ANALYSIS AND OPTIMIZATION OF A TWO-WAY VALVE USING RESPONSE SURFACE METHODOLOGY

Andrea Vacca and Matteo Cerutti

Industrial Engineering Department – University of Parma, Italy
andrea.vacca@unipr.it, matteo.cerutti@htc.de.unifi.it

Abstract

This paper describes the use of a numerical procedure developed by the authors for the analysis and optimization of hydraulic components. The element taken as reference is a two-way priority spool valve, typically utilized in steering systems with a load sensing control strategy in the presence of other actuators. The valve's purpose is to control the primary port flow rate, the exceeding flow being discharged to the secondary output port.

The optimization algorithm is based on Response Surface Methodology techniques, adopting the path search method known as Steepest Descent. For this purpose, the component's behaviour is analytically described by means of a properly defined objective function. The procedure approximates this objective function with a simple model whose coefficients are evaluated using an AMESim® model of the valve, previously verified using test results. The simulations required to find the fitting model are planned using Design Of Experiments (DOE) methods.

Because of the large number of factors characterizing valve design a preliminary analysis (screening) based on DOE algorithms was performed in order to identify the parameters which significantly influence valve behaviour. This allows the important factors to be considered for the optimization phase.

The entire numerical procedure was implemented through MATLAB® scripts which automatically execute the AMESIM® simulations to perform the screening analysis or optimization.

Considering a configuration pertinent to a stock version of the valve as starting point of the procedure, the paper proposes an optimal configuration. Experimental investigations performed on a prototype reveal the improved performance achieved with the proposed design in comparison with the behaviour observed in different stock versions of the valve, highlighting the potential of the optimization procedure developed.

Moreover, the results presented in the paper illustrate how the procedure can also be utilized to perform other analyses of component behaviour, for example, proving, useful guidelines for the definition of dimensional tolerances.

Keywords: hydraulic valves, priority valves, flow divider valves, optimization, design of experiments, response surface methodology

1 Introduction

Despite existing literature on the topic of design and optimization methods in engineering, an engineer often relies on judgement, experience, heuristics, intuition and analogy to solve a design problem, rather than on the specific knowledge of a suitable procedure.

Taking advantage of experiments and especially of the latest simulation techniques, many configurations of a component can be analysed in a short time, so that an expert designer can give a preliminary new design using their theoretical and industrial know-how acquired through previous experience.

This manuscript was received on 24 April 2007 and was accepted after revision for publication on 8 October 2007

Nevertheless, the number of parameters to be considered in order to define an optimal design is often too high for an exhaustive parametric analysis to be done by means of simple intuition (based on the results provided by good predictive models or a limited number of experiments). Consequently, in many cases only a limited number of factors, chosen by intuition and not in accordance with a specific criterion, are taken into account, while the others are kept to fixed values (based on existing configurations). With these assumptions, the designer is often tempted to follow a sort of "best guess approach": when a promising configuration does not attain the desired results, another "guess" must be made by varying the combination of the factors' levels. This approach often works reasonably well if the designer has a great deal of technical or theoretical knowledge of the system they are studying, as well as considerable practical experience. Regardless, this optimization method cannot guarantee success: in fact, supposing the initial guess produces an acceptable result, the designer is tempted to stop and neglect new configurations although there is no guarantee that the best solution has been reached.

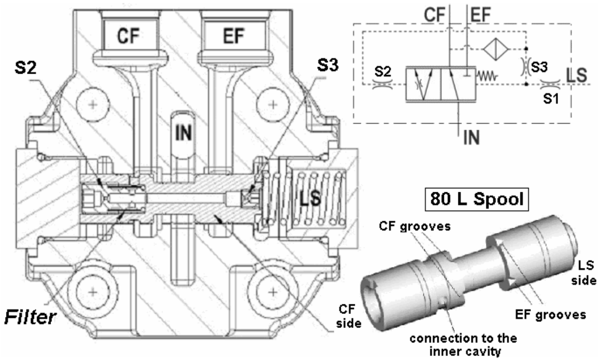


Fig. 1: *The valve and its equivalent ISO scheme (Casappa PLP20). Particular of the 80L stock spool*

The hydraulic component taken as reference in the present study, namely a load sensing flow divider valve (Fig. 1), gives an example of the concepts mentioned above. Experiments carried out on different stock versions of the valve point out possibilities for improvements in their design. However, although a simulation model of the valve, described in (Casoli et al., 2003; Berta et al., 2003), is available and can be utilized instead of real experiments, the optimization task is difficult and not intuitive. This is due to the great number of design parameters and the effects of their reciprocal interactions on the component's behaviour.

The case of the valve considered in this work shows what frequently happens in small fluid power industries – even if they are equipped with up-to-date machinery or numerical simulation tools – during the development of new components. From this point of view a crucial role is played by good knowledge of the optimization techniques and, above all, by effective utilization of R&D facilities (i.e. simulation tools, test benches) available towards the optimization of the component's design.

Literature describes many mathematical methods suitable for design optimization, although in the fluid power field the adoption of sophisticated optimization techniques remains uncommon. Few works demonstrate the efficacy of different optimization methodologies utilized for hydraulic components: Papadopoulos et al., (2004) employed a sequential quadratic method as an algorithm for the selection of an optimal hydraulic component; Dahlén et al., (2003) used the method of moving asymptotes to optimize a distributor valve; in Wiens et al., (2005) a genetic algorithm was utilized to develop a new variable ratio flow divider valve.

Unfortunately, methods used for optimization (like the ones utilized in the works mentioned) refer to well-posed design problems, where the inputs and constraints are completely and unequivocally specified, and the objective is exactly quantified in terms of proper objective function(s), which must be minimized (or maximized) by the optimization algorithm. However – as happens in this work – the real problems are seldom textbook problems: goals are usually vague, data are incomplete and often expressed in a qualitative rather than quantitative fashion, and constraints are weak.

All the aspects mentioned have limited the use of numerical algorithms for optimization in fluid power industries. In addition, the mathematical procedures for optimization are suitable for a limited number of parameters, while for hydraulic elements the number of variables is often high. Therefore, in order to obtain an efficient optimization process, the number of initial input factors must be limited to the most influential factors only. This step, also known as variable selection, has a strong influence on the optimization procedure, and – for this purpose – any degree of subjectivity must be avoided.

Following this idea, the authors have developed a numerical procedure based on Design Of Experiments (DOE) and Response Surface Methodology (RSM) for the analysis and the optimization of a wide variety of components. Despite the generality of the procedure, the present work describes its application for the analysis and optimization of the hydraulic valve shown in Fig. 1. Contrary to many fields of engineering where DOE- and RSM-based analyses are widely adopted, in hydraulics the literature contains only few examples –one of which is described by Vesely (2003) – and only the latest releases of some simulation tools typically used for the analysis of hydraulic systems and components allow for very simple DOE analyses. Through MATLAB® scripts developed for this purpose, the RSM procedure utilized in this work allows for the analysis and optimization of the valve, executing simulations with an AMESim® model of the valve. The procedure analyzes and proposes a new design of the valve on the basis of two different Objective Functions (OFs), representative of the component's behaviour. For a proper definition of the OFs the study takes advantage of what is discussed in (Vacca, 2006), where a similar MATLAB® procedure was used for a complete screening analysis of the same valve, for one of the two OFs considered in the present work. Accounting for the requirements that characterize the valve design, the present study considers the multi-objective optimization problem of realizing the best compromise for both of the defined OFs. For this purpose, a screening analysis has been made to find the main parameters that have a major influence on the OFs' values. On the basis of the screening results, the numerical optimization procedure has then been used to formulate an optimal design of the valve.

Once an optimal configuration has been found, the present work shows how the methodology adopted can provide many useful guidelines for geometrical tolerances.

The last part of the paper focuses on the experimental verification of the design proposed: a prototype of the optimal valve has been realized and tested, and its performance has been compared with the one pertinent to the stock versions of the valve.

2 Optimization using DOE and RSM

One (or more) objective function(s) is (are) defined as a function of (all) the significant performance parameters of the component. The optimization consists in finding the proper extremes of the OF, under the applicable set of constraints.

Many analytical methods are available for design optimization when an analytical model for the system can be defined, in terms of relationship between performance parameters (OFs) and system factors. Detailed descriptions concerning several methods can be found, for example, in Eschenauer et al., (1990). Obviously, describing the real system with mathematics is not an easy task, and is often accompanied by simplifying assumptions, introducing inaccuracies. Moreover, in many problems, once the goals of the design task are assigned, it is very hard to reach a mathematical formulation of the OFs, because of the large number of factors or the incomplete understanding of all the phenomena related to the system's behaviour. For these cases, many kinds of strategies have been developed to solve the optimization problem. As described by Frangopoulos (2003), the optimization algorithms can generally be classified into two subcategories: evolutionary algorithms and algorithms derived from the combinatorial optimization branches. The latter include many heuristic search methods.

The experimenter may also encounter situations in which the full analytical model would not be appropriate. Then variable selection or model-building techniques may be used to identify the best subset of regressors to include in a regression model. Identifying and fitting an appropriate response surface model from experimental data requires some use of statistical experimental design fundamentals, regression modelling techniques, and optimization methods. All three of these topics are usually combined into Response Surface Methodology (RSM), a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. The method introduced originally by Box and Wilson (1951) was conceived as an important branch of experimental design with the main idea to use a sequential experimental procedure to obtain an optimal response. As described in (Myers, 1999; Myers et al., 2002), RSM was also applied to both random and deterministic simulation models, assuming that both the real and the simulated system can be treated as a black box. RSM aims to define empirical statistical models in order to develop an appropriate approximating relationship between the yield and the process variables. Most applications of RSM, like the one considered in this study, are sequential.

