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Closed-loop actuator identification for Brazilian Thrust Vector Control development

Timo Wekerle * **Euler Gonçalves Barbosa** ** **César Moura Batagini** ** **Luís E. V. Loures da Costa** *** **Luís Gonzaga Trabasso** ***

* *Aeronautics Institute of Technology (ITA) and Institute of Aeronautics and Space (IAE), São José dos Campos, SP, Brazil (e-mail: timotw@ita.br).*
** *Institute of Aeronautics and Space (IAE), São José dos Campos, SP, Brazil (e-mail: euleregb@iae.cta.br and cesarcmb@iae.cta.br).*
*** *Aeronautics Institute of Technology (ITA), São José dos Campos, SP, Brazil (e-mail: loures@ita.br and gonzaga@ita.br).*

Abstract: This paper presents the current status of the development of a Thrust Vector Control system for new Brazilian launch vehicles, looking for the highest performance by closed-loop servo hydraulic actuator identification. Therefore, a test environment with a mass-spring test bench is introduced. Engineering models of two different types of actuators, three-way and four-way valve controlled pistons with direct drive control valves are developed. The dynamic responses are experimentally determined and subsequently mathematically modeled.

Keywords: GNC, Attitude control, Thrust Vector Control, Actuators, Closed-loop identification

1. INTRODUCTION

The Brazilian Institute of Aeronautics and Space (IAE) and the German Aerospace Center (DLR) are cooperating in the development of the sounding rocket VS-50, a sub-orbital launch vehicle for micro-gravity experiments. The first flight of the VS-50 is planed for 2018, consisting of a two-stage sounding rocket using the existent upper stage motor S44 and the S50 motor as first stage, currently under development in Brazil. Based on VS-50, a satellite launch vehicle for Mini-, Micro-, and Nano-Satellites is projected, called VLM-1 (Veículo Lancador de Microssatelites or Microsatellite Launch Vehicle). A first possible configuration may be a 3-stage solid propelled launch vehicle with two S50 motors and one S44 motor as upper stage, depicted in Fig. 1. For the first stages of VLM-1 vehicle a Thrust Vector Control (TVC) system is being developed in Brazil.

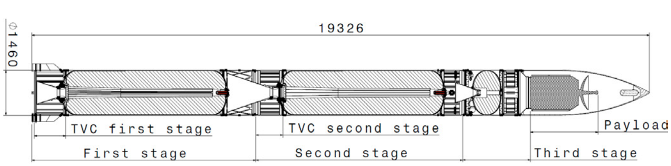

Fig. 1. Concept for VLM-1 satellite launch vehicle

2. THRUST VECTOR CONTROL

Thrust Vector Control systems can be used in sounding rockets in order to reduce the impact dispersion, simulating a kilometer long launcher rail. That can be achieved by keeping the attitude of the vehicle constant during the guidance period. According to Ljunge (2009), actuation systems may also reduce the sensitivity to wind and thrust misalignment can be compensated. For a satellite launch vehicle the mission defines its trajectory. The trajectory in turn is defined by the specification of the vehicles attitude during flight and can be determined by linear and angular velocities over time. The reference trajectory acts as input of the attitude control system, which determines amongst others performance parameters of the TVC system.
The mechanism of a Thrust Vector Control of rocket motors and engines is responsible for deflecting the exhaust gases in order to guide and steer the vehicle. Using a single nozzle which is aligned with the vehicle main axis, angular velocities and accelerations of pitch (raise or lower the nose of a vehicle) and yaw (turn the nose sideways) can be controlled, as schematically depicted in Fig. 2. In order to control roll moments, different mechanisms can be used like aerodynamic fins, vanes, separate roll thrusters, gas generator output, solid motors, hot or cold gas system.

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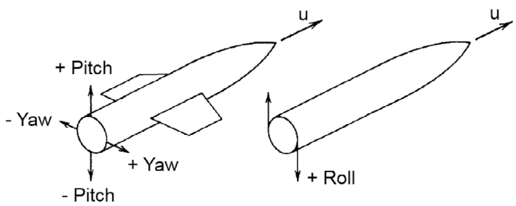

Fig. 2. Pitch, yaw and roll moments applied to vehicle, after Sutton and Biblarz (2010)

There are several mechanisms used to deflect the combustion gases for a single nozzle that result in pitch and yaw moments. According to Sutton and Biblarz (2010), of all mechanical deflection types, movable nozzles with a flexible joint, a flexible laminated bearing, are the most common type and the most effective one because the thrust and specific impulse are not significantly reduced and due to its low weight.

