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Electromechanical TVC using direct engine deflection measurement feedback for reusable stages

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Abstract

Most commonly, control architecture of electromechanical TVC (Thrust Vector Control) is made of nested loops using actuator stroke, electrical motor rotating speed and phase currents feedbacks, sometimes coupled with additional actuator force feedback to increase damping of selected dynamics whenever needed. With such an architecture, all the sensors are directly put on TVC equipment, which makes it handy to control all along product life cycle. The present paper focuses on the benefits of adding (or replacing actuator stroke by) a direct engine deflection measurement feedback in the frame of liquid propulsion. Main motivations are on the one hand a potential simplification of the actuator design aiming at reducing its cost and on the other hand static accuracy improvement or simplified achievement which is of particular interest for reusable launchers: first stages indeed request the use of multi engine bay to achieve high range thrust modularity, leading in the end to very compact engines stacking. More direct engine deflection assessment allows a better relative positioning of the engines, enabling to avoid mechanical or thermal interferences between engines especially in case of failure of one engine TVC. From a control standpoint, different architectural options are discussed to handle the fact with such a feedback there is no co-localization of the sensor and the effector which can affect the stability of the TVC control loop. Also the risk of conflict between engine deflection feedback and actuator force feedback is analyzed to be able to reject perturbations of various frequency ranges. Finally a control structure is proposed to handle the different control objectives (stability, set-point tracking and regulation). Going from functional to physical architecture, considerations about sensor technology and where to implement it are then presented, taking into account the engine environment constraints. The preferred solution here is to put one angular sensor per gimbal joint degree of freedom. From those measurements, useful data along actuation lines can be derived based on actuators accommodation (TVC electronics control unit both powering the sensor and implementing its related measurement and treatment chain). Finally, from a programmatic standpoint, in the near future, the first potential application for ArianeGroup might be to equip Prometheus engines with such a feature in the frame of Themis T3 demonstrator, to be able to increase its Integration Readiness Level for next generation of reusable launchers.

1. Introduction

The main goal of TVC (Thrust Vector Control) is to master the thrust torque applied to the vehicle for attitude control purpose (it is the actuator of the attitude control loop from a control viewpoint). For expandable launchers, using most of the time one engine per stage, TVC static accuracy is generally not such a big issue (as long as deflection stays far enough from deflection domain border) because vehicle attitude control loop is able to observe the overall thrust deflection offset and correct it. As a consequence, the benefit of using direct engine deflection measurement does not compensate the added complexity: it is indeed quite comfortable when all the sensors used for TVC control are put on TVC equipment to simplify industrial organization, enabling to perform needed control all along product life cycle. For those applications, actuator stroke sensor is most commonly used as it is sufficient to achieve required performances. Now, when considering reusable launchers, the situation is significantly modified and this trade-off worth being reopened. This is precisely the objective of the present paper which presents some benefits of adding a direct engine deflection measurement in section 2. Then section 3 looks at it from a control viewpoint with a special

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focus on how to deal with this not co-localized sensor. The sensor physical implementation and technological perspective is presented in section 4. Finally, some applications are identified in the near future in the frame of Themis demonstrator to contribute to the preparation of next generation of reusable launchers.

2 Motivation

2.1 Baseline limitations

Classical control architecture for EMAs [1] is made of at least 3 nested loops, listed below from the outer loop to the inner loop:

- Actuator stroke control loop
- Electrical motor speed control loop
- Electrical motor phases current loop(s)

When needed, in addition to this classical control architecture, a dynamic force feedback can be added [2] to increase, by mean of active control, the damping of observable dynamics like engine pendulum mode (corresponding to the exchange between engine swivelling kinetic energy and actuator attachment stiffness potential energy).