Phase 0: ideas are generated concerning which factors or variables are likely to be important in the response surface study. It is usually called the screening phase. The objective of factor screening is to reduce the list of candidate variables to a relatively few so that subsequent experiments – or simulations - will be more efficient and require fewer runs or tests.

Phase 1: The designer's objective is to determine if the current settings of the independent variables result in a value of the response that is near the optimum. If the current settings or levels of the independent variables are not consistent with optimum performance, then a set of adjustments to the process variables must be determined to move the process toward the optimum. Many techniques, known as patterns search methods, have been developed to perform this optimization phase of RSM. As highlighted by Montgomery (1997), the most adopted of these latter methods is the method of Steepest Ascent (Descent).

Phase 2: This phase begins when the process is near the optimum (end of Phase 1). At this point the designer usually wants a more complex model than the one used in Phase 1, which will accurately approximate the true response function within a relatively small region around the optimum. Once an appropriate approximating model has been obtained, this model may be analyzed to determine the optimum conditions for the process.

The methods and techniques suitable for each phase of RSM are included in a branch usually called Design of Experiments (DOE). DOE was initially conceived for experiment conducting and planning, and provides a collection of stochastic techniques mainly built on the foundations of the analysis of variance (ANOVA). DOE was first introduced in the early 1920s by Sir R. Fisher (1935), but the design principles that he developed have been successfully adapted to industrial and military applications since the late 1940s thanks to the efforts of G. Taguchi, who made this experimental technique more user-friendly, as described by Ranjit (2001). Today literature indicates DOE as one of the most effective quality building tools used by engineers in all types of manufacturing activities.

DOE is an important formal method of maximizing information (in terms of dependence of the system's response on the input factors) gained while minimizing the required resources. Neglecting the techniques typical for experimental design (i.e. blocking, randomization, replication), DOE provides the best set of system configurations (usually called design) to perform the three phases of RSM. In particular, DOE proposes factorial strategies for the screening phase as the correct approach to deal with several factors, allowing the interactions between factors to be easily detected. DOE efficient designs are based on a fractional factorial plan, which allows an experiment (or observation) to be conducted with only a fraction of all the possible experimental combinations of parameter values. A detailed description of how fractional factorial designs are constructed is beyond the scope of this paper. However, it is important to mention the primary concept given by the resolution. Using fractional design some factors are generated from the interactions of a low order full factorial design. As a result, the design does not give a full resolution; this means there are certain interaction effects that are identical to other effects. Detailed accounts can be found in the literature mentioned and in (Antony, 2003).

Data provided from the ANOVA analyses of fractional two-level factorial designs are sufficient to determine which explanatory variables have an impact on the response variable(s) of interest. On the other hand, concerning the RSM phases after screening, more complicated DOE designs (such as three-level factorial designs, central composite designs, etc.) are often used to define second (or higher)-degree polynomial models.

In the approach adopted in the present work the DOE analysis is based on a numerical model instead of real experiments. This implies the use of the simulation model outside the range of its verification on the basis of experimental data. Therefore, a further verification of the final results of the procedure (optimum point) is inevitable. In spite of this disadvantage, the numerical procedure guarantees a great sensitivity of the results on the value of each input parameter. The latter aspect is an important advantage for DOE analyses based on simulation results, often difficult to achieve when the DOE analysis utilizes experimental data, because of the instrumental errors, uncertainties and other measurement errors.

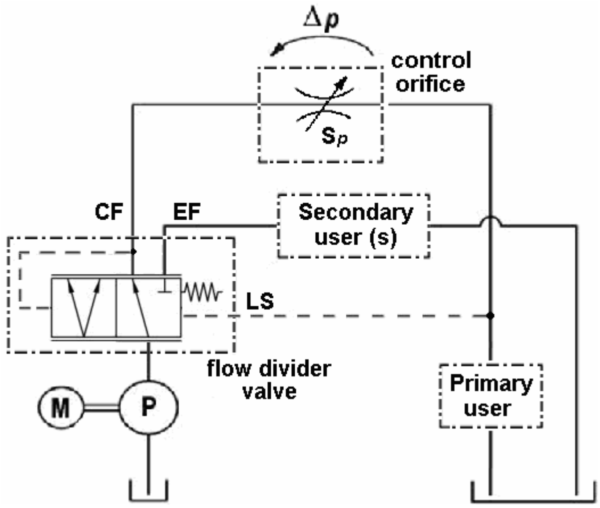


Fig. 2: *Typical application of the valve*

3 Valve Description and Requirements

The component considered for the RSM analysis in this work is a particular flow divider valve, namely a two-way, load-sensing, flow-divider spool valve. The typical application of this component is in circuits where a single pump feeds the steering system, with a load sensing control strategy, and other actuators. As described by Nervegna (2003), a common use of the valve is represented in the hydraulic system of fork lift trucks.

As reported in Fig. 1, the valve splits the inlet flow between two outputs, named CF (controlled flow) and EF (exceeding flow). Fig. 1 reports Casappa's integrated solution, in which the valve casing is also the cover of the pump (a gear pump) connected to the inlet port.

With some simplifying assumptions (for further details, see the appendix), the spool equilibrium in steady state conditions gives the relationship between the pressures at CF and LS (load sensing) ports:

$$\Delta p_{\mathrm{w}} = p_{\mathrm{CF}} - p_{\mathrm{LS}} = \frac{F_{\mathrm{m}}}{\Omega_{\mathrm{s}}} \cdot \left[1 + \left(\frac{d_{\mathrm{S3}}}{d_{\mathrm{S1}}} \right)^{4} \right] \tag{1}$$

In typical operating conditions, the spool position is confined within a small range, so that the value of F_{m}, and therefore of Δp_{w}, is approximately constant. The insensitivity of the Δp_{w} value is an important requirement because it permits an easy control of the flow rate through port CF by means of an orifice, *Sp* (representative of a working steering system), located between output port CF and input signal port LS, as shown in Fig. 2. In fact, as a consequence of Eq. 1 the value of the flow rate through CF is a function only of the orifice area. Equation 1 also emphasises the effect of orifices S1 (located on the hydraulic signal port LS) and S3 (located on the inner cavity of the spool) on the value of Δp_{w}.

Experimental results show that the valve's Δp_{w} during its functioning is significantly influenced by the value of the flow rate on the input port and on other parameters not accounted for in Eq. 1. This is due to the significant effects neglected by Eq. 1, in particular the fluid dynamics effects, as thoroughly discussed in (Casoli et al., 2003; Berta et al., 2003).

Another important prerequisite characterizing the design is given by the losses that affect the flow diverted to the exceeding port, which are to be limited as much as possible. The latter necessity acquires primary importance, being $Q_{\mathrm{EF}} >> Q_{\mathrm{CF}}$, in the most typical operating conditions of the valve.

4 The Numerical Model of the Valve

The valve's actual behaviour as a function of its operating conditions, strongly related to the valve's design parameters, can be predicted with a numerical lumped parameter model presented in Casoli et al. (2003) and Berta et al. (2003). The model is based on a sub-division of the valve in a number of control volumes connected by fixed or variable orifices. The flow through the control volumes is described with Bernoulli and mass conservation equations. Moreover, the model carefully evaluates:

- the flow forces acting on the spool, with a simple formulation of the momentum equation for both steady and unsteady conditions;
- the flow areas of the connection between the valve inlet port and the output ports, accounting for the peculiar geometry of spool and casing (Fig. 1);
- the leakages between spool and valve casing;
- the influence of the spool position on the force generated by the spring;
- the friction forces, considering the effect of static, dynamic and viscous frictions, including the Stribeck effect with the Karnopp model (Karnopp, 1985).

The simulation code was developed in the AMESim® environment (Fig. 3 displays its representative sketch), developing C++ submodels in order to better consider the effects mentioned, as described in detail in (Casoli et al., 2003). The model is easy to use and permits fast simulations of the valve in generic hydraulic circuits thanks to AMESim® facilities.

