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Submitted on 29 Mar 2023

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## FLUID POWER RESEARCH CENTRES WORLD-WIDE

**Power Transmission and Control  
Ampère Lab (UMR CNRS 5005)  
Institut National des Sciences Appliquées de Lyon, France**



### 1 Background

#### *Ampère Lab and the Fluidtronic research team*

The Fluid Power research activity started in Lyon about 30 years ago initiated by the Professor Serge Scavarda. Until 2007, this research group was part of the Laboratoire d'Automatique Industrielle (LAI) of the Institut National des Sciences Appliquées de Lyon (INSA). In 2007, it merged with the Centre de Génie Electrique LYonnais (CEGELY) and a microbiology group to form a joint laboratory among the French National Center for Scientific Research (CNRS), INSA Lyon, Ecole Centrale de Lyon and University Lyon I.

The Ampère Lab is made up of 6 research teams collaborating in 8 scientific activities (Fig. 2). The research activities are funded by government, institutional funding and industry at around 3 500 00 € per annum. The Lab is staffed by a director, 50 academics, 10 researchers (CNRS) 19 support staff (8 CNRS), 11 post-docs, and 80 PhD students.

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**Internet:** [www.ampere-lab.fr](http://www.ampere-lab.fr)

#### *The Department*

The fluidtronic research team is mainly linked to 2 of the 9 departments at the Institut National des Sciences Appliquées de Lyon (Fig. 1). The 500 students of the Mechanical Engineering Design Department (GMC) and the 350 students of the Electrical Engineering Department (GE) follow a 3-years generalist program in Engineering. Strong international relationships have been established: dual diplomas, international academic exchange, industrial internship abroad, Erasmus Mundus Master of Mechanical Engineering.



**Fig. 1:** Institut National des Sciences Appliquées of Lyon

#### *The Institut National des Sciences Appliquées of Lyon*

Celebrating last year its 50<sup>th</sup> anniversary, INSA Lyon ([www.insa-lyon.fr](http://www.insa-lyon.fr)) is one of the top French Engineering schools for offering one of the best preparation for the professional world. Its strength:

quality of education and pedagogy, an emphasis placed on educational staff and applied research, and international outlook. There are over 6 000 students taking first and higher degrees at INSA Lyon.

*The scientific objectives of the Ampère Lab*

The Ampère Lab has a general scientific objective, namely the *efficient management and the rational utilization of energy in systems in relation with their environment*, with respect to a wide range of fields:

- Domains: System and Control, Electrical and Electromechanical Engineering, Microbiology,
- System range: from power transmission components to energy systems,
- Frequencies of the phenomena: from static to microwave (GHz),
- Application range: from transport systems to energy, environment and bioengineering,
- A general approach in engineering: understand the physical phenomena in order to design complex systems.

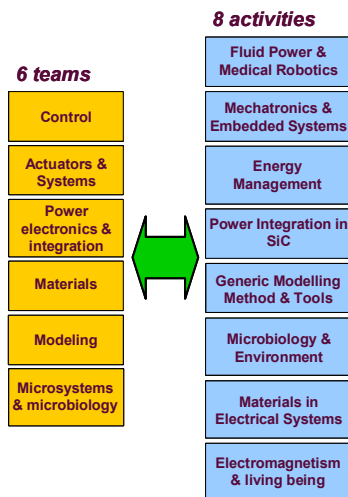


Fig. 2: The Ampère Lab organisation

Scope of activities and key words are:

- dielectric and magnetic materials, power electronics, high voltage, electromagnetic compatibility, electromagnetic modelling,
- power transmission and control, mechatronics, Fluid Power, robotics, diagnostics and operational security,
- ecological engineering, bacterial adaptation and gene transfer.

Among the 6 research teams of the Lab, the "Actuators and Systems", and the "Control" research groups are collaborating in the "Fluid Power and medical Robotics" scientific activity.

## 2 Research

The study of the transmission of power using a fluid (oil, water or gas) constitutes, with electrical power transmission, complementary aspects to one of the major research problem at the present time, that is to say the design of energy efficient systems.

