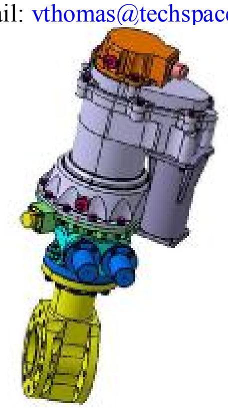
ELECTRICALLY ACTUATED HOT GAS VALVE FOR LIQUID PROPELLANT ROCKET ENGINE

V. Thomas [(1)], J.C Bomal[(1)]

[(1)]Techspace Aero, B-4041 Milmort, Belgium,
Ph. +32 (0) 2705132, fax +32(0)4 2788034, Email: vthomas@techspace-aero.



ABSTRACT

Valve electrification will be one of the main challenges in the development of future valves for liquid propellant engines and namely for the High Thrust Engine (HTE) that will probably replace Vulcain engine close to 2025. Looking at electrification technologies allowing more electric future engines, Techspace had the opportunity to develop a "Hot" Technology Breadboard Demonstrator covered by an ESA GSTP project [1]. Selected candidate is the Vulcain2 hot gas valve (HGV) that is developed and manufactured by Techspace-Aero. This valve is currently actuated using a pneumatic actuator in flight and a hydraulic actuator for ground adjustment. Goal of the project is to adapt this HGV with a single actuator ensuring accurate bi-stable positioning in flight and a proportional highly accurate positioning on the ground (also usable in flight). Goal is also to test this valve at a TRL6 level on the Vulcain-x demonstrator in Snecma Vernon during a test campaign of a demonstrator of power-pack consisting in a new hydrogen turbopump , a new gas generator and the electrical HGV. This test campaign is contracted by CNES to Snecma Vernon.

Possible target application is evolution of Vulcain on A5 ME

1. INTRODUCTION

The Vulcain 2 HGV is an important valve localized between the gas generator outlet and the Oxygen Turbo Pump (TPO) inlet.

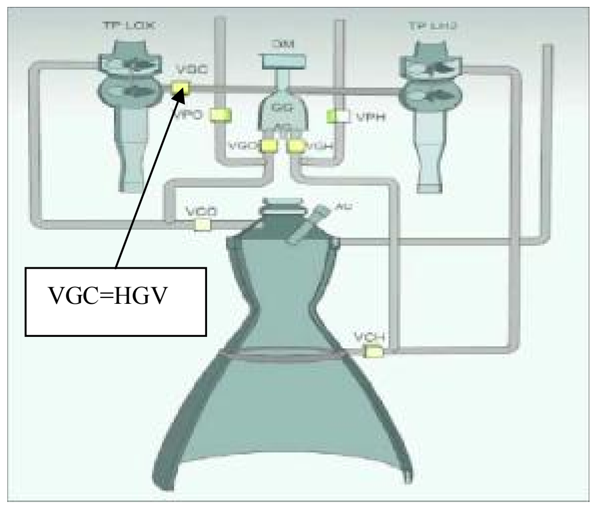


Figure 1. HGV on Vulcain2

This valve allows to adjust the gas flow entering in the TPO and so to adjust the global engine mixture ratio. Current HGV is a butterfly valve that must resist to high temperature (1000K)
Two configurations are in use, ground test and flight configurations enabling two different and complementary actuators: a hydraulic actuator for ground testing and a pneumatic actuator for flight purposes.

[1] ESA contract n° 19646/06/NL/IA

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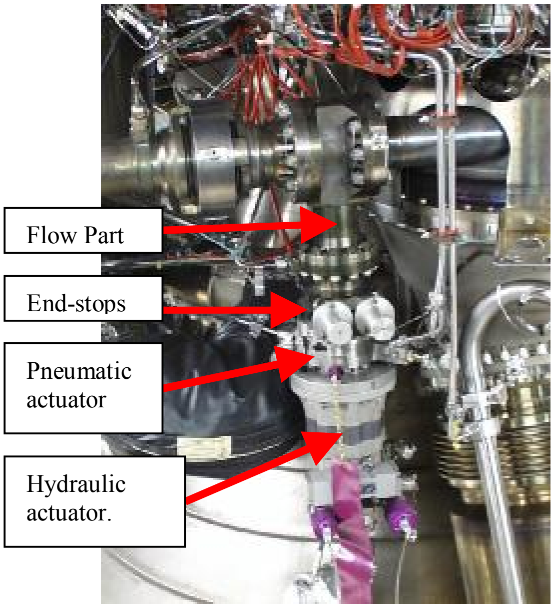


Figure 2. HGV on Vulcain2

In flight configuration, the valve is opened and switched between two pre-set positions (defined by end stops) modifying the flow pressure drop, hence the turbo-pump speed and the engine rummy point.