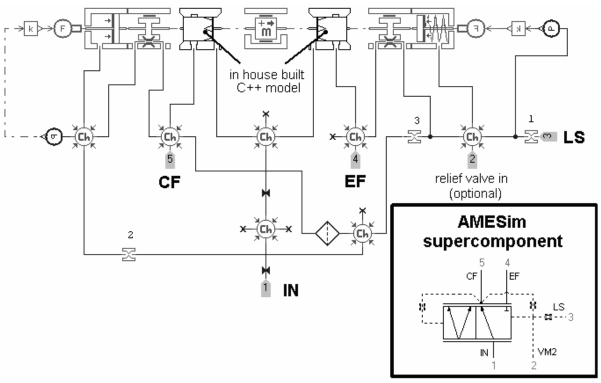
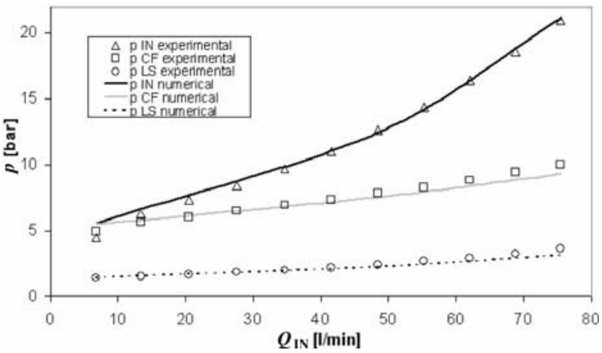
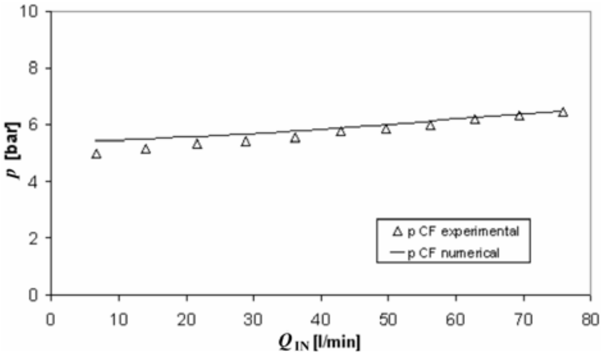


Fig. 3: *Sketch of the AMESim model of the valve*



a)



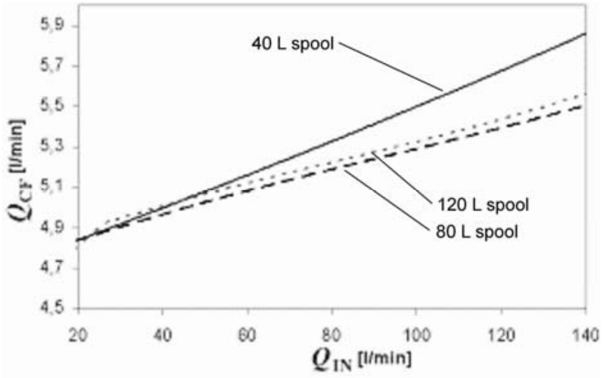
b)

Fig. 4: *Experimental data and simulated results for a working condition (a) and a stand-by condition (b)*

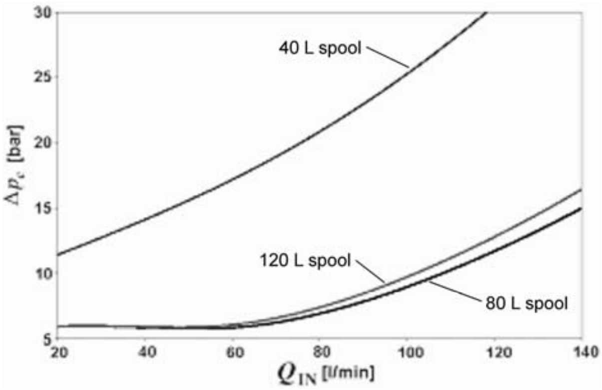
A model verification was performed by comparing its results with some experimental data, accounting for the two typical working conditions:

- stand-by, when the flow rate on the CF port is null and all the inlet flow is diverted to the EF port (this condition is representative of a non-working steering system connected to CF);
- working, when the valve splits the inlet flow between the two output ports, satisfying Eq. 1.

Experimental data were collected from a test campaign performed at the manufacturer's laboratory on several versions of the Casappa PLP20 valve (Fig. 1). Many details concerning the test rig are reported in (Casoli et al., 2003; Berta et al., 2003), and a wide discussion on the comparison between experimental data and simulation results is provided. For the sake of brevity, only two significant diagrams are reported here to highlight the potential of the model in Fig. 3: Fig. 4a refers to a working condition, Fig. 4b to a stand-by one.



a)



b)

Fig. 5: *Simulated results: a) controlled flow on port CF (working condition) b) pressure drop between IN and EF ports (for a stand-by condition)*

Both diagrams in Fig. 4 highlight the actual behaviour of the valve in steady state conditions, evidenced by the dependence of Δp_w on the value of the inlet flow rate. This involves an analogous dependence of the resulting Q_{CF} (assuming a fixed orifice downstream the CF port *Sp*, in Fig. 2).

5 Objective Functions and Parameters Considered in the Analysis

The valve taken as reference supplies the two output ports (CF and EF) with two different requirements:

- constant value Δp_w; this allows for good control of the port CF flow rate by means of the orifice *Sp* (Fig. 2),
- minimum losses Δp_c for the flow through the secondary port (EF).

As typically happens for spool valves, different stock versions are produced using the same casing and varying the spool's design on the basis of the operating conditions faced by the valve. Figure 5 shows the performance of the CASAPPA PLP20 stock valves (assuming the same configuration of orifices, spring and casing). Although each spool was conceived for a definite range of flow rates for the valve considered here, the two figures highlight the necessity for optimization: the courses displayed in Fig. 5, obtained by the spool suggested for the lowest inlet flow rates (40L), are worse than the one achieved with the spool designed for the medium flow rates (80L). Similar considerations can be made observing the plots realized by the 120L spool.

Table 1: Factors considered in the analysis

ID	Design Parameters (predictor variables)	Unit	Level min	Level max
A	Orifice S1 diameter	mm	0.5	1.5
B	Orifice S3 diameter	mm	0.5	1.5
C	Spring Stiffness	N/mm	8.099	23.131
D	Underlap CF side (Fig. 6)	mm	4.7	5.2
E	Underlap EF side (Fig. 6)	mm	-1.5	-1
F	Spring Preload	N	40.49	173.48
G	Groove length CF (Fig. 6)	mm	1	2.5
H	Groove length EF (Fig. 6)	mm	1	2.5
I	Groove angle CF (Fig. 6)	degree	21.8	46
J	Groove opening angle CF (Fig. 6)	degree	90	120
K	Groove angle EF (Fig. 6)	degree	21.8	46
L	Groove opening angle EF (Fig. 6)	degree	90	120
M	Number of grooves (CF side)	-	1	8
N	Number of grooves (EF side)	-	1	8
O	Orifice S2 diameter	mm	0.5	1.5
P	Spool internal diameter	mm	9	11

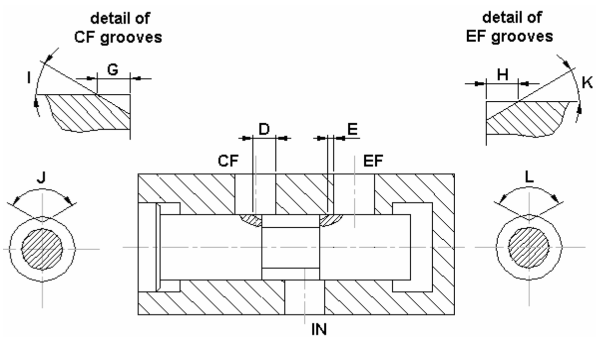


Fig. 6: *Spool geometrical parameters of Table 1*

A proper RMS - DOE analysis of the valve requires a suitable description of its performance by means of analytical equations. This can be achieved through the definition of two OFs that are null for the ideal case and should be minimized for the sake of realizing the optimal design: function Φ_1 represents the average pressure drop suffered by the flow deviated to the secondary output port, EF, within the considered inlet flow rate range:

$$\Phi_1 = \frac{1}{p_{\text{ref}}} \cdot \frac{1}{\left(Q_{\text{IN,max}} - Q_{\text{IN,min}}\right)} \int_{Q_{\text{IN,min}}}^{Q_{\text{IN,max}}} \Delta p_{\text{c}} \cdot dQ_{\text{IN}} \quad (2)$$

function Φ_2 represents the influence of the input flow rate on the working pressure Δp_w. Assuming a fixed orifice *Sp*, between the ports CF and LS (Fig. 2), the changes of the Δp_w value cause variations in the flow through primary output port CF:

$$\Phi_2 = \frac{Q_{\text{ref}}}{p_{\text{ref}}} \cdot \frac{1}{\left(Q_{\text{IN,max}} - Q_{\text{IN,min}}\right)} \int_{Q_{\text{IN,min}}}^{Q_{\text{IN,max}}} \left| \frac{\partial \Delta p_{\text{w}}}{\partial Q_{\text{IN}}} \right| \cdot dQ_{\text{IN}} \quad (3)$$

In Eq. 2 and 3 the first factor makes both Φ_1 and Φ_2 dimensionless functions. The analysis and the optimization performed in this work refer to steady working conditions, therefore all evaluations of functions Φ_1 and Φ_2 ignore transients.

The design parameters considered for the analysis are listed in Table 1 (some of these are displayed in Fig. 6). Parameters of the casing - which is the most expensive part of the valve – are not included in this analysis, as the goal is represented by the definition of the optimal design of valve spool, combined with the best choice of the orifices and the spring parameters.

Table 2: Operating conditions considered for the screening analysis

Operating condition		Range Q_{IN} [l/min]	ID	Range Q_{IN} [l/min]	ID
stand-by	Q_{CF} = 0 l/min	[0÷140]	1	[60÷140]	2
working	$Q_{CF} \approx$ 6 l/min	[0÷140]	3	[60÷140]	4
working	$Q_{CF} \approx$ 30 l/min	[0÷140]	5	[60÷140]	6

6 Screening Analysis of the Valve

The first goal of this study is the screening analysis, namely the identification of the parameters in Table 1 that have a significant influence on the valve's behaviour, according to Eq. 2 and 3. As its first step, screening analysis requires the definition of the region of interest for the parameters. Considering a two-level factorial design suitable for screening analysis, the region is completely defined by the upper and the lower levels of the design parameters (Table 1). Thus, the set of configurations taken into account in the analysis represents all the possible combinations of the levels specified in Table 1. Hence, particular attention must be given to the choice of values in order to steer clear of impossible configurations[1] and avoid the generation of valves that cannot work as required by the ISO scheme in Fig. 1. For this purpose, each configuration considered has been checked utilizing a parametric CAD 3D model of the valve.

