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FDI AND ADAPTIVE THRESHOLD DETECTION OF PILOT BY APPLICATION DEVELOPMENT OF AVAILABLE MODELS USING BOND GRAPH METHOD

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ABSTRACT

Hitherto, in the field of aerospace science and industry, some acceptable results from control behavior of human operator (pilot), are caught using usual methods. However, very fewer research, has been done based on personal characteristics. The performed investigations, show that many of happened faults (especially in helicopter), would result to the loss of natural behavior of system, and eventually some fatal accidents. Therefore, development of tools of assessment of pilot in this dynamical system, is one of the vital necessities. The tools of management of system, should be such that, can show the fault. The object of this paper is assessment of the modelled pilot in a simulator, in presence of standard fly inputs. For this purpose the performance of the pilot for collective control of the helicopter, is investigated. By now, some models for the human operator is presented, and in this paper one of them that is presented by Hess is used, and the helicopter systems that perform the controlling action are modeled by bond graph. The existence of uncertainties in the simulator system and the modeled pilot's behavior, causes creation of fault threshold, for human behavior of pilot. By having these fault thresholds, the improper actions of the pilot, cause creation of behavioral reminders, which can perform the assessment of the pilot. By other speech, using fault detection and isolation (FDI), by bond graph method in state space, the assessment is performed and a non-zero reminder shows existence of fault in the system.

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Therefore, in this paper there are the novelties for modeling the pilot's body performance and the helicopter's systems integrally and designing a fault detection system for it that shows the source of the fault, and obviously it can be useful in aviation industry.
Keywords: Helicopter Control, Human Model, Fault Detection and Isolation, Human Fault, Bond Graph.

INTRODUCTION

In the investigations of various boards of assessment of human faults in aviation accidents occurrence, including International Transport Safety Board, it is seen that the most major reasons and factors of accidents occurrence, are human faults (about 88% to 91%). Also, in many of them human faults beside other reasons, cause the accident. It should be noticed that, in human faults, it is not only the pilot that is responsible of it, but other people that are working in the aviation industry are included too. However, the pilot is the most major source of the human faults, such that it is included in 81% of human faults.

A lot of definitions and interpretations from the human faults have been done, and various models of it has been presented and investigated the reasons of accident occurrence in the case of chain theory, from Heinrich in 1931 [1], to Industrial Safety Rules of Reason's Swiss Cheese in 1990 [2]. In 2000 a comprehensive and overall term was presented by Wiegman and Shappell [3], that is consist of all of the work conditions and stages of physical and mental activities. In 1991 an useful map for human faults was suggested by Sender and Moray [4], that has four classifications:

1. Prospective emerge classification (neglect, Switch action substitution and ...).
2. Internal process classification (one route motion control fault, additional task density and decision fault).
3. Neurological psychological mechanism classification (amnesia, stress and mental pressure, notice).
4. External process classification (incorrect and weak designing of tools).

In 1993, it was said by McCormik and Sanders [5], that human fault is a human improper or unexpected decision or behavior that reduces effectiveness, safety and action of the system, or has the potential of its reduction. Of course, this fault can consist of other people than the pilot, such as the manager, designers of the system, repairing and maintenance engineers and others. It was alleged by Petersen in 1996 [6] that in the back of each accident, human fault is hidden as the main reason.

For investigation of human fault, some models for human operator have been presented. Arnold Tustin was the pioneer of modeling of human operator. In the mid-1940s, he was studying on the artillery turret, and in 1947 published a paper by the name of "The nature of human operator response in manual control and its concepts for control designing" [7]. It was supposed by Tustin that human can be showed by a linear and constant differential equation coefficient. At that time, linear servomechanisms theory was well developed and could be used in manual control tasks analysis. In 1969 a viewpoint for human operator modeling was presented by McRuer [8], which is returned to crossover models. The nature of this model is its consistency by machine dynamics, and the effect that is calculated for nonlinearity in human-machine system, was presented by it. An optimal control model (OCM) was developed in 1970 [9], which well shows the behavior of human operator by a nearly optimal method, considering its personal limitations, constraints and lack of control. A model was presented in 1985 by Ronald Hess that tried to mimic psychomotor structure of human [10,22]. Recently, some studies for optimization and development of Hess's model has been done by Cardallo that its nature consist of force and motion responses in the model [11].

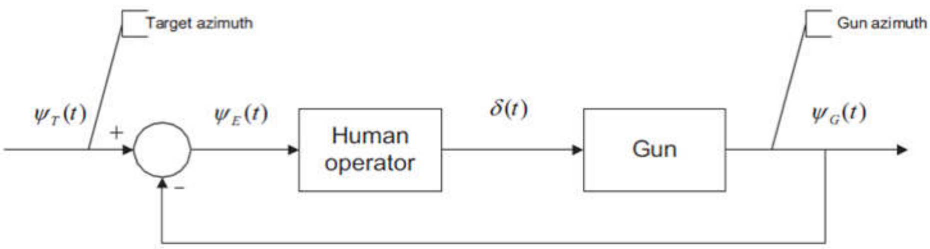

Fig.1. The block diagram of the control system of artillery turret [7]

The methods of model-based Fault Detection Isolation as a research field have been used very much in the control systems. These methods are based on consistency tests, which in them the measurements from the physical system are compared to the available information in the model. The resulted differences are called remainders, which are sensitive to the existence of fault in the system. A reminder that is non-zero shows non-consistency or unusual deviation of an estimated parameter in the system. However, the modelling misses and perturbations in the complicated engineering system are unavoidable, so the reminders even in the case that no fault has been occurred, don't become exactly zero, always. Therefore, it is necessary that fault detection algorithms, be robust against the noise and uncertainty of the parameters.

For considering uncertainty of parameters a detailed model of the system is required, that uncertainty of parameters be considered in it. For simulation of each mechanism, firstly the equations that are ruled over it should be extracted, and then these equations should be solved by a proper method. Some of the available methods for extracting the equations are Newton-Lagrange method, block diagram, flow diagram, linear graph of the system and bond graph method. Between of them bond graph is one of the most powerful methods for simulation of dynamical systems. Its advantages are that: first, all of the equations are integrally, so the number of equations will be not more than state equations, and more important that, systems in various energy domains including electrical, mechanical, chemical, hydraulic, pneumatics and …, can be modeled by it. Furthermore, there is no need to suppose the system, linear. This method was used for modeling dynamical systems firstly, in 1961[12]. Later, in 1999 it was used for observability and controllability, using its structural characteristics, by Dauphin-Tanguy [13,23]. After that, in 2001, bond graph was developed for fault detection and isolation using causality analysis method [14]. Although, quantity analysis by bond graph method for simple systems for the first time in 1995, was used for retaining the reminder [15], but this method was developed by Ould-Bouamama in 2003 [16].

