PARALLEL ROBOT MOTION APPLIED TO FLIGHT SIMULATOR CONTROL LAW SYNTHESIS

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Abstract:

The herein proposed method of synthesis of the parallel robot applied as flight simulator motion system control laws came from author's 20 year experience in developing, integrating and testing the control laws and their software dedicated to different simulators. The goal of the simulator motion control law synthesis at the proposed method is not minimizing cost function taken a priori *at the beginning of that synthesis process but achieving positive assessment by the operator (e.g. pilot) team on the basis of simulator motion perception. Procedures adopted for those simulators FAT (Final Acceptance Tests) within proposed method were based on standard military equipment testing methods. Performing the final and the most important tests by the real device operators (pilots) was the new element here. The other important modification of the classical method was introducing the simulated object acceleration derivative into the filters controlling the simulator motion system. It appeared to be particularly effective in the cases of highly manoeuvrable airplane simulators.*

Keywords: *simulator motion system, parallel robot.*

1. Introduction

The first simulators were equipped with the motion systems - they were flight simulators. Their function was to support the training of the future pilots. The first flight simulator [1] was the Model B without tail and engine sections. It was used in 1910 for the training of Wright's “Flyer B” piloting. It was supported in the way allowing banking, crucial for piloting that airplane. The cam was driven by electric motor, continuously changing the roll motion of the simulated airplane. When the student properly operated the controls, achieving the horizontal position of the wings was possible. After a few hours of such training the proper reaction habits appeared. The other training device constructed around year 1910, being one of the first simulators was shown in the Fig.1. It was manually driven and consisted of two halves of the barrel, mounted one on the top of the other. They were imitating the simulated airplane roll and pitch motion. The trainee goal was to keep the level reference bar in a horizontal position.

Even in that pioneering time the importance of the motion stimuli for the motion object control was appreciated. They are of particular meaning when the human-operator is tightly connected with the controlled object, like it takes place at the airplane, space vehicle, car, railway locomotive or ship. For those objects controlling human-operator uses the motion stimuli caused by the object motion. Those stimuli have the shape of acceleration, velocity, translation (linear or rotational). As the visual stimuli are not easy to replicate but easy to evaluate, then the motion stimuli are both difficult to replicate and evaluate. Their evaluation is usually more subjective than the other stimuli.

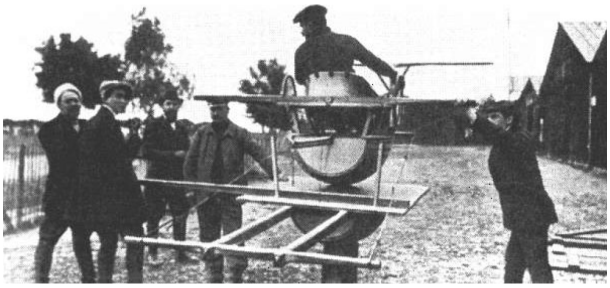


Fig. 1. "Antoinette" one of the first synthetic flight simulators.

For the controlled moving objects, which contain their operator on-board, the motion stimuli are priceless information source on the object orientation and its changes. For the human they constitute the basic source of information on the motion. So that object simulator should imitate those stimuli in the way allowing the human-operator controlling the object in the simulator the same way as in the real device.

For the simulator evaluation the formal, objective methods have been applied for years. As the result, formally correct simulator was received by the end user. Unfortunately the end user operators didn't accept the simulator, and particularly its motion system, as not similar to the real object. Those critical remarks have lead to the eliminating the motion systems from many types of the simulators, e.g. many flight and mission simulators operated by USAF. In such a situation the other way of simulator evaluation had to be found. The final goal was creating the simulator evaluation and testing method, which could lead to its acceptance by the end user operators. That problem stroke the author of the paper and his co-operators in the mid of the 80. of the previous century, when the work on “Iapetus” (Fig. 2) full mission simulator of the subsonic jet trainer airplane started. The work was continued in Poland for some years.

2. Anthropocentric algorithm of simulator motion control

The object controlled by the system described in that paper is the parallel robot, called in the simulator world:

classical, synergetic, hexapod motion system. The reference systems adopted in that paper are standard ones; their detail description one can find in. [2] Also the kinematical and dynamic simulator motion platform equations will not be listed here, as they are well known. The matter of the paper is the new type algorithm of the wash out filters controlling the simulator platform motion.

