Fault Detection and Isolation for a Rocket Engine Valve

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Abstract: In this article a fault detection and isolation scheme based on H_∞ theory is presented for a rocket engine actuator valve. The simulation model of the engine corresponds to a Vulcain 2-like rocket engine used to study the applicability and capabilities of FDI techniques towards real-time validation in an engine test-bench. The obtained FDI design is capable of detecting and estimating (biases, ramps and including oscillatory) fault for the selected valve in a robust manner. The design methodology allows re-use of the design process for other valves with minor modifications and tuning.

Keywords: fault detection, fault diagnosis, H-infinity, engine valve

1. INTRODUCTION

The Future Launcher Preparatory Program (FLPP) of the European Space Agency (ESA) aimed at preparing the next generation of launchers to be developed in Europe (Pilchen et al 2008, Letoumeur et al 2008, Ramusat et al 2008). The FLPP was a system-driven programme that targeted long term applications as well as possible short/mid-term spin-offs of technologies and components related to the next generation of launchers.

The activity was driven by the Joint Propulsion Team (JPT), a consortium led by SNECMA (France), EADS-Astrium ST GmbH (Germany) and AVIO SpA (Italy). One of the two main tasks for the JPT was to study and trade-off technologies in the different launcher engine components (e.g. turbo-pumps, thrust chamber…) as well as to support the development of a health management system (HMaS) – also known as health monitoring system (HMS) -- for engine.

As part of the 2nd set of activities in the FLPP Period 2 – Step 2, Deimos was tasked with demonstrating the potential and applicability of H_∞ fault detection and isolation (FDI) for the hydrogen gas valve (VGH). In order to provide good understanding of the technique's applicability and potential capabilities, a didactic approach was followed whereby the demonstration focused on methodology, tuning capabilities and implementation issues. Thus, despite the highly nonlinear and sophisticated nature of the engine simulation model used for verification and validation the valve actuator model was relatively simple (1st order model but with nonlinearities such as saturation and discrete switches).

In this article, the methodology, design process and results of such application are presented. The layout of the paper is as follows: Chapter 2 presents the basic theoretical aspects of model-based and H_∞ FDI. Chapter 3 presents the residual generation design process while Chapter 4 deals with the residual evaluation. Chapter 5 presents the validation results and Chapter 6 ends with the conclusions.

2. MODEL-BASED FAULT DETECTION & ISOLATION

The essence of model-based open-loop fault detection and isolation (FDI) or fault detection and diagnosis (FDD), problem is depicted in Figure 1 and can be formalized as follows (Chen and Patton 1999):

FDI/FDD problem: Given a model of the nominal system G_u *and knowledge (measured or estimated) of the inputs u and outputs y of the system, determine a filter* $F=[F_U\ F_Y]^T$ *that provides a fault estimate* $res=\hat{f}$ *with information on the faults f entering the system (through* G_f*).*

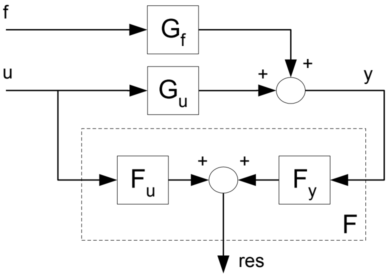

Figure 1 Basic FDI/FDD design architecture

The fault estimate *res* can provide an indication of the fault's presence (fault detection), an indication of the fault location/source (fault isolation) or of its nature (fault diagnosis). Fault detection requires only a scalar while fault isolation requires a vector of fault estimates in order to be able to distinguish between faults.

H_∞ is a design technique where specification of performance and robustness objectives is the main driver in correctly posing the mathematical optimization problem (Zhou et al 1996, Balas et al 1998). This is in contrast to other synthesis techniques where satisfaction of the objectives is evaluated after the design. The design objectives are defined in the H_∞ framework through proper weight design around an interconnection that interfaces for synthesis purposes with the to-be-designed FDI filter. The main trade-off, as always, is between the opposing performance and robustness objectives.