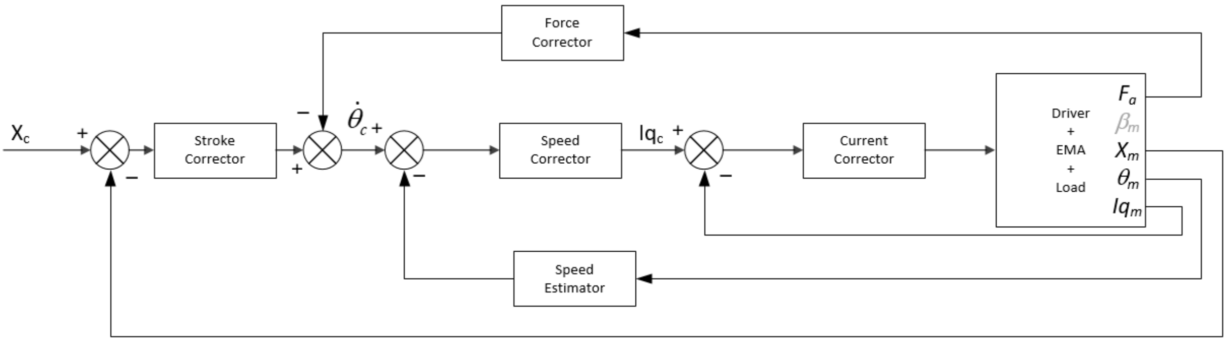
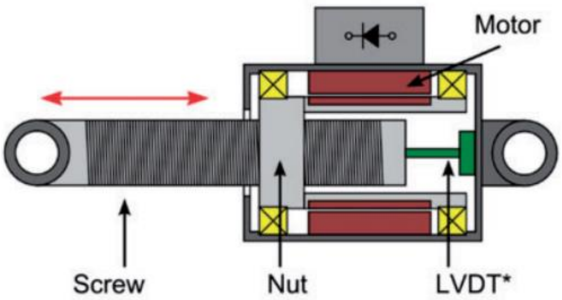


Figure 1: EMA control architecture with force feedback

With such an architecture, all functional sensors remain inside TVC equipment perimeter and that autonomy makes it easier to perform tests all along its product life cycle, from acceptance to check-out logic. However there are some limitations mainly linked to static accuracy or actuator design. Indeed there are uncertainties between actuator stroke and engine deflection because for instance beyond kinematics relationship, EMA attachment flexibilities might be loaded by EMA transmitted force which cannot always be compensated. Notably, gimbal joint dry friction torque is not easy to compensate and in the end, to achieve acceptable performance, gimbal joint design is constrained to limit dry friction which induces expensive design. Another potential cost driver is the use of internal LVDT inside EMA to be used as stroke measurement sensor, which is often selected as it is very robust. Here the drawback is that it requires the use of hollow roller screw for rotation to translation conversion, which is again a rather expensive solution as such roller screw can hardly be found Off the Shelf.



[3]

Figure 2: LVDT implemented inside hollow shaft screw

DOI: 10.13009/EUCASS2023-538

2.2 Benefits from using a direct engine deflection feedback

First, when using a direct engine deflection sensor may be the opportunity to suppress EMA LVDT or to achieve redundancy without strong design side effect. Also, using a direct engine deflection measurement, it becomes possible to improve perturbation rejection as the sensor is closer to the final objective (thrust deflection) than actuator stroke. Notably, the attachment stiffness loading previously mentioned can be compensated at low frequency. If the allocation becomes easier to fulfil, it also means that external design drivers can be relaxed for cost effectiveness purpose. For instance, the gimbal joint dry friction might be relaxed opening the way to use simpler designs. The design driver then becomes the difference between static and dynamic dry friction as it may lead to limit cycles, which is acceptable as long as the amplitude stays low. In the same spirit, the stiffness of structures where the EMAs are attached to can be reduced to some extent which can help to save mass as they are usually stiffness driven rather than stress/strain driven.

However, the main benefit arises in the frame of reusable stages with the multi-engine bay context. To achieve sufficient throttle ability as requested by reusable stages (heavy at lift-off requiring high thrust and light at landing requiring low thrust), such an architecture is indeed mandatory [5]. Also engines packing constraints lead to very compact bay, where the engines are close one from the others as could be seen on Figure 3. Knowing precisely the deflection of each engine, allows a good knowledge of their relative deflection which makes it easier to avoid mechanical/thermal interferences between engine nozzles/plumes. When there is room for displacement, large step responses performances are focusing on rise time essentially, without strong need of trajectory control [6] from the initial position to the final one. In case interferences can occur, it may become important to control the trajectories of the different engines in a sort of formation flying [7]. And if this is already true under nominal configuration, it becomes even more crucial in case one engine is blocked in one deflected position and may limit the deflection domains of adjacent engines. Let finally mention some operational benefits like potential engine alignment simplification.