3. DEVELOPMENT OF THRUST VECTOR CONTROL SYSTEMS

For the development of a launch vehicle, the verification and validation of the performance of the control system is fundamental. Using only digital simulation may neglect real hardware effects and characteristics. The tool that combines software simulation with real hardware elements is called hybrid simulation or Hardware-in-the-Loop (HWIL). In these tests physical components like actuators, sensors and on-board computer with flight control law algorithms are embedded as well as simulation of the vehicles dynamics consisting of the rigid body dynamics, bending modes, a gravity and an aerodynamic model, as described in Carrijo et al. (2002). The vehicles rotational movement can be reproduced by installing the sensors into a rotational simulator with three degrees of freedom. In Fig. 3 the characteristic test assembly is represented.

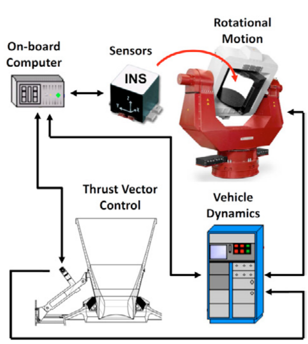

Fig. 3. Test assembly for HWIL

Carrijo et al. (2002) describe the HWIL simulation strategy starting with Phased-A in order to validate the implementation of the flight control law algorithms using only the on-board computer as physical component. The actuation system is simulated by a mathematical model, a transfer function that can be obtained from the experimental characterization concluded in this paper. In Phase-B the actuation system is implemented into the loop in order to substitute the mathematical model. Therefore, a mockup of the solid rocket motors nozzle and aft skirt is being developed, depicted in Fig. 4. In Phase-C the actuation system is again substituted by a mathematical model and the sensors, the Inertial Measurement Unit (IMU) is introduced. The IMU consists of gyroscopes for measurement of the angular positions p, q and r and accelerometers for measurement of the specific forces a_x, a_y and a_z. In the final Phase-D only the vehicle is simulated and all possible hardware components (on-board computer, actuation system and sensors) are implemented into the loop. This creates the most real condition possible within a simulation environment before the actual flight.

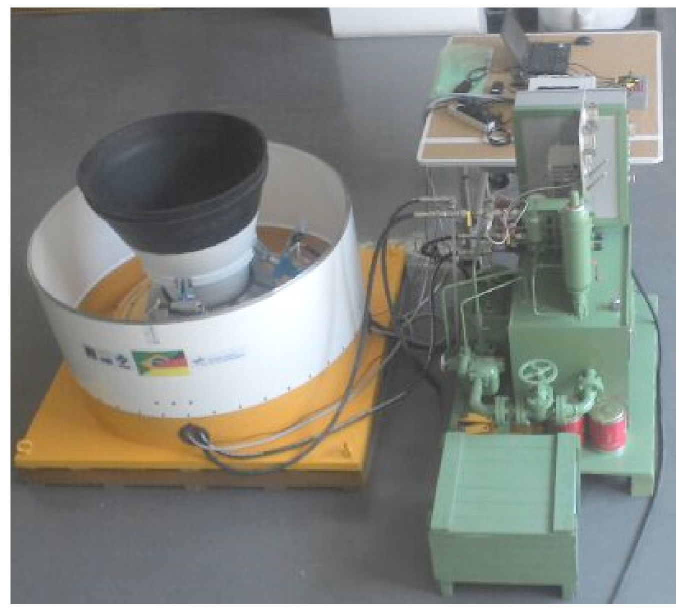

Fig. 4. Mockup of rocket motor nozzle with aft skirt including the actuation system

4. TVC DESIGN

Wekerle et al. (2015) analyze and compare the performance of different TVC systems. An approach for generation of performance requirements for TVC systems is introduced that is being applied to the VLM-1 TVC, resulting in a working envelope for the system. A maximum deflection of 3° and a minimum slew rate of $15°/s$ is defined.

For TVC applications a high power-to-weight ratio is required. As a linear actuation device, hydraulic power elements with direct drive servovalve and piston is chosen with a theoretical maximum operating efficiency of 67% compared to a pump controlled system with 100% theoretical efficiency. In spite of less efficiency, faster response capability of the valve controlled system makes it more advantageous for a TVC applications (see Merritt (1967)). The choice for a hydraulic actuation system is caused by the possibility of using commercial off-the-shelf components (COTS), the high power density and and the inexpensiveness compared to electromechanical actuators.