H_∞ is selected as the technique for FDI design due to:

1. The transparency of the design approach and its methodological support. As subsequently detailed in the next section and elsewhere (Marcos 2012), there is a clear systematic procedure to design H_∞ FDI residual generators. The theoretical underpinning of the approach is, although mathematically involved, very elegant and allows developing and using a step-by-step methodology.

2. The explicit consideration of design objectives and uncertainty –through the use in the design interconnection of frequency-dependent "weights". The definition of the weights is rooted in engineering knowledge which further facilitates its tuning. For example, the detection time can be 'mapped' into rise time of a 1st or 2nd order transfer function and used as the performance objective.

3. The potential for gain-scheduling and missionization. This arises from the last point as well as from the ease of changing the state-space model used in the design interconnection. By means of the later, it is very straight forward to keep the same interconnection (and thus objectives) and change the model in order to obtain FDI filters at different operating points. Indeed, for telecom satellites (Philippe 2011) this advantage has been exploited to define a common control design interconnection for all the satellites within a family where only the plant is changed followed by a methodological tuning of the interconnection weights.

4. The high industrialization of the approach. For example, H_∞ controllers are being used in the Ariane launcher (Mauffrey et al 1996), telecom satellites (Philippe 2011) and even in the recently operational European Automated Transfer Vehicle (ATV) (Bourdon et al 2004). In terms of H_∞ FDI, in a recent European FP7 project entitled ADDSAFE (Goupil and Marcos 2012, Marcos 2012, Henry et al 2012), and related to the application of advanced model-based techniques for commercial aircraft FDI, it was clearly shown the high potential of the technique. The success of this high industrialization is also due to the availability of very well known and tested software implementations of the H_∞ synthesis algorithm (Balas et al 1998).

Typically, a full FDI design (for any technique) entails:

- Residual generation. This first step has the objective of creating a residual signal which in the ideal case will be identical to zero if no fault is present in the system and different to zero otherwise, regardless of exogenous and endogenous perturbations (i.e. noise, commands, uncertainty or operating changes).
- Residual evaluation. As it is well known in practice, the ideal case is always far from reality. Thus, a residual evaluation logic is implemented to help increase the robustness of the residual generator. This step can be used to tailor the identification of specific fault profiles or to remove the possibility of false alarms (which is the most critical specification of an FDI).

3. H_∞ RESIDUAL GENERATION DESIGN

Within the task of residual generation, and from the H_∞ perspective, the methodology used for the design of an optimal FDI filter is as follows (Appleby 1990, Niemann and Stoustrup 2002, Marcos et al 2005):

3.1 Define the for-design linear time invariant (LTI) model

This implies obtaining the LTI descriptions of the nonlinear system at appropriate operating points.

A typical, and general, actuator model is given in Figure 2. It consists of a gain *Kvlv* which can be construed as a controller, a saturation component and the actual physical model. The latter is typically highly nonlinear based on pressure chamber differences (if a mechanical actuator is used) and additional saturation functions.

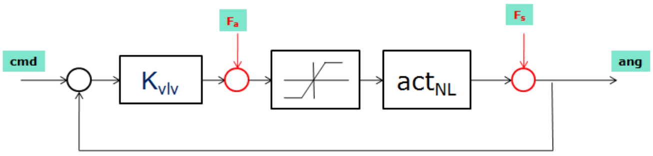

Figure 2 General actuator model

Rather than getting a state-space model for the above loop (a simple linearization of the system after removing the saturation function will provide it), in order to generalize the current model to other valves, we use as the *for-design plant* a simple integrator and will take care of the *Kvlv* from within the design interconnection.

3.1 Set the H_∞ FDI interconnection

The H_∞ interconnection represents the posing of the mathematical FDI optimization problem. It specifies the input and output channels and establishes the design rationale. The idea behind the H_∞ interconnection is for the designer to define the transfer functions that the optimizer will try to minimize in synthesizing the FDI filter to achieve the desired fault performance and robustness trade-off.

