ELECTRICALLY ACTUATED REGULATION VALVES FOR ROCKET ENGINES

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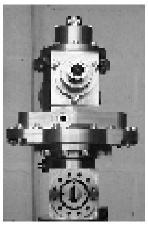


1. ABSTRACT

From technical point of view, Liquid propellant Rocket Engine (LRE) control architectures have to be designed in such a way that: (i) complexity/weight for control and actuation power of valves is minimal, (ii) the engine working point is as far as possible adapted to actual requirements throughout the mission, and (iii) RAMS requirements are complied with .

In this context, investigations related to proportional electrically actuated LRE valves are of particular interest in order to investigate the implications of "All Electric Engine control" or in-flight control of the LRE operating point, identify mechanism and electronic controller architectures which present a maximum potential for standardisation and growth, and provide a hardware demonstration of a representative electric valve which can be used for a LRE firing test.

As part of the ESA-GSTP2 program, Techspace Aero conducted a market survey identifying the needs for proportional actuation. Based on these considerations, a Technical Specification has been established and a valve demonstrator has been designed and successfully tested (Alcatel ETCA for electronic aspects).

2. INTRODUCTION

History shows that since the early beginnings of rocket designs, most of the new Liquid propellant Rocket Engine development programs also contain one or more valve design projects. The main reasons for this situation might be:

- The definition of valve specifications are often made after the specifications of the more critical active components (pumps, chambers, …). Hence, they often have to compensate for all the deficiencies of a specific cycle (need for reproducibility and accuracy of pressure drop characteristic versus time and angle, …) and therefore, the resulting valve requirements vary significantly from application to application.
- Very often, valve manufacturers are not entitled to use the same hardware for different customers (funding and confidentiality issues).

This situation can be improved when

- Enough customisable "off the shelve" valve designs exist and manufacturing capability is maintained even after the end of a given rocket engine manufacturing program.
- Rocket Engine manufacturers know which valve types exist on the market. In this context, as for other industrial fields, it is interesting to have a minimum of standardisation rules available.

Besides supposing that the engine designer concerns are understood, the first point supposes a strategy of progressive technology acquisition and a corresponding customisation approach.

In order to anticipate the needs for future valves, it is first of all important to analyse the market and classify the needs, the main classification criteria being the following:

- Type of fluid to be controlled, temperature, pressure, leak constraints,
- Type of actuation energy (pneumatic, hydraulic, electric),
- Accuracy (absolute, resolution, reproducibility),
- Speed (fast, slow), available peak power,
- Available control architecture (electrovalves, electric servovalve interface, servovalves, dedicated engine controller, …),
- Degree of versatility, specific ground testing and operation constraints.

Considering that for each of the six items of this (non exhaustive) list of criteria one could give at least three value ranges (very conservative), this leads to more than $3^6 = 729$ typical valve specifications!

Taking into account that, the cost of development of valves represents typically about 5% of an engine development budget (with about five valve types to be developed per engine), one can conclude that in order to obtain a complete palette of "off the shelve" valve technologies one would require the unaffordable budget equivalent to at least 7 rocket engine development programs!

Typically, the following actuation concepts should be analysed and standardised:

- Pneumatic ON/OFF ;
- Hydraulic ON/OFF
- Electric ON/OFF
- Proportional hydraulic
- Proportional pneumatic
- Proportional electrical
  (slow/fast accurate/not accurate)

In order to reduce the investigation cost by several orders of magnitude the application of the following principles make sense:

- Focus on versatility and growth potential.
- Focus the R&D efforts on "more standardised" valve flow-part and valve actuator subsystems.

Applying this logic to valves, and capitalising on the experience of the already developped (mainly pneumatic) European Ariane engine valves, the advantages of ***high accuracy***, ***proportional, high-dynamics, electric*** actuation become evident, but as one major drawbacks of electric actuation is the specific weight of the actuator (compared to the pneumatic technology) the limitation of required actuation efforts becomes an important issue.

The often raised issue of recurring cost of electronics can be addressed by the following argumentation:

- Standardisation leads to higher serial output and hence to lower cost.

- Prices of electronic components are constantly decreasing for the following reasons: (i) monopolies are being broken by healthy competition (ii) prices of electronic control components are constantly decreasing due to the generalisation of control equipment in nearly all of the domestic housekeeping, audio, video, PC devices and (iii) the cost of power control components (semiconductor switches) will decrease with the generalisation of electric power for automotive vehicles.

The above mentioned issues were taken as the starting point of the GSTP2 ERV project which was started in May 1998.

The technology presented hereafter has been chosen (at least) for ground development tests of a new Ariane 5 upperstage engine. Other applications of this technology are presently in preparation.

