Oscillatory Failure Case Detection in the Electrical Flight Control System Benchmark using a Residual Energy Derivative Approach

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Abstract: This paper presents the results of the application of a residual energy evaluation approach to the oscillatory failure case (OFC) for the electrical flight control system benchmark. The proposed approach is based on calculating the variation of the residual energy and the comparison with a properly selected threshold. Such a criterion provides better performance for OFC detection than the residual energy evaluation. In the current problem of OFC detection, the residual energy criterion fails to work due to the nature of the considered uncertainties and proposed fault scenarios that lead to a strictly increasing energy value of the (low-pass filtered) residual signal. On the other hand, its derivative has an oscillatory behavior and does not grow unbounded.

Keywords: Five to ten keywords, preferably chosen from the IFAC keyword list.

1. INTRODUCTION

The goal of the electrical flight control system benchmark is to detect an oscillatory failure in the electrical flight control system as described in [1]. The oscillatory failure case (OFC) is considered as a sinusoidal fault signal which is added to the actuator input or sensors. Some already proposed approaches can be found in [2]. OFC signals shall be detected with a fixed but unknown frequency between 1 and $10Hz$ and with amplitudes as small as possible for both liquid and solid cases at the rod sensor or current input of the actuator. Besides, it should be detected within three periods of oscillation.

Most of the model-based methods for dealing with the fault detection problem were generally about the determination of residual signal that is evaluated using a threshold. However, for the detection of OFC, methods based on the calculation of the residual energy as the one presented in [3] seems more adequate.

This paper presents the results of the application of a residual energy evaluation approach for the OFC in the electrical flight control system benchmark. The proposed approach is based on calculating the variation of the residual energy and the comparison with a properly selected threshold. We will show that such a criterion can be more useful for OFC detection than the residual energy.

The structure of the paper is the following: Section 2 presents the proposed method. Section 3 presents some mathematical details of the proposed method. Section 4 illustrates the obtained results using the simulation provided. Finally, Section 5 draws the main conclusions.

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2. THE PROPOSED METHOD

The main idea of the proposed approach is to calculate online the variation value of the residual energy signal (in particular, the derivative of the residual signal energy) and to compare it with a properly selected threshold. Such a criterion has been proved in the simulations to be more useful for OFC detection than the residual energy. In other words, in the current problem of OFC detection, the residual energy criterion fails to work due to the nature of the considered uncertainties and proposed scenario of fault which leads to a strictly increasing energy value of the (low-pass filtered) residual signal. On the other hand, its derivative has an oscillation behavior and does not grow unbounded.

In the proposed approach, the detection threshold is based on evaluating the maximum magnitude of the residual energy derivative in the non-oscillatory mode considering the uncertainties affecting the residual signal. Due to the uncertainties and disturbances affecting the system, it seems that the only way to determine the threshold is to consider the maximum value of residual energy derivative signal during the non-oscillatory mode. Along the time, by considering such terms in the actuator model, the amount of residual energy derivative signal changes will be reduced. Hence, such a threshold is determined in the non-oscillatory period. Whenever the fault detection signal exceeds its threshold, the fault alarm can be turned on. For preventing false alarms and decreasing the fault detection time, the proposed criterion will be combined with the