A complete screening analysis must also deal with the different possible working conditions faced by the valve. This particular kind of priority valve is utilized for both small-size or high-size steering systems (implying different values of Q_{CF}); moreover the inlet flow – and consequently the flow at the exceeding port – can vary (to values greater than 100 l/min), according to the requirements of the auxiliary circuit connected to the EF port. For these reasons, six different conditions (listed in Table 2), representative of the possible operating conditions of the valve, have been considered for the screening analysis.

As reported in Table 2, different values have been assumed for Q_{CF}: 0 l/min is representative of a stand-by condition, while 5 l/min and 30 l/min pertain to two different working conditions. For each operating condition in

1 Impossible configurations stem from non-feasible dimensioning of valve drawings, but also derive from the requirements of the machining tools utilized during the manufacturing process. For this purpose, the authors have adopted indications provided by Casappa S.p.A.

Table 2, two separate analyses (varying the Q_{IN} range) have been carried out for the sake of better describing the effects of valve saturation. As shown in Fig. 7, saturation conditions are reached when the flow at the inlet port Q_{IN} exceeds the request at the priority port, Q_{CF}. Hence, considering separate screening analyses for different ranges of Q_{IN}, it is possible to estimate the influence of the factors in Table 1 as a function of the inlet flow rate.

On the basis of the design parameters of Table 1, a two-level full factorial analysis would require the evaluation of the OFs for 2^{16} configurations (the experimental plan, or design), for every condition in Table 2. A significant reduction in the number of configurations has been achieved considering a 2^{16-11}_{IV} fractional factorial design, in accordance with the standard nomenclature used by most DOE textbooks, which contains only a fraction of the configurations included in the full factorial design. This assumption implies aliasing effects (parameters and interactions between them whose effect is confused with interactions of higher order). However, for fluid power elements it is suitable to study only the main effects of each variable on the two-factor interactions, while three-factor and higher-order interactions are rarely important and difficult to understand. The choice of the proper defining relation (in terms of generators of the fractional design) is a fundamental aspect concerning the resolution of the design, and consequently, determines which parameters and interactions can be confused (Box et al., 1987; Montgomery, 1997). The particular four-resolution design adopted for the analysis performed in this work is reported in Table 3. The defining relations are summarized in Table 4. As pointed out in Table 4 and similar to the analysis made in (Vacca, 2006), no main effects are confused with each other or with any two-factor interaction; but several two-factor interactions are aliased, and there are main effects aliased with three (or more)-factor interactions.

For each configuration of the valve, effects are computed adopting the Yates algorithm, as reported in (Box et al., 1987; Montgomery, 1997). Screening results can then be graphically represented. Typical plots used in the DOE ambit are the diagnostic plots of residuals, square and cube plots, surface and contour plots, normal probability plots of effects and Pareto charts of effects. These two latter plots are widely used – and probably the most effective – for communicating screening results. In particular, normal probability plots represent the effect estimates (rank ordered) related to each of the factors (and of the main interactions), against the normal probability; negligible effects are normally distributed and will tend to fall along a straight line (representative of a normal distribution), whereas significant effects will have nonzero means and will not lie along the straight line. In the Pareto charts the ANOVA effect estimates are sorted from the largest absolute value to the smallest absolute value.

Table 3: The 32 configurations of the 2^{16-11} design considered for the valve screening (for dimensions see Table 1). Factors from A to E are chosen as generators of the design

Run n.	Predictors															
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*
1	0,5	0,5	8,08	4,7	-1,5	40,49	1	1	90	21,8	21,8	120	8	8	1,5	9
2	1,5	0,5	8,08	4,7	-1,5	203,55	2,5	2,5	90	46	46	90	1	1	1,5	11
3	0,5	1,5	8,08	4,7	-1,5	203,55	2,5	1	120	46	21,8	90	1	8	0,5	11
4	1,5	1,5	8,08	4,7	-1,5	40,49	1	2,5	120	21,8	46	120	8	1	0,5	9
5	0,5	0,5	23,131	4,7	-1,5	203,55	1	2,5	120	21,8	46	90	8	1	0,5	11
6	1,5	0,5	23,131	4,7	-1,5	40,49	2,5	1	120	46	21,8	120	1	8	0,5	9
7	0,5	1,5	23,131	4,7	-1,5	40,49	2,5	2,5	90	46	46	120	1	1	1,5	9
8	1,5	1,5	23,131	4,7	-1,5	203,55	1	1	90	21,8	21,8	90	8	8	1,5	11
9	0,5	0,5	8,08	5,2	-1,5	40,49	2,5	2,5	120	21,8	21,8	90	1	1	0,5	11
10	1,5	0,5	8,08	5,2	-1,5	203,55	1	1	120	46	46	120	8	8	0,5	9
11	0,5	1,5	8,08	5,2	-1,5	203,55	1	2,5	90	46	21,8	120	8	1	1,5	9
12	1,5	1,5	8,08	5,2	-1,5	40,49	2,5	1	90	21,8	46	90	1	8	1,5	11
13	0,5	0,5	23,131	5,2	-1,5	203,55	2,5	1	90	21,8	46	120	1	8	1,5	9
14	1,5	0,5	23,131	5,2	-1,5	40,49	1	2,5	90	46	21,8	90	8	1	1,5	11
15	0,5	1,5	23,131	5,2	-1,5	40,49	1	1	120	46	46	90	8	8	0,5	11
16	1,5	1,5	23,131	5,2	-1,5	203,55	2,5	2,5	120	21,8	21,8	120	1	1	0,5	9
17	0,5	0,5	8,08	4,7	-1	40,49	1	1	90	46	46	120	1	1	0,5	11
18	1,5	0,5	8,08	4,7	-1	203,55	2,5	2,5	90	21,8	21,8	90	8	8	0,5	9
19	0,5	1,5	8,08	4,7	-1	203,55	2,5	1	120	21,8	46	90	8	1	1,5	9
20	1,5	1,5	8,08	4,7	-1	40,49	1	2,5	120	46	21,8	120	1	8	1,5	11
21	0,5	0,5	23,131	4,7	-1	203,55	1	2,5	120	46	21,8	90	1	8	1,5	9
22	1,5	0,5	23,131	4,7	-1	40,49	2,5	1	120	21,8	46	120	8	1	1,5	11
23	0,5	1,5	23,131	4,7	-1	40,49	2,5	2,5	90	21,8	21,8	120	8	8	0,5	11
24	1,5	1,5	23,131	4,7	-1	203,55	1	1	90	46	46	90	1	1	0,5	9
25	0,5	0,5	8,08	5,2	-1	40,49	2,5	2,5	120	46	46	90	8	8	1,5	9
26	1,5	0,5	8,08	5,2	-1	203,55	1	1	120	21,8	21,8	120	1	1	1,5	11
27	0,5	1,5	8,08	5,2	-1	203,55	1	2,5	90	21,8	46	120	1	8	0,5	11
28	1,5	1,5	8,08	5,2	-1	40,49	2,5	1	90	46	21,8	90	8	1	0,5	9
29	0,5	0,5	23,131	5,2	-1	203,55	2,5	1	90	46	21,8	120	8	1	0,5	11
30	1,5	0,5	23,131	5,2	-1	40,49	1	2,5	90	21,8	46	90	1	8	0,5	9
31	0,5	1,5	23,131	5,2	-1	40,49	1	1	120	21,8	21,8	90	1	1	1,5	9
32	1,5	1,5	23,131	5,2	-1	203,55	2,5	2,5	120	46	46	120	8	8	1,5	11

Table 4: Defining relations of the adopted design and three-factor interactions confused with main effects

Design generator
F = ABC, G = ABD, H = ACD, I = BCD, J = ABE, K =ACE, L = BCE, M = ABCD, N = ABCE, O = ABDE, P = ACDE, Q = BCDE
Defining relations
df = ABCF = ABDG = ACDH = BCDJ = = ABEK = ACEL = ABCDM = ABCEN = = ABDEO = ACDEP =BCDEQ = ABCDER
Three factor interactions aliased with main effects
A = BCF = BGD = CDH =BEJ =CEK B = ACF = ADG = CDI =AEJ C = ABF = ADH = BDI = BBJ D = ABG = BCI; E = ABK =ACK F = ABC ; G = ABD; H = ACD; I = BCD; J = ABE; K = ACE; L = BCE M, N, O, P, Q = (No three factor interaction aliased)

Screening analysis, as well as the following optimization process, has been performed by MATLAB® scripts developed by the authors. The tasks of the computer-based procedure can be summarized as follows:

- Definition of the best experimental plan: data reported in Table 3 are an example of possible results of the developed tool. The procedure searches for the experimental plan that realizes the best compromise between the minimum number of configurations and maximum design resolution according to the common DOE fractional techniques.
- Execution of the simulations, using the AMESim® model previously described. The values of the two OFs (Φ_1 and Φ_2) are evaluated through simulations controlled by MATLAB® scripts;
- Data post processing (ANOVA analysis) and graphical representations (Pareto histograms and normal probability plots) of results.