3. TECHNICAL SPECIFICATION

In early 1998, a screening of the market needs showed interesting opportunities for proportional 2 inch regulation valves for cryogenic expander engines. An anticipation of the technical specification for the valves of this type of application showed that a proportional actuator with high dynamics could power both regulation and chamber injection valves, provided they are designed for electrical actuators. In order to address the uncertainties which are inherent to space mechanisms (large temperature range, vibration, …), the ECSS design rules were applied. In particular, this led to a very significant motorisation margin (> 8 for nominal case; >3 for peak load case).

The resulting ***actuator*** spec was:

- Supply: >50VDC; <100W (moving valve); 10 W (position control)
- Max Torque >32 Nm
- Resolution <0.1°
- Accuracy <0.3°
- Temperature range (peak values) –110°C → +200°C
- Bandwidth (-3dB/ displ 0.1°): 15 Hz

Flow-part

- Peak actuation torque < 4 Nm
- Versatile butterfly concept
- Shaft seals compatible with expander bypass valve flow conditions
- MEOP > 200 bar

Reliability

- Failsafe concept

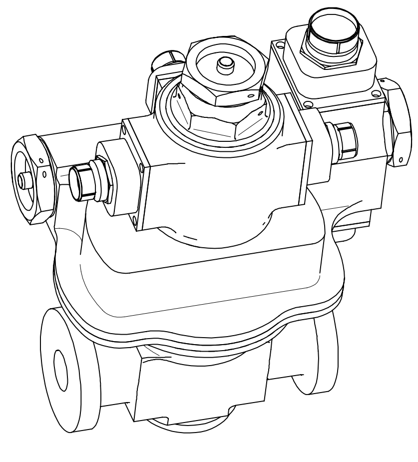
4. ELECTRIC VALVE ACTUATION CONCEPTS

A trade-off analysis has been conducted between various concepts.

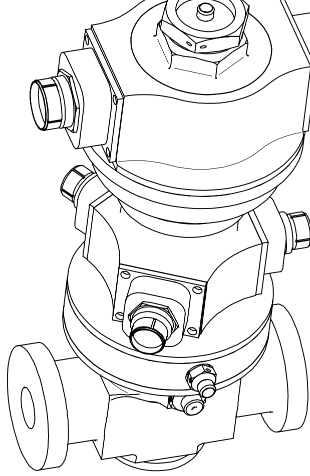
A. **Electro pneumatic concept:** this concept combines a pneumatic actuator with small electric servovalves and can be applied to control existing pneumatic valves electrically. Allthough this configuration leads to a very dynamic and compact solution, it is usually the best choice when the level of integration with the flow part may be very high. This contradicts the standardisation requirement.

B. **Direct drive**: implementing full ECSS margins, this concept only makes sense when required dynamics and hysteresis constraints are one order of magnitude higher than the present specification.

C. **High reduction ratio** transmission (>12). This concept minimises power consumption during position control phases but leads to unacceptable power peaks when fast moves are required.



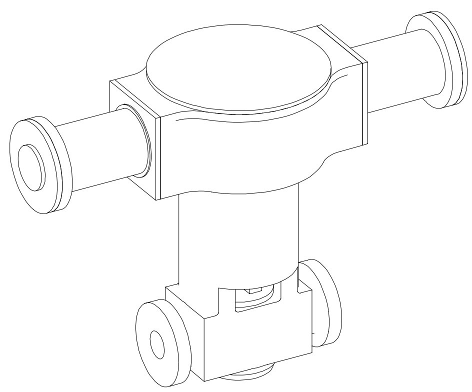
Worm wheel transmission



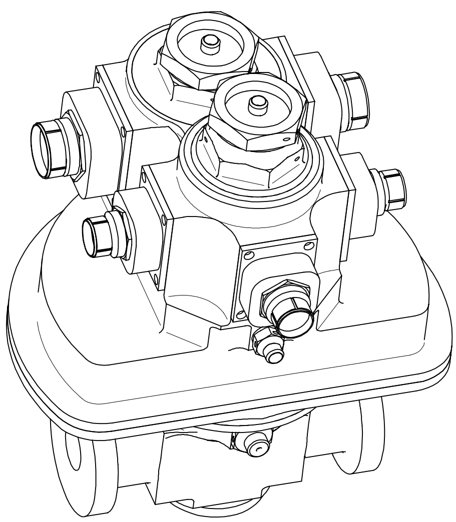
Harmonic Drive transmission

D. **One stage gear transmission**. This concept is (from mechanical point of view) nearly as simple as the Direct Drive concept presented above and leads to an interesting compromise in terms of position control power, peak power for the required dynamics. In addition, the angular sensors which are used for closing the position loop can also be used to control the brushless DC motor in case it needs a sensor. The reduction ratio of 8 was chosen.

Having chosen the reduction ratio, a second level of trade-off analysis has been conducted in order to obtain the most advantageous configuration in terms of speed reducer concept, location of the angular sensors and electric connectors. Some of these concepts are shown below. Finally a simple spur gear concept won the race.