In this paper it is tried to model collective and cyclic control system of the helicopter including the pilot's hand that moves the handle. Then the bond graph FDI method is used for obtaining reminders.

Hess Structural Model of Human Operator

In this paper for modelling the pilot of the helicopter a model that has been presented for human operator by Hess, is used. This model was designed for usage in quality of operation of aircraft, and was placed in a group of human operator models, similar to the human. This group was named physiological induction model. The structure of this model mimic signal processing in central nervous and muscular-nervous systems in the time that human is doing a work. The key idea of this model is that, it simulates feedback routes from various quality sensors (figure 2).

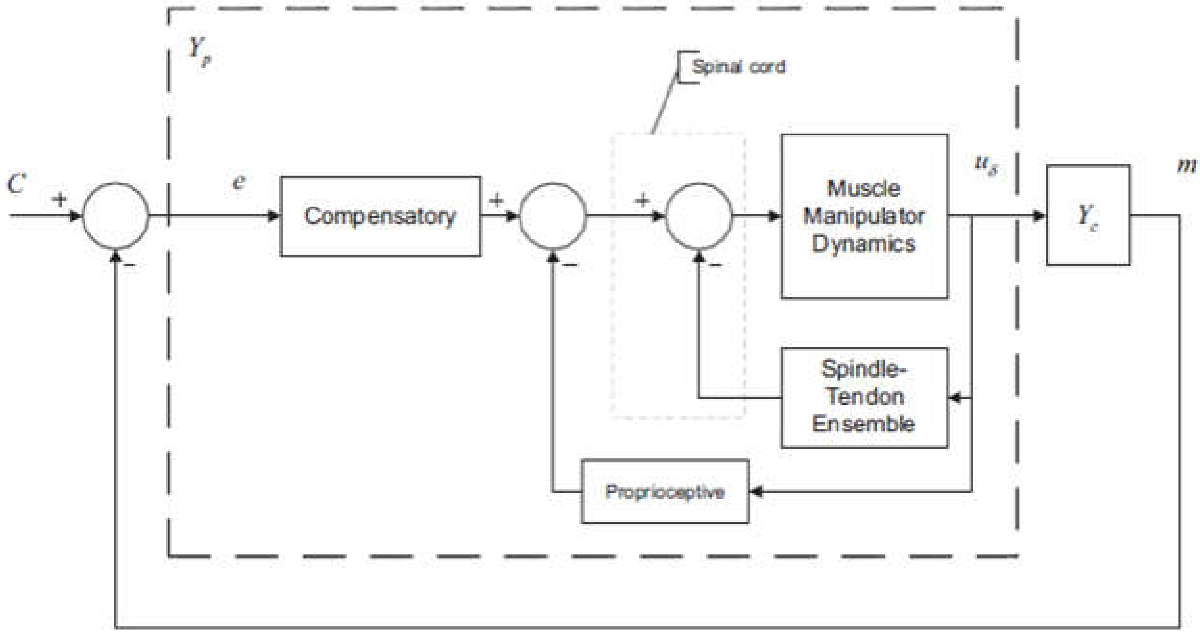

Fig.2. Main route line of the operator for compensating tracing

Human simulation by feedback that is called motivation feedback by Hess, is performed. Further to it, this structural model was designed and its parameters was tuned such that, in the best state, works near to crossover frequencies. The action parameters of Hess model are described as below (figure 3):

- The error signals of the system that are dependent to human vision are shown by K_ε.
- If there are any motion signs, the output signal that is the change rate of m, is sensed by auricular system, then multiplied in K_v and subtracted from u_ε.It should be noticed that if the researching system is non-motional, K_s would be zero.
- The resulted signal u_1 is passed from a delay, which is because of nervous data processing of nervous conduction motor and etc.
- The input for a closed loop system is produced by u_c. In the way of open loop system, there is a Y_{p_n} model of organs, which cause the initial control motion.

- The dependent feedback to the human motion system is consist of two loops with Golgi tendon organs models and Muscle spindles, that are shown respectively by Y_m and Y_f blocks. Notice to Hess model, it is the human motion system feedback, that model the basic capability of the human.

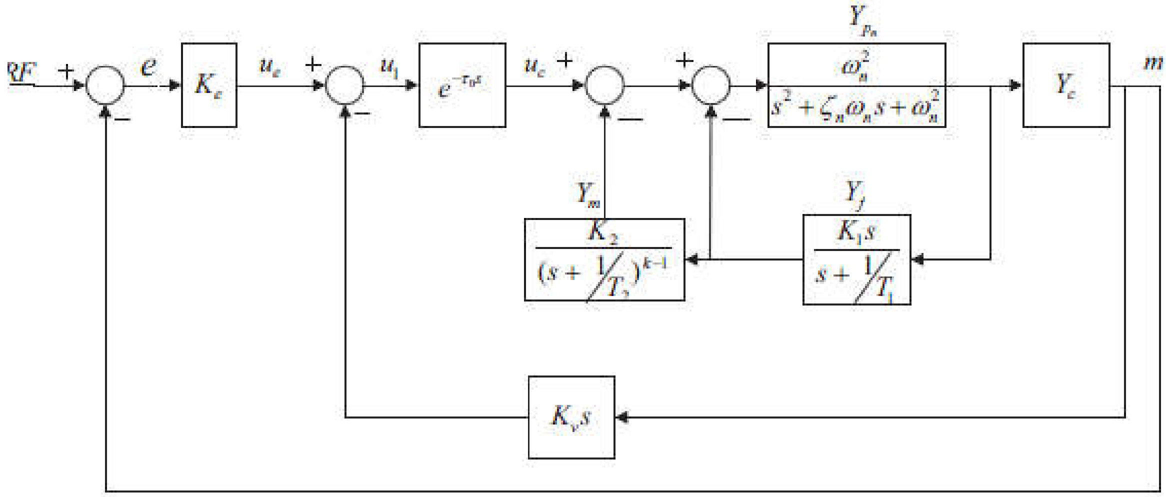

Fig.3. Hess structural model of the human operator

Collective and Cyclic Control System of Helicopter

Collective and cyclic control system are two systems of helicopter, which the first one defines the step angle of the main rotor and the second one defines the angle of the plate that the main rotor is rotating in it [17]. The overall schematic of both systems can be seen in figure 4.

Collective control system is manipulated by an one-degree freedom handle than can be moved by the pilot's hand. The force from the handle through some rods is transmitted to a ball bearing that is installed under the rotor. The transmission rods system is consisting of some parts that may move directly or rotate to transfer the movement to the ball bearing. At the end of it, there is four beams that move parallel and synchronic to each other to up and down that make the ball bearing, to go to up or down. The ball bearing is connected to the attack side of the blades of the rotor, so this movement changes the angle of the blades.