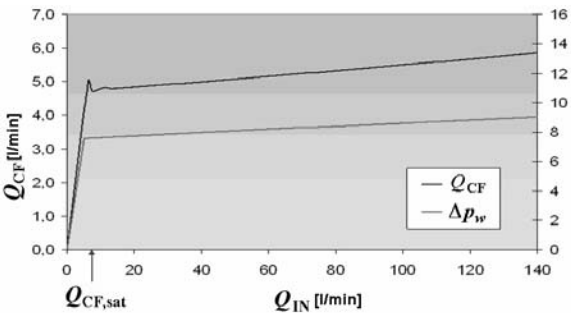


Fig. 7: *Valve saturation for a working condition*

Screening results refer to the operating conditions in Table 2. With configurations 1 and 2, only function Φ_1 has been evaluated (function Φ_2 is irrelevant, for stand-by conditions, being Q_{CF} null); while both functions Φ_1 and Φ_2 have been considered for the remaining working conditions in Table 2. Figures 8a and 8b show the results for function Φ_1 evaluated for conditions 1 and 2 in Table 2; in these figures normal probability plots highlight the most significant parameters that characterize the value of Δp_c in the cases considered. Orifices S1 and S3 and the parameters of the EF grooves (H, N, E) appear as the most significant parameters in both conditions examined. Hence, for the stand-by condition, it is possible to deduce the absence of a relevant influence of the input flow rate range on the predictors' dominance classification.

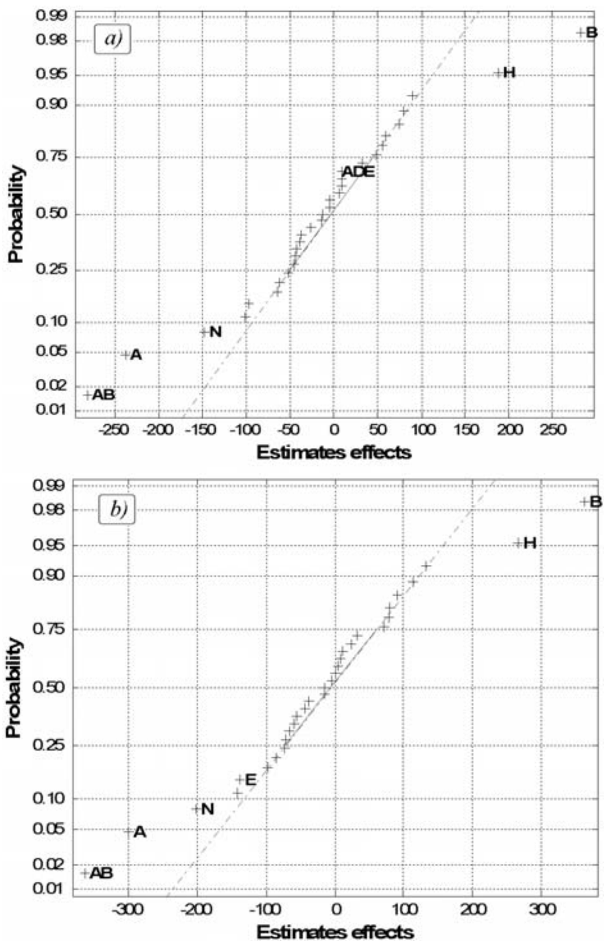


Fig. 8: *Normal probability plot for conditions 1 (a) and 2 (b) of Table 2, for objective function Φ_1*

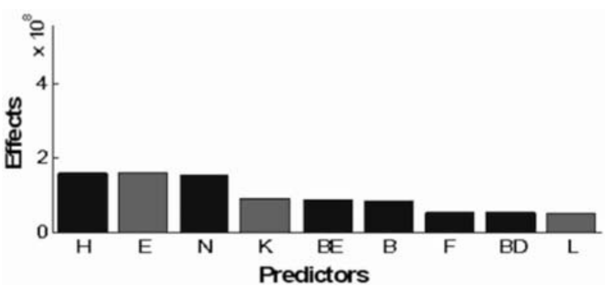


Fig. 9: *Normal probability plot for condition 6 (Table 2) for objective function Φ_1*

An analogous consideration can be made about Φ_1 for the working conditions considered in Table 2; although, as shown in Fig. 9 through a Pareto chart, there are differences in the weights of the most relevant parameters: factors A and B acquire lower importance compared to the stand-by conditions. In Fig. 9 a different colour is used to represent a negative – or positive – influence on the OF (light bars are used for factors for which an increase in value causes an augmentation of Φ, dark bars for other factors).

With the objective function Φ_2 the results obtained in this analysis differ from those reported in (Vacca, 2006). These discrepancies can be explained by slight differences in the definition of the spool factors considered for the screening (Fig. 6), and above all by the different ranges of values assigned to each parameter that implicitly defines the region of interest. As mentioned in (Vacca, 2006) these aspects have a strong influence on the screening results. In particular, compared to results discussed in (Vacca, 2006), effects of saturation on function Φ_2 acquire lower importance. For brevity, Fig. 10a and 10b show the results obtained for the two different working conditions in Table 2. Both figures (especially Fig. 10b) confirm the validity of the basic model of the valve (expressed by Eq. 1) identifying the importance of parameters A, B and H. However, as emerges from Fig. 10a, other parameters, in particular those related to the shape of the spool grooves, play a significant role on the value of function Φ_2.

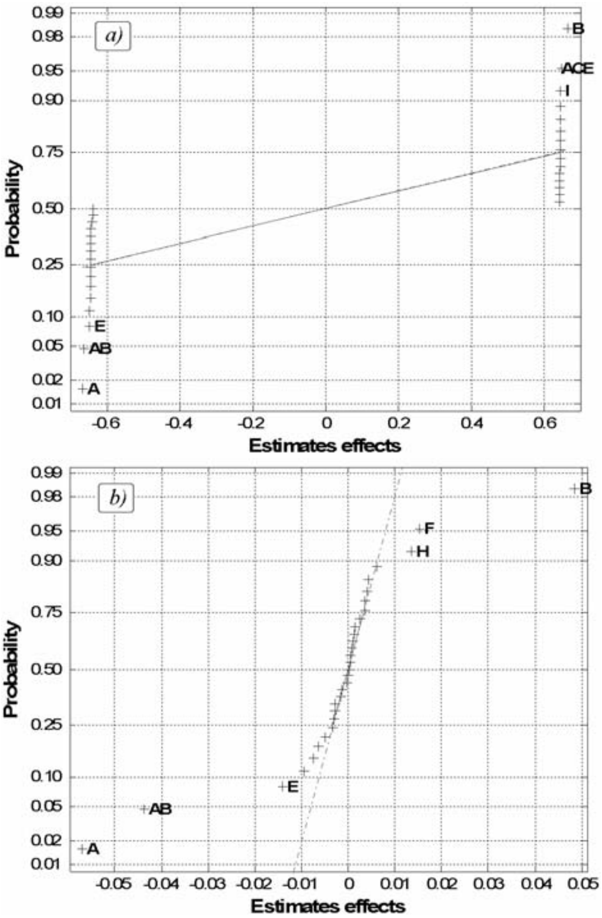


Fig. 10: *Normal probability plot of conditions 4 (a) and 6 (b) of Table 2 for objective function Φ_2*

7 Valve Optimization

Although the screening analysis points out the most significant parameters describing valve behaviour, an optimization of the valve's design cannot be performed on the basis of screening results only. This is due to the large influence displayed by the amplitude of the region of interest of the factors considered (Table 2). Moreover, an easy optimization based on screening results can be performed whenever few factors acquire significant importance on the OFs, but – as evident for the case displayed in Fig. 10a – for the component considered in this study there are cases in which many parameters have similar weight. Therefore, the optimization of valve design requires a suitable technique; the RSM-Steepest Descent method has been chosen in this work. In detail, this approach aims to find the minimum of a given objective function reproducing its shape iteratively by means of continuous changes in settings of the fitting equations used by the RSM model. In other terms, the coefficients used for the fitting equations may change during the optimization process; this is in contrast to the classic approach, conceived for fixed and given functions. Some disciplines interpret RSM completely differently: RSM becomes a one-shot approach that fits a single response surface - either a second-order polynomial or a Kriging model - to the I/O data of a random or deterministic simulation model, over the whole experimental area (instead of a series of local areas). Next, that single model is used to estimate the optimal input combination. For details see (Sacks et al., 1989; Simpson et al., 2001).

Starting from a given configuration of the system (for example a stock configuration), the search for the optimal configuration is made through "movements" within the region of interest, carried out in the direction of maximum improvements (in terms of OF values). This method, described in literature (i.e. Box et al., 1987; Myers, 1999), is represented in Fig. 11: it is based on a sequence of line searches in the direction of maximum improvement. The search sequence is continued until there is evidence that the direction chosen does not result in further improvements.

A general formulation for the fitting model for the OF is given by the second-order polynomial:

$$\hat{y} = b_0 + \boldsymbol{x}'\boldsymbol{b} + \boldsymbol{x}'\mathbf{B}\boldsymbol{x} \tag{4}$$

where $\hat{y}$ approximates the OF considered near the point considered, while $\boldsymbol{x}$ indicates the input variables vector ($\boldsymbol{x}'$ its transpose), b_0 the mean value of responses, $\boldsymbol{b}$ the first-order fitting coefficient vector, and $\mathbf{B}$ the 2nd-order fitting coefficient matrix. Coefficients $\beta_{ij...k}$ (with $\mathbf{i} \neq \mathbf{j} \neq ... \neq \mathbf{k}$) in $\mathbf{B}$ represent the full *k*-order interactions between factors.