The anthropocentric algorithm is of the classical type. [3] It is nonlinear washout, which parameters are tuned up to perception of the selected group of the test human-operators, e.g. pilots. Standard input data into that algorithm, calculated by the "simulated object dynamics" module are: both linear and rotational accelerations and velocities. During development of the "Iapetus" flight simulator motion system driving algorithms author has found, that the standard input data are not enough. The other additional signals were checked and tested, and among them the derivative of acceleration acting on the pilot appeared to be the best for our purpose. The same algorithm structure was applied into the simulators of the following objects: supersonic fighter-bomber airplane Su-22, medium multipurpose helicopter W-3WA "Sokol" and electric locomotive EP-09.

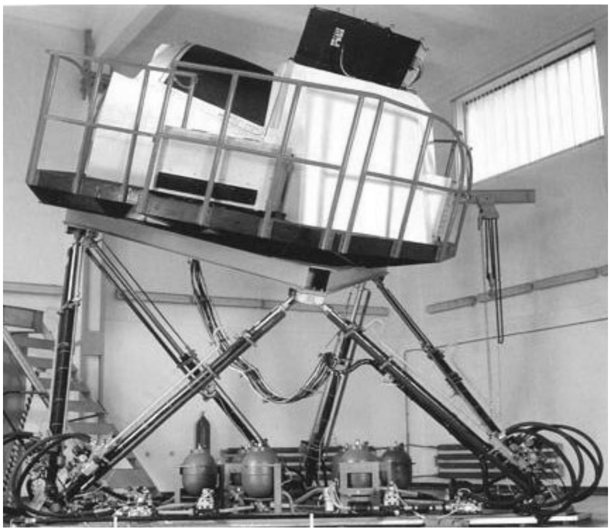


Fig. 2. "Iapetus" research flight simulator.

For the sake of avoiding the repeating of the equations, well known among their developers, only the new equations, characteristic for that method, will be presented here in detail. The scheme of proposed algorithm is presented in the Fig.3. After reading the input data calculated in the "object dynamics module" the first step of the algorithm is calculated. It is calculation of the specific force acting on the human-operator in the simulator. Next the specific force gradient is being calculated. After that, algorithm performs the translational and rotational motion filters calculations, and corrects the actuators required moves, at the end.

2.1. Translational motion filters

In the anthropocentric algorithm, the coordinated filters equations are developed for the following motions:

- longitudinal (surge in aviation) and pitch,
- lateral (sway in aviation) and roll.

The non-coordinated filters are developed for the following channels:

- vertical (heave in aviation),
- yaw.

2.1.1. Longitudinal motion

The simulator moving platform accelerations which are to be performed in that channel, in the reference system connected with that platform, are the following:

$$\ddot{x}_p = \ddot{x}_{p\dot{U}} + \ddot{x}_{p\dot{Q}} \tag{1}$$

where:

$\ddot{x}_{p\dot{U}}$ - platform acceleration component imitating the linear acceleration $\dot{U}_D$ of simulated object;

$\ddot{x}_{p\dot{Q}}$ - platform acceleration component imitating the rotational acceleration $\dot{Q}_D$ of simulated object.

The platform acceleration component imitating the linear acceleration $\dot{U}_D$ of simulated object, one can get from the formula:

$$\ddot{x}_{p\dot{U}} = (grad\dot{U})\frac{\tau_{G\dot{U}}}{\tau^2_{p\dot{U}}} - \frac{2\zeta_{p\dot{U}}}{\tau_{p\dot{U}}}\dot{x}_{p\dot{U}} - \frac{1}{\tau^2_{p\dot{U}}}x_{p\dot{U}} \tag{2}$$

where:

τ_p, ζ_p - coefficients of the filter controlling the platform motion. Additional indexes precisely indicate their function and belonging to the particular filters.

The platform acceleration component imitating the rotational acceleration $\dot{Q}_D$ of simulated object can be calculated using the formula:

$$\ddot{x}_{p\dot{Q}} = -g \cdot \sin\Theta_p \tag{3}$$

It compensates the human-operator incorrect feeling of the specific force component at the simulator, coming out of the simulated object pitch acceleration simulation.

