Adaptive Fault Tolerant Servo Scheme For Launch Vehicle Control Actuation System

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***Abstract*— Next generation satellite launchers have demanding performance requirements under a variety of mission environments. This calls for reliable and fault tolerant onboard systems, which can be achieved by efficient Fault Detection and Isolation schemes along with essential minimum hardware redundancy. A fault detection and isolation scheme for the control actuation system of a new generation launch vehicle is discussed in this paper. The stringent requirements on performance and reliability of servo actuation system have necessitated the development of a systematic method for the timely detection of system faults. The scheme proposes the combination of hardware and analytical redundancy concepts for the quick detection of faults and avoidance of false alarms. A simple innovative way of fault detection scheme with adaptive threshold concept is proposed. The scheme has been incorporated in the above said actuation system and adequacy has been established through various levels of practical system testing.**

Keywords— Fault detection, Adaptive threshold, Actuation system, Launch vehicle.

I. INTRODUCTION

The new generation satellite launch vehicles have complex mission requirements and involve high development and realization cost. These missions call for highly reliable onboard systems. Efficient Fault Detection and Isolation (FDI) scheme along with necessary hardware redundancy is the best approach for reliable and fault tolerant onboard systems. The FDI scheme adopted for the Flex Nozzle Control (FNC) system of the booster stage of a new launch vehicle is discussed in this paper. A simple innovative way of fault detection scheme with adaptive threshold has been adopted in this design.

The fault detection using mathematical model is existing [1] for many years and it has find application in various systems failure detection. Along with model based fault detection scheme, other methods like observer based fault detection scheme [2], parity relation based residual generation for fault detection [3], Parameter estimation methods [4] are also evolved during these years. Data driven methods like Partial least square [5], Independent component analysis [6], principal component analysis [7], Fisher Discriminant Analysis [8] are widely used for failure detection. A model based approach to prognosis and health measurement for flight control actuators is briefed [9] where the physical mathametical model is used for fault detection. Hybrid approach for fault detection of a launch vehicle control actuation system using an exhaustive nonlinear mathematical model [10] is a blend of data driven and model based approach. This has some limitation with respect to flight implementation due to the complexity of model.

The launch vehicle under consideration is steered in pitch, yaw and roll directions by means of thrust vector control using electro-hydraulic servo actuators. These actuators make use of a combination of Direct Drive Valve (DDV) driven by Linear Force Motor (LFM) and Hydraulic Amplifier Valve (HAV) for flow control. A five layer analog feedback controller consisting of LFM current loop, DDV position loop, HAV position loop, Dynamic Pressure Feedback (DPF) loop and actuator position loop are required for the optimal performance of the servo system. As the failure of any components in the servo actuation system is critical, dual redundancy is provided for control electronics and sensors.

II. DESIGN APPROCH

Fault tolerance in dynamic systems is generally achieved through the use of hardware redundancy. Additional hardware elements (actuators, measurement sensors, process components etc.) are usually distributed spatially around the system to provide protection against localized damage. Such scheme typically operates in a triplex or quadruplex redundancy configuration and redundant outputs (or measurements) are compared for consistency. The major drawbacks of the hardware redundancy include increased mass, software complexity, larger space requirements and cost increase.

Some of the above mentioned problems are avoided in analytical redundancy schemes, which uses the dynamic model of the system for fault tolerance [11]-[13]. The general procedures for fault tolerant control based on analytical redundancy consist of three major steps, Fault detection, Isolation and Reconfiguration. Fault detection is carried out by constantly monitoring the system responses to the control system commands and comparing it with the predicted responses by the model of the healthy system. For fault isolation, the actual system response is compared with responses of models representing systems with specific failure modes. Reconfiguration is effected rapidly and automatically once the degradation or failure of component is confirmed. The reconfiguration can be done using responses stored for each fault condition. Once the fault is identified and isolated, system will design a new control law based on the characteristics of the perceived fault. The major problems with this scheme are the requirement of high speed processors to execute the system model and the nonavailability of reconfiguration options for certain faults.

The new scheme adopted in the FNC system is a blend of the above two FDI concepts. A second order model with rate limiting is used to mimic the system behaviour in the frequency range of interest. Position output of the model is used as the reference and it is compared with the actuator position sensor output for fault detection. End to end parallel hardware consisting of, control electronics, compensator, motor coil and sensors, is used as the redundant chain for reconfiguration through a controlled switch. A simple innovative way of fault detection scheme with varying threshold concept is developed for timely detection of system faults. The requirements of complicated algorithms and fast processors are avoided by realizing the model and the FDI algorithm through analog circuits.