As for the evaluation of each direction of maximum improvement, the technique adopted in this work fits a first order polynomial to the inputs, for a small region around the point considered. Hence, during this phase of the optimization process all terms in matrix **B** are null. However, a test of adequacy is carried out before moving to a new direction, to determine if the estimated first-order model adequately describes the behaviour of response in the region of factors considered. These tests are implemented using the method of Least Square Estimators, based on the analysis of variance (ANOVA), and are performed through additional runs performed until a central composite design is achieved. Thanks to the small intervals considered for each parameter (at each point where Eq. 4 has been evaluated, including the final point too, i.e. the optimum), the first-order model can be accepted, being the effect of curvature of the OF considered negligible.

The suitability of each local first-order model found is also achieved thanks to the tiny step sizes adopted at each movement (see Fig. 11). Literature describes many criteria for the selection of the optimal step size (Kleijnen et al., 2002); and the common RSM procedures for optimization (especially for planning experiments) take a step length of each factor proportional to its parameter's estimates. However, in this case, considering the restricted range of parameters and thanks to the possibility of realizing fast simulations using the AMESim® model of the valve, it is possible to consider a constant – but conservative – fixed value of the step length during the entire procedure.

The estimation of ***b*** coefficients, representative of the first-order effects in fitting Eq. 4, is based on the Ordinary Least Squares method. Points required by this estimation are evaluated with a fractional two-level resolution-3 design. Then, the local gradient of the fitted model is used to determine the Steepest Descent directions. For a single response system, the direction of maximum improvement is determined by the negative of the gradient of $\hat{y}$:

$$\vec{g} = \left(\frac{\partial \hat{y}}{\partial X_1}, \frac{\partial \hat{y}}{\partial X_2}, ..., \frac{\partial \hat{y}}{\partial X_n} \right) \quad (5)$$

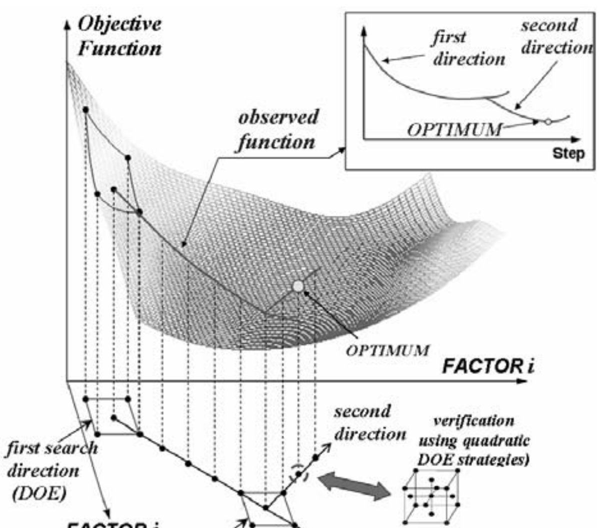


Fig. 11: *Steepest descendent direction methodology for optimization*

where X_i represents the coded factor of parameters in Table 1; for example, X_1 is obtained from data of factor A, according to the equation:

$$X_1 = \frac{A_i - (A_{min} + A_{max})/2}{(A_{min} - A_{max})/2} \quad (6)$$

The coding convention of Eq. 6 has been adopted in order to obtain scale-independent parameter estimates, leading to a more reliable search direction process.

The optimization of the priority valve design is a multi-response problem, as two of the OFs (Φ_1 and Φ_2) need to be minimized simultaneously. For this purpose the procedure follows a weighted priority approach. In other terms, the proper directions are obtained by applying assigned weights to the unit vectors provided by the two gradients; in detail:

$$\vec{u} = w_{\Phi_1} \cdot \vec{u}_{\Phi_1} + w_{\Phi_1} \cdot \vec{u}_{\Phi_2} \quad (7)$$

where $\vec{u}_{\Phi_1} = \dfrac{\vec{g}_{\Phi_1}}{\left|\vec{g}_{\Phi_1}\right|}$; $\vec{u}_{\Phi_2} = \dfrac{\vec{g}_{\Phi_2}}{\left|\vec{g}_{\Phi_2}\right|}$.

Using Eq. 7, the different orders of magnitude taken by the two OFs do not compromise the evaluation of each optimal direction. On the basis of the manufacturer's experience, the valve optimization has been performed assigning 90% to w_{Φ_1} and 10% to w_{Φ_2} ; therefore the highest priority has been given to the pressure drop for flow diverted to the EF port.

The procedure used for the optimization, implemented in MATLAB®, is summarized in Fig. 12, which highlights how the coefficients of the fitting models are evaluated on the basis of predictions given by the AMESim® model of the valve, with simulations planned through DOE techniques. The parameters considered for the optimization are those reported in Table 1, with the exception of the internal diameter of the spool, whose effects are negligible in steady state conditions.

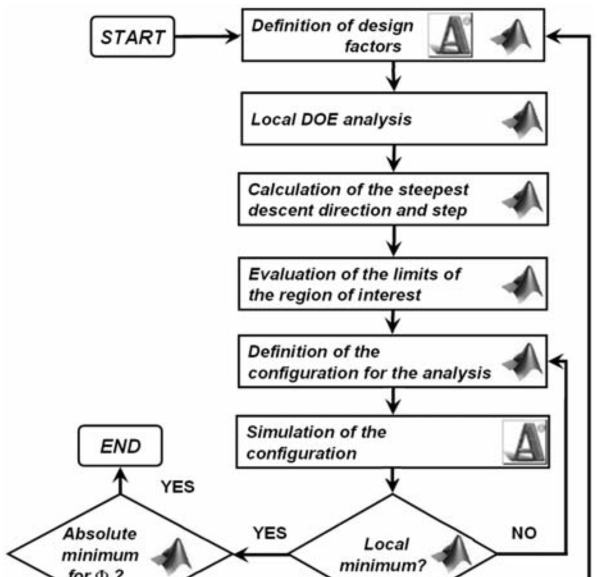


Fig. 12: *Schematic flow chart of the RSM optimization procedure developed for the valve optimization. Symbols indicate the software (AMESim® / MATLAB®) used to perform each operation*

Similarly to the configurations accounted for in the screening analysis, each set of parameter values considered by the procedure in Fig. 12 – at each step of the path search process – has been verified, checking the design of the valve and its consistency with the ISO scheme in Fig. 1. The local approach that characterizes the optimization process allows for the consideration of a wider region of interest for the parameters, compared to the values used for the screening analysis, reported in Table 1.

Figure 13 reports the details of the path followed by the procedure for the valve optimization, assuming the 80L stock configuration as the starting point. The procedure evaluates the OFs referring to operating condition 3 in Table 2. In detail, the procedure begins with a rapid change in the value of orifices and underlap parameters (first 44 steps); then it operates four changes of direction and after a quick optimization of the spring parameters all the parameters are slowly optimized.

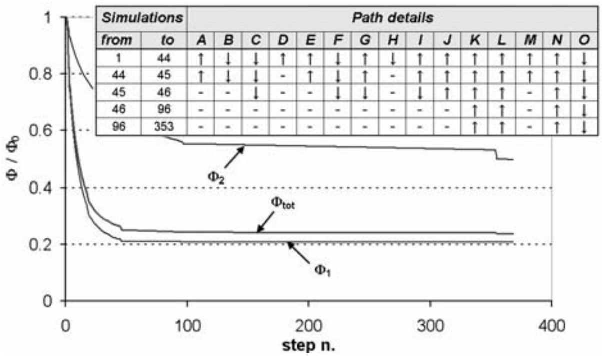


Fig. 13: *Optimization of the valve. Path followed by the Steepest Descent procedure (↑ = increment; ↓ = decrement; - = constant value)*

Table 5: Optimal configuration of the LS valve. Guidelines for the tolerance of spool parameters

ID	*Design Parameters*	*Value*	*Importance of tolerance*
A	Orifice S1 diameter	0.09375 d_s	
B	Orifice S3 diameter	0.03125 d_s	
C	Spring Stiffness	8.08 N/mm	
D	Underlap CF side (fig. 6)	0.3250 d_s	Critical
E	Underlap EF side (fig. 6)	0.0625 d_s	Critical
F	Spring Preload	40.49 N	
G	Groove length CF (fig. 6)	0.11125 d_s	Not important
H	Groove length EF (fig. 6)	0.06250 d_s	Critical
I	Groove angle CF (fig. 6)	0.411 θ_{ref}	Important
J	Groove opening angle CF (fig. 6)	1.333 θ_{ref}	Not important
K	Groove angle EF (fig. 6)	0.444 θ_{ref}	Important
L	Groove opening angle EF (fig. 6)	1.333 θ_{ref}	Important
M	Number of grooves (CF side)	8	
N	Number of grooves (EF side)	8	
O	Orifice S2 diameter	0.0625 d_s	

The resulting final point lies on the border of the region of interest. For this reason, a further verification carried out by means of centered runs or second order models is not required for the verification of the minimum condition for such point. Furthermore, the same configuration is also reached by repeating the procedure starting from a different initial point. The final configuration, represented by the data reported in Table 5, was achieved after 353 steps and can be considered as the optimal one.