In order to facilitate the subsequent operational tuning and application to other valves, the selected design interconnection is simplified as much as possible but with sufficient flexibility to cover all the necessary performance versus robustness design trade-offs.

The final interconnection design is given in Figure 3 and consists of five components: an LTI *for-design* valve plant (including valve model and controller) and four design weights ("*Wn*", "*Wcmd*", "*Wf*" and "*Wres*").

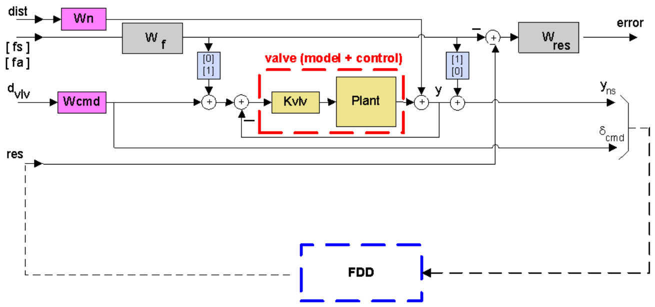

Figure 3 Design case A: high-performance

Since perfect decoupling of the effects of the control commands and disturbances on the residual signal is never perfect, and the original FDI design objective is only detection, the weights' selection *Wres* and *Wf=sbs(Wfs, Wfa)* is done trying to maximize the fault effects and minimize the effects of disturbances and control commands. Nevertheless, using algebraic manipulations on the interconnection it is clear that unless the disturbances *dist*, output faults *fs* and input faults *fa* act on different frequency region there will be difficulties to separate their effect. Note that this frequency separation problem is intrinsic to the FDI problem, i.e. all FDI techniques face the same challenge.

3.3 Definition of optimization weights

The general ideas behind H_∞ weight design are:

- Noise weights. Typically high-pass weights to indicate the high-frequency noise associated with measurement units. They can be used to fine tune robustness.
- Error/performance weights. These weights, together with the following ones, represent the main performance tuning knobs.
- Ideal/command-shaping/fault weights. First and second order low-pass weights that contribute to shape the bandwidth and performance of the FDI filter.

To facilitate the tuning and the comprehension of the weights and models, a generic first-order transfer function model is used, see Eq. (1), where the low-frequency gain is given by $K_{LF}=K$, the high-frequency gain by $K_{HF}=Ka/b$ and the bandwidth by $\omega_B = K_{LF}/b = K_{HF}/a$.

$$W = K\frac{as+1}{bs+1} = K_{LF}\frac{K_{HF}/\omega_B\, s+1}{K_{LF}/\omega_B\, s+1} \qquad (1)$$

General tuning rules are:

- The speed of detection and the fault frequency range of interest can be modified respectively in *Wres* and *Wf* through ω_B.
- The low-frequency gain K_{LF} of *Wres* and *Wf* can be used to satisfy the satisfaction of objectives (i.e. $\gamma < 1$) and to tune the residuals magnitude response to faults.
- The tuning is guided by analyzing the transfer functions of the FDI but principally by the time responses of the designed filter obtained in the linear and nonlinear assessment (see subsequent section and chapter).

3.4 Synthesis

H_∞ synthesis may yield unstable designs due to algorithmic complexities but this is easily corrected by residualization or slight tuning of the weights. Also, recall that the resulting H_∞ filter will have a state dimension equal to the total number of states used in the interconnection.

The resulting H_∞ FDI filter has a γ level of 0.1598 and 4 states with a largest eigenvalue around 100 Hz (very large frequency poles could result in an implementation problem).

3.5 Verification

In order to ensure that FDI filter satisfies the objectives, at least in the linear case, a series of analyses are performed sequentially. These analyses include:

1. **Frequency responses**. Using the weighted interconnection from Figure 3, the magnitude bode from the different channels to the filter output are plotted. The exogenous channels (for example, the commands) should have a very small magnitude while those from the faults (which the filter is trying to detect or estimate) should be close to 1 in the frequency range of interest.

