A NEW APPROACH TO LONGITUDINAL MOTION'S FLIGHT CONTROL SYSTEM DESIGN

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1. Introduction

Aircraft is a nonlinear and significant nonstationary object of control. Use of adaptive control systems for reduction of parametrical disturbances which are not satisfied a quasi-steady hypothesis, is restrained by the difficulties both theoretical and practical character [1].

In practice, design of stable higher-order adaptive control systems is complicated for many reasons (measurement errors, lags of adaptation loops and others) [2, 3]. Moreover the main disadvantage of adaptive flight control systems with reference model (both explicit and implicit) lies in that they don't guarantee stability of the system.

In the research summarized herein the problem of longitudinal control is solved in the class of control systems with mathematical model - indirect adaptive flight control systems (IACS). Identification of aircraft unknown aerodynamic parameters is carried out by adjustment of such a model. A new approach proposed in this paper is based on using of global multiparametric optimization in the identificator of IACS. As such a method Halton method was suggested and investigated. It is shown, that Halton method offers advantages over traditional methods of adaptive flight control systems design.

2. Description of the problem

The wind-tunnel data of light supersonic fighter-bomber F-101B were taken as input data for validation of proposed method (table 1). Structural model of aircraft in longitudinal motion (fig. 1) was obtained from the following system of linearized equations:

$$\begin{cases} \dot{\Theta} = \overline{Y}_a^{\alpha} \cdot \alpha + \overline{Y}_a^{\delta} \cdot \delta, \\ \dot{\omega}_z = \overline{M}_z^{\omega_z} \cdot \omega_z + \overline{M}_z^{\dot{\alpha}} \cdot \dot{\alpha} + \overline{M}_z^{\alpha} \cdot \alpha + \overline{M}_z^{\delta} \cdot \delta, \\ \dot{\alpha} = \omega_z - \dot{\Theta}, \\ n_y = \dfrac{V \cdot \dot{\Theta}}{g \cdot 57.3}, \\ \delta = W(s) \cdot u, \\ u = K_{\omega z} \cdot \omega_z + K_{ny} \cdot n_y + K_{st} \cdot n_t, \end{cases}$$

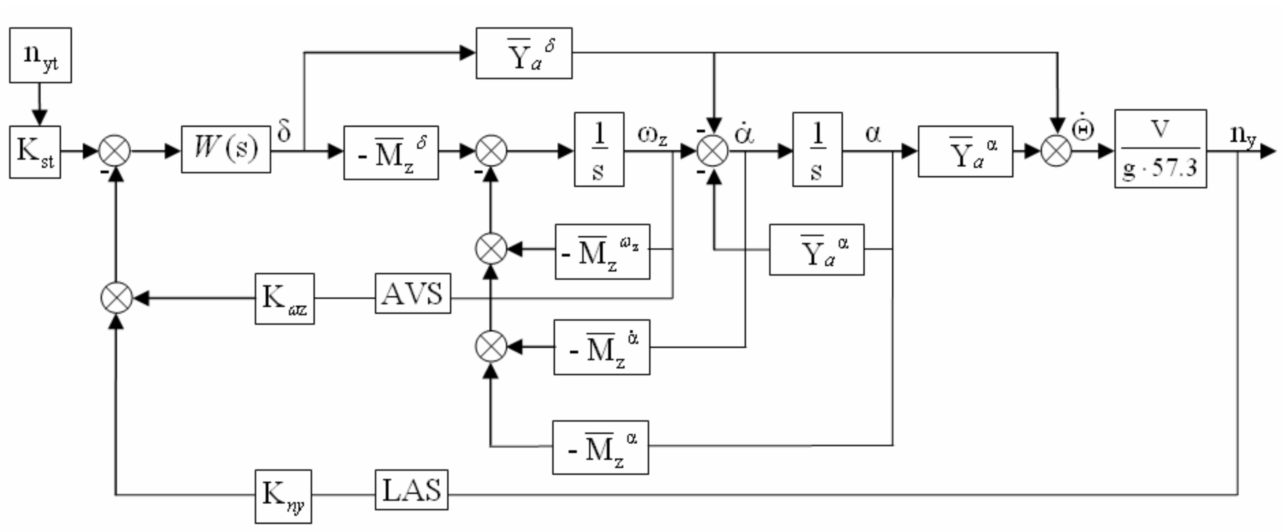

Fig. 1

where θ – flight path angle (deg), α – angle of attack (deg), δ – angle of elevator deflection (deg), ω_z – angular pitch velocity (deg/sec), measured by angular velocity sensor AVS, V – flight velocity (m/s), n_y – normal acceleration measured by linear acceleration sensor LAS. All variables (except for V) are perturbations from their trim values at horizontal flight.