2.1.2. Lateral motion

The simulator motion platform lateral acceleration, described in the reference system connected with that platform, has the form:

$$\ddot{y}_p = \ddot{y}_{p\dot{V}} + \ddot{y}_{p\dot{P}} \tag{4}$$

where:

$\ddot{y}_{p\dot{V}}$ - platform acceleration component imitating lateral acceleration of the simulated object,

$\ddot{y}_{p\dot{P}}$ - platform acceleration component imitating components of roll acceleration $\dot{P}_D$ of the simulated object.

The acceleration component is calculated from the high pass filter equation, where the input signal is the acceleration gradient, without gravity component:

$$\ddot{y}_{p\dot{V}} = (grad\dot{V})\frac{\tau_{G\dot{V}}}{\tau^2_{p\dot{V}}} - \frac{2\zeta_{p\dot{V}}}{\tau^2_{p\dot{V}}}\dot{y}_{p\dot{V}} - \frac{1}{\tau^2_{p\dot{V}}}y_{p\dot{V}} \tag{5}$$

The $\ddot{y}_{p\dot{P}}$ component of the motion platform lateral acceleration is described as following:

$$\ddot{y}_{p\dot{P}} = g \cdot \sin \Phi_p \tag{6}$$

It compensates the human-operator incorrect perception of the specific force, which is connected with the imitating the simulated object roll acceleration.

2.1.3. Vertical motion

The simulator motion platform vertical acceleration $\ddot{z}_p$ in the reference system connected with that platform is being calculated from the vertical acceleration gradient of the simulated object. There is no rotational motion component in that channel. The formula for calculating the $\ddot{z}_p$ is the following:

$$\ddot{z}_p = (grad\dot{W})\frac{\tau_{G\dot{W}}}{\tau_{p\dot{W}}} - \frac{2\zeta_{p\dot{W}}}{\tau_{p\dot{W}}}\dot{z}_{p\dot{W}} - \frac{1}{\tau^2_{p\dot{W}}} z_{p\dot{W}} \tag{7}$$

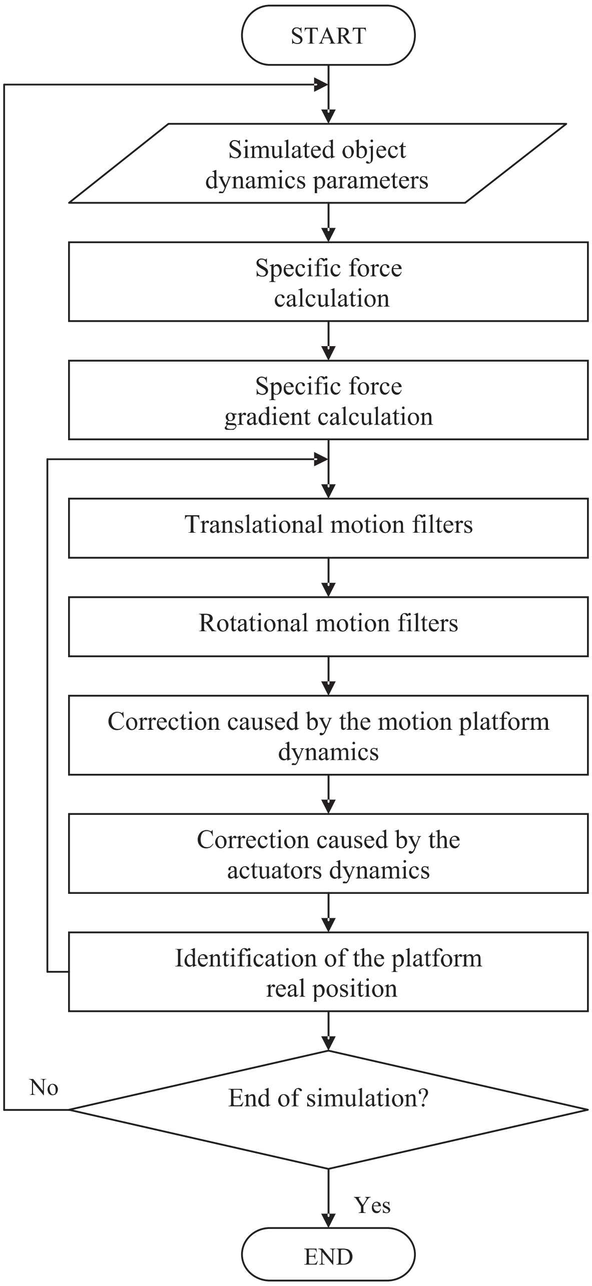


Fig. 3. Simulator platform main calculation loop scheme.