Bevel gear transmission with sensors between flow-part and bevel gear.



Spur Gear transmission (PDR design)

5. MAIN DESIGN ISSUES

Besides the classical valve design issues (structural sizing, material compatibility, choice of the exact motor configuration, …) the following issues have attracted particular attention:

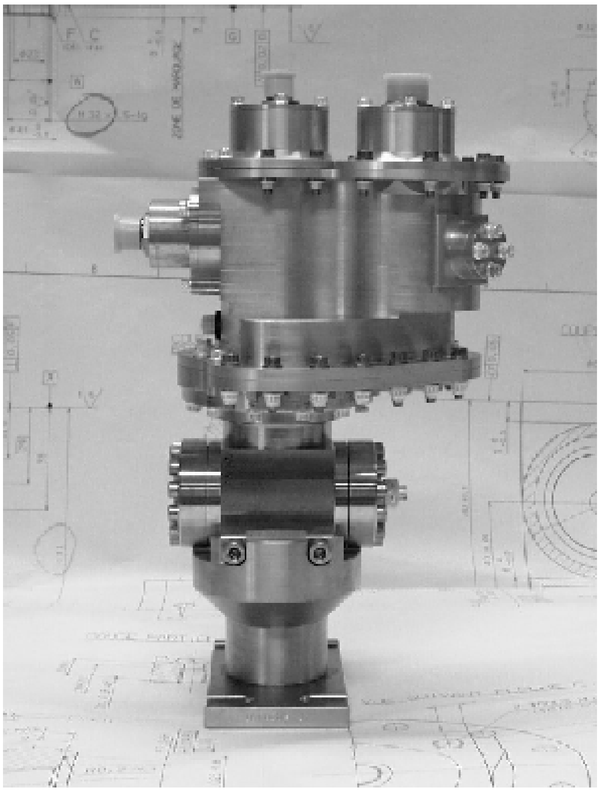
- Minimisation of leak peaks above 10 Scc/sec which can appear during actuation moves.
- Design of shaft seals in such a way that the actuation torque remains below the required value, in compliance with ECSS motorisation margins. In this context particular attention was paid in order to reduce the radial stiffness and increase the autoclave characteristics of the dynamic seals.
- Electric interfaces inside the valve.

The main identified issues for the here described study are given in the table hereafter:

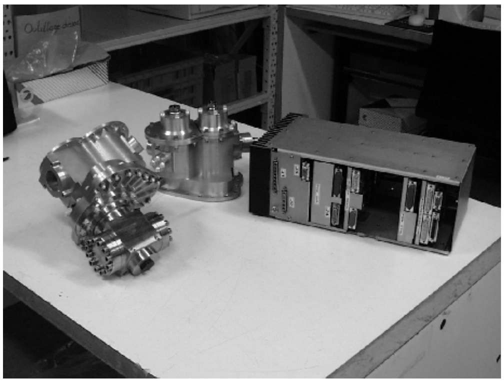
	Issue	Approach
1	Minimisation of friction and hydraulic efforts in the flow part	Specific shaft sealing concept with specific lip seals.
2	Minimisation of electric power peaks	Design and manufacture of a dedicated electronic controller able to test various control strategies and speed profiles.
3	Reliability	A dedicated electronic architecture has been defined, implementing hot redundancy.
4	Accurate angular sensors for large temperature variations	Design and manufacture of specific high precision and temperature robust resolvers
5	Motor for high and low T°	Design and manufacture of a dedicated temperature robust motor with sleeved SmCo Magnets
6	Tribology of speed reducer.	Excellent behaviour although neither coatings nor lubricants were used (launcher => short life duration!)

The resulting prototype is shown on the picture hereafter. In addition to the above mentioned architecture, it integrates the following specific features :

- Double wound three phase brushless DC motor
- Triple redundant resolvers
- Adjustable backlash concept allowing to adjust the backlash to virtually zero for any temperature in the operating T° domain.



The obtained valve
(on a assembly support)



Two ERV prototypes with controller

6. TESTING

6.1 Pneumatic and climatic bench

In order to verify the ERV performance, a test bench has been manufactured. The main functions of this facility are:

- He pressurisation of the flow part (→ 200 bar)
- LN_2 Inmersion cooling (77K)
- Resistive heating (400°C)
- Leak measurement (0.01 to 1000 Scc He)

Data acquisition system : .