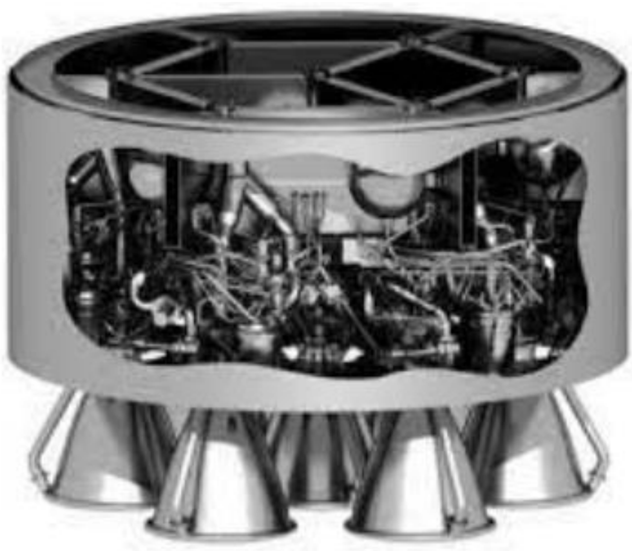


Figure 3: Engine packing inside multi engine bay

3 Control viewpoint

3.1 Co-localization, modal landscape and stability

From a control viewpoint, using a direct engine deflection feedback may have some impact on TVC stability because the sensor is not co-localized with the effector (i.e. the electrical motor of the EMA). If they were, the alternated poles and zeros of the open loop behavior would simplify the stability analysis. Here it is then crucial to identify the dynamics which could introduce some phase lag between the angular position of the electrical motor rotor and the engine deflection in the control bandwidth.

DOI: 10.13009/EUCASS2023-538

For heavy engines, the most impacting dynamics are:

- the engine pendulum modes (where the engine transversal inertia is mainly exchanging energy with actuator attachment stiffness related to the local flexibility of the structures where the actuator is attached),
- lateral and longitudinal engine modes (where the mass of the engine is mainly exchanging energy with stiffness in the neighborhood of the engine gimbal joint)

Pendulum mode frequency is generally the lower one and the engine deflection will not stay in phase with rotor angular displacement above pendulum mode frequency.

Let consider below the simplified study case of a 1 degree of freedom engine with a single actuator (3000 rad.s^{-1} current loop bandwidth) and assuming perfect kinematics efficiency.

Table 1: Parameters of the simplified model

Parameter	***Notation***	***Value***
Engine lateral inertia / Gimbal Joint	J_e	2000 kg.m^2
Actuator lever arm	L	0.8 m
Equivalent attachment stiffness	K_{att}	6 x 10^6 N.m^{-1}
Equivalent attachment damping	C_{att}	3000 Ns.m^{-1}
Actuator roller screw pitch	p	8 mm
Actuator rotating parts inertia	J_m	2 x 10^{-2} kg.m^2
Current loop bandwidth	ω_{curr}	3000 rad.s^{-1}

Calling F_a the actuator force, the open loop behavior of the plant can be derived with commanded electrical motor torque as input and actuator stroke x, engine deflection beta and force F_a as ouputs.