2.1.4. Translational motion wash out filters

The simplest description of the wash out filters can be achieved with the use of the inertial reference system $O_1x_1y_1z_1$. The translational accelerations of the motion platform in that system are as follows:

$$\begin{aligned}\ddot{x}_1 = {} & \ddot{x}_p \cdot \cos\Theta_p \cdot \cos\Phi_p + \\ & + \ddot{y}_p(\sin\Phi_p \cdot \sin\Theta_p \cdot \cos\Psi_p - \cos\Phi_p \cdot \sin\Psi_p) + \\ & + \ddot{z}_p(\cos\Phi_p \cdot \sin\Theta_p \cdot \cos\Psi_p + \sin\Phi_p \cdot \sin\Psi_p)\end{aligned} \tag{8}$$

$$\begin{aligned}\ddot{y}_1 = {} & \ddot{x}_p \cdot \cos\Theta_p \cdot \sin\Psi_p + \\ & + \ddot{y}_p(\sin\Phi_p \cdot \sin\Theta_p \cdot \sin\Psi_p + \cos\Phi_p \cdot \cos\Psi_p) + \\ & + \ddot{z}_p(\cos\Phi_p \cdot \sin\Theta_p \cdot \sin\Psi_p - \sin\Phi_p \cdot \cos\Psi_p)\end{aligned} \tag{9}$$

$$\begin{aligned}\ddot{z}_1 = {} & -\ddot{x}_p \cdot \sin\Theta_p + \ddot{y}_p \cdot \sin\Phi_p \cdot \cos\Theta_p + \\ & + \ddot{z}_p \cdot \cos\Phi_p \cdot \cos\Theta_p\end{aligned} \tag{10}$$

Then the wash out filters equations take the shape:

$$\ddot{x}_{pp} = \ddot{x}_1 - \frac{2\zeta_{xp}}{\tau_{xp}}\dot{x}_{pp} - \frac{1}{\tau^2_{xp}} x_{pp} \tag{11}$$

$$\ddot{y}_{pp} = \ddot{y}_1 - \frac{2\zeta_{yp}}{\tau_{yp}}\dot{y}_{yp} - \frac{1}{\tau^2_{yp}} y_{pp} \tag{12}$$

$$\ddot{z}_{pp} = \ddot{z}_1 - \frac{2\zeta_{zp}}{\tau_{zp}}\dot{z}_{pp} - \frac{1}{\tau^2_{zp}} z_{pp} \tag{13}$$

where:

$\ddot{x}_{pp}, \ddot{y}_{pp}, \ddot{z}_{pp}$ - simulator motion platform accelerations after the wash out filters transformation.

2.2. Rotational motion filters

2.2.1. Pitch motion

Simulator motion platform pitch angle Θ_p is defined as following:

$$\Theta_p = \Theta_{pd} + \Theta_{pg} \tag{14}$$

where:

Θ_{pd} - platform pitch angle generated by the low pass filter for the slow-speed changing courses coming out of the platform pitch angle Θ_p and acceleration component coming out of the gravity,

Θ_{pg} - platform pitch angle generated by the high pass filter for the high-speed changing courses connected with the pitch acceleration of the simulated object.

Simulator motion platform pitch angle Θ_{pd} comes out of the coordinated simulation of the longitudinal and pitch motion of the simulated object. That angle reflects the platform pitch caused by the low-speed changing, long lasting, and longitudinal acceleration imitation. Low pass filter allows the changing of the platform pitch angle below the human-operator perception threshold.

Comparing the longitudinal specific forces acting at the centre of reference systems connected with the simulated object and the simulator motion platform, one can achieve the equation:

$$\dot{U}_D + g \cdot \sin\Theta_D = g \cdot \sin\Theta^*_{pd} \tag{15}$$

where:
Θ^*_{pd} - simulator platform pitch angle before the filtering, which imitates the low-speed changing component of the longitudinal acceleration.