$\overline{Y}_a^{\alpha}$, $\overline{Y}_a^{\delta}$, $\overline{M}_z^{\omega z}$, $\overline{M}_z^{\alpha'}$, $\overline{M}_z^{\alpha}$, $\overline{M}_z^{\delta}$ are the aerodynamic coefficients (AdC), and depend on altitude H and Mach number M (i.e. flight condition). Information of the values of AdC at any moment during the flight allows to calculate the values of controller gains $K_{\omega z}$, K_{ny}, K_{st} that will provide desired stability characteristics. There are no sensors for measuring of AdC on board in flight. Usually they are measured in ground-based experiments using wind tunnel (table 1 for F-101B). In such a way adjustment of control system gains $K_{\omega z}$, K_{ny}, K_{st} in flight is typically done by just their switching at change of flight condition to the values calculated before, it doesn't allow to take into account dynamic of AdC and appearance of additive disturbances. Adaptive control systems functioning on board in flight in real time are deprived of such disadvantage.

3. Classes of adaptive flight control systems

There are two basic classes of adaptive flight control systems (ACS): ACS with reference model (explicit or implicit) and indirect adaptive flight control systems.

3.1 Adaptive flight control systems with reference model

Block diagram representation of the ACS with explicit reference model is shown in fig. 2.

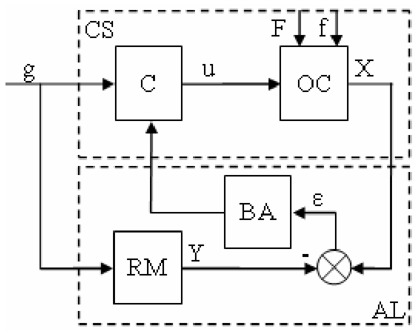

Fig. 2

Here, elements within the dashed box CS represent the main control loop; within AL – adjustment loop; OC is the object of control (aircraft); C - controller; BA – block of adjustment; RM – reference model; g – input signal;

u – control signal; X, Y – measured state vectors of OC and RM respectively; ε – vector of errors; F, f – quasi-steady additive and multiplicative disturbances respectively.

The main disadvantage of such systems with both explicit and implicit reference models lies in that they don't guarantee stability of the system: optimization is carried out on functioning object, it means changes of AdC will have an affect on accuracy and reaction time of block of adjustment and in some cases it causes instability of even stable system. That was verified by the computer simulation results achieved for 7 adjusting parameters [2].

3.2 Indirect adaptive flight control systems

Indirect adaptive flight control systems contain identificator (fig. 3). The process of control consists of two iterative consecutive steps: AdC identification and adjustment of controller gains. In such systems there is no reference model (in explicit form); desired dynamic and static characteristics of stability are included in controller coefficients calculation.

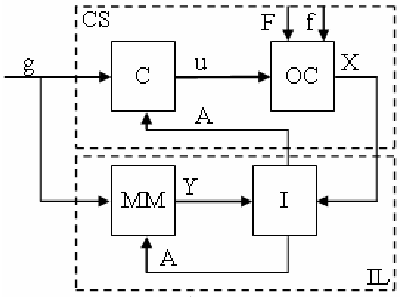

Fig. 3

Here, I is identificator that identifies vector of AdC; IL represents identification loop; MM – adjusting mathematical model realized the control system structure.

Thus, in IACS with identificator the procedure of optimization is out of functioning system and in such a way there is no negative influence of process in IL on the quality of control.

4. Identification of dynamic parameters using Halton Method

4.1 Halton method. Brief description

The Halton method is a little-known method of global multiparametric optimization and constitutes a deterministic analog of global random search. The method consists in use of so called pseudo-random evenly sequences of points as the trial test points.

For random search independent random points are selected as trial test points evenly distributed in allowable area. The probability that at least one point will fall in the small vicinity of a point of minimum U is equal to $P = 1-(1-U)^N$ and tends to 1 at N tends to ∞, i.e. the method converges.

For nonrandom search points are evenly selected (as usual in regular intervals) on allowable area (fig. 4a). But as early as 1957 it was mentioned in [4] that a lot of function calculations are executed needlessly especially if objective function essentially depends on m<n arguments.

Idea of Halton method consists in use of Halton's sequence. In [5] it is proved that the global search on any points from pseudo-random evenly sequences (fig. 4b) converges at big enough N.