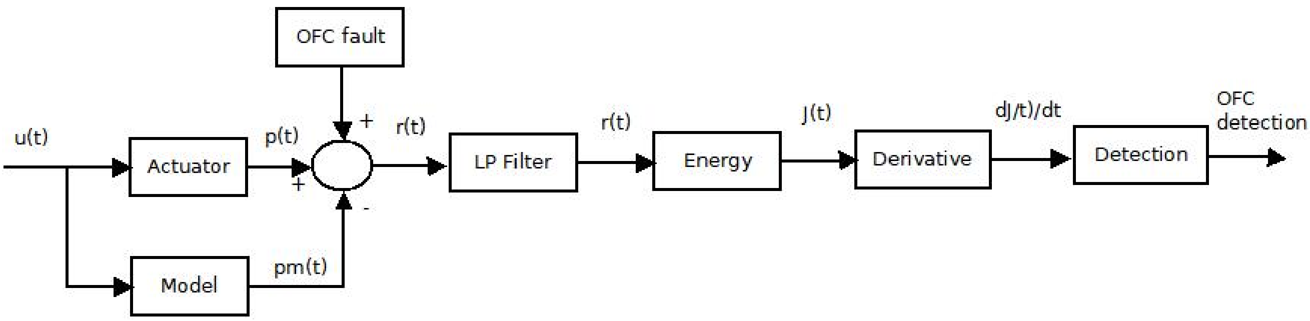


Fig. 1. Derivative-based residual energy OFC detection scheme

residual threshold. The proposed fault detection may not work for the smaller OFC scenarios. However, it can be concluded that faults with small magnitudes that may not be distinguished from the uncertainties are not detectable. Figure 1 presents the block diagram of the derivative-based residual energy OFC detection scheme.

Another criterion is to determine the residual energy threshold and to compare with the residual energy derivative signal as proposed in [3]. The residual energy threshold is determined considering the effect of parameter uncertainty in the residual. However, because of the special structure of the OFC problem and the resulting strictly increasing nature of the energy signal, the adaptive residual energy threshold is not applicable. Such a method, if applicable, maybe has to lead to better performance for detecting smaller OFC. In the approach based on evaluating the residual energy [3], the criterion for detecting a fault is similar to the one considered in the proposed approach summarized in the block diagram presented in Figure 1.

3. MATHEMATICAL DESCRIPTION

There are two types of OFC described as liquid and solid faults. In the case of liquid faults $f_l(t)$, the residual $r(t)$ is given by

$$r(t) = p(t) + f_l(t) - \hat{p}(t), \tag{1}$$

and in the case of solid faults $f_s(t)$, the residual is computed as follows:

$$r(t) = f_s(t) - \hat{p}(t). \tag{2}$$

The residual energy for both cases in the time domain using a time window L is determined as follows

$$J(t) = \sqrt{\int_{t-L}^{t} r'(\tau) r(\tau) d\tau}. \tag{3}$$

By computing the derivative of the energy function

$$\frac{dJ(t)}{dt} = \frac{d}{dt}\sqrt{\int_{t-L}^{t} r'(\tau) r(\tau) d\tau}, \tag{4}$$

the residual energy variation is obtained. Considering a discrete-time implementation with a sampling period Δt, such a variation can be determined as follows

$$\Delta J = J(t + \Delta t) - J(t). \tag{5}$$

On the other hand, the threshold value $Th_{\Delta J}$ for the energy variation is evaluated as

$$Th_{\Delta J} = \max_{t \in (0, t_u)} \frac{dJ(t)}{dt}, \tag{6}$$

where t_u determines the non-oscillatory time period. This period is used to bound the effect of uncertainty and disturbances on the residual signal. It is considered that the maximum fault-free magnitude of $\frac{dJ(t)}{dt}$ will appear in such a period of time. In some cases, this threshold can be computed in anticipation according to the system, uncertainty, and disturbance model which is not applicable in the considered case study. Then, the point that the energy derivative function overpasses the threshold indicates the OFC (solid or liquid) occurrence. The smallest OFC amplitude that is detectable depends on the model quality and disturbance magnitude.

4. SIMULATION RESULTS

In this section, the results obtained applying the proposed approach of the OFC benchmark [1] will be presented.

4.1 Implementation details

By following the instructions of the benchmark, the proposed method is applied using '*ofc_benchmark_example.slx*' file which contains the model of the actuator. The first step is to run '*ofc_benchmark_energy_run.m*' by setting the desired OFC parameters (such as frequency, amplitude, failure type, location, etc.). In the second step, the simulation file '*ofc_benchmark_example.slx*' is run to calculate the residual signal. Finally, '*ofc_benchmark_energy_plot.m*' can be used to plot the results.