The equation (15) is used for calculation of the Θ^*_{pd} angle. The low pass filter equation is as follows:

$$\Theta_{pd} + 2\tau_{\dot{Q}d}\zeta_{\dot{Q}d}\dot{\Theta}_{pd} + \tau^2_{\dot{Q}d}\ddot{\Theta}_{pd} - \dot{\Theta}^*_{pd}\tau_{D\dot{Q}} = 0 \tag{16}$$

Low pass filter of the longitudinal motion

After differentiating and implementing into the Eq. (16) one can achieve the equation for the Θ_{pd} angle:

$$\Theta_{pd} + 2\tau_{\dot{Q}d}\zeta_{\dot{Q}d}\dot{\Theta}_{pd} + \tau^2_{\dot{Q}d}\ddot{\Theta}_{pd} - \frac{\dfrac{\dot{U}_D}{g} + \sin\Theta}{\sqrt{1 - \left(\dfrac{\dot{U}_D}{g} + \sin\Theta\right)^2}} + \tag{17}$$

$$-\left(\frac{\dot{U}_D}{g} + \dot{\Theta}\cdot\sin\Theta + \Theta\cdot\cos\Theta\right)\arcsin\left(\frac{\dot{U}_D}{g} + \sin\Theta\right) = 0$$

High pass filter of the pitch acceleration

High pass component Θ_{pg} of the simulator pitch angle is felt by the human-operator at the majority of the simulated object motion control tasks as the disturbance of the specific force. Because of that, during simulation of those phases of the motion, that component has to be comparatively small. That is guaranteed by the high pass filter:

$$\Theta_{pg} + 2\tau_{\dot{Q}g}\zeta_{\dot{Q}g}\dot{\Theta}_{pg} + \tau^2_{\dot{Q}g}\ddot{\Theta}_{pg} - \ddot{Q}_D\cdot\tau_{G\dot{Q}} = 0 \tag{18}$$

From that equation one can get the Θ_{pg} component of the equation (14).

2.2.2. Roll motion

The simulator motion platform roll imitates in a coordinated way the low-speed changing component of lateral specific force and roll acceleration of the simulated object. Platform roll angle is described by the following equation:

$$\Phi_p = \Phi_{pd} + \Phi_{pg} \tag{19}$$

where:
Φ_{pd} - platform roll angle generated by the low pass filter for the low-speed courses coming out of the Φ_p platform roll caused by the gravity component,
Φ_{pg} - platform roll angle generated by the high pass filter for the high-speed courses coming out of the simulated object roll acceleration.

Low pass filter of lateral motion

Comparing the low-speed changing components of the lateral specific forces acting at the centre of reference systems connected with the simulated object and the simulator motion platform, one can achieve the equation:

$$\dot{V}_D - g\cdot\sin\Theta_D\cdot\sin\Phi_D = -g\cdot\sin\Phi^*_{pd}\cdot\cos\Theta^*_{pd} \tag{20}$$

From the above equation one need to calculate the Φ^*_{pd} angle, using the value of Θ^*_{pd} angle calculated in the pitch channel. Next it goes to the equation for the low pass filter in the roll channel:

$$\Phi_{pd} + 2\tau_{\dot{P}d}\zeta_{\dot{P}d}\dot{\Phi}_{pd} + \tau^2_{\dot{P}d}\ddot{\Phi}_{pd} - \dot{\Phi}^*_p\tau_{D\dot{P}} = 0 \tag{21}$$

Value of the $\dot{\Phi}^*_p$ one may calculate from the following formula:

$$\Phi^*_p = \arcsin\left(\frac{\dot{V}_D - g\cdot\cos\Theta\cdot\sin\Phi}{g\sqrt{1 - \left(\dfrac{\dot{U}_D}{g} + \sin\Theta\right)}}\right) \tag{22}$$

but in practice more effective way is to use the Newton method for its calculation.