2. **Time responses**. Using a non-weighted interconnection (essentially the same used for design without the weights), independent steps are introduced in each input channels (i.e. commands and faults) and the response of the residual is observed.

   The step from the command channel should not produce any residual output if the filter has perfect decoupling properties, while those from the faults should show a non-negligible response (if only detection was desired) or completely track the step (if estimation was pursued during the design).

3. **Mu analysis**. The above linear analyses can be performed also introducing uncertainty in the interconnection but a much better approach is to employ µ analysis (Balas et al 1998) to assess the filter's robust performance.

   This type of analysis allows determining, from a frequency domain perspective, the degradation caused in performance from the nominal to the robust objective. It does this by calculating a so-called upper-bound whose inverse value provides the level of normalized uncertainty that the system can be guaranteed to absorb before violating the performance objective. In addition, the calculation of the lower bound allows determining the guaranteed level of normalized uncertainty that degrades the performance above the objective (if both bounds are 'sufficiently' close then the µ value can be said to be practically exact).

In Figure 4 and Figure 5, the linear time responses and μ analysis for the FDI filter are provided. Figure 4 shows that the command has no effect on the residual while the sensor and actuator faults are very quickly estimated almost exactly. Figure 5 concurs (see the very good nominal performance *NP*) but it also shows that the filter greatly degrades, albeit still satisfying by an ample margin the FDI objectives, as uncertainty is introduced (i.e. see the much higher, but below 1, upper robust performance bound RP_{upper}).