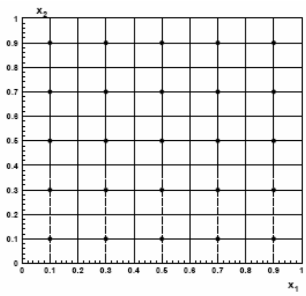

Fig. 4a

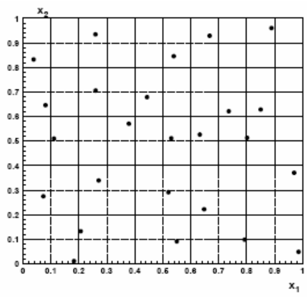

Fig. 4b

The Halton's sequence. If $r_1, r_2, \ldots, r_n$ are the prime numbers, then the Halton's sequence is the sequence of points with Cartesian coordinates $P_i = (p_{r1}(i), p_{r2}(i), \ldots, p_{rn}(i))$, $i = 1, 2, \ldots$, where $p_r(i)$ is the numerical sequence defined as follows.

If in r-based notation $i=a_m a_{m-1} \ldots a_2 a_1$, then in r-based notation $p_r(i)=0.a_m a_{m-1} \ldots a_2 a_1$ (a_s are the integer r-based notation digits, i.e. they are equal one of the follow values 0,1,…, r-1). So in a decimal notation is obtained

$$i = \sum_{s=1}^{m} a_s \cdot r^{s-1}; \; p_r(i) = \sum_{s=1}^{m} a_s \cdot r^{-s}.$$

The advantages of method lie in its more fast convergence in comparison with random search at high accuracy, calculation of Halton's sequence is simple and easy to programming; for application of this method it is not required not only differentiability of objective function (this condition is necessary for application of gradient methods), but even its analytical form - needs only to have an opportunity to calculate values of the objective function in any points of its range; as distinct from other methods this one is effective for solving the problem of large dimensionality (more than 50 variables).

4.1 New approach. Halton Method for dynamic system

A new approach proposed in this work is based on using of global multiparametric optimization in the identificator of IACS. As such a method Halton method was suggested and investigated. The following nomenclature will be used for description of AdC identification and control processes.

n_{cut} – number of measurements of state vector X for each identification cycle;
t_{cut} – time needed for n_{cut} values of X measurements; is equal to the product of least from sensors (AVS, LAS) frequencies and n_{cut} ;
t_{ident} – time of identification;
$t_{st} = t_{ident} + t_{cut}$ – time to start next identification cycle;
$X_{init} = X(t_{st})$ – vector X at time t_{st} ;
$Act_{init} = Act(t_{st})$ – vector of output signals of integrators in actuator at time t_{st} .

Multiparametric optimization for considered problem was formulated as follows: minimization of objective function over unknown parameters. The objective function to be minimized is the sum of errors squares, i.e. squares of differences between measured signals and those of simulated mathematical model respectively:

$$I(A) = \varepsilon = (\omega_z - \omega_{zm})^2 + (n_y - n_{ym})^2, \qquad (1)$$

$$I(A_{opt}) = \min_{a_j} I(A),$$

where a_j are AdC to be identified, ω_z, n_y represent measured output signals of aircraft, ω_{zm}, n_{ym} - output signals of simulated mathematical model respectively.

Fig.5 illustrates identification process (without control) of the proposed approach.