High pass filter of the roll acceleration

The Φ_{pg} component of the simulator motion platform roll angle is being calculated in the same way as the high pass component of the platform pitch angle. The high pass roll filter is the following:

$$\Phi_{pg} + 2\tau_{\dot{P}g}\zeta_{\dot{P}g}\dot{\Phi}_{pg} + \tau^2_{\dot{P}g}\ddot{\Phi}_{pg} - \ddot{P}\cdot\tau_{G\dot{P}} = 0 \tag{23}$$

2.2.3. Yaw motion

It is imitated in the uncoordinated way. The high pass filter in that channel goal is to dump the simulated object low frequency yaw acceleration changes. The filter equation has the form:

$$\Psi_{pg} + 2\tau_{\dot{R}g}\zeta_{\dot{R}g}\dot{\Psi}_{pg} + \tau^2_{\dot{R}g}\ddot{\Psi}_{pg} - \ddot{R}\cdot\tau_{G\dot{R}} = 0 \tag{24}$$

2.2.4. Rotational motion wash out filters

As it was at the translational motion case, the most suitable is to transform the simulator platform velocities into the inertial reference system. Then they take the shape:

$$P_{p1} = P_p + Q_p\sin\Phi_p\cdot\tan\Theta_p + R_p\cos\Phi_p\tan\Theta_p \tag{25}$$

$$Q_{p1} = Q_p\cos\Phi_p - R_p\sin\Phi_p \tag{26}$$

$$R_{p1} = Q_p\frac{\sin\Phi_p}{\cos\Theta_p} + R_p\frac{\cos\Phi_p}{\cos\Theta_p} \tag{27}$$

Those are the input data for the simulator platform rotational motion wash out filters:

$$P_{pp} = P_{p1} - \frac{1}{\tau_{\Phi p}}\Phi_p \tag{28}$$

$$Q_{pp} = Q_{p1} - \frac{1}{\tau_{\Theta p}}\Theta_{pp} \tag{29}$$

$$R_{pp} = R_{p1} - \frac{1}{\tau_{\Psi p}}\Psi_{pp} \tag{30}$$

2.3. Correction of the required actuator movement

2.3.1. Correction caused by the motion platform dynamics

During the simulator operation, one can meet the case, when required move of the platform and/or its position at a certain calculation step could cause the motion dangerous for the platform itself. The most common case of that type is requirement of the move resulting with the exceeding the platform maximum load. That limit is usually caused by the limits of the equipment mounted on top of the platform, e.g. presentation system or computers. The necessity of implementing of those limits into the calculation of the required moves of the platform, introduces the non-holonomic constraints into the solved filter equation systems, making them much more complicated. That problem is usually omitted during the formal, literature analysis, but in the real system it needs to be solved for avoiding the equipment damage.

The author's experience shows, that for some types of the simulated objects, with the "high dynamics" characteristics, when the quick and/or big simulator platform moves are required, quite effective solution is introduction of the second level gain coefficient into the filter equations. The values of dynamic parameters at which that second level coefficients are switching on into the calculations, should be established a priori and tested with the operators of the simulated object.

2.3.2. Correction caused by the actuator dynamics

The next stage of the actuator moves correction is taking into consideration their characteristics. Each actuator has its own maximum values of the acceleration, velocity or displacement. Those limits cannot be crossed during the simulator work. So at each step of the actuator control, one has to check whether: acceleration gradient, acceleration, velocity and displacement limits for each of the actuator are not exceeded. If one of the limits could be crossed, then the required parameter (acceleration gradient, acceleration, velocity or displacement) of the endangered actuator has to be corrected up to the limit. If it is the case of a few endangered actuators parameters in the same control calculation step, one needs to correct the endangered parameters of each actuator to the same extent as the worst case actuator.

During that correction process, one needs to remember the most important goal of the motion stimuli generation, i.e. the proper motion cue generation. Practically we can say that the motion system goal is to replicate the specific force vector in the simulator as it would be in the real object during the simulated phase of that object motion. The most important parameter of that vector is its sense, next direction and the less important its module. Keeping that in mind, we can say that the optimum way of actuators required moves correction is correcting all the actuators moves proportionally to the worst case actuator limit exceeding. In that way we can loose only the module of the simulated acceleration.

2.3.3. Identification of the platform real position

It looks like the obvious step, but it is not taken into consideration during the simulator platform motion control algorithm analysis. Usually it is taken implicit assumption, that platform is able to perform any required motion. Unfortunately, in the real system that assumption cannot be accepted. In the real system one can meet loosing or distorting an actuator control signal. Sometimes one can also meet unexpected delays of the data transmission in the simulator computer system, which could destabilize the work of the motion system. For those reasons we need to check at every control step the real position of each actuator. If it is different than required one, the proper correction value needs to be added to the next step control signal. Of course, such corrected signal has to be subject of the corrections described above (par. 9 and 10).