In cyclic system a two-degree freedom handle is used that the pilot can move it in longitudinal and latitudinal directions. Like the collective control system, the movement is transferred to the ball earing by a transmission rods, but this time the beams under the ball bearing don't move synchronically, that makes the angle of the its plate be changed, and this angle is applied to the rotor's plate too.

It should be noticed that because the human force of the pilot is not enough to move the heavy rotor, a secondary hydraulic system is used to help the pilot to move the handles.

In this paper collective control system, is the topic of research and is used for modeling beside the pilot.

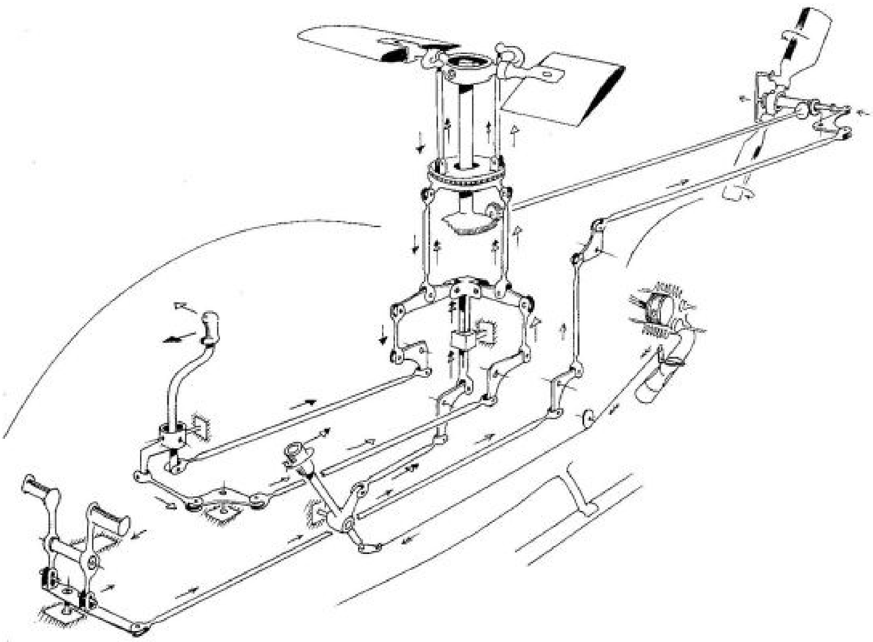

Fig.4. Schematic of collective and cyclic control system of helicopter

Designing the FDI Bond Graph of the System

In this section it is tried to bond graph model of the objected system of this paper, be established. This model is consisting of the model of the pilot using Hess model that is modeled by signal block diagram, and helicopter systems that perform collective control that is modeled by bond graph. For the secondary hydraulic system, a bi-directional jack with a standard 5/3 valve is used, that its bond graph model may be found in [18]. The designed bond graph model of the collective system is connected to the block diagram of the pilot and it may be seen in figures 5. In this figure Laplace relations blacks are merged together and then will be converted to the time domain. For doing this one problem is converting $e^{-\tau_0 s}$, and it is done by Padé approximant.

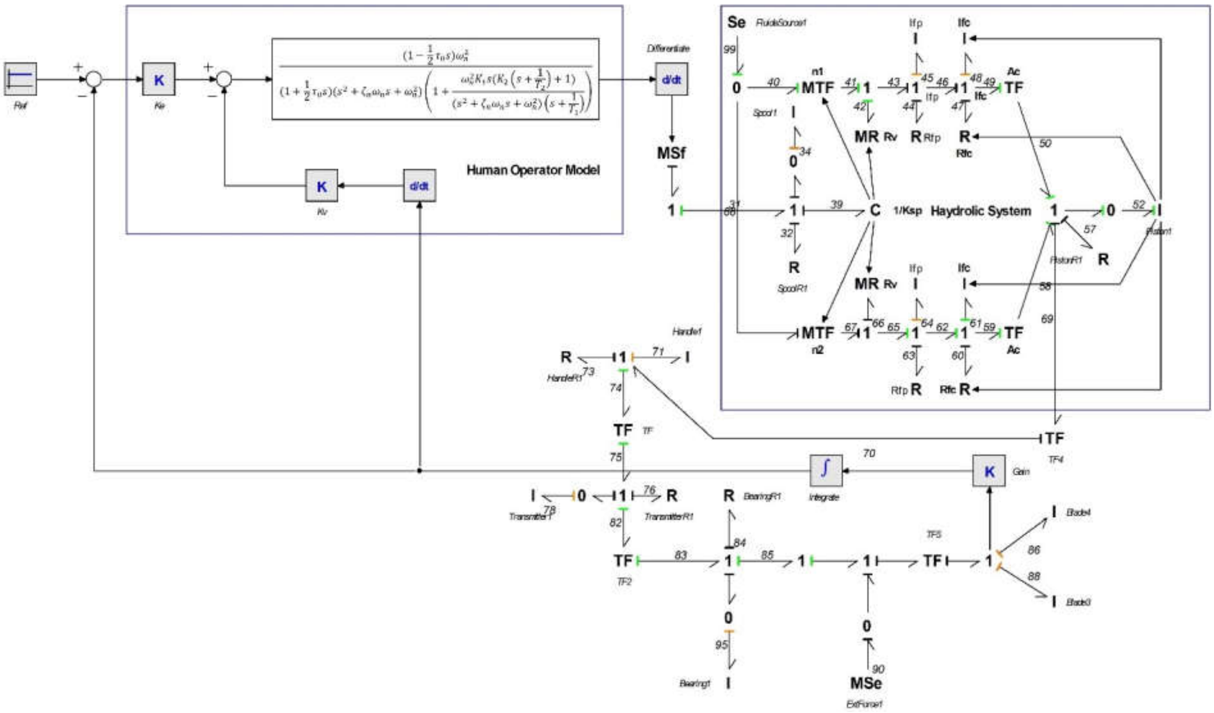

Fig.5. Bond graph model of collective control system of helicopter

In the next step sensors will be added to the models. In this task 9 sensors are used, in each bond graph model. It should be noticed that, when bond graph is used for extracting state equations, the measured values from the sensors, act as output from the system, while bond graph is used for fault detection, they act as input to the system, so the causalities will be different. In the used method for modeling sensors [14], [19], beside the real sensor a virtual sensor is used also, that calculates the reminder value. In the ideal state this value should be equal to zero, but in reality, an accepted range for it should be defined. A reminder value that is outside of its secure range, shows existence of fault in the system. The bond graph model of both the system with sensors may be seen in figure 6. In this model virtual sensors are specified by * sign.