From this point of view, the Ampère Lab is unique

in France since it has a recognized expertise of all these technologies for power transmission. This expertise is essential when considering the previous economic and scientific issues. The research in Power Transmission and Control is divided in 3 main scientific areas:

- multi-domain and multi-scale modelling,
- methods and tools for system design,
- system control.

The specificity of our research is to deal with multi-disciplinary aspects on the theoretical viewpoint as well as on the experimental side.

### 2.1. Multi-domain and multi-scale modelling

This research activity tackles theoretically as well as experimentally the modelling of multi-energy power transmission systems, and particularly when fluid energy is used.

On the theoretical side, a unified and structured approach of the modelling for multi-physic and multi-scale systems (Bond Graph) is developed, aiming at preserving the real nature of the mathematical models before any step of space and time discretization.

Concerning the simulation aspects, the problem of coupling numerical codes for fluid mechanics and for system dynamics is also considered, this in order to globally optimize a component or a circuit, considering simultaneously the mutual influence of control and local flow phenomena.

Finally, on the experimental side with a strong link with industry, the expertise acquired on the pneumatic technology is still reinforced.

Since 2007 research works have also been done coupling electrical drives and conventional power transmission (hybrid vehicles), and recently very original research projects have been initiated (pneumatic-electric battery). Based on the Bond Graph energy conservation principles, complex models have been developed for automotive industry and lead to the implementation of several libraries in AMESim (LMS-IMAGINE).

#### Structured modelling and multi-scale systems

Models of Fluid Power transmission systems have to represent complex behaviour based on nonlinear equations of infinite dimension with strong interaction between local and macroscopic scales. In this domain, computation time is still high. Local phenomena such as turbulences, cavitations, or shock waves have influence on the performances at the macroscopic level (for example, turbulence may influence the stability of a piloted poppet).

At the system level, the representation of this kind of relation is more important than the characterization of these phenomena in any point of space. To describe these interactions, a bond graph representation based on boundary energy flow using port variables is used. It relies on a geometric structure, called a Stokes-Dirac structure, which encodes a relation between internal dynamics and boundary exchanges (1), in a power-conserving manner (Fig. 3). The main interest of this approach is that the mathematical structure is preserved. It allows an easier interconnection of sub-

models, multi-domain modelling, mixing conservative and irreversible processes, and structure analysis (controllability, observability, inverse methods, and passivity).

$$\int_Z (e_p \wedge f_p + e_p \wedge f_p) + \int_{\partial Z} e_b \wedge f_b = 0 \quad (1)$$

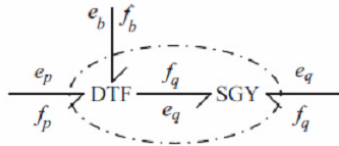


Fig. 3: Decomposition of a Stokes-Dirac structure.

### System optimization with parameterization in CFD

In the design of fluid power components or systems, Computational Fluid Dynamics (CFD) can play a key role for flow optimization, but also in the performance analysis of the whole system. To study the sensitivity of the flow to parameter changes (geometry, boundary conditions), we apply a novel approach based on the parameterization of the CFD computed solution. It consists in the calculation of an approximation of the complete Navier-Stokes equations around a reference point.

This method is particularly efficient and makes easier the coupling of local approaches to macroscopic system simulation (Fig. 4), avoiding long computational schemes. This parameterization method can give all the results corresponding to a continuous variation of the design parameters from one single design step, which means one single flow computation on one single mesh.

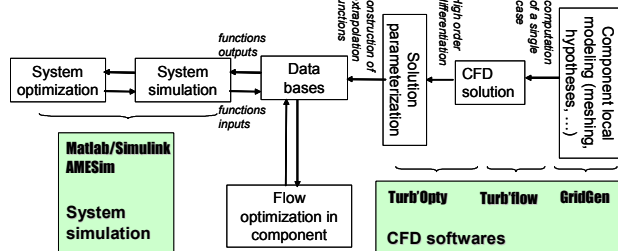


Fig. 4: Parameterization in CFD for system simulation and optimization.

### New experimental procedures in pneumatics

Complementary to the previous approaches, our research group has developed a strong experimental knowledge of the pneumatic technology, crucial in relation with industry.