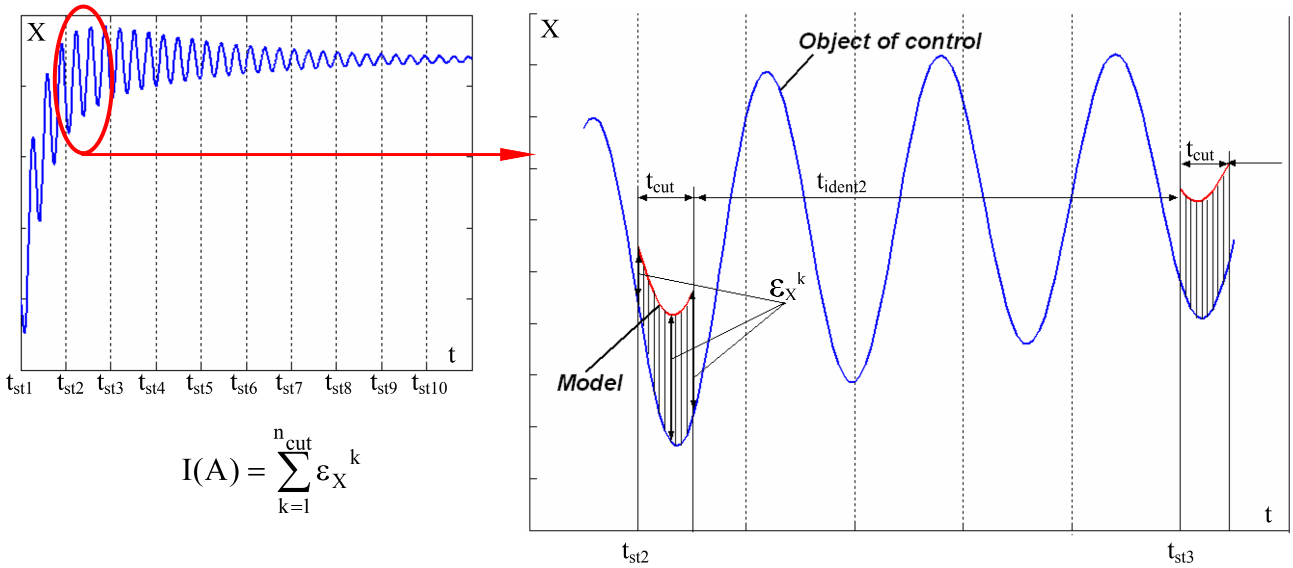

Fig. 5

Basic data for identification are:

1) mathematical model that realized the structure of flight control system;

2) allowable ranges of AdC to be identified;

3) stop of identification condition(s).

Algorithm of identification and control can be described as following sequence of steps (fig. 6).

1) At time t_{st} :

n_{cut} values of measured vector X^m are stored in vectors X^m_{init}, measured vectors Act of actuator are stored in vectors Act^m_{init} and measured vector of input signal g is stored in vector g^m_{init} , where m=1,…, n_{cut}. This process will take t_{cut};

2) Setting in the model:

input signal vector - g^m_{init} (m=1,…, n_{cut});

initial states on integrators X^1_{init}= $X(t_{st})$, Act^1_{init}= $Act(t_{st})$;

3) generation of next AdC vector by Halton method:

$$A_j = A_{j\min} + P_j \cdot (A_{j\max} - A_{j\min}),$$

where [$A_{j\min}$, $A_{j\max}$] is allowable range of coefficient A_j;

4) simulation of the mathematical model on [t_{st}, $t_{st}+t_{cut}$] ;

5) vector of errors ε calculation (Eq. 1);

6) if $\varepsilon<\varepsilon_{min}$ then ε_{min} is equated to ε, i.e. ε is stored as the best value of objective function, current vector A is stored as the current solution of optimization problem;

7) checking of whether stop of identification condition(s) is(are) satisfied or not. They were proposed three conditions:

- by number of calculated trial test points;
- by maximum of time specified for identification;
- by objective function (error) value;

8) if one of the described above stop of identification conditions is satisfied then :

- calculation of controller gains and setting their values in controller of functioning flight control system and mathematical model are carried out;
- next identification is started at time $t_{st} = t_{ident} + t_{cut}$.

Else: continuation of current identification cycle.