The ground test configuration provides means to test and tune a variety of valve positions helping to define the two pre-set positions. To that purpose, the valve must be actuated in discrete mode and a ground test actuator is mounted on top of the assembly of the flight actuator and end stop setting device.

The main advantages of electrification are:
- Improved engine acceptance → Reduction of the acceptance tests
- Higher tuning precision: less uncertainty → Better ullage management →Potentially more payload
- Engine control multi-position flexibility → Increased operating margins→ Impulsional mode
- Potential active propellant control in flight

2. TECHNICAL SPECIFICATION

- Remain in the current Vulcain2 hot gas valve envelope and limit the actuator mass and inertia.
- High environmental constraints (high vibration, high temperature of about 1000K,…).
- No additional onboard electronics for ON-OFF mode → brush motors.
- Use available Ariane 5 power grid.
- The actuator must be irreversible.
- High accuracy (+/-0.27° of reproducibility at butterfly level)
-High resolution capacity at butterfly level
- 2 command modes: Closed loop position regulation and ON-OFF operation against end stops
- Natural speed limitation in ON OFF mode

3. DESCRIPTION

3.1. The design guidelines

Two main requirements are at the origin of the main design guidelines.

1st requirement was to have a very good precision of the control of the angular position of the valve.
Because of the rather low stiffness of the shaft of the reused part of the valve, the requirement for the accuracy for the electrical actuator accuracy has been set to a quite severe value (< 0.1 °)

The following guidelines have been followed to reach this challenging specification:

- reduce the backlash in the transmission system (speed reducer with low backlash, coupling with very low mechanical play)
- place the position sensor at the best place
- use a high accurate sensor

The requirement of natural speed limitation and the position resolution for the irreversibility requirement leads to the following design constraints:

- low impedance motors with high electromotive constant
- need of a high speed reducer ratio

3.2. Flow Part

The flow part is almost similar to Vulcain 2 hot gas valve with a butterfly supported on both sides by bearings. The only change implemented here is a small shift of butterfly shape to minimize hydrodynamic torque and so the required actuation torque.

The electrical actuator is heavier than the pneumatic actuator The current HGV flow part is not foreseen to resist to launching vibration due to this additional load. In case of use on a real engine, flow part will have to be reinforced. Goal of the project is only optimisation of the actuator and flow part is so used as it is namely for budget reason

The end-stop system is composed of 2 adjustable fingers fixed on the housing limiting the valve angle by entering in contact with a dedicated part fixed on the flow part shaft. This part is also re-used from Vulcain 2 HGV.

3.3. Actuator architecture

The selected architecture is composed of 2 brush motors on a shared shaft, a torque limiter, a double stage speed reducer (i= 960), 2 position sensors and a mechanical coupling between actuator and flow part