3. Filter synthesis evaluation

3.1. Evaluation method

During many years of simulators exploitation different methods of their evaluation were used. The best example for that are the flight simulators, as only for them there are existing formal standards and requirements. In the 80-ies and 90-ies years of the previous century there was a trend for developing the strict definition of the flight simulator quality with the use of a set of measurable, objective parameters, e.g. [4] Very often the final result of such an evaluation method was flight simulator fulfilling all or the most number of those formal requirements but evaluated by the pilots as "not similar to the real airplane".

The method applied by the author of that paper together with co-operators at the end of 80-ies of XX century, took different attitude. The goal was to get the flight simulator evaluated by the pilots as the "acceptable and similar to the real airplane". For achieving that goal the simulator evaluation method was developed. The simulator motion system evaluation was performed in three phases:

1. initial validation of the motion platform control filters parameters, with the use of standard methods applied in the control theory,
2. during the company tests simulator was being evaluated by the test pilots or very experienced real device operator, like engineer of the electric locomotive,
3. during final acceptance (state) tests simulator was being evaluated by the pilots flying routinely, every day the simulated type of the airplane (also applies to other simulated objects types).

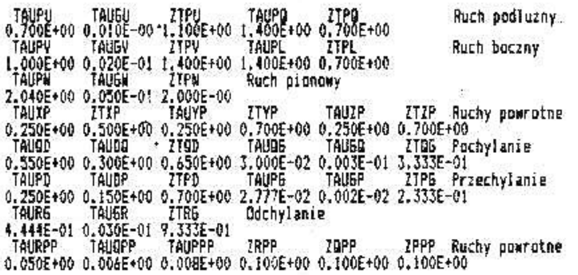
That method appeared to be very effective way of calibration of all the simulator parameters, particularly simulator motion system. The result was the motion system control filters with "optimized" set of parameters, allowing for the simulating of the whole flight. envelope of the simulated object. Also the simulator itself was accepted by the end users as an "acceptable and similar to the real airplane".

As the example some chosen results of the "Iapetus" flight simulator tests will be presented in the paper. That simulator is still in use at the Military Institute of Aviation Medicine in Warsaw, as the research flight simulator. That simulator imitates two engines, subsonic jet trainer airplane.

For the simulator motion system tests the piloting tasks important from the training and critical from the platform motion control point of view, were adopted. They were the following:

1. turns: left next right stable turn with slow ascending and stable velocity,
2. loop,
3. rolls: slow, controlled rolls into both directions,
4. Take off.

Filter parameters were calibrated initially for each of the task during the first validation phase, next some "optimization" among their values was performed and then during the company tests the real test pilots verified those values. The final values of the filter parameters were achieved with the help of the "mono-type" pilots of the simulated airplane. The set of input data, with the motion platform control filter parameters values checked and changed during the tests is presented in the Fig. 4.



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 TAUPU     TAUGU     ZTPU      TAUPQ     ZTPQ              Ruch podluzny.
0.700E+00 0.010E-00 1.100E+00 1.400E+00 0.700E+00
 TAUPY     TAUGV     ZTPV      TAUPL     ZTPL              Ruch boczny
1.000E+00 0.020E-01 1.400E+00 1.400E+00 0.700E+00
 TAUPW     TAUGW     ZTPW      Ruch pionowy
2.040E+00 0.050E-01 2.000E-00
 TAUXP     ZTXP      TAUYP     ZTYP      TAUZP     ZTZP  Ruchy powrotne
0.250E+00 0.500E+00 0.250E+00 0.700E+00 0.250E+00 0.700E+00
 TAU9D     TAUDQ     ZT9D      TAUQG     TAUGQ     ZTQG  Pochylanie
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 TAUPD     TAUDP     ZTPD      TAUPG     TAUGP     ZTPG  Przechylanie
0.250E+00 0.150E+00 0.700E+00 2.777E-02 0.002E-02 2.333E-01
 TAURG     TAUGR     ZTRG      Odchylanie
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 TAURPP    TAUQPP    TAUPPP    ZRPP      ZQPP      ZPPP  Ruchy powrotne
0.050E+00 0.006E+00 0.008E+00 0.100E+00 0.100E+00 0.100E+00
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Fig. 4. Example input data set of filter parameters.