III. Formulation of FDI Problem

Ideal fault detection (FD) logic should detect any minor fault in the system, at the same time avoiding any false alarm during the normal system operations or testing. In order to meet these requirements, we should have the perfect mathematical model of the system with perfect measurements of various system feedback signals as well as external disturbance signals to create the reference signature of the healthy system. However, such an ideal condition could not be met due to practical difficulties like,

- Measured system variables are insensitive / less sensitive with respect to some of the component faults.
- Input system commands or its derivatives are of insignificant levels to excite the faulty behavior of some components.
- Measurement noise of system variables.
- Unmodelled system dynamics.
- Unmodelled system disturbance signals.

Hence, there is always an uncertainty band about the actual boundary between the faulty and the healthy system as shown in Fig 1. The width of such uncertainty band will depend on signal amplitudes as well as on system nonlinearities. As it is generally better to sacrifice some minor undetected faults on the cost of avoiding false alarm, we have to restrict the zone of fault detection as shown in Fig.1.

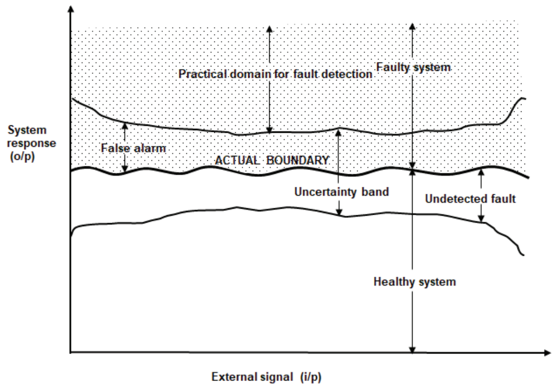


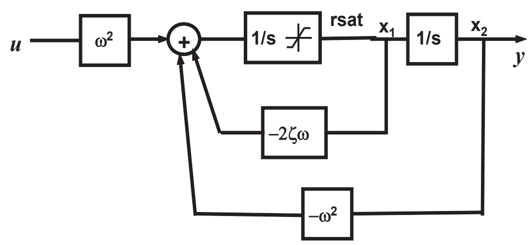
Fig.1 Concept of Fault Detection

Electro hydraulic actuator with two stage control valve, which is proposed for the thrust vector control of the launch vehicle, calls for a reliable FDI scheme. The actuation system has to go through various levels of tests before integrating to the launch vehicle. The FDI scheme is an integral part of the electronics and will be subjected to all levels of tests. The diverse level of testing sequence excites the actuator for a wide range of commands and frequencies. The FDI scheme should detects failures fast but should avoid false alarm during normal conditions.

The practical input range for the design of FDI scheme is selected same as that of the normal test signal range of actuation system with respect to command amplitude and frequency. For example, the minimum position command amplitude for both step and sinusoidal signal is selected as 5% and the maximum as 100%. The frequency range for sinusoidal command is selected as 1 to 30 Hz for 5% & 10% amplitudes whereas for 100% amplitude, the frequency range is selected as 0.2 to 5 Hz.

IV. Model of actuation system

The actuation system is a position servo which tracks the autopilot command closely within the range of frequency and command amplitudes. The actuation system includes LFM, DDV, HAV, Load, different sensors and control electronics. A comprehensive nonlinear mathematical model is required to



represent the system dynamics completely for the full range of operating conditions. A processor with sufficient computational capability is required to implement and simulate the nonlinear model in real time. In order to make the model hardware realizable, the dominating dynamics of the system is represented by a transfer function. The proposed scheme uses a second order model of the closed loop system with rate limit. The configuration of the model is shown in Fig.2.

Fig.2 Representation of rate limited second order model for actuator

Rate limit feature represents the flow limit characteristics of flow control valve in the actuation system. The parameters of this model are tuned in such a way that it gives the best match with respect to frequency response and step response for the full amplitude range of system commands. The step response of the model with and without rate limit for 100% command amplitude is shown in Fig.3. The actuator position is sensed by LVDT and the output corresponding to the maximum movement is 10V. The response with rate limit closely matches with the experimental response of the actual system.