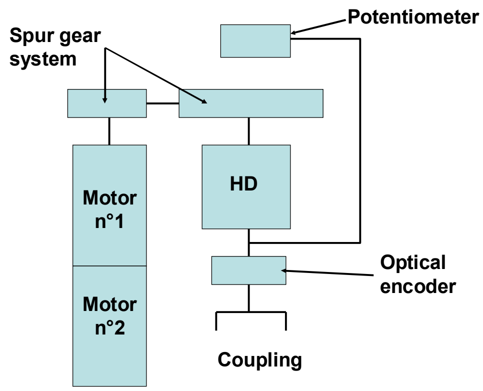


Figure 3: Actuator architecture

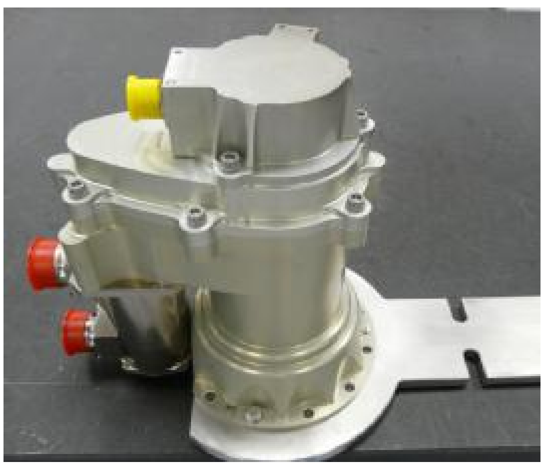


Figure 4. Assembled Actuator

3.4. Actuator/flow part coupling

This coupling is designed to compensate for the possible misalignment between flow part shaft and actuator shaft namely due to machining tolerances and assembly.

Required properties:

Transmit operational + impact torque
Low mechanical play (< 0.04°)
Alignment in 4 axes: 2 centring (0.135 mm) and 2 tilts (0.16°) with minimum alignment loads
Support pressure effect ➔ 0.15mm axial movement

Selected solution

One membrane only + use of flexibility of flow shaft itself. Connection by 2 rigid cylindrical dowel pins

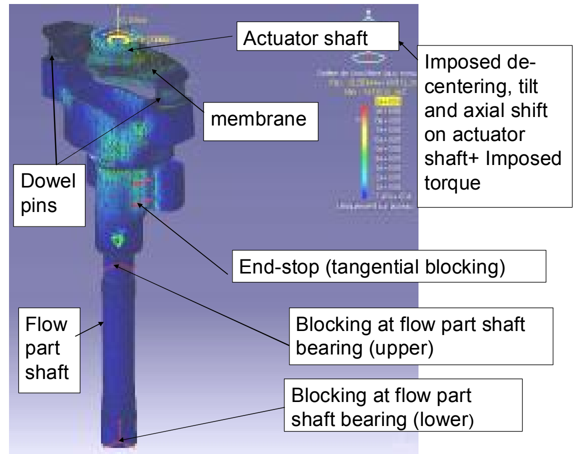


Figure 5. Actuator/flow part coupling

Computation gives a safety factor of 1,3 on the membrane and of 1,41 on the dowel according to respective yield limits

3.5. Reducer and lubrication

The selection of the reducer ratio is one of the main parameter defining the actuator architecture. It is mainly a compromise between the actuator mass and the limitation of the impact torque on end-stops. A reducer ratio of 960 is finally selected using 2 reduction stages 1st stage is a spur gear system and 2nd stage is a Harmonic Drive.

Figure 6. spur gear system

Figure 7. Harmonic Drive kit

From precedent HD experiences, it was decided to use dry lubrication on WG bearing, at flexpline interface and on teeth system with the objective to avoid efficiency drop at -40°C.

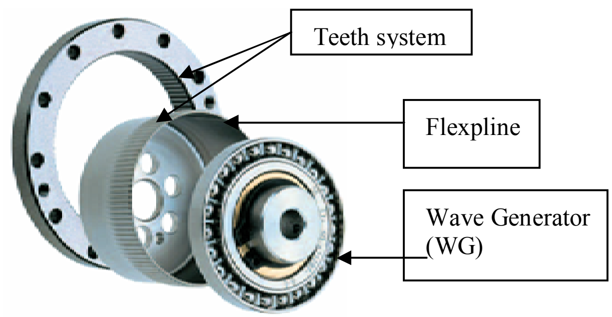


Figure 8: HD components

Cycling at different temperatures and in vacuum was performed by the supplier on a Harmonic Drive using an existing rig at ESTL. Efficiency reduction was small at cold temperature.
Cycling was stopped after 180 cycles during the hot cycle phase (~ 1200 total cycles completed) due to:

- Abnormal value fluctuation
- Audible change

Due to this problem, it was decided to put vacuum grease on WG and teeth system. A new cycling campaign was performed in this condition. About 5000 cycles at the 3 different temperatures were performed in this configuration. Test campaign was successful and no damage was observed on the different parts after these cycles.

Small quantity of grease was also applied on the spur gears supporting bearings.
Note that using grease has decreased the global efficiency of the actuator of about 13% in cold condition. Motorization margin is now slightly less than 3 but it was accepted by the customer for this demonstrator.