A further local DOE analysis, performed in a small interval around the optimal configuration, analogous to the ones required to find the directions of maximum improvement, can easily provide useful information concerning the importance of tolerances assigned to each dimension. As a matter of fact, results of the ANOVA analysis can be used to attribute importance to the tolerances assigned to each parameter considered in the study. Table 5 reports a qualitative judgment of each dimension of the spool. In this way a further criterion is provided for the designer in order to establish the tolerances in the spool drawings, in addition to experience and/or machining requirements.

8 Experimental Verifications

According to the data reported in Table 5, a prototype of the optimized valve was manufactured (Fig. 14) and tests were carried out in the laboratories of Casappa S.p.A., with the aim of comparing its performance with the stock versions.

Fig. 14: *Prototype of the optimal valve*

Figures 15 and 16 show a picture of the apparatus utilized and a simplified ISO scheme of the hydraulic circuit used for the measurement of the Δp_w and Δp_c values in steady conditions. In particular, a variable displacement pump was utilized to feed the valve in the 0–150 l/min range. To simplify the measurements, the valve – whose casing also acts as pump cover – is placed on a dedicated hydraulic support block. A variable orifice (*Sp*) is used as the control orifice, allowing the experimenter to manually select the flow rate desired on the CF port. Two control valves, placed on the two output lines (CF and EF), allow different loads to be established at the valve ports; through these valves the software used to control the test rig allows to determine the valve's operating condition (stand-by or working) at each test. More details concerning the apparatus utilized are reported in (Casoli et al., 2003; Berta et al., 2003).

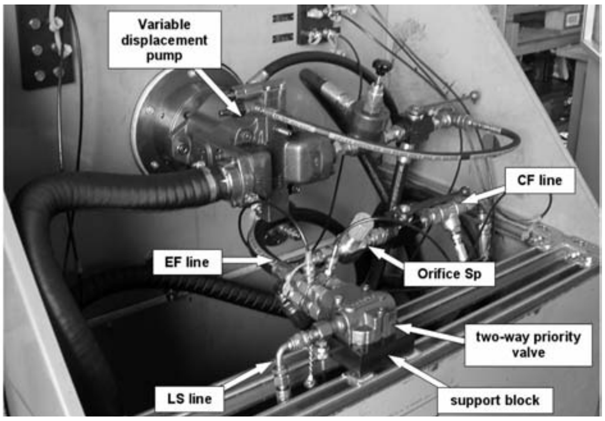


Fig. 15: *Picture taken during the verification tests*

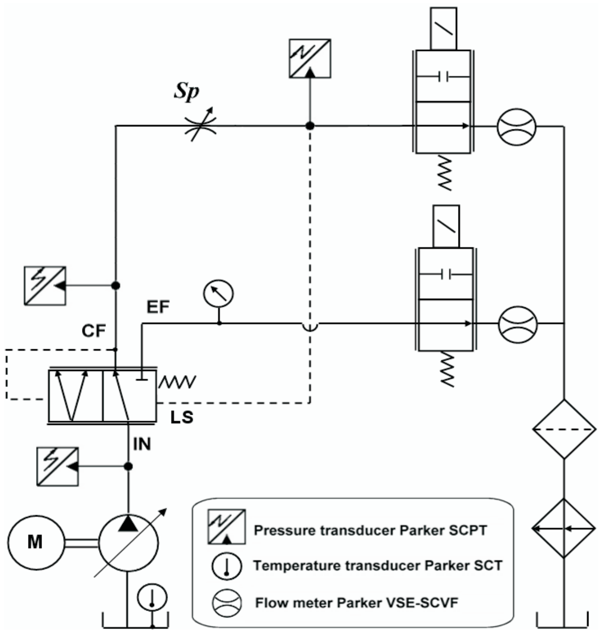


Fig. 16: *Simplified sketch of the circuit used for the experimental setup*

A detailed description of the experimental charac-teri-zation of the new prototype concerning the effects in-duced by the external loads, by a different choice of the internal orifices S1, S2, S3, and of the spring parameters, will be provided in a future work. This paper only reports a few experimental results in order to demonstrate the efficacy of the procedure. Although many different work-ing conditions have been investigated, only the results pertinent to two conditions are here considered for the comparisons. Diagrams reported in Fig. 17 describe the behaviour of the new spool (indicated with the acronyms 120Ln) compared with the standard versions 120L and 80L, assuming the same configuration of the spring and orifices S1, S2 and S3.

The improved behaviour achieved through the adoption of the new spool (120Ln), in terms of both Δp_c (and consequently Q_{CF}) and Δp_w versus the inlet flow rate emerges from all the experimental results, especially at the highest flow rates. This was the initial goal of the study. For both working conditions ($Q_{CF} \approx 6$ L/min, Fig. 16a and 16b; $Q_{CF} \approx 15$ L/min, Fig. 16c and 16d), the value of Q_{CF} is kept with lower sensitivity on the inlet flow rate, and at the same time a lower value of the pressure drop through the EF port is obtained.

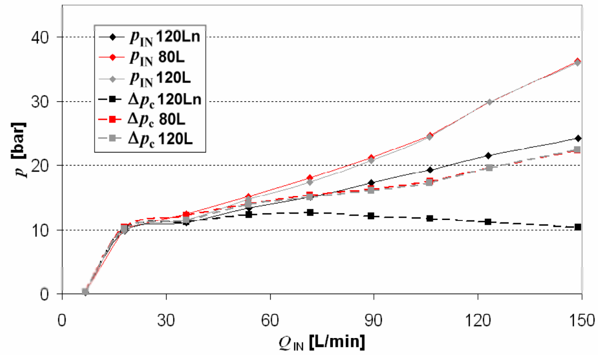


Fig. 17a: *Experimental results: Inlet pressure and Δp_c (working condition; $Q_{CF} \approx 6$ L/min*

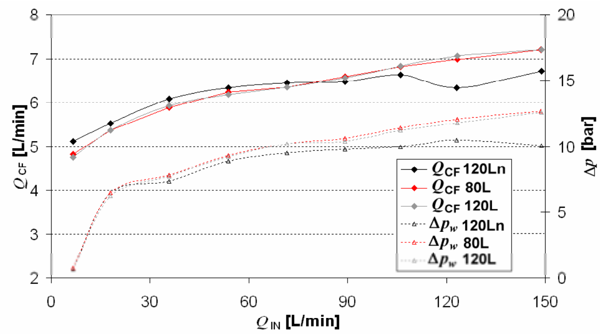


Fig. 17b: *Experimental results: Controlled flow rate and Δp_w (working condition; $Q_{CF} \approx 6$ L/min)*

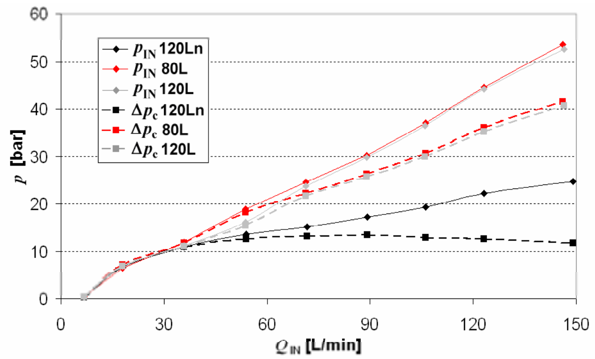


Fig. 17c: *Experimental results: Inlet pressure and Δp_c (working condition; $Q_{CF} \approx 15$ L/min)*

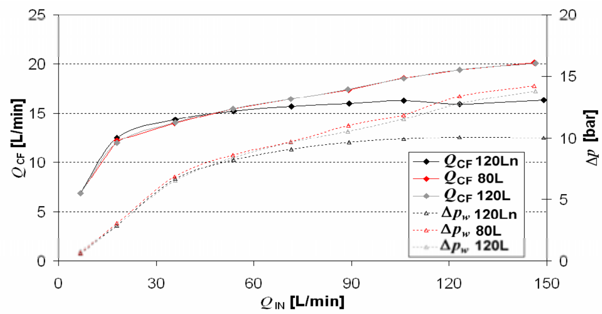


Fig. 17d: *Experimental results: Controlled flow rate and Δp_w (working condition; $Q_{CF} \approx 15$ L/min)*

8 Conclusions

This paper focuses on the description and adoption of a numerical procedure suitable for the analysis and optimization of hydraulic components. The algorithm, implemented by the authors, is based on the RSM-Steepest Descent method and takes advantage of DOE techniques. Despite its generality, the procedure has been utilized in this work for a two-way, load-sensing, flow-divider spool valve.

The analysis of the valve is based on two analytical objective functions, defined for the complete description of its performance.

The first part of the study deals with a screening analysis of the valve; for this purpose a proper two-level fractional DOE design permitted the identification of the parameters which significantly affect the valve's behaviour. Only easily modifiable design parameters (i.e. spool dimensions, orifices and spring parameters) were considered for the analysis. An optimal configuration of these parameters was then found following the particular Steepest Descent methodology.

An integrated MATLAB®-AMESim® procedure was developed for both the screening and optimization processes. In particular, an AMESim® model of the valve (previously verified through comparisons between simulation results and test data) generated the data required for the stochastic evaluation on which DOE-RSM methods are based.