Mathematical representation of the model of the actuation system is as follows.

$$\dot{X} = AX + Bu \qquad -(1)$$

$$y = CX \qquad -(2)$$

Where X=[x1 x2]' represents the states of the model, y is the actuator position output and u is the actuator command from autopilot. The matrices are as given below.

$$A = \begin{bmatrix} -2\varsigma\omega & -\omega^2 \\ 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} \omega^2 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

Where, ω is the natural frequency and ζ is the damping factor of the second order model. The internal state which corresponds to the velocity is limited to slew rate of the actual system and can be expressed as

$$x_1 = x_1 \quad if\ |x_1| < rsat,\ else\ x_1 = rsat \times sign(x_1) \quad -(3)$$

where rsat is the rate limit of the actuation system.

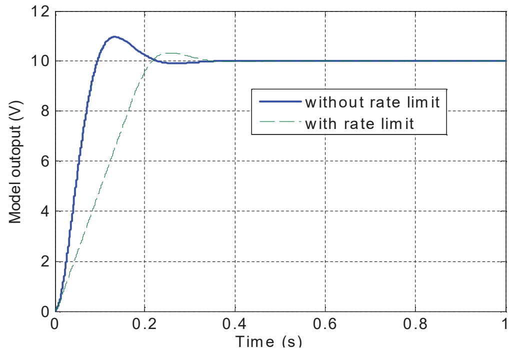


Fig.3 Response of second order model with and without rate limit

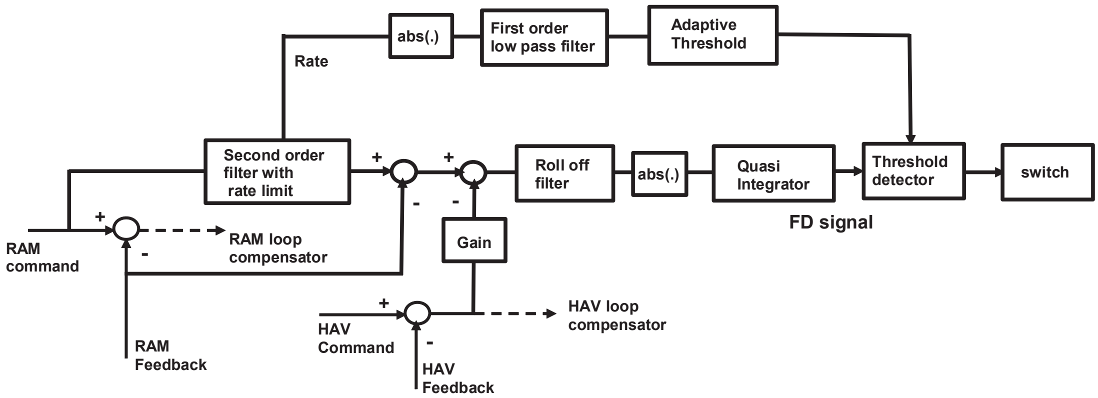


Fig.4 Block schematic of the fault detection scheme

V. Fault Detection (FD) signal generation

Conventionally, in model based FDI scheme the difference between the actual system output and model output is used as the residual for failure detection [14]. In order to improve the fault detection time for inner loop component failure, the HAV loop error is also used for the generation of fault detection signal. The block schematic representation of the fault detection scheme is shown in Fig.4 and the flow chart is as shown in Fig.5.

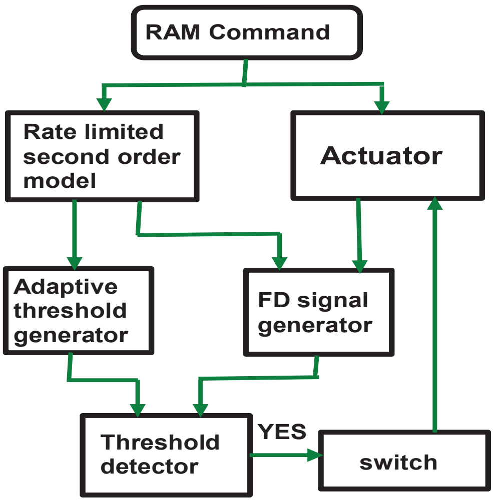


Fig.5 The FDI scheme

The position output of rate limited second order model is used as the reference command signal for FD logic to compare with the actuator position sensor output for fault detection. This will considerably reduce error signal for step commands during the initial transients as well as error signal for sinusoidal commands caused by system phase lag and amplitude attenuation. Thus the rate limited second order model helps in reducing the amplitude of FD signal during healthy system condition, thereby reducing the probability of false alarms.