3.6. Encoder

Combination of 2 position sensors: one ground adjustment sensor and one flight monitoring sensor.

Ground adjustment sensor
Very compact optical sensor for high accuracy (40") already used on satellite. Integrated in the flow part ➔ localised at the best possible location directly on the valve shaft to improve adjustment performances. Allow suppression of the signal noise. Off-the shelf bellows also provided by the encoder supplier

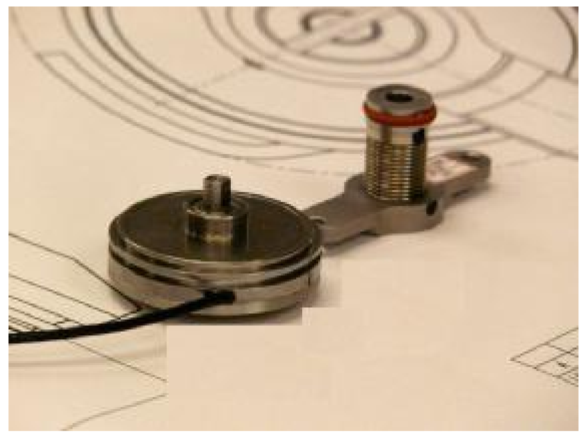


Figure 9. Optical encoder and its bellows

Flight monitoring sensor
Potentiometer already used on Ariane5 (and so compatible with the onboard A5 electronics)
Localised on the top of the actuator and connected to the Harmonic drive output shaft through HD hollow shaft: Advantage: autonomous actuator acceptance test possible and thermal isolation from the flow part (hot temperatures).

Possibility to use both sensors on the ground in a redundant configuration

3.7. Motor

Global actuator architecture: 2 classical brush motors (for redundancy) with natural speed limiter on shared shaft and a torque limiter,

<u>Motor</u>
The motor assembly is an off- the-shelf brush motor with 2 rotors (windings and commutator) shared on the same shaft and included in the same housing. The motor's stators and the connectors are fixed to the housing. Motors are computed to activate the valve alone with a margin of about 3 (ECSS rules).

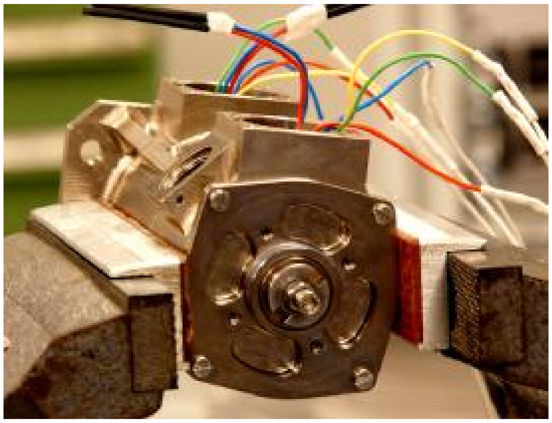


Figure 10: motor during assembly

Irreversibility

Specification Requirements: precise position keeping un-powered, no friction based device and active devices not allowed

Design choice: irreversibility made by the cogging torque of the motors. Designed according to the active torque = aero torque (i.e. no friction torque).

Implementation: need to synchronise cogging torque => 2 motors on a same shaft is easier

Torque limiter

The configuration of "2 motors on a same shaft" is interesting for a easy placement of torque limiter which has to limit the total torque given by the **2 motors**

Torque limiter is computed to transmit a given torque and to un-clutch above this given torque keeping a residual torque transmission namely when reaching the end-stops

MODELLING ACTIVITIES

A thermal model of the valve was made to determine the temperature and thermal gradient seen by each component during a typical flight sequence (about 600s). The model shows namely that temperature at actuator level never exceed 120°C. Temperature of the optical encoder (localised on the top of the flow part) is of about 170°C. As already said, this encoder is not used during flight and can resist mechanically until 220°C.

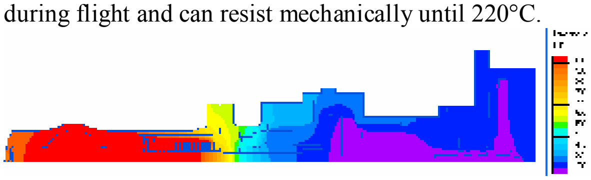


Figure 11: valve thermal model

A dynamic system model has been made to analyse the behaviour of the system in end stop commutation transient and to allow regulation loop adjustment.