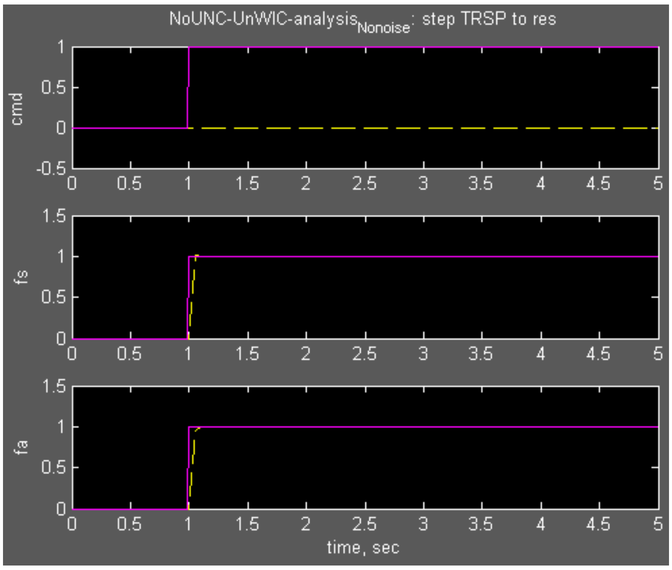

Figure 4 Verification: linear time response, independent steps

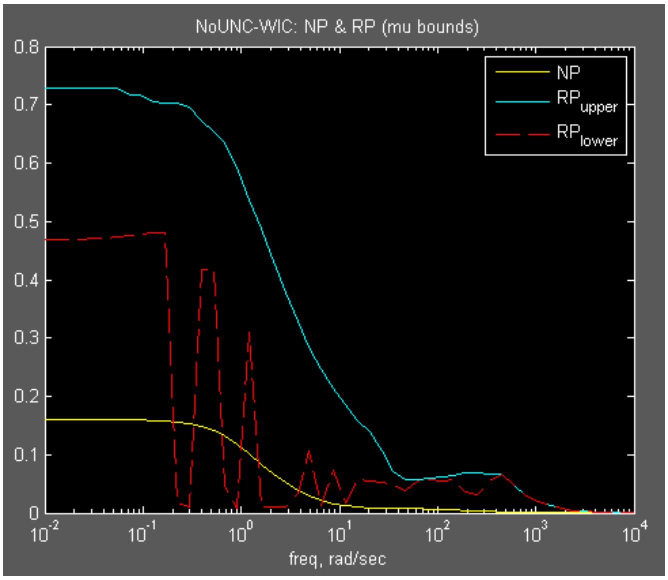

Figure 5 Verification: Mu analysis

4. RESIDUAL EVALUATION DESIGN

As mentioned before, typically a 2nd step in the FDI design process is required to take into account in the nonlinear framework the impossibility of ideal decoupling from the exogenous (disturbances and noise) and endogenous (commands and uncertainty) perturbations. In this 2nd step, called residual evaluation, a logic scheme is implemented to take into account the effect of the previous perturbations on the FDI residual. The logic usually includes static thresholds (i.e. constant values) or more complex logic solutions such as adaptive thresholds (based on time or other measurements).

The manner to proceed for defining the residual evaluation logic is to test the FDI residual generator under a plethora of conditions resulting in a wide tuning-set, i.e. no fault and fault cases at different levels of uncertainty perturbations. It is recommended to use a limited (in number of runs) random perturbation assessment for a large set of fault types/profiles in order to design, tune and implement the logic against false alarms and missed detections –the most important drivers.

4.1 False alarm logic

The main FDI specification for most systems is to not have false alarms since this will undesirable result in downtime or limited functionality. The test to look at for establishing the correct false alarm threshold in the residual evaluation is the no-fault case for a range of uncertainty values.

Figure 6 shows the VGH time response, the introduced fault and the FDI residual signal corresponding to the nonlinear simulation of the max/min/nom uncertainty. It is noted, that there is an effect from the valve command into the residual. This effect is specially noted around the 2-3 seconds region where a high-nonlinearity of the command results in a peak of magnitude -0.5 for the residual. In addition, after analysis of several fault cases it is observed that similar residual peaks are obtained but always for a longer period of time. Thus, a constant magnitude threshold of value 0.6 can used but whose violation for less than 0.8 seconds is not considered a fault, rather a transient effect. This is complemented by a simple constant threshold of value 2 in order to ensure fast detection of faults with critical effects (such as closing faults).

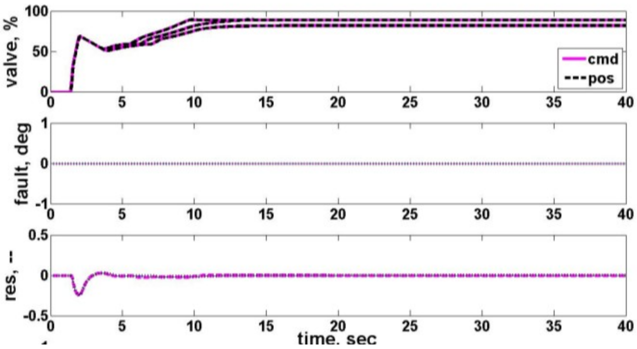

Figure 6 No fault, min/nom/max uncertainty: VGH valve response (top), fault (top) and FDI residual (top).

4.2 Missed Detection Logic

After running several different fault cases, it was observed that all, except for the oscillatory case, could be detected with the selected constant thresholds and the residual generator filter. Thus, a missed-detection logic had to be added for the specific case of oscillatory faults.

Looking at the response of the default oscillatory fault case for the nominal case, and after a little trial and error, a counting-peak logic was established. This logic counts the number of peaks *npeak* that occur in the residual during an established period of time *tonb* starting after the residual surpass a constant threshold *THonb*. The selected values are: *npeak*=4, *tonb*=1 and *THonb*=0.15, meaning that if there are 4 residual peaks above 0.15 degrees in less than 1 second there is an oscillatory fault.

4.3 Logic implementation

The final FDI implementation is shown in Figure 7 where it is observed (from left to right) the continuous state-space for the residual generator ('FDI' block), the false-alarm logic ('mag & time threshold' block) and the missed-detection logic ('counting peaks for a given time' block). This implementation is the one that will be validated in the next section.