The screening analysis provided much useful information in dealing with a qualitative improvement of the valve's design. However, the results point out the necessity for the adoption of an appropriate numerical procedure for component optimization. In particular, the method developed permits one to simultaneously optimize the two objective functions considered and allows for a suitable definition of the factors' domain according to valve requirements (functionality and manufacturing processes).

An optimal design of the valve was proposed on the basis of the results of the procedure developed. A prototype was then manufactured and tested with the aim of confirming the improvements compared to the stock versions and on the basis of experimental results. The preliminary results discussed in the paper emphasize the advantages obtained by adopting the proposed configuration of the valve, concerning its main functions (constant value of the flow rate on the priority port, minimum pressure drop through the exceeding port). The DOE-based procedure implemented establishes the importance of each design parameter on the valve's behaviour near the optimum configuration, thus providing the designer with a useful criterion that can be used to define the tolerances which must be assigned to each parameter.

Nomenclature

A…P	Valve design parameters
$\boldsymbol{B}$	2nd order fitting matrix
F	Force
Q	Volumetric flow rate
S	Orifice
Sp	Control orifice
X	Coded factor
$\boldsymbol{b}$	1st order fitting vector
b_0	Mean value of responses
cq	Coefficient of discharge
d	Diameter
g	Gradient function
p	Pressure
$\boldsymbol{u}$	Unit vector
w	Weight
$\boldsymbol{x}$	Vector of input variable
$\hat{y}$	Fitting model
Ω	Area
β	Correlative Factor
Φ	Objective Function
θ	Angle

Subscripts

c	Crossing
i,j,k	Index of parameter
l	Left side
m	Spring
max	Maximum
min	Minimum
n	Number of parameters
r	Right side
ref	Reference value
s	Spool
w	Working

Abbreviations

CF	Controlled Flow
DOE	Design Of Experiments
EF	Exceeding Flow
IN	Inlet
LS	Load Sensing
OF	Objective Function
RSM	Response Surface Methodology
S	Orifice

Acknowledgements

The authors would like to thank Casappa S.p.A, in particular Dr. Marco Guidetti, for providing test facilities and hardware, and Professor G.L. Berta for his great help in reviewing the paper.

References

Antony J. 2003. Design of Experiments for Engineers and Scientists. *Butterworth-Heinemann Elsevier*.

Berta, G. L., **Vacca, A.**, **Franzoni, G.** and **Guidetti, M.** 2003. Load Sensing-Prioritätsventile – Model für die Funktionssimulation. O+P, *Ölhydraulik und Pneumatik,* No. 10.

Box, G. E. P. and **Wilson, K. B.** 1951. On the Experimental Attainment of Optimum Conditions (with discussion). *Journal of the Royal Statistical Society*, Series B 13(1), pp. 1-45.

Box, G. E. P. and **Draper, N. R.** 1987. *Empirical Model Building and Response Surfaces Methodology*. J. Wiley & Sons.

Casoli, P., **Vacca, A.** and **Franzoni, G.** 2003. A Numerical Model for the Simulation of Load Sensing Spool Valves. *The 18th Int. Conference on Hydraulics and Pneumatics*, Prague, Czech Republic.

Dahlén, L. and **Crlsson, P.** 2003. Numerical Optimization of a Distributor Valve. *Int. Journal of Fluid Power*, Vol. 4, No. 3, pp. 17-25.

Eschenauer, H., **Koski, J.** and **Osyczka, A.** 1990. *Multicriteria Design Optimization*. Berlin, Springer Verlag.

Fisher, R.A. 1935. *The Design of Experiments*. Edinburgh: Oliver & Boyd. RE, RI.

Frangopoulos, C. A. 2003. Methods of Energy System Optimization. *Proc. of the Summer School Optimization of Energy Systems and Processes*, Gliwice, Poland.

Karnopp, D. 1985. Computer Simulation of Stick Slip Friction in Mechanical Dynamic Systems. *Trans. of ASME, Journal of Dynamic Systems, Measurement and Control*, Vol. 107, pp. 100-103.

Kleijnen, J. P. C., **Hertog, D.** and **Angün E.** 2002. Response Surface Methodology's Steepest Ascent and Step Size Revisited. *Proc. of the 2002 Winter Simulation Conference*, pp. 377-383.

Myers, R. H. 1999. Response Surface Methodology - Current Status and Future Directions (including discussion), *Journal of Quality Technology*, 31, No. 1, pp. 30-74.

Myers, R. H. and **Montgomery, D. C.** 2002. *Response Surface Methodology: Process and Product Optimization Using Designed Experiment*. J. Wiley and Sons.

Montgomery, D. C. 1997. *Design and Analysis of Experiments*. J. Wiley & Sons.

Nervegna, N. 2003. *Oleodinamica e Pneumatica: Sistemi, Componenti, Esercitazioni.* Vol. 1 and 2, Politeko, Turin (Italy).

Papadopoulos, E. and **Davliakos, E.** 2004. A Sistematic Methodology for Optimal Component Selection of Electrohydraulic Servosystems. *Int. Journal of Fluid Power*, Vol. 5, No. 3, pp. 15-24.

Ranjit, R. K. 2001. *Design of Experiments Using the Taguchi Approach: 16 Steps to Product and Process Improvement.* J. Wiley & Sons.

Sacks, J., **Welch, W. J.**, **Mitchell, T. J.** and **Wynn, H. P.** 1989. Design and Analysis of Computer Experiments. *Statistical Science*, 4, No. 4, pp. 409-435.

Simpson, T. W., **Mauery, T. M.**, **Korte, J. J.** and **Mistree, F.** 2001. Kriging metamodels for Global Approximation in Simulation-Based Multidisciplinary Design Optimization. *American Institute of Aeronautics and Astronautics Journal*.

Vacca A. 2006. Proposal of a Load Sensing Two-Way Valve Model, Applying "Design of Experiments" Techniques to Simulations. *IMECE2006, 2006 ASME Int. Mech. Eng. Congress and Expo.*, Chigago (IL), USA.

Vesely F. 2003. Design of Pilot Operated Relief Valve by Use of the Simulation, *The 18th Int. Conference on Hydraulics and Pneumatics*, Prague, Czech Republic.

Wiens, T., **Burton, R.**, **Schoenau, G.** and **Ruan J.** 2005. Optimization and Experimental Verification of a Variable Ratio Flow Divider Valve*. Int. Journal of Fluid Power*, Vol. 6, No. 3, pp. 45-53.

Appendix –Basic Model of the Valve

Equation 1 describes the valve's principle of operation: based on the control of the value of Δp_w, the valve permits to easily control the flow rate on the primary port, according to the scheme in Fig. 2.

A derivation of Eq. 1 can be made from the spool equilibrium in steady state conditions, neglecting friction, leakages, distributed pressure losses and the influence of flow forces. With reference to Fig. 18, the spool equilibrium states:

$$p_l - p_r = \frac{F_m}{\Omega_s} \tag{8}$$

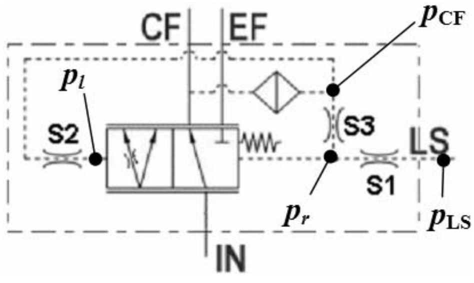


Fig. 18: *Equivalent circuit of the valve*

In steady state condition Q_{S2} is null, while Q_{S1} and Q_{S3} are equal. Consequently, the pressure p_l acting on the left side of the spool is equal to p_{CF}, while the pressure p_r acting on the right side of the spool can be easily written as a function of p_{CF} and p_{CF} from the orifice equations:

$$Q_{S1} = cq_{S1}\Omega_{S1}\sqrt{2\left(p_{dx} - p_{LS}\right)/\rho} \tag{9}$$

$$Q_{S3} = cq_{S3}\Omega_{S3}\sqrt{2\left(p_{CF} - p_{dx}\right)/\rho} \tag{10}$$

Assuming cq_{S1} equal to cq_{S3}, $\Omega_{S1} = \frac{\pi d_{S1}^2}{4}$ and $\Omega_{S3} = \frac{\pi d_{S3}^2}{4}$, the value of p_r is:

$$p_r = \frac{p_{LS}\cdot\left(\frac{d_{S1}}{d_{S3}}\right)^4 + p_{CF}}{1+\left(\frac{d_{S1}}{d_{S3}}\right)^4} \tag{12}$$

Equation 1 is then obtained by substituting the value of p_l and p_r in Eq. 8 with p_{CF} and the expression of Eq. 12 respectively.

Andrea Vacca
He received his Master's degree in Mechanical Engineering in 1999, at the University of Parma (Italy). In 2005 he became Ph. Doctor, at University of Florence, with a thesis in the field of Heat Transfer and Gas Turbine Blade Cooling Technology. Now he is Assistant Professor at the Industrial Engineering Department, University of Parma (Italy), where his main research interests are the analysis and simulation of fluid power systems and components, such as valves, gear and piston pumps.

Matteo Cerutti
He acquired his Master's degree in Mechanical Engineering in 2005 at the University of Parma (Italy), with a thesis on Designed Experiment techniques applied to hydraulic components. He is now a Ph.D student at the Dep. of Energetics of the University of Florence (Italy) and cooperates with the Dep. of Industrial Engineering of the University of Parma for his research activities.