4.2 Threshold value determination

As the first step, a reliable threshold should be chosen for the residual energy variation. To this end, having the system dynamics and the nature of uncertainty and disturbance, it is possible to compute a robust positive invariant (RPI) set describing the maximum effect of the uncertainty and disturbance on the residual signal. Hence, it would possible to determine, the threshold as the border of such an RPI set. However, in this benchmark, there is not an analytical method to derive such a bound and threshold. Therefore, we propose a simulation-based method to select the threshold for residual energy threshold. Hence, we simulate the fault-free case subject to various values of admissible uncertainty and disturbances (as embedded in original simulation blocks) to get the peak value of residual energy variation and, to prevent false alarms. The reliable threshold will be selected as 1.3 times of the peak value. As shown in Figure 2, the peak value is less than 0.03 while we consider the threshold equal to 0.04.

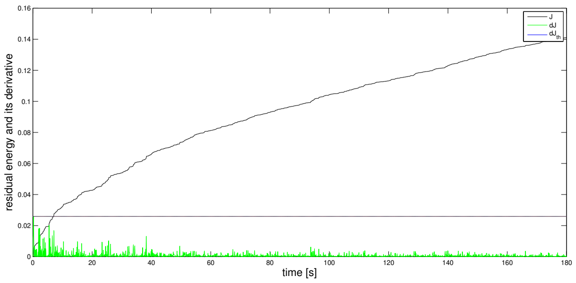
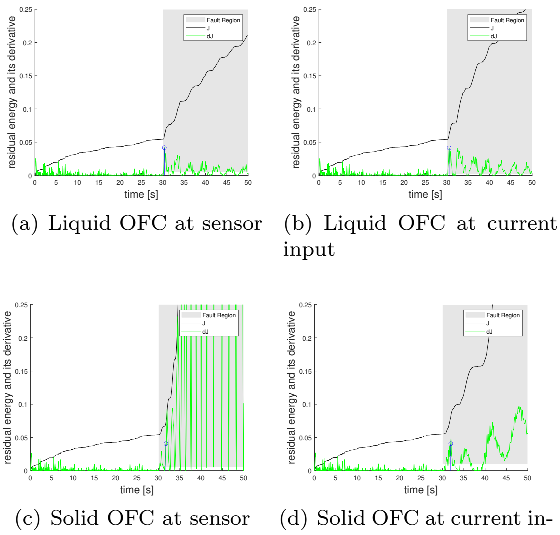


Fig. 2. A simulation of fault-free case for benchmark [1] in $3min$

4.3 Fault scenarios

According to the problem statement in the OFC benchmark, four scenarios are considered to evaluate the proposed approach: (a) liquid OFC at the sensor, (b) liquid OFC at current input, (c) solid OFC at the sensor, (d) solid OFC at current input. All of these scenarios have been examined with different values of frequency. The time of OFC is selected equatl to 30 s in all scenarios. The goal is to detect the OFC with an amplitude as small as possible within three periods of oscillation.



(a) Liquid OFC at sensor (b) Liquid OFC at current input

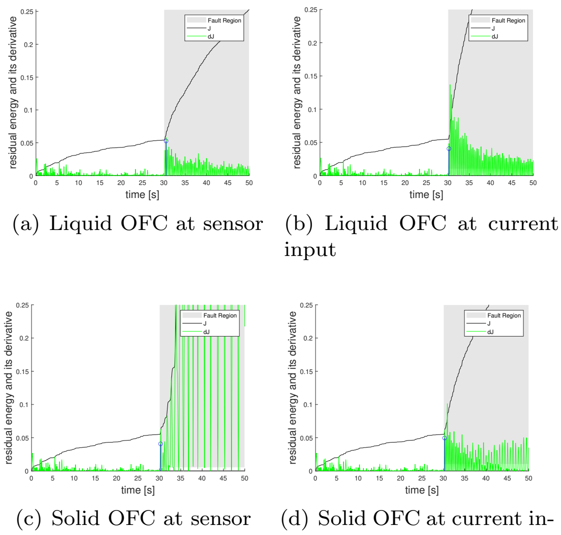
(c) Solid OFC at sensor (d) Solid OFC at current input