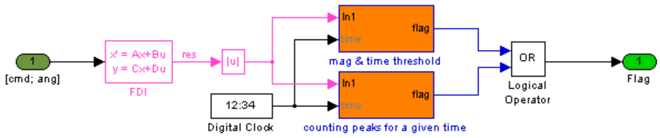

Figure 7 Residual generation and evaluation logic

5. VALIDATION

The last step in the process is to validate the FDD design. Two campaigns are performed for a total of 1,504 nonlinear simulation cases. In the first campaign, termed deterministic, the values for the engine uncertain parameters are fixed to min/nom/max. In the 2nd campaign, termed probabilistic, a random sampling of the uncertain parameter space is performed. The validation set-up includes two different engine thrust profiles, different uncertainty values, up to 6 fault types (closing with slow ramp or step, oscillation with different magnitude/frequency and slow ramp or step biases) and different fault occurrence times (e.g. at 1, 8 or 20 seconds to consider initial, transient and "cruise" operations). The simulation model is a high-fidelity nonlinear model of the engine but without sensor noise and relatively simple valve actuators (1st order models with saturations and discrete switches but no complex mechanical/pressure model).

The statistics show that the maximum detection time is about 9.705 seconds for the slow ramp fault (with almost negligible effects) and as fast as 0.015 seconds for the step closing fault. There are no false alarms nor missed detections. Thus, the designed filter satisfies all the FDI performance and robustness objectives.

A selected set of the probabilistic campaign results is given in Figure 8 and Figure 9. Each plot presents the FDI-related signals (from top to bottom): the valve command and angle position, the introduced fault, the FDI residual (from the residual generator) and the FDI flag signal (produced by the residual evaluation component and signifying that there is a fault when >0). Note that the simulation is stopped when the fault is detected (i.e. when the flag gets to 1).