This model gave a good correlation with the test results and allowed us to converge quickly on the tuning of the control loop parameters.

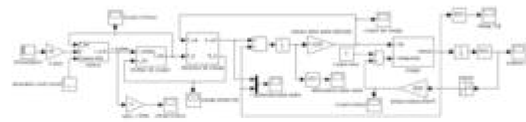


Figure 12: valve dynamic model

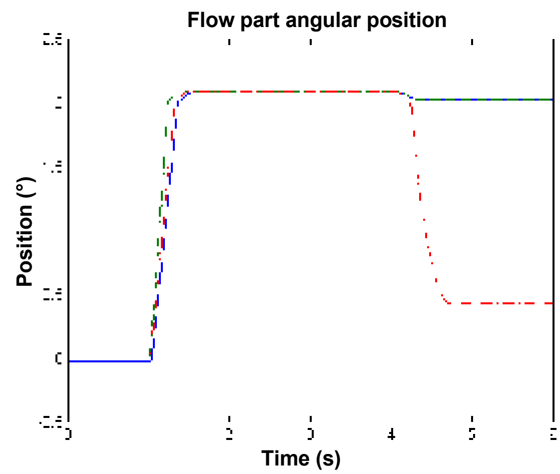


Figure 13 end-stop commutation transient :

4. TESTING

The test campaign was divided in four main phases

- Technological test on components
- Flow part test
- Actuator test
- Global valve test

4.1. Technological tests on components

Technological test were made on the speed reducer gear, on the motors and on the torque limiter to verify the performance and life time capacity in similar environment (Temperature, vacuum and dry gas)

4.2. Flow part tests

Flow part test were made to verify:

- The stiffness of the flow shaft with the coupling part (no back lash coupling)
- seal tightness
- axial shaft movement with pressure

4.3. Actuator tuning an endurances tests

Following tests were performed:

Actuator characterisation tests

Actuator characterisation tests were performed on a dedicated loading test bench.

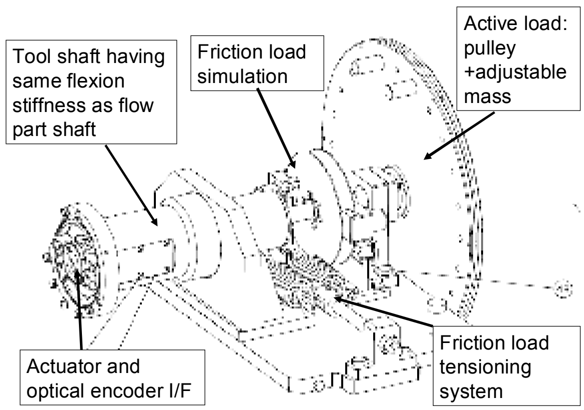
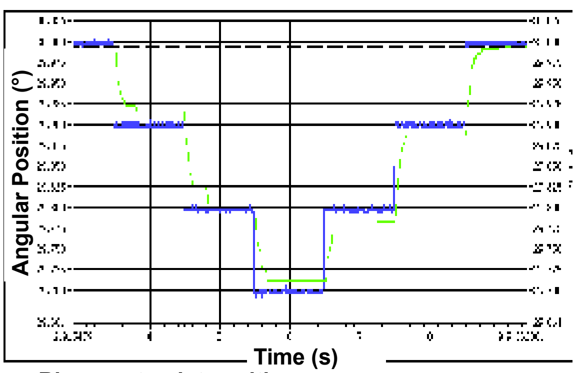


Figure 14: Actuator loading test bench

The following characteristics have been verified:

-resolution at the tooling shaft
-position reproducibility
-bandwidth of the system
-dynamic range for large angular displacement
- irreversibility capacity



Blue = set point position

Green = encoder position

Figure 15: Resolution and repeatability test results

Pre-endurance" test on actuator part

The pre-endurance tests (300 movements of about 20°) were performed in regulation mode at 3 different temperatures: 20°C, -40°C and +100°C in a climatic room applying the total torque (friction and active load).