Achieving such set of "optimized" values of control filter parameters required extensive tests to be done. The input data set "optimal" for one task appeared to be very "non optimal" for the other tasks. Achieving really good set of those values without the real human-operator co-operation would be very long, frustrating and ineffective way of performing that task. Simulator motion platform controls filter parameters values achieved during the company tests, with the test pilots participation were almost fully accepted by the mono type pilots. During that final tests phase only some slight changes into those values were introduced. But that final stage of test cannot be avoided. During that phase some changes of the simulator elements could be done, and then some additional calibrating of the filter parameters values would be necessary.

Some example integrated results of the platform motion are presented in the Fig. 5; more results one can find in Ref. [2]. As the reference real airplane data, the flights simulated on the "Iapetus" simulator with the motion platform turned off were used. Of course, having the proper data from the real airplane flights would be the best, but acquiring them was impossible for such broad extent of the required data, because of the financial reasons. So there was taken the decision to use as a reference the data from flights on the simulator with the motion platform turned off. Those reference flights were chosen by the experienced pilots and researchers as the most similar to the ones, which would be performed on the real airplane in the environment conditions similar to the simulated flights.

The example results of registered simulated motion flights show some substantial control mistakes made by the pilots. They allow for analysis of representing the accelerations by the simulator motion system during the complex phases of simulated flight. Those piloting mistakes simplify that analysis, because they produce the substantial values of cross components in combined control channels, confirming also the correctness of their action.

They also show, that after loop completing pilot started to induce roll oscillations, which were caused by the incorrect performance of the loop itself. The full set of results showing the complexity of controlling of the simulator platform motion and therefore platform motion system synthesis is presented in Ref. 2.

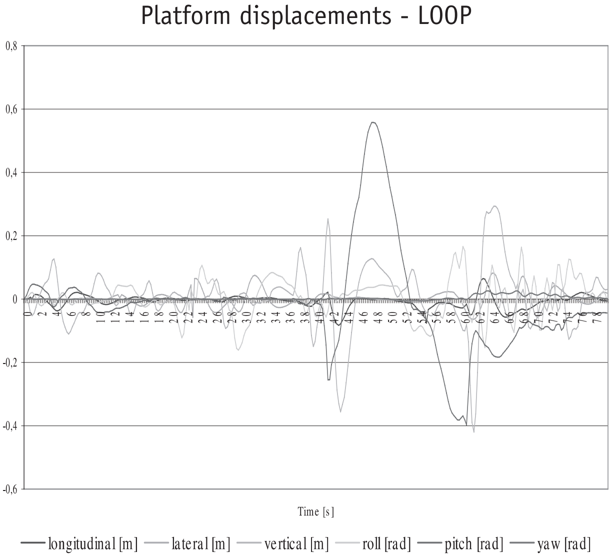

Fig. 5. Example results of loop simulation.

4. Conclusions

Anthropocentric method of flight simulator motion system control law synthesis presented in the paper allows for effective development and implementation of such system into the simulators of different types of objects, not only airplane or helicopter. It was verified in practice during development, manufacturing, integrating and testing of the following simulators:

- research flight simulator "Iapetus" of the subsonic jet trainer airplane,
- mission simulator of the supersonic, swept wing fighter-bomber airplane Su-22,
- electric locomotive EP-09,
- mission simulator of the medium, multi purpose helicopter W-3WA "Sokol".

Above simulators represent the moving objects with broad range of dynamic properties, starting from electric locomotive able to pull heavy train or make "solo" ride, through subsonic jet airplane, and supersonic, high manoeuvrable airplane, ending at helicopter. For those all simulators their motion systems developed with the use of presented method were successfully tested and evaluated. Also their multi year exploitation proved their correctness, i.e. the human-operators control habits learned at the simulators were easily transferred into the controlling of the real objects.

Also taking the acceleration derivative as input signals into the filter equations appeared to be the correct decision. It caused the minimization of the platform with the mounted on it simulator modules inertia influence on the quality of generated motion cues.

Adopted structure of the control laws was positively verified for the all listed above simulators, imitating dynamically so different objects. Motion cues generated by those control laws were accepted by the human-operators of all the simulated objects, and those laws differ only with the values of their parameters.

The presented method of simulator motion system control law synthesis appeared to be the effective engineering tool for the developing, testing and validating of the simulator motion systems of any type of the dynamic object, which can be controlled by the human-operator.

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