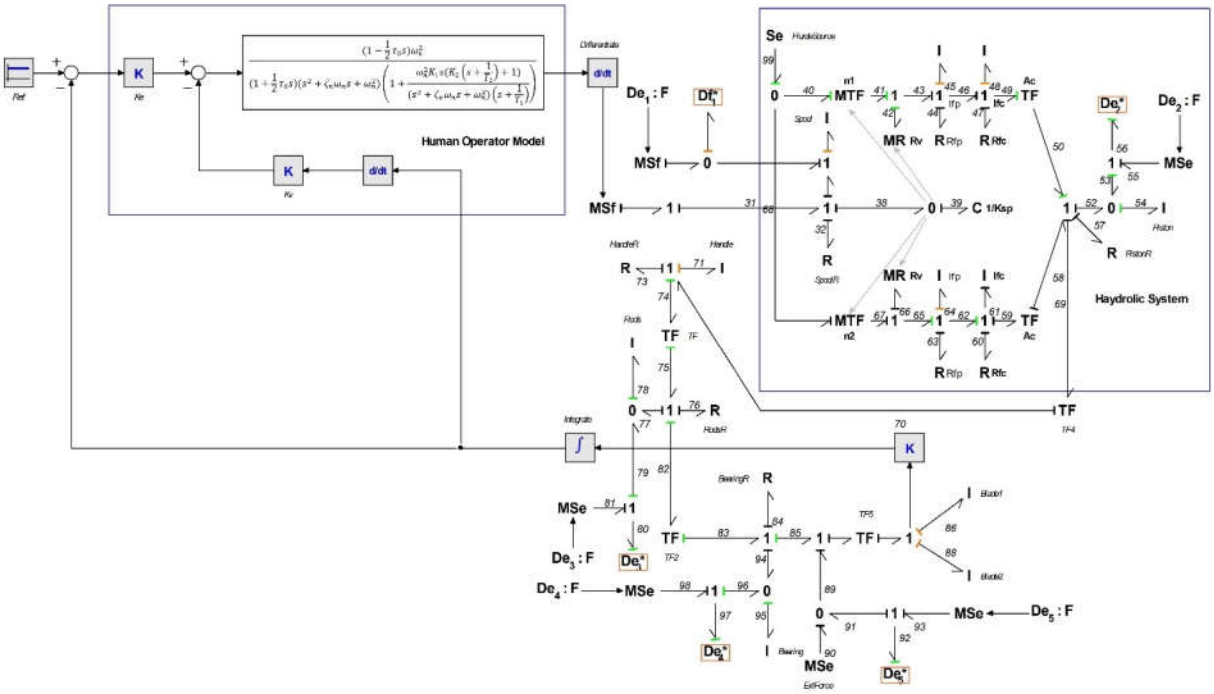

Fig.6. Bond graph model of the collective control of the system with sensors

Uncertainty Bond Graph Model

The study and analysis of robust control, for confidence from well performance of the control system against uncertainties, is the topic of many of today's researches. The analysis of robust control is performed for the purpose of designing controlling rules, such that with changing of the system's parameters in a specified range, the stability of the system be satisfied. Two models are used for studying, the stability of linear systems. The first one is recognized as canonical form, and the second one that is used in this paper, is recognized as standard interconnection model or internal feedback loop (LFT) [20]. In this form the uncertainties are isolated from the nominal parameters of the model, and their effects, are entered to the model as a feedback (Figure 7). The state equations in this form are as equation 1:

$$\begin{cases} \dot{x} = A_n x + B_n \omega + B_{2n} \\ z = C_n x + D_{11} \omega + D_{12} u \\ z = C_{2n} x + D_{21} \omega + D_{22n} u \\ \omega = \Delta . z \end{cases} \tag{1}$$

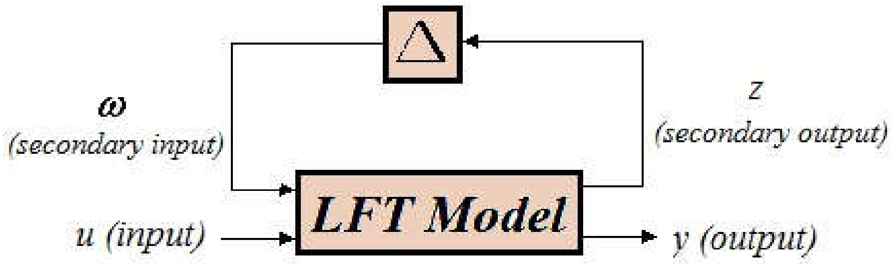

Fig.7. LFT stability form

In this equation $B_{2n} = B_n, C_{2n} = C_n, D_{22n} = D_n$ and z are secondary input and output of the system, respectively, and is a diagonal matrix, that is consist of rational uncertainty of parameters.

The uncertainty of parameter θ can be shown as $\theta = \theta_n + \Delta\theta$. If the showing of uncertainty is desired, it is better that parameters be shown as multiplex of nominal parameter and the uncertainty term:

$$\theta = \theta_n + \Delta\theta = \theta_n\left(1 + \frac{\Delta\theta}{\theta_n}\right) = \theta_n(1 + \delta_\theta),\ \ \delta_\theta = \frac{\Delta\theta}{\theta_n} \quad (2)$$

If in the ruled relation over the element, the parameter be shown in the case $1/\theta$, the uncertainty of the parameter in the LFT form can be shown as below:

$$\frac{1}{\theta} = \frac{1}{\theta_n + \Delta\theta} = \frac{\theta_n}{\theta_n(\theta_n + \Delta\theta)} = \frac{(\theta_n + \Delta\theta) - \Delta\theta}{\theta_n(\theta_n + \Delta\theta)} = \frac{1}{\theta_n}\left(1 - \frac{\Delta\theta}{\theta_n + \Delta\theta}\right) = \frac{1}{\theta_n}\left(1 + \delta_{1/\theta}\right),\ \delta_{1/\theta} = -\frac{\Delta\theta}{\theta_n + \Delta\theta} \quad (3)$$

In bond graph modeling, for showing the parameters in the standard form, when parameters have uncertainty, modulated sources are used [21], [22], [23].

The bond graph models of the system that is the topic of this paper, in the case that LFT model for uncertainty is added to them, are shown in figure 8.