This situation is presented on Figure 1 with a Nichols chart of the plant open loop

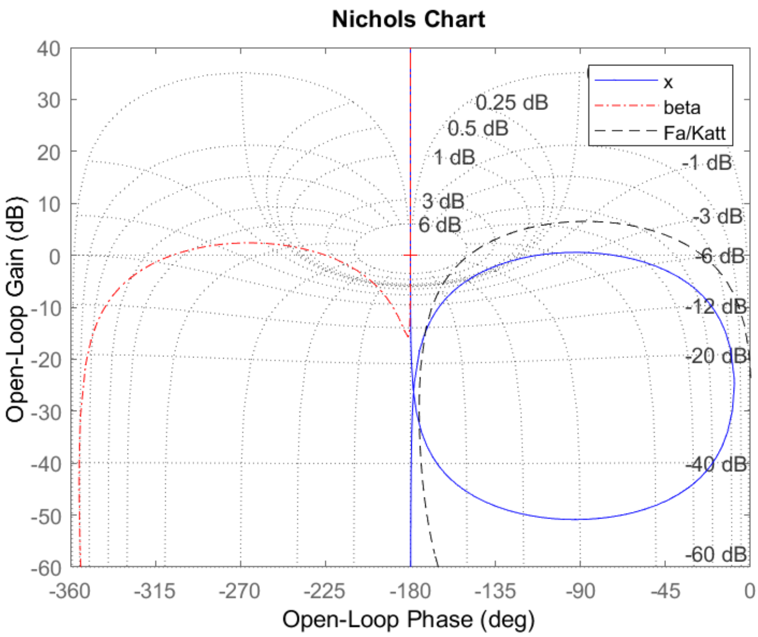


Figure 4: Simplified model Nichols plot (gains x 1000)

DOI: 10.13009/EUCASS2023-538

It appears that the zero/pole sequence is different for the stroke measurement and for the engine deflection measurement. For the stroke measurement there is a zero before the pole corresponding to the pendulum mode frequency and as a consequence the phase range stays between -180° and 0° around pendulum mode frequency (this situation corresponds to the case of a co-localized system). For the engine deflection measurement, there is no such zero and as a result, the phase range is between -360° and -180°. To get sufficient stability margin, the classical structure is to use a PD controller or in a similar approach to use speed and position nested loops with P controllers (or PI controller for the speed loop). It then becomes quite clear that the stroke feedback is better suited for stability control.

Conversely, as the main advantage of the engine deflection feedback is to be able to improve static accuracy, it is of course of interest to use it at low frequencies. At higher frequencies it does not help much so it can be preferably replaced by a more co-localized measurement to ensure stability, either using actuator stroke measurement if available or even an estimator derived from rotor angular position. Finally, using filters in quadrature with a cutting frequency below pendulum frequency allows to benefit from both feedbacks.

3.2 Control structure and interaction with a force feedback

A force feedback is considered to be able to actively add damping to the pendulum mode and consequently improve the perturbation rejection (limiting the actuator force response when an exogenous torque is applied to the engine). It can be noted that the force feedback and the engine deflection feedback are linked and used for different purpose which might be antagonist. However this interaction is limited by the frequency separation of the actions (engine deflection feedback being used at low frequency whereas force feedback is used around pendulum mode frequency).
The control structure is then depicted below.