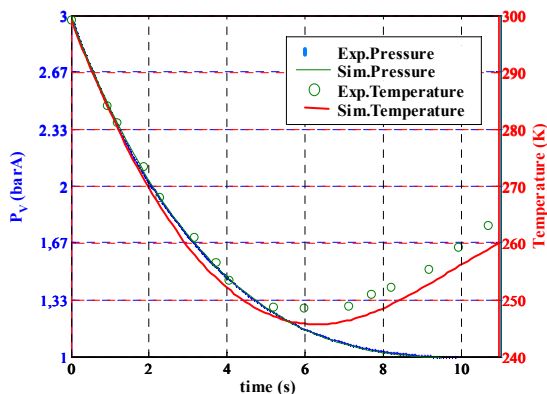


Fig. 5: Simulated vs. measured pressure and temperature for a tank discharge.

Since 2006, in the framework of the ISO<sup>1</sup>, we have worked on new experimental procedures for the characterization of pneumatic components. The proposed method relies on the discharge or the charge of a tank in order to identify the mass flow rate. This identification procedure requires naturally a good knowledge of the heat transfer (convection) and experimental procedures to identify the model parameters. Good results have been obtained (Fig. 5) and this allows a wide range of applications to be explored now.

Beyond the multi-disciplinary approach for the modelling of power transmission systems, the originality of these works relies mainly on the continuity between theory, virtual prototyping and experimentation. This expertise plays a crucial role in the quality of our research and its application in industry.

### 2.2. Methods and tools for system design

The main objective of this research work is the theoretical and methodological development of tools for studying the generic and intrinsic properties of systems. Our approach, based on an inverse methodology, is a break with the conventional simulation methods applied in engineering since it tries to avoid the conventional try/error/correction iterative procedure (Fig. 6). Because inverse approaches are the natural way to define design problem (generally, output are specified variables while inputs are unknown), it leads to more efficient and relevant methods (a single calculation is required).

The final goal is here to give simple rules and methods that can easily be used in industry for design purposes. These works are based on Bond Graph energy conservation principles, causality concepts, model inversion techniques, algebraic approach, and operational analysis in infinite dimension.

#### Inverse approaches

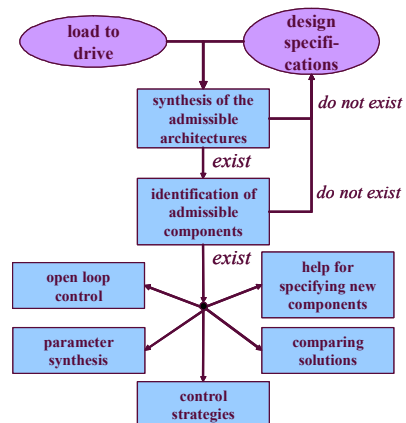


Fig. 6: Inverse approach for system design.

### Design model / design problem adequacy

The purpose is here to define properly the design problem before any numerical work. Structural analysis tools for studying the system controllability, inversion,

<sup>1</sup> International Standard Organisation

I/O decoupling, are useful to show the right choice. With our approach based on causal and bicausal concepts, this information can be obtained at the early stages of the design project (on the Bond Graph model). This indicates how to change the architecture, the output specifications or the component choice in order to reach the required performances for the system (Fig. 6). Recently, for MIMO linear systems, essentiality orders have efficiently been applied to determine if there is a control law that enables the system to be statically decoupled and inverted.

Software developments within MS1 (Lorenz Simulation) and Modelica (Modelica Association) are now available and have been tested in industry.

#### Help for defining design specifications

The purpose of this second aspect is to couple inversion techniques to dynamic optimization in order to tackle the energy efficiency problem in system design. It consists in solving simultaneously the component choice and the optimal control problems. Due to numerical difficulties for computing the initial conditions on the co-state of the optimization problem, this method has presently been implemented for MIMO linear systems only.

The Ampère Lab is one of the worlds leading research group in this domain. The expected results should solve a wide range of problems in engineering, such as system design, choice of component technology and system architecture, robustness, control law structural analysis. A wide range of application is covered by this approach: mechatronics, hybrid vehicles, Fluid Power, etc.