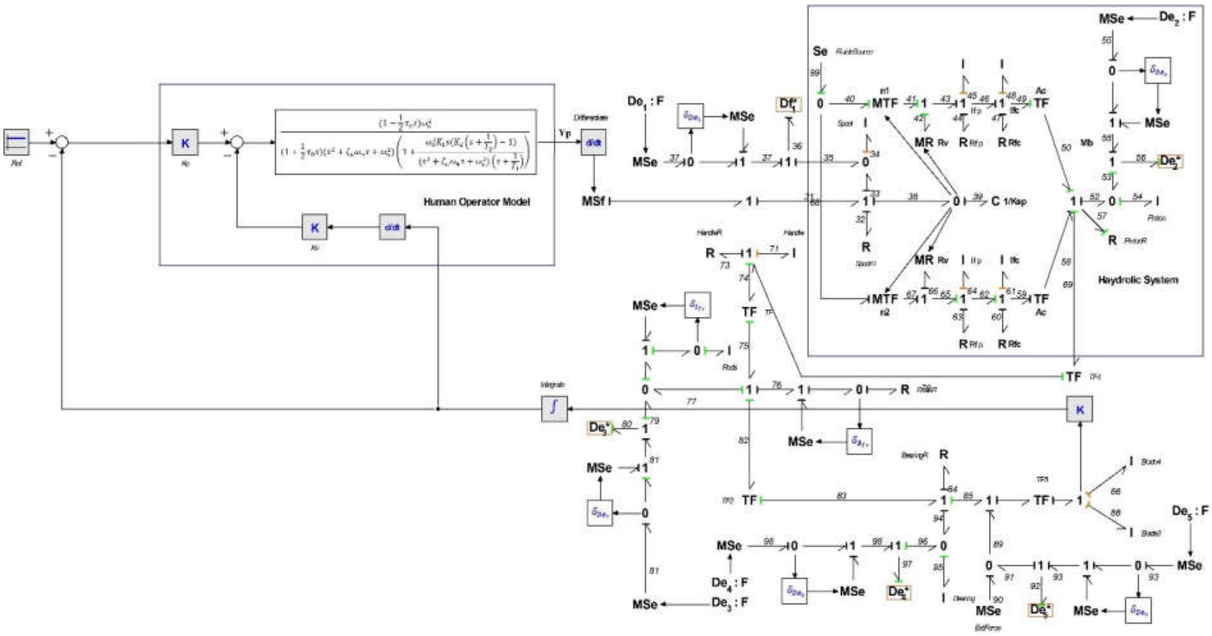

Fig.8. Bond graph model of the collective control of the system with LFT model

The state equations are extracted as below:

$$ARR_1 = Df_1 - \dot{Y}_p \pm \omega_1 \tag{4}$$

$$\omega_1 = \delta_{Df_1} Df_1$$

$$
\begin{aligned}
ARR_2 = De_2 - A_{Cylinder}\Bigg(& n_1 Se_{Fluide-Source} \\
& - \frac{A_{Cylinder}\left(R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}\right)\int De_2}{I_{Piston}} \\
& - \frac{A_{Cylinder}\left(I_{fluide-pipe-1} + I_{fluide-cylinder-1}\right)De_2}{I_{Piston}}\Bigg) \\
& - A_{Cylinder}\Bigg(n_2 Se_{Fluide-Source} \\
& - \frac{A_{Cylinder}\left(R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}\right)\int De_2}{I_{Piston}} \\
& - \frac{A_{Cylinder}\left(I_{fluide-pipe-2} + I_{fluide-cylinder-2}\right)De_2}{I_{Piston}}\Bigg) + \frac{R_{Piston}\int De_2}{I_{Piston}} \\
& + Tf_4\Bigg(Tf\Bigg(\frac{TfTf_4R_{Rods}\int De_2}{I_{Piston}} + \frac{TfTf_4I_{Rods}De_2}{I_{Piston}} \\
& + Tf_2\Bigg(\frac{TfTf_2Tf_4R_{Bearing}\int De_2}{I_{Piston}} + \frac{TfTf_2Tf_4\left(I_{Bearing} + Tf_5\left(I_{Blade_1} + I_{Blade_2}\right)\right)De_2}{I_{Piston}} \\
& - Mse_{Eternal}\Bigg)\Bigg) - \frac{Tf_4R_{Handle}\int De_2}{I_{Piston}} - \frac{Tf_4I_{Handle}De_2}{I_{Piston}}\Bigg) \pm \omega_1 \pm \omega_2 \pm \omega_3 \pm \omega_4 \pm \omega_5 \\
& \pm \omega_6 \pm \omega_7 \pm \omega_8 \pm \omega_9 \pm \omega_{10} \pm \omega_{11} \pm \omega_{12}
\end{aligned}
\tag{5}
$$

$$
\begin{cases}
\omega_1 = \delta_{De_2} \int De_2 \\
\omega_2 = \delta_{De_2} \dfrac{A^2_{Cylinder}\left(R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}\right)\int De_2}{I_{Piston}} \\
\omega_3 = \delta_{De_2} \dfrac{A^2_{Cylinder}\left(I_{fluide-pipe-1} + I_{fluide-cylinder-1}\right)De_2}{I_{Piston}} \\
\omega_4 = \delta_{De_2} \dfrac{A^2_{Cylinder}\left(R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}\right)\int De_2}{I_{Piston}} \\
\omega_5 = \delta_{De_2} \dfrac{A^2_{Cylinder}\left(I_{fluide-pipe-2} + I_{fluide-cylinder-2}\right)De_2}{I_{Piston}} \\
\omega_6 = \delta_{De_2} \dfrac{R_{Piston}\int De_2}{I_{Piston}} \\
\omega_7 = \delta_{De_2} \dfrac{Tf^2 Tf_4^2 R_{Rods}\int De_2}{I_{Piston}} \\
\omega_8 = \delta_{De_2} \dfrac{Tf^2 Tf_4^2 I_{Rods} De_2}{I_{Piston}} \\
\omega_9 = \delta_{De_2} \dfrac{Tf^2 Tf_2^2 Tf_4^2 R_{Bearing}\int De_2}{I_{Piston}} \\
\omega_{10} = \delta_{De_2} \dfrac{Tf^2 Tf_2^2 Tf_4^2\left(I_{Bearing} + Tf_5\left(I_{Blade_1} + I_{Blade_2}\right)\right)De_2}{I_{Piston}} \\
\omega_{11} = \delta_{De_2} \dfrac{Tf_4^2 R_{Handle}\int De_2}{I_{Piston}} \\
\omega_{12} = \delta_{De_2} \dfrac{Tf_4^2 I_{Handle} De_2}{I_{Piston}}
\end{cases}
$$

$$
ARR_3 = De_3 - \frac{1}{Tf}\left(\frac{1}{Tf_4}\left(A_{Cylinder}\left(n_1 Se_{Fluide-Source} - \frac{A_{Cylinder}\left(R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}\right)\int De_2}{I_{Piston}} - \frac{A_{Cylinder}\left(I_{fluide-pipe-1} + I_{fluide-cylinder-1}\right)De_2}{I_{Piston}}\right) + A_{Cylinder}\left(n_2 Se_{Fluide-Source} - \frac{A_{Cylinder}\left(R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}\right)\int De_2}{I_{Piston}} - \frac{A_{Cylinder}\left(I_{fluide-pipe-2} + I_{fluide-cylinder-2}\right)De_2}{I_{Piston}}\right) - De_2 - \frac{R_{Piston}\int De_2}{I_{Piston}}\right) - \frac{Tf_4 R_{Handle}\int De_2}{I_{Piston}} - \frac{Tf_4 I_{Handle} De_2}{I_{Piston}}\right) + \frac{Tf Tf_4 R_{Rods}\int De_2}{I_{Piston}} + Tf_2\left(\frac{Tf Tf_2 Tf_4 R_{Bearing}\int De_2}{I_{Piston}} + \frac{Tf Tf_2 Tf_4\left(I_{Bearing} + Tf_5\left(I_{Blade_1} + I_{Blade_2}\right)\right)De_2}{I_{Piston}} - Mse_{Eternal}\right)\right) \pm \omega_1 \pm \omega_2 \pm \omega_3 \pm \omega_4 \pm \omega_5 \pm \omega_6 \pm \omega_7 \pm \omega_8 \pm \omega_9 \pm \omega_{10} \pm \omega_{11} \pm \omega_{12} \quad (6)
$$