The error between the second order model output and actuator RAM LVDT feedback is added with HAV loop error and filtered through a first order roll off filter to remove the sensor noise. The filtered signal is passed through a precision full wave rectifier to get the absolute value. The rectified signal is passed through the quasi integrator to provide FD signal amplification in the event of fault persistence.

VI. Adaptive Threshold Generation

A rate limited second order transfer function model cannot represent the dynamics of the system for the complete range of frequency and amplitude of interest. The second order model represents only the dominating dynamics of the actual system which is a higher order system. The frequency response of the model rolls at 40 dB per decade after the bandwidth point whereas the actual roll off in the hardware is less than this due to the nearby dynamics after the bandwidth. As the model does not completely represent the actual hardware for the full range of frequency and command, it calls for certain modifications in the FD scheme to avoid false alarm. It has been observed through simulation that, such command processing through second order model alone is not sufficient to avoid false alarms for higher command rates of the system. Hence it has been decided to vary the fault detection threshold level as a function of command rate, which is readily available in the second order model mentioned above. The scheme employed for the generation of this 'adaptive threshold' logic is as in Fig.4a. The rate from the second order model is passed through a precision full wave rectifier followed by a peak detector circuit. The peak detector gets charged only when the model rate exceeds a threshold level. A graphical representation of the adaptive threshold is shown in Fig.6.

The design of adaptive threshold generator is carried out based on extensive simulation studies of various healthy and faulty cases of the FNC system to get the optimal performance with respect to fault detection. When the model rate output is below the minimum value, the output of threshold generator is constant and when the rate increases beyond the minimum value, the threshold level also increases proportionally as shown in Fig.6.

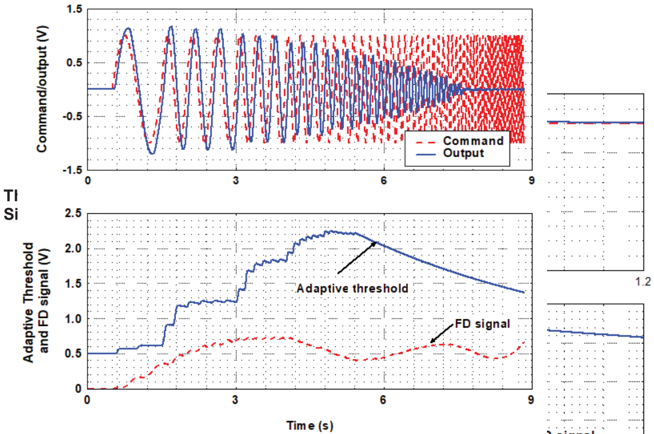


Fig.6 Gra
signal

Fig.8 Response of FNC system FD scheme for 10% sweep command (1-30 Hz) (No fault case)

Fig.7 Response of FNC system FD scheme for 100% step command (No fault case)

VII. Simulation Results and Analysis

The performance of the FD scheme described has been evaluated with respect to false alarm and fault detection for various commands and probable failures through simulation. The various parameters of the FD scheme have been tuned to get optimum performance. The performance of the FD scheme during healthy conditions for 100% step and 10% sinusoidal sweep commands are shown in Figs 7-8. During 100% step command, as the model is not representing the system for large command rate, the error between the model and system output is more and this increases the FD signal. However the adaptive threshold signal is also increasing as a function of command rate and the FD signal always remain below the adaptive threshold. Thus the rate dependent adaptive threshold eliminates the probability of false alarms due to the increase in FD signal for normal test commands. During 10% sweep command also, the FD signal increases for some frequencies where the model is deviating from the actual system but the adaptive threshold automatically increases as a function of rate to avoid false alarms.