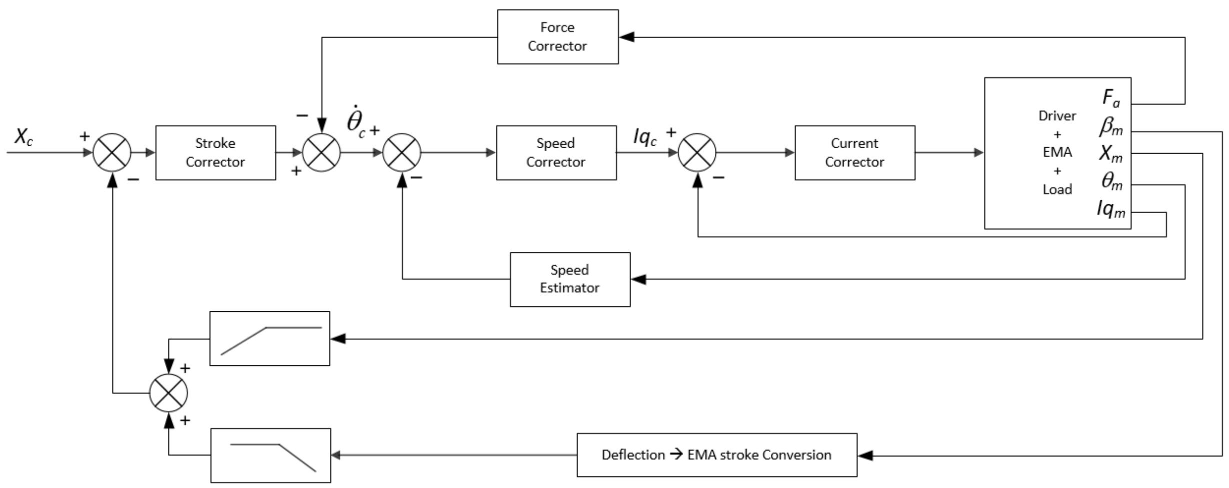


Figure 5: Control architecture with direct engine deflection feedback

After controller parameters tuning, the following performances are achieved.

DOI: 10.13009/EUCASS2023-538

- Stability

Figure 6 corresponds to the open loop of the controlled system (with actuator position, engine deflection, force and speed loops being opened) showing quite comfortable stability margins.

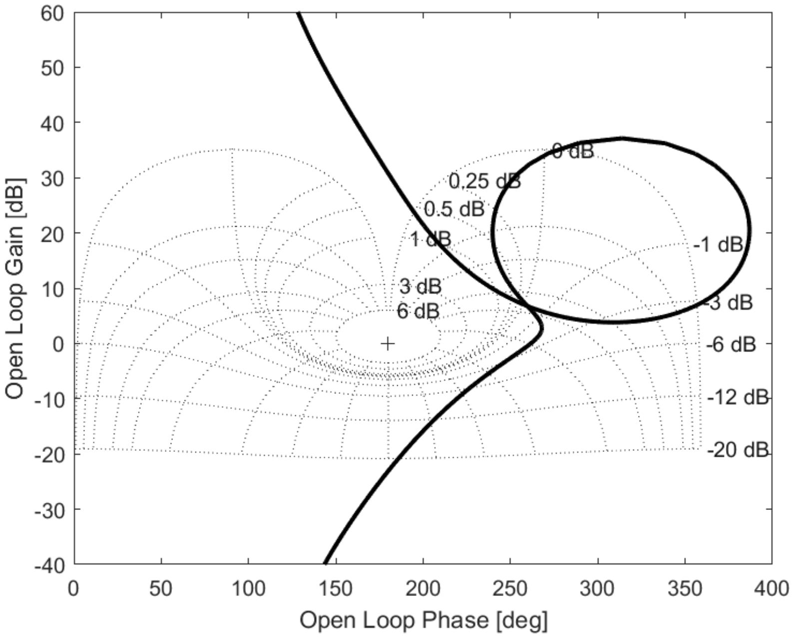


Figure 6: Nichols plot of the controlled system

- Set-point tracking performances

Achieved set-point tracking performances are given by Figure 7 for EMA stroke (dashed lines) and engine deflection equivalent stroke (plain lines) showing a good damping of the pendulum mode about 7 Hz thanks to force feedback.