$$
\begin{cases}
\omega_1 = \delta_{De_3} \int De_3 \\
\omega_2 = \delta_{De_2} \dfrac{A_{Cylinder}^2 (R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}) \int De_2}{TfTf_4 I_{Piston}} \\
\omega_3 = \delta_{De_2} \dfrac{A_{Cylinder}^2 (I_{fluide-pipe-1} + I_{fluide-cylinder-1}) De_2}{TfTf_4 I_{Piston}} \\
\omega_4 = \delta_{De_2} \dfrac{A_{Cylinder}^2 (R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}) \int De_2}{TfTf_4 I_{Piston}} \\
\omega_5 = \delta_{De_2} \dfrac{A_{Cylinder}^2 (I_{fluide-pipe-2} + I_{fluide-cylinder-2}) De_2}{TfTf_4 I_{Piston}} \\
\omega_6 = \delta_{De_2} \dfrac{De_2}{TfTf_4} \\
\omega_7 = \delta_{De_2} \dfrac{R_{Piston} \int De_2}{TfTf_4 I_{Piston}} \\
\omega_8 = \delta_{De_2} \dfrac{TfTf_4 R_{Rods} \int De_2}{I_{Piston}} \\
\omega_9 = \delta_{De_2} \dfrac{TfTf_2^2 Tf_4 R_{Bearing} \int De_2}{I_{Piston}} \\
\omega_{10} = \delta_{De_2} \dfrac{TfTf_2^2 Tf_4 \left(I_{Bearing} + Tf_5 (I_{Blade_1} + I_{Blade_2})\right) De_2}{I_{Piston}} \\
\omega_{11} = \delta_{De_2} \dfrac{Tf_4 R_{Handle} \int De_2}{Tf I_{Piston}} \\
\omega_{12} = \delta_{De_2} \dfrac{Tf_4 I_{Handle} De_2}{Tf I_{Piston}}
\end{cases}
$$

$$
\begin{aligned}
ARR_4 = De_4 - \frac{1}{Tf_2}\Bigg(\frac{1}{Tf}\Bigg(\frac{1}{Tf_4}\Bigg(A_{Cylinder}\Bigg(n_1 Se_{Fluide-Source} - \\
\frac{A_{Cylinder}(R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}) \int De_2}{I_{Piston}} - \frac{A_{Cylinder}(I_{fluide-pipe-1} + I_{fluide-cylinder-1}) De_2}{I_{Piston}}\Bigg) + \\
A_{Cylinder}\Bigg(n_2 Se_{Fluide-Source} - \frac{A_{Cylinder}(R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}) \int De_2}{I_{Piston}} - \\
\frac{A_{Cylinder}(I_{fluide-pipe-2} + I_{fluide-cylinder-2}) De_2}{I_{Piston}}\Bigg) - De_2 - \frac{R_{Piston} \int De_2}{I_{Piston}}\Bigg) - \frac{Tf_4 R_{Handle} \int De_2}{I_{Piston}} - \frac{Tf_4 I_{Handle} De_2}{I_{Piston}}\Bigg) - \\
\frac{TfTf_4 R_{Rods} \int De_2}{I_{Piston}} - De_3\Bigg) + \frac{TfTf_2 Tf_4 R_{Bearing} \int De_2}{I_{Piston}} + \frac{TfTf_2 Tf_4 Tf_5 (I_{Blade_1} + I_{Blade_2}) De_2}{I_{Piston}} - Mse_{Eternal}) \pm \omega_1 \pm \\
\omega_2 \pm \omega_3 \pm \omega_4 \pm \omega_5 \pm \omega_6 \pm \omega_7 \pm \omega_8 \pm \omega_9 \pm \omega_{10} \pm \omega_{11} \pm \omega_{12} \pm \omega_{13}
\end{aligned} \tag{7}
$$

$$\begin{cases} \omega_1 = \delta_{De_4} \int De_4 \\ \omega_2 = \delta_{De_2} \dfrac{A^2_{Cylinder}(R_{V_1} + R_{fluide-pipe-1} + R_{fluide-cylinder-1}) \int De_2}{TfTf_2Tf_4I_{Piston}} \\ \omega_3 = \delta_{De_2} \dfrac{A^2_{Cylinder}(I_{fluide-pipe-1} + I_{fluide-cylinder-1})De_2}{TfTf_2Tf_4I_{Piston}} \\ \omega_4 = \delta_{De_2} \dfrac{A^2_{Cylinder}(R_{V_2} + R_{fluide-pipe-2} + R_{fluide-cylinder-2}) \int De_2}{TfTf_2Tf_4I_{Piston}} \\ \omega_5 = \delta_{De_2} \dfrac{A^2_{Cylinder}(I_{fluide-pipe-2} + I_{fluide-cylinder-2})De_2}{TfTf_2Tf_4I_{Piston}} \\ \omega_6 = \delta_{De_2} \dfrac{De_2}{TfTf_2Tf_4} \\ \omega_7 = \delta_{De_2} \dfrac{R_{Piston} \int De_2}{TfTf_2Tf_4I_{Piston}} \\ \omega_8 = \delta_{De_2} \dfrac{TfTf_4R_{Rods} \int De_2}{Tf_2I_{Piston}} \\ \omega_9 = \delta_{De_2} \dfrac{TfTf_2Tf_4R_{Bearing} \int De_2}{I_{Piston}} \\ \omega_{10} = \delta_{De_2} \dfrac{TfTf_2Tf_4(I_{Bearing} + I_{Blade_1} + I_{Blade_2})De_2}{I_{Piston}} \\ \omega_{11} = \delta_{De_2} \dfrac{Tf_4R_{Handle} \int De_2}{TfTf_2I_{Piston}} \\ \omega_{12} = \delta_{De_2} \dfrac{Tf_4I_{Handle}De_2}{TfTf_2I_{Piston}} \\ \omega_{13} = \delta_{De_3} \dfrac{De_3}{Tf_2} \end{cases}$$

$$ARR_5 = Mse_{Eternal} - De_5 \pm \omega \quad (8)$$

$$\omega = \delta_{De_5} De_5$$

The resulted ARRs from these relations can be shown as:

$$ARR_i: r_i + \sum \omega_i = 0 \Rightarrow r_i = -\sum \omega_i \quad (9)$$

This relationship expresses that, in the normal state operation of the system, the numerical values of the reminders, may not be zero, exactly, because of uncertainty in measurement, system parameters and modeling. Therefore, in the case that the reminders be in the allowed range. The fault detection alarm would not be triggered, despite that reminders be not zero.