The FD scheme is validated for all probable failure cases through simulation and two typical cases are provided here. Fig.8 shows the fault detection performance of the system for the failure of HAV sensor, (zero condition) while the system is commanded to 5%, 1 Hz sinusoidal command. Fig. 9 shows the same for a failure in DDV power amplifier, where the power amplifier output is zero. It is found that the failure is detected within a short period before the system is deviating much from the actual command. The failure detection time depends on various conditions like the command to the system, failed at what state, time of failure, etc. The failure detection time is 140 msec and 270 msec for the two failure cases shown in Fig.9 and Fig.10. Dual redundancy is provided in the system for all sensors, electronics and LFM windings. Normally the system will work in prime chain. Hardcore

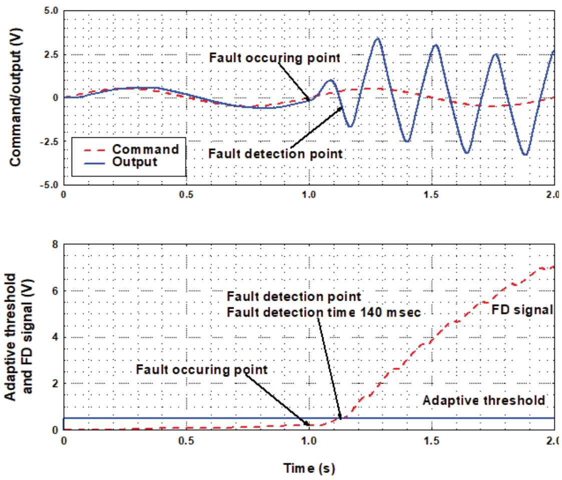


Fig.9 Fault detection of FNC system for HAV LVDT failure at zero output state

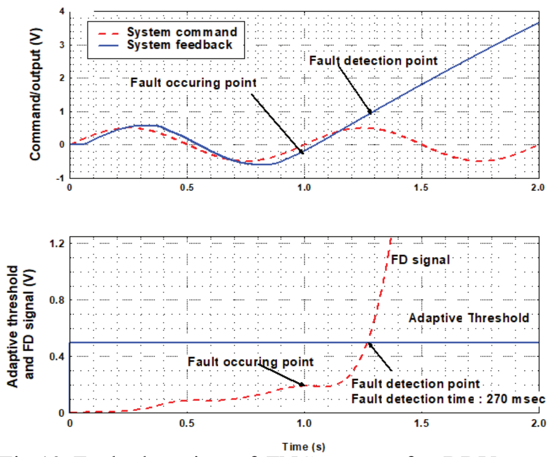


Fig.10 Fault detection of FNC system for DDV error amplifier failure at zero output state

switch is provided to switch over the system from prime chain to redundant. As soon as the failure is detected, the hardcore switch will switch over the system to the healthy redundant chain.

VIII. Experimental Evaluation

The FDI scheme was implemented in the newly developed hydraulic actuation system control electronics meant for the booster stage of a new series launch vehicle. The actuation system was tested to evaluate its performance at various test facilities. The tuning of various parameters were carried out to optimize the performance of the FD scheme along with actuator testing. The natural frequency and damping factor of the second order model were tuned to get a match with the system bandwidth specification. The rate limit was tuned to get a match with slew rate of the system. The model mimics the actuation system for wide ranges of frequencies and commands. The various gains and filter cut off frequencies were tuned to have sufficient separation between FD signal and threshold during normal operating conditions and minimum fault detection time for failure conditions.

The FD signal and adaptive signal observed during a ground static test of the vehicle stage for a wide range of command profiles are shown in Fig.11. The adaptive threshold is constant for commands having lower rates and varies

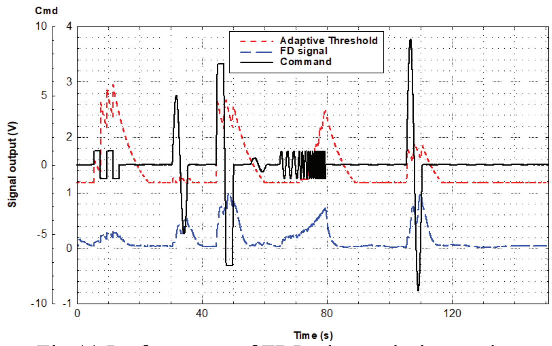


Fig.11 Performance of FDI scheme during static test

according to the command rate for larger rate commands. The FD signal was always within the adaptive threshold and there were no false alarms. The performance of the FD scheme with sinusoidal sweep command to actuation system is shown in Fig.12 and the same for step command is shown in Fig.13.

Various failure conditions were simulated during ground test and performance of the system with respect to failure detection time were validated satisfactorily. Fault detection during DDV LVDT failure is shown in Fig.14. Fig.15 shows the fault detection performance for HAV LVDT failure. Typical case of failure in the command path to prime chain is created and the FDI performance is evaluated and is shown in Fig.16. In all these failure cases the FD signal amplitude increased beyond the adaptive threshold and the faults were detected. The failure detection time varied according to the failure condition, type of failure and time at which failure occurs.

