (**CU**) of mini/macro scaled Hydraulic/Pneumatic Drives (See **Figure 2** in Part 1 of this article).

About the Author:

Vadym Buyalsky, PhD., has over 30 years of experience in fluidics and microfluidics. He has written 75 scientific works and papers and holds 27 patents. He was the executor of nine science and research programs in Ukraine, Russia, and the former Soviet Union. He also served as a Fellow of Scientific Councils for Object "Shelter" at the Chernobyl Nuclear Power Plant and the Kiev Civil Aviation University. Dr. Buyalsky is currently a member of the research and development team for CTRL Systems, Inc., a provider of solutions for nondestructive testing and flow control. He can be reached at vbuyalsky@ctrlsys.com *or 410 876-5676.*

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[Captions]

FIG. 1: Interfacing of Microfluidic Platform with Control Units of Mini/Medium/Macro Scaled Hydraulic or Pneumatic Drive by applying of **JPHA** or **JHHA**.

FIG. 2: General Layout of Microfluidic Modular Assembly (**MiFluMA**).

Table 1: Specification Figures of Pure Fluidic Amplifiers pertained to Sequent Generations.

(To be continued in ***Part 2*** of this article, where **ICIF** and **AMC** methods on origination of **IT** for future **MiFluMA** will be illustrated and explained using Figures 3,4 and 5).