Further to it, regard to statistics and probabilities, uncertainties can both recover and robust each other, so the allowed range for reminders must be shown as:

$$a = \sum|\omega_i \quad (10)$$

The numerical value of *a* shows the adapted threshold.

Using these equations ARR table can be established as below. If each of the elements, be present in each reminder's equation, 1 is written in its cell in the table, and otherwise 0 is written. In this table M_b is observability index, and I_b is the separability index. When some faults in the system is detected, the value 1 for the reminders that are out of range is set. If the result is like one of the rows of the table, it shows that its element has fault. It can be seen that the front and back muscles are not separated from each other, but it can be found from the direction of the desired movement.

	r_1	r_2	r_3	r_4	r_5	M_b	I_b
Df_1	1	0	0	0	0	1	1
De_2	0	1	1	1	0	1	1
De_3	0	0	1	1	0	1	1
De_4	0	0	0	1	0	1	1
De_5	0	0	0	0	1	1	1
Y_{human}	1	0	0	0	0	1	1
MSe_{90}	0	1	1	1	1	1	1
Se_{99}	0	1	1	1	0	1	1

Table 1. ARR table for the collective system

Now using this table, it is tried to test the operation of the system. In this paper some approximate data for helicopter parameters is used. The used data for parameters of the human model are as below:

$$K_e = 1.54, k = 0, K_v = 0, K_1 = 1, K_2 = 1, T_1 = 5, T_2 = 1, \tau_0 = 0.14, \omega_n = 10, \zeta_n = 0.707$$

In this work it is supposed that the pilot decides to increase the height of the helicopter, about 100 meters, so manipulate the collective handle for this purpose. The changes of height may than is extracted from simulation of the system is shown in figure 9.

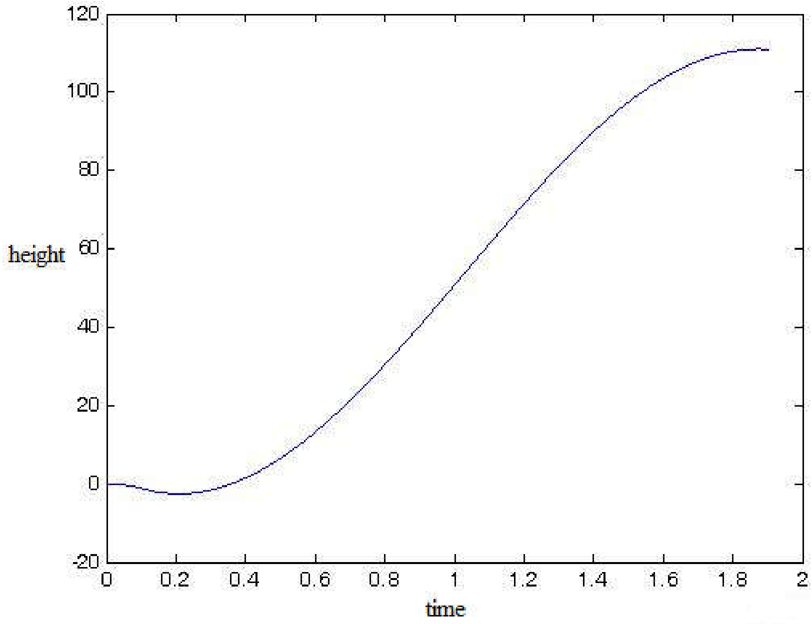

Fig.9. Increase in height of the helicopter

Now, it is supposed that, in the middle of the operation, the value of ω_n increased to 10.5, eventually. The results of simulation are shown in figures 10 to 14. In these figures the reminders values are shown by blue line, and threshold values are shown by red lines. It can be seen that after occurrence of the fault, only 1 reminder falls out of range. Therefore, it means that the source of the fault is the human operator or the pilot.