### 2.3. System control

Started 20 years ago, this activity focuses at the adaptation, synthesis, implementation and comparison (performance, economical... criteria) of modern control laws, issued from the new development in control theory of the international automatic community. The Lab has wide theoretical and experimental experience on gains scheduling, nonlinear I/O linearization, adaptative, first order and higher sliding mode, flatness, backstepping control, with aims to adapt these different strategies in prototypes or experimental test rigs.

During the last three years, high order sliding mode control, techniques based on strictly positive real systems (SPR) and control strategies without sensors have mainly been studied. Generally, the applied methodology can be described as follows:

- first, simulation models are used and analyzed in order to obtain reduced models,
- second, the control strategies are adapted and implemented with co-simulation tools (Fig. 7): system simulation with AMESim and control with Matlab/Simulink),
- third, the control strategy are implemented using rapid control prototyping tools (dSPACE) and tested on experimental rig,
- the last step, the implementation of the control algorithm on the appropriate electronic will be

developed in the future with an other research group of the Lab.

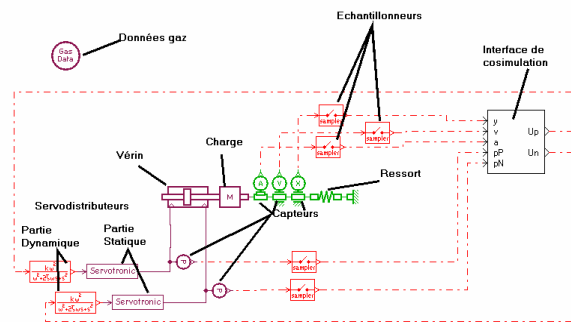


Fig. 7: Virtual bench test about rudder control

#### High order sliding mode Control

A drawback of the sliding mode is that the discontinuous control signal may excite high frequency dynamics neglected at modelling stage such as non modelled structural modes, time delays and so on. This causes fast, finite-amplitude oscillations known as chattering, which would result in loud noise, high wear of moving mechanical parts and thus should be definitely eliminated. The consequence of this phenomenon concerns the wearing effect of power modulator and actuator. Exceed of energy consumption and high frequency excitation can be very harmful to the system.

A classical solution to reduce the chattering consists to use a threshold in control law, but the undesirable effect concerns that the robustness advantage is inhibit theoretically and a static error appears experimentally. Another complex solution consists to use high order sliding mode algorithm. This technique is study at the Ampère Lab. We proved the interest of this technique for a missile rudder pneumatic positioning compared to gains scheduling approach. This work leads also to the development of specific observers (extended or not) using only one mechanical sensor. Figure 8 shows the test bench developed for testing specific control algorithms.

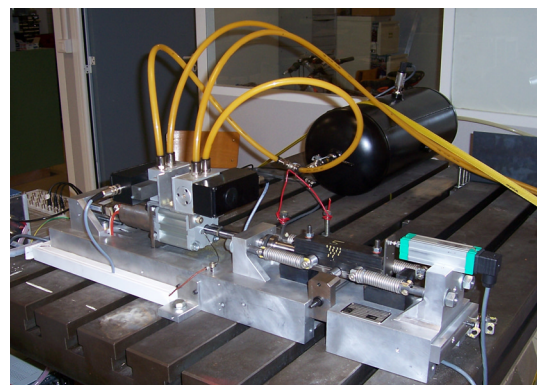


Fig. 8: Experimental test bench for rudder control

#### Control without sensor

It concerns the study of electro-pneumatic actuators in environment with high perturbations, for example the observation of the perturbation in aeronautic context using a minimum of physical sensors. The robust nonlinear control can be a solution to reject the perturbations, but this approach leads to the knowledge

of all variable states. Our work aims at the development of specific control strategies with high performances, without position sensor or pressure sensor but using observers to obtain the unknown information.