4.4. Vibration test

The material was tested in 3 axes with the following sequences:

- Low Level Sinus
- Natural frequency identification
- Random vibration test at "acceptance test level
- Low level Sinus for natural frequency identification
- After each axis, activation will be done to control the no-load current

Strain gauges and accelerometers were used to measure stress level at critical location and acceleration on the vibration I/F plate, on the top encoder, on the motor I/F and on the motor extremity.

Figure 16: VGCX on vibration test bench

After vibration on the first axis (lateral direction) one of the 2 motors (motor n°1) had some troubles. Some current drops were observed (4 times a turn) as seen on figure 17.

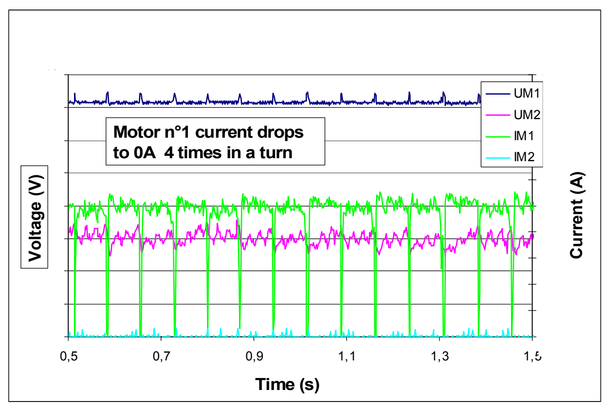


Figure 17: Motor characteristics after vibration

Decision was taken to continue the campaign with vibration tests on the 2 other axes. Motor n°2 was still functioning after the full vibration campaign. No problem detected on the actuator and on the encoders.

During motor expertise, some connections were found broken between winding and commutator on motor n°1. According to the motor supplier, origin of the failure is due to relative movement between collector and rotor during vibration. Motor 1 is more sensitive to shaft flexion mode because winding/commutator connection of motor 2 has smaller arm lever compared to supporting bearings.

Analysis of that vibration result curves shows that a big amplification is observed at the motor extremity close to 570Hz probably due to a cross coupled vibration mode between the actuator and the motor itself.

It was decided by the motor supplier to modify the motor to resist to this shaft flexion mode. Distance between winding and commutator was slightly increased to allow having a longer connection wire giving enough flexibility to resist to this amplified flexion mode. New motor is currently in characterisation tests and will be re-checked in vibration alone before delivery..

4.5. Global valve tests

Figure 18: VGCX in climatic room

After integration of the actuator on the flow part, the following tests have been performed on the complete valve in the climate room:

- Characterization of the dynamic seal tightness (primary and secondary seal)
- Measurement of positioning accuracy on the end stops (end stop reproducibility) and motor current during end stop (torque limiter characteristic)
- Closed loop tests
- With and without pressure in the flow part, carry out the following measurements: resolution and position reproducibility
- System response at 1 Hz for 2.5° angular stroke
- dynamic range for large angular displacement
- Test of the influence of flow part pressure on commutation torque and position on end stop.

4.6. Test conclusion

The design of the actuator and the evolution of the flow part design have allowed to reach a position regulation accuracy better than 0.04°.

The performances of irreversibility and of end stop adjustment have met the challenging requirements.

Valve will be delivered at Vernon (Snecma) in July to be integrated on the Vulcain-X demonstrator. The tests concerning the electrical HGV will start in September 2009. These tests will be fully representative for the HGV in term of flow, pressure and partially temperature (test is shorten than real flight duration).

5. LESSONS LEARNT

As actuation torque of the flow part has a much higher impact on the resulting actuator weight for electric actuated valve, it is important to design the flow part in such a way that

– hydraulic torque is minimized
– shaft seals generate minimum torque.

Very challenging electric power requirements can only be met by detailed electromechanical modelling and adequate choice of control laws.

Harmonic Drive reducer presents several advantages because of its high reduction ratio in a small envelope allowing fully integrated concept. Lubrication selection is important. Dry lubrication didn't give good results and vacuum grease had to be used to allow a correct functioning. This grease induces a reduction of the global actuator efficiency in cold condition (at -40°C) and this effect must be taken into account for future projects early in the project design phase.

Motor and actuator design must include the vibration aspect. Flow part mode, actuator mode and motor modes must if possible not be coupled to avoid important amplification namely at the motor level.

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