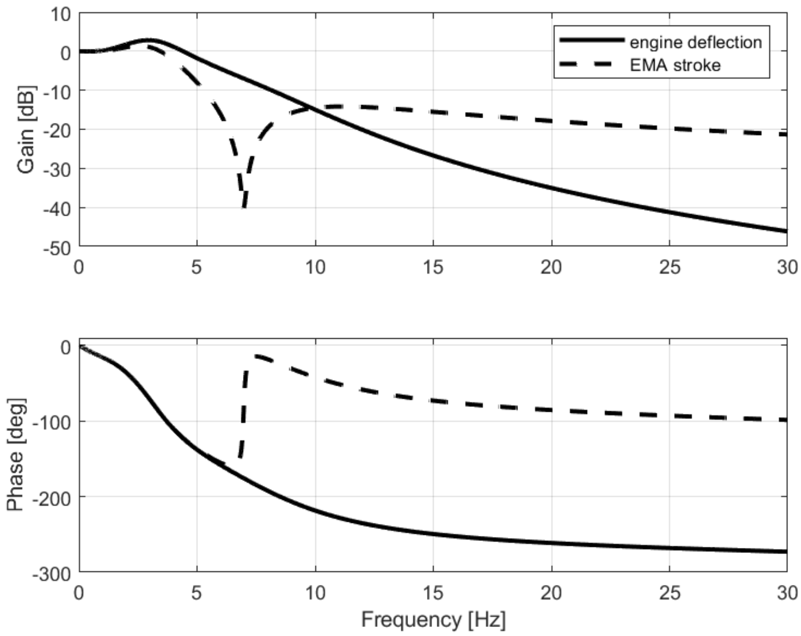


Figure 7: Actuator stroke and engine deflection set-point tracking performances

- Perturbation rejection performances

2 kind or perturbation rejection performances are considered: the first one consists in limiting the actuator force with respect to dynamical exogenous torque applied to the engine, the other one consists in limiting the engine deflection with respect to a quasi-static exogenous torque applied to the engine. To underline the benefit of the various control

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actions, 4 controllers are considered using or not a force feedback and using or not an engine deflection feedback (by adjusting the value of the cut-off frequency of the filters in quadrature). Figure 8 shows the clear benefit of force feedback to limit the actuator force as a response to exogenous torque near pendulum frequency.

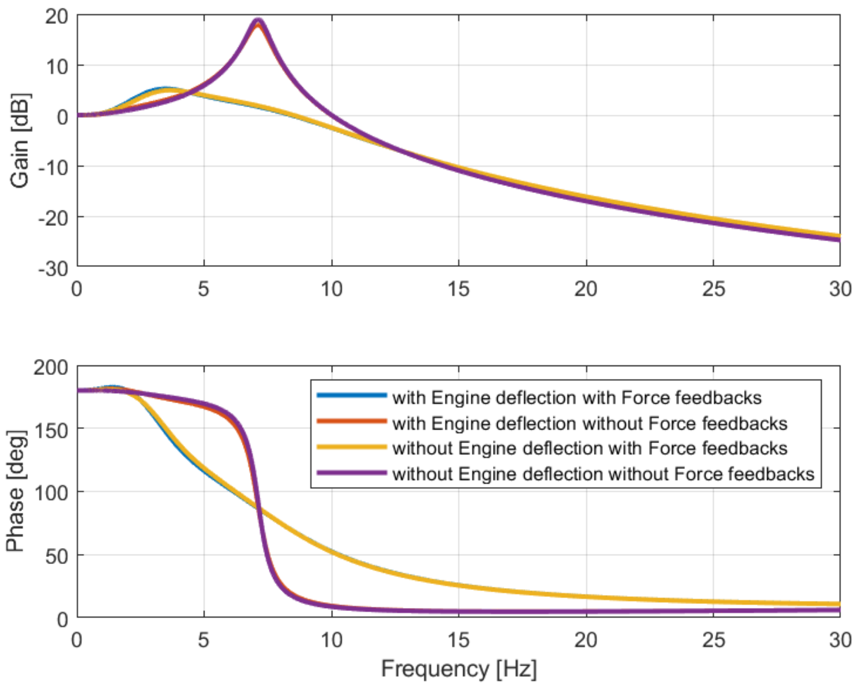

Figure 8: Actuator force response to exogenous engine equivalent torque

Figure 9 shows at low frequencies the benefit of using a direct engine deflection feedback to improve by at least one order of magnitude the quasi static tracking error resulting from the application of an exogenous torque without significant degradation at higher frequencies.