Fig. 3. Failure detection with OFC frequency $1Hz$ and threshold value 0.04

Figures 3 and 4 illustrate the residual energy, its derivative, obtained threshold, and the fault alarm for different scenarios in the worst-case. The OFC occurs in time 30 s and the alarm should be activated as soon as possible, preferably, in less than 3 periods of oscillation. The alarm has been shown with a red circle in all figures. It is clear from the figures that the residual energy derivative (the blue signal) has a sinusoidal behavior which is closer to the nature of the OFC. On the other hand, the residual energy (the black signal) is strictly increasing during all times before and after the OFC occurrence and it indicates that the methods based on residual energy such as [3] and [2] are not applicable to this benchmark.

With regard to the Figures 3, 4, and other additive 3 and 6 Hz frequencies, the quantitative results are shown in Tables 1 and 2 for all scenarios. Table 1 presents the minimum detectable OFC amplitude with desired conditions and there is no problem for larger amplitudes. The resolution for amplitudes is set to 0.01 mA for the current fault and 0.01 mm for sensor fault. However, the proposed method also is able to detect OFCs with smaller amplitudes corresponding to cases (c) and (d). The number of periods needed to detect the OFC in each scenario is shown in table 2. The related OFC amplitude value is reported in the corresponding cell in table 1. It is clear that in each scenario, the needed time for the detection of OFC is less than three oscillation periods. Also, for the smaller frequency and also in the liquid case, it is clear that the OFC detection time is significantly smaller than the required three oscillation periods. However, in any of the considered scenarios, the detection time decreases as the amplitude of OFC increases.

The simulated cases are the worst case and the larger amplitude of OFC, clearly, makes the method more effective in detection and hence, does not presented in this report. Also, the OFC amplitude less than the considered value could be categorized as a disturbance.



(a) Liquid OFC at sensor (b) Liquid OFC at current input

(c) Solid OFC at sensor (d) Solid OFC at current input

Fig. 4. Failure detection with OFC frequency $10Hz$ and threshold value 0.04

5. CONCLUSIONS

This paper has presented the results of the application of a residual energy evaluation approach to the oscillatory failure case (OFC) for the electrical flight control system

Table 1. Minimum detectable OFC amplitude (mm)

f(Hz)	Liquid		Solid	
	sensor	current	sensor	current
1	0.17	0.14	0.01	0.01
3	0.3	0.15	0.1	0.05
6	0.35	0.3	0.1	0.1
10	0.42	0.39	0.21	0.21

Table 2. OFC detection alarm time (v.s. OFC period)

f(Hz)	Liquid		Solid	
	sensor	current	sensor	current
1	0.350	0.525	1.875	1.975
3	2.940	2.700	2.850	1.290
6	1.500	1.500	1.800	1.980
10	2.750	2.500	2.750	2.500

benchmark. The proposed approach is based on calculating the variation of the residual energy and comparing with a properly selected threshold. Such a criterion provides better performance for OFC detection than the residual energy. In the proposed OFC benchmark, the residual energy criterion fails to work due to the nature of the considered uncertainties and the proposed scenarios of fault which lead to a strictly increasing energy value of the (low-pass filtered) residual signal. On the other hand, its derivative has an oscillatory behavior and, therefore, is applicable to the current problem. With regard to the different examined OFC scenarios, the simulation results demonstrate the effectiveness and efficiency of the proposed approach.

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