#### *Strictly positive real system and stick-slip phenomenon*

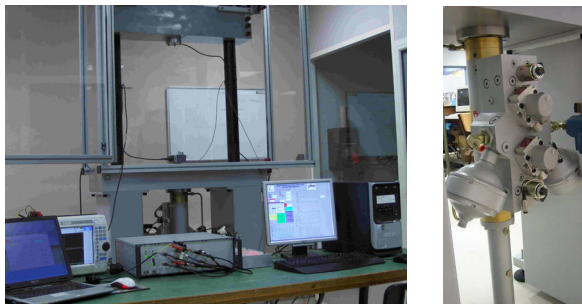
From 2007, some works have permit to propose a new method to study the stability of the equilibrium set of nonlinear models. It has been applied to path planning of electro-pneumatic actuator. Moreover using an appropriate switching strategy between different control laws (path planning or pressure regulation), the undesirable stick slip occurrences have been reduced to zero.

#### *Control of electro-hydraulic system*

A high performances electro-hydraulic test bench has recently been developed. It offers high acceleration, high precision, micro-displacement at very low velocity, with high bandwidth servovalves (**Fig. 9**). Classical control strategies have been implemented in simulation and experimentally. Actually, an accurate virtual model is developed including servovalve, hydraulic lines and pressure supply nonlinear characteristics and dynamic.

#### *Control of hybrid Fluid Power systems*

An actuator controlled by on/off valves is structurally considered as a hybrid dynamic system. This class of system presents simultaneously continuous dynamic (actuator) and discrete behavior (on/off valves). Due to the recent development of fast on/off valves, it is now possible to replace classical servovalves by low cost servosystems using the appropriate control algorithm. A first application of this technique in the Lab is the development of a specific electro-pneumatic haptic system for learning perfect movements in the medico-chirurgical context.



**Fig. 9:** Electro-hydraulic test bench (actuator on right hand)

These know-how and original contributions leads to an important expertise in term of Control in Fluid Power, from theory to application. Today, researches focus on energy efficiency, stick-slip in pneumatic systems and robustness. The main aim is still to be able to specify which control law is the more appropriate to a specific Fluid Power system.

### 3 Experimental Facilities

The Ampère Lab has 7 laboratory facilities located at the different Engineering schools supporting the Lab:

- Electromagnetic Compatibility test centre,
- Environmental microbiology laboratory,
- High Voltage test centre,
- Diagnostic platform for electrical systems,
- Characterization and Reliability platform for passive components,
- Characterization platform for power SC components and systems,
- Fluid Power Centre.

The Fluid Power experimental facilities are located at INSA Lyon on 140 m<sup>2</sup>. It consists in a range of electro-pneumatic and electro-hydraulic rigs used for different purposes such as virtual prototyping (modelling) and rapid prototyping (control implementation). The main characteristics are given below:

- Fluid energy supply: air supply (2500 NI/mn at 7 bar), hydraulic supply (18,5kW, 46 l/mn à 210 bar), vacuum pump,
- high performance hydraulic drive (300 mm stroke, 20 kN maximum static force, 2 servovalves @ 1kHz +/- 5% control),
- electro-pneumatic drive benchmark for the performance evaluation of control algorithm,
- flow/pressure rigs for pneumatic component and circuit characterization (ISO6358), isothermal tank,
- sensors, acquisition system, rapid prototyping equipments (dSpace),

### 4 International links

The Fluidtronic group is a founder member of the Fluid Power Centres of Europe ([FPCE](#)<sup>2</sup>), a grouping of the foremost research institutions in the field. Each year international scholars, mainly from North Africa, North and South America, are visiting the Lab for long or short stays. It welcomes also PhD students from scientific programs with China, South America, and North Africa.

### 5 Relation with industry

The Fluidtronic research activities are for most of them industry focussed. These collaborations are built around PhD, undergraduate and MSc projects of the Department of Mechanical Design Engineering. Recent collaborations on research and consultancy projects include:

PSA PEUGEOT CITROËN, VOLVO TRUCKS, VOLVO POWERTRAIN, DGA (Ministry of Defence), CETIM, CNES (French Aerospace Agency), BOSCH, BOSCH-REXROTH, EDF, NUMATICS-ASCO JOUCOMATIC, LMS-IMAGINE, SHERPA ENGINEERING, LORENZ SIMULATION, FLUOREM SA, PLASTIC OMIUM AE, IRISBUS, LOHR INDUSTRY, ALSTOM, KNORR, HCL (Hospice civil de Lyon), ...

<sup>2</sup> <http://www.fpce.net/>