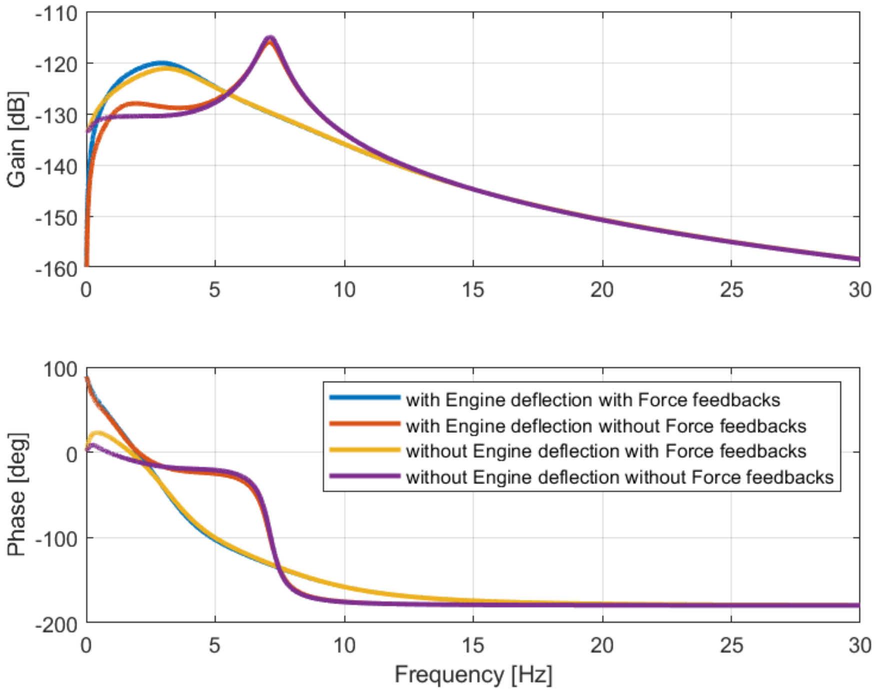

Figure 9: Tracking error response to exogenous engine torque

DOI: 10.13009/EUCASS2023-538

4 Implementation and technological sensing viewpoint

The principle consists in directly measuring the rotating move at engine gimbal joint where the kinematics is simple enough to use single rotating move sensors. A typical sketch is given by Figure 10 where the sensors can be accommodated close to gimbal axes.

Figure 10: Possible location of the gimbal joint rotating motion sensors

Different sensor technologies (magnetic sensors like RVDT or resolver, optical encoders, potentiometers) can be considered and the final choice will be made according to a trade-off between measurement accuracy and ability to sustain the environmental conditions (vibration, pollution…).
Then knowing the sensor kinematics and the accommodation of the TVC actuators, it is possible to derive 2-dimensionnal conversion tables to transform engine gimbal deflections into actuator equivalent strokes. Such a conversion is used upfront of the filters in quadrature for the engine deflection part to mix comparable inputs. It could also be used to merge the data from the actuator resolver and the engine deflection to assess indirectly actuator stroke if needed.
Another opportunity is to use engine deflection feedback and engines accommodation to derive engines deflection in stage coordinates system to be able to properly deflect the complete set of engines in case of multi engine bay by acting at stage or multi engine bay level to take into account the current engines deflection and compensate for discrepancy which may occur due to various exogenous loads applied to the different engines or even different azimuth of the engines as performance along actuation plane is often different than the one along bisecting plane for instance.

5 First target and future applications

The first target is to put such a sensor on Prometheus definition with a first use for Themis T1+ demonstrator and then for Themis T3 demonstrator (including a multi engine bay with 3 engines). Here, the idea is really to learn by doing in order to assess the benefit in various phases from integration to flight and exploitation. As a consequence, the control structure will be rather opened in order to be able to use the feedback or not during the flight as primary or redundant solution or just for initialization. Depending on the behavior and the quality of the sensing, a step wise approach will be used.

DOI: 10.13009/EUCASS2023-538

Figure 11: Themis T3 engine bay view

At a longer projection, the goal is to be ready and mature enough in terms of IRL for the preparation of Ariane Next using for its first stage a multi engine bay with 7 or more likely 9 engines.

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Acronyms

EMA	Electro Mechanical Actuator
IRL	Integration Readiness Level
LVDT	Linear Variable Differential Transformer
P	Proportional (controller)
PD	Proportional and Derivative (controller)
PI	Proportional and Integral (controller)
RVDT	Rotating Variable Differential Transformer
TVC	Thrust Vector Control

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