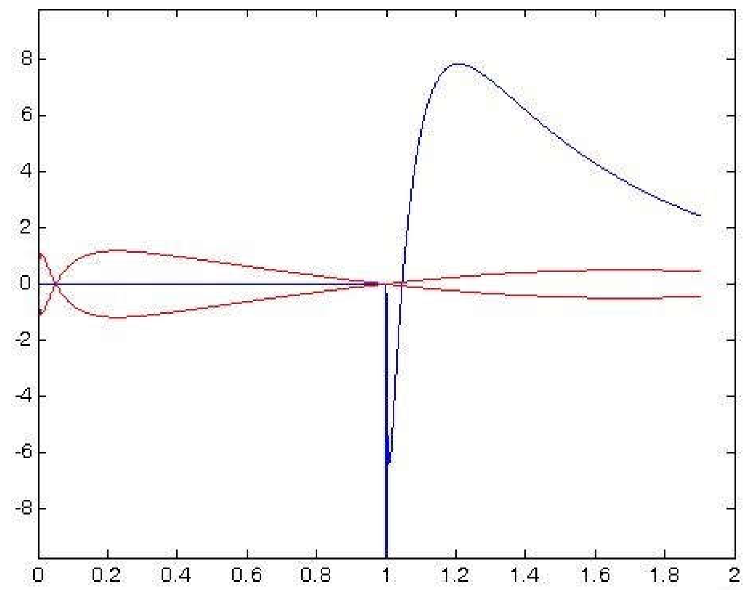

Fig.10. The results of reminder 1

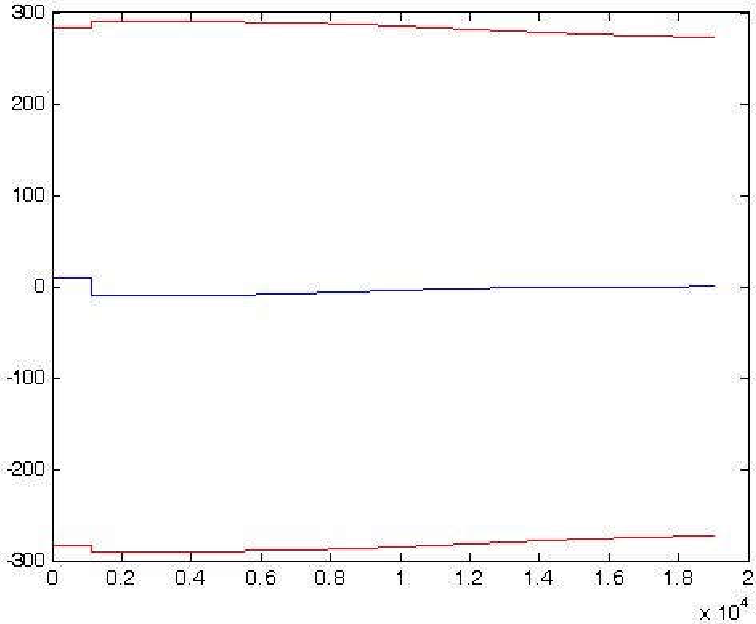

Fig.11. The results of reminder 2

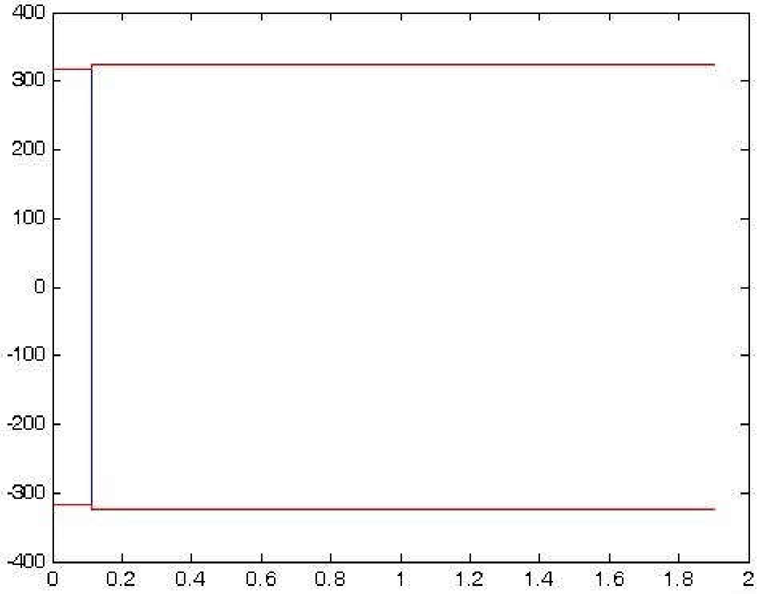

Fig.12. The results of reminder 3

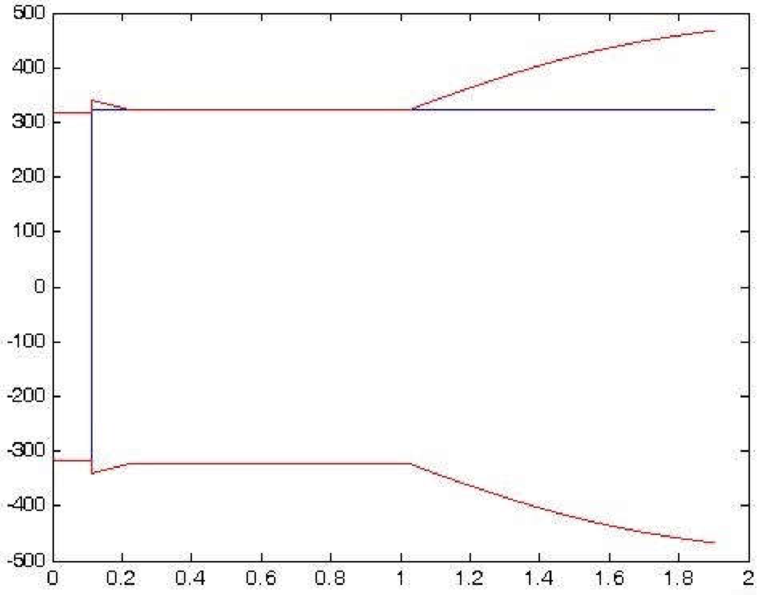

Fig.13. The results of reminder 4

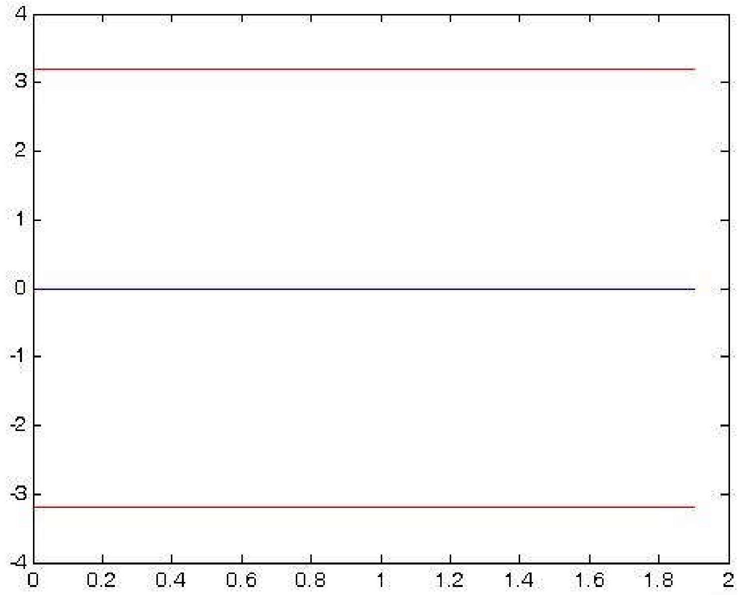

Fig.14. The results of reminder 5

CONCLUSION

The object of this papers was developing a model for the integral system, containing the controlling systems of the helicopter and the pilot's body, and using it for creation of a fault detection system, that can detect the source of the fault. For this purpose, the collective control of the helicopter was selected, that the pilot manipulates it by a handle. For modeling the helicopter system bond graph modelling method was selected because of its powerfulness in modeling dynamical and nonlinear systems. Also its ability to model multi-domain of energy systems, is a very prominent advantage that can be useful for this work. For modeling the pilot some models for human operators that has been presented by researchers were investigated, and one of them was selected. This model was drawn by block diagram, and then it was connected to the bond graph model of the helicopter. After designing the bond graph model of the system, sensors that control the systems added to the model, using FDI method for modeling sensors in bond graph modeling. Additionally, the presence of uncertainty in the systems was considered. For modeling a stable system that be robust against uncertainty, internal feedback loop (LFT) method was used. After that the overall model of the system that consist of fault detection and LFT model, was presented, and the equations for calculating the reminder values of the sensors was extracted and written. Using the produced equations ARR table for assessment of the system was stablished that could show the source of the fault. For validation of the system, a sample simulation for increasing the height by collective control system was simulated, and it was supposed in it that in the middle of the operation one of the parameters of the human model deviate from its original value, and the results of simulation found out it. Therefore, the performed task in this paper can be useful in aviation industry to obtain the source of any fault that is occurred in a flying helicopter.

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