- in the bench: pressures and temperatures;
- in the electronic valve controller: 1000Hz acquisition of currents, angular position of valve shaft…

ERV test bench (front view)

ERV test bench (rear view)

6.2 Hydraulic test bench lay out

In order to test hydraulically the design of the valve shutter elements (butterflies and balls), a specific water[1] loop test bench has been used. This bench provided a database of pressure drop characteristics and flow uniformity downstream from the valve. Target of this analysis was

- To reproduce via appropriate Re similitude, the flow conditions of an upperstage engine chamber injection of feed valve.
- To analyse the perturbation induced by the valve in the downstream flow. For this purpose, eight displaceable pitot tubes were introduced in four sections of the downstream pipe. This allowed to obtain flow profiles in the sections and to give an idea about which

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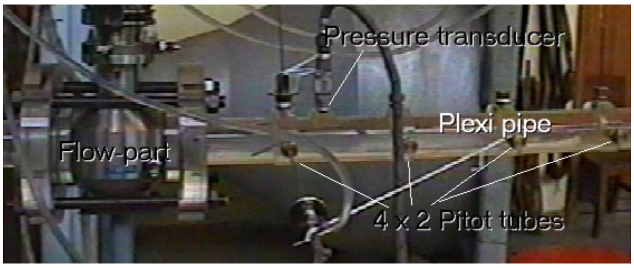
[1] Gas tests had already been performed during previous programs.

conditions the downstream equipment (e.g. a turbopump subject to cavitation) could be subject to.

Actuator



view of the water test bench

6.2 Test plan

Besides the specific electronic and control performance testing, the test plan addressed all aspects that are tested in the frame of valve development. Two prototypes were tested:

- Vibration testing (Ariane 5 specification)
- Endurance tests (80 Typical flight missions at cold, ambient and hot temperatures)
- Climatic tests (at extreme temperatures).
- During these tests, the leak was followed permanently.

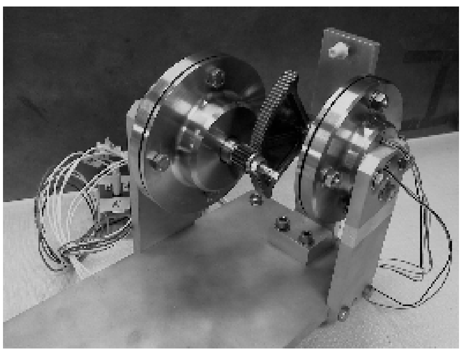
6.3 Test results

Electrical tests

Although in the design of the valves some mechanical resonance frequencies could not be avoided in the 0→2000Hz spectrum, and virtually no viscous friction damps potential oscillations, the control laws could be tuned in such a way that

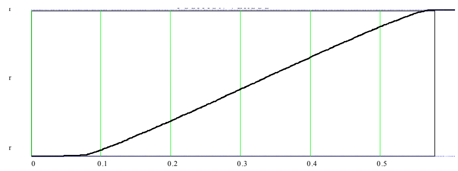
- no unstable behaviour could be observed during all the characterisation tests
- the dynamics of the valve were compliant with the initial requirements
- the peak power requirements were compliant with the requirements, even under the most constraining test conditions. Without a careful choice and tuning of control laws these peaks would have been significantly higher.

These tests were performed on a specific valve simulation tooling (for the tuning of the control laws) and on the main test bench (for the evaluation of pressure and temperature on the electric power consumption).



Test tooling for debug of electronic driver

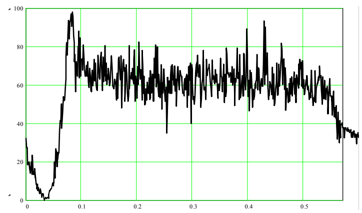
Typical results are given hereafter:



(angle [°] versus time[s])

Typical record of an actuation:, despite absence of viscosity and irregular dry friction virtually no noise can be observed

100 W



0 W

Typical record of the electrical power (power[W] versus time[s])

Vibration tests

The vibrations were performed according to the Ariane 5 specifications. The flow part was clamped in order to simulate the configuration of the valve on the engine piping.

No anomaly was reported during these tests.

Endurance tests

Endurance tests consisted of huge sequences of actuation cycles with different travel angles, simulating engine start transients, a phase of numerous very small steps (following a typical control law from a virtual engine controller) and an engine shut-down transient.

These cycles included variations in temperature (starting cold with a progressive temperature increase). Typically, one life duration test contained more than one million of mainly small moves.

Besides periodic recordings of the power curves, the maximum leak values were recorded.

LESSONS LEARNT

- Unlike pneumatic valves, electric valves require a much more careful design of the shaft seals. As actuation torque of the flow part has a much higher impact on the resulting actuator weight, it is important to design the flow part in such a way that

– hydraulic torque is close to zero (the hydraulic force vector crosses the axis of the valve shaft.
– shaft seals generate minimum torque.

- Very challenging electric power requirements can only be met by detailed electromechanical modelling and subsequent adequate choice of control laws.
- Sometimes the cheapest solution is really the best. In the present case (short life duration), dry running NiCo alloy toothed wheels are acceptable.

June 2001