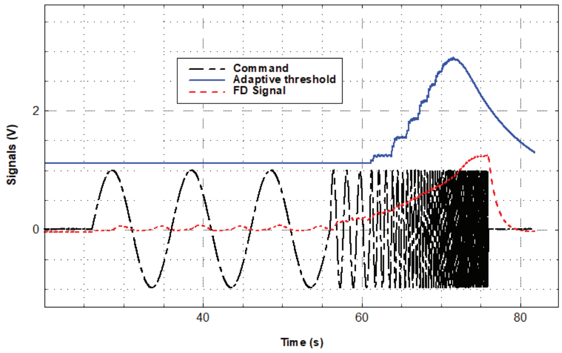


Fig.12 Performance of FDI scheme during integrated test for sine sweep command

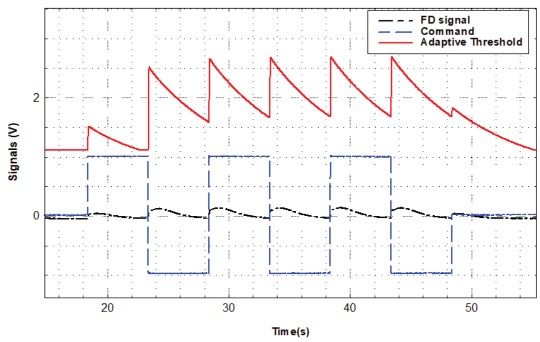


Fig.13 Performance of FDI scheme during integrated test for step command

IX. Conclusions

An innovative fault detection and isolation scheme with adaptive threshold, which blends the concepts of hardware and analytical redundancy using a hardware realizable model, is discussed in this paper. The scheme used a rate limited second order model of the closed loop system and an adaptive threshold generator to eliminate false alarms during the system functioning. Various test cases with healthy as well as faulty system dynamics were simulated using the nonlinear mathematical model of the system and the performance of theproposed method has been validated. The designed scheme is implemented in a newly developed actuation system for a future launcher and the efficacy of the FDI scheme has been validated through various levels of practical system testing.

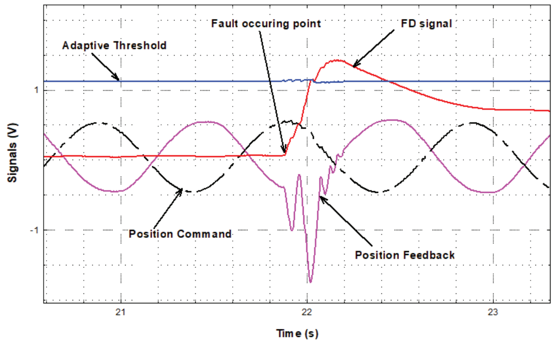


Fig.14 Fault detection during DDV LVDT failure

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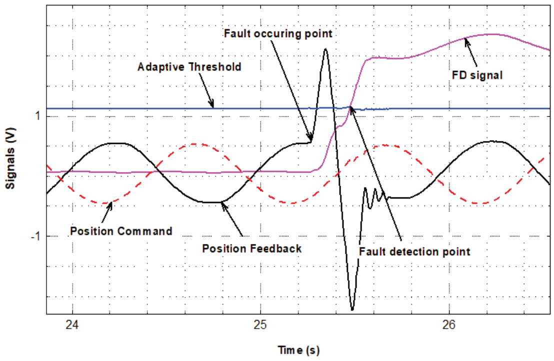

Fig.15 Fault detection during HAV LVDT failure simulation

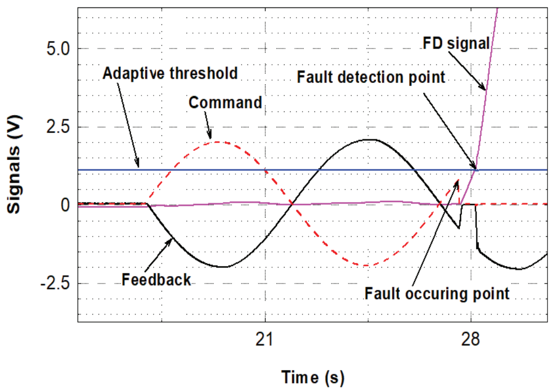

Fig.16 Fault detection under prime command failure condition

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