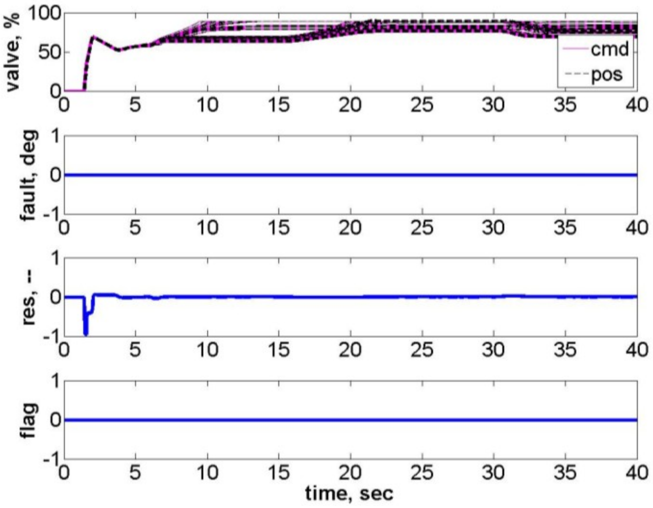

Figure 8 Validation: probabilistic, no fault

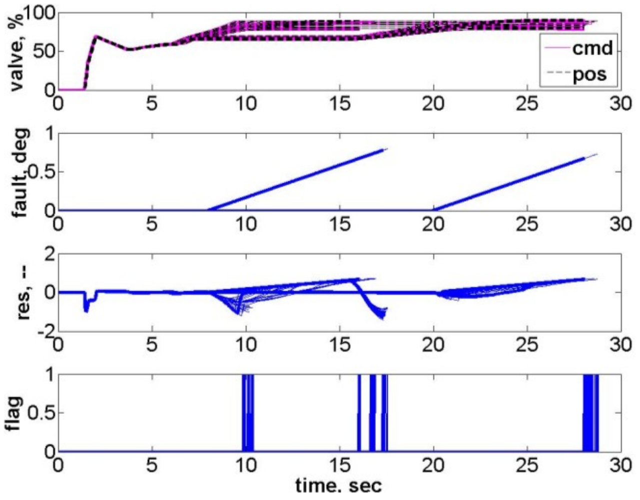

Figure 9 Validation: probabilistic, 'slow ramp bias' fault

In order to conclude this section, a more focused examination of the diagnosis characteristics of the filter is performed looking at the ideal introduced fault, the fault-effect response (obtained by subtracting from the actual actuator output the actuator command) and the residual –see Figure 10 and Figure 11. This analysis allows examining the FDI behaviour in terms of attenuation of the nonlinear/uncertain effects (notice, especially how the fault effect is very attenuated in the residual) as well as the diagnosis of the fault effects (see the insets). It is seen that the FDI scheme successfuly decouples in the residual the influence of commands and nonlinearities (i.e. notice the residual magnitude in comparison to the large fault effect around the 2 seconds region) while accurately diagnosing and estimating the fault after its occurrence (i.e. the quite well "tracking" of the fault effect by the residual when there is a fault).

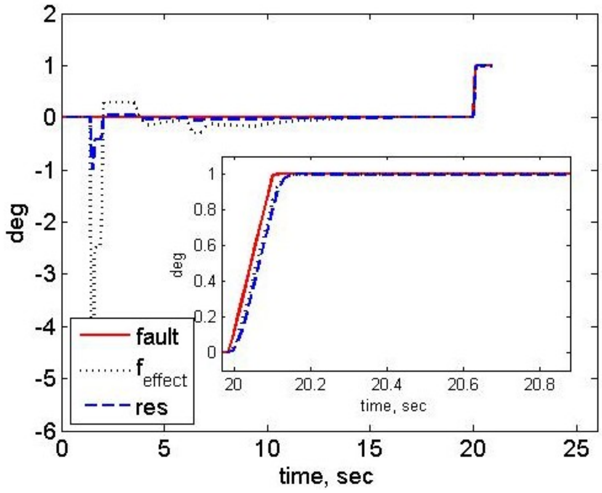

Figure 10 Validation: 'bias step' fault, zoom

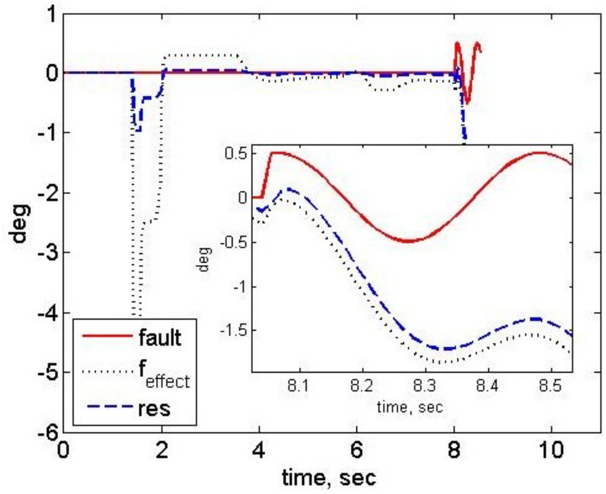

Figure 11 Validation: 'oscillation 0.5deg/1.5hz' fault, zoom

6. CONCLUSIONS

This article presented the full design cycle for the design and validation of an H_∞ fault detection and isolation filter for a hydrogen gas valve (VGH) of a Vulcain-like rocket engine.

H_∞ optimization was selected as the technique for FDI design due to: (i) the transparency of the design approach and its methodological support; (ii) the explicit consideration of design objectives and uncertainty, (iii) ease of scheduling and tuning and (iv) the high industrialization of the approach.

The results indicate that for the VGH engine valve the synthesized filter has very good FDI robustness and performance properties (including estimation of the fault effects).

As a matter of conclusion, it is noted that the results presented in here have used only a simulation model of the engine (and one without sensor noise or highly complex actuator systems, but including a complex FADEC and high-fidelity engine behaviour). This was acceptable at this stage of the FLPP activity due to its orientation towards evaluation of the FDI technique but it is recognized that for a full test in an engine bench, a more complex engine model and/or real data should be used.

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