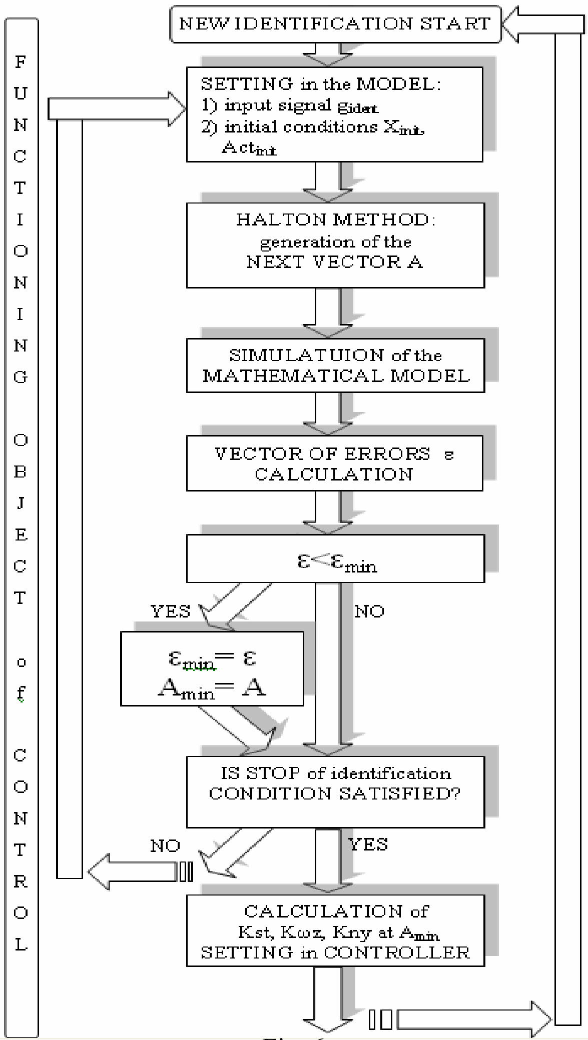

Fig. 6

After each identification cycle is completed identified AdC are used to flight control by calculating and setting of controller gains values. Table 2 shows the formulas obtained on the assumption of $Y_a^\delta = 0$. For simulation it was considered a linear actuator of the second degree with Laplace-domain transfer function :

$$W(s) = \frac{b}{s^2 + a_1 \cdot K_{act1} \cdot s + a_0 \cdot K_{act2}},$$

where $a_1=28$, $a_0=400$ – actuator's unchanged parameters, K_{act1}, K_{act2} are the adjustable gains for control. The most common and troublesome of nonlinearities existed in the aircraft description is actuator saturation, particularly rate saturation. Extension of the method described herein to such a nonlinearities will be investigated.

5. Simulation results

Simulation has been conducted by using Matlab. Block diagrams of aircraft and mathematical model were created in Simulink. The main program automates of identification which has been described above and is written in m-file that can be easily transformed into executable code for using on board. Moreover it was created a graphical user interface provided users to choose optimization parameters and to see all results in real time on screen in interactive mode.

The effectiveness of the presented method was confirmed from the computer simulation. Proposing method was validated on 2-6 unknown parameters to be identified. Table 3 summarizes some simulation results.

Herein, allowable ranges of AdC were taken from data of F-101B wind-tunnel for H=10 - 13.5 km (table 4). It's possible to consider all flight conditions (H=0 – 13.5 km), results of such simulation showed that the method works with same stability, but without quite adequate compromise between accuracy and desired time of identification.

Table 3

Results of simulation

number of unknown parameters	number of test points	parameter	Parameter value		accuracy, %	time of identification	Controller gains		
			real	estimated			gain	for real values	for identified values
2	50	$\overline{M}_z^{\omega_z}$	0.918	0.96719	5.36	1.041	K_{st}	0.000228372	0.000228074
		$\overline{M}_z^{\delta}$	23.87	23.9012	0.13		K_{act1}	0.08368	0.08192
							K_{act2}	-0.0755	-0.0756
							K_{wz}	-0.0023	-0.0019
							K_{ny}	0.22634	0.22627
3	100	$\overline{M}_z^{\omega_z}$	0.918	0.91797	0.00	2.023	K_{st}	0.000228372	0.000225562
		$\overline{Y}_a^{\alpha}$	0.667	0.67531	1.25		K_{act1}	0.08368	0.08338
		$\overline{M}_z^{\alpha}$	0.0782	0.0768	1.79		K_{act2}	-0.0755	-0.0755
							K_{wz}	-0.0023	-0.0022
							K_{ny}	0.22634	0.22367
4	100	$\overline{M}_z^{\delta}$	23.87	24.5156	2.7	2.043	K_{st}	0.000228372	0.000278783
		$\overline{M}_z^{\alpha}$	31.7	32.5004	2.52		K_{act1}	0.08368	0.08703
		$\overline{Y}_a^{\alpha}$	0.667	0.532	20.24		K_{act2}	-0.0755	-0.077
		$\overline{M}_z^{\omega_z}$	0.918	0.95918	4.49		K_{wz}	-0.0023	-0.0029
							K_{ny}	0.22634	0.2881
5	100	$\overline{Y}_a^{\delta}$	0.0782	0.049219	36.90	2.041	K_{st}	0.000228372	0.00024992
		$\overline{M}_z^{\delta}$	23.87	24.2222	1.48		K_{act1}	0.08368	0.08332
		$\overline{M}_z^{\omega_z}$	0.918	0.9944	8.32		K_{act2}	-0.0755	-0.0737
		$\overline{M}_z^{\alpha}$	31.7	31.0064	2.19		K_{wz}	-0.0023	-0.0021
		$\overline{Y}_a^{\alpha}$	0.667	0.60063	9.92		K_{ny}	0.22634	0.23628
6	100	$\overline{M}_z^{\omega_z}$	0.918	0.98359	7.15	2.053	K_{st}	0.000228372	0.000252401
		$\overline{Y}_a^{\alpha}$	0.667	0.61152	8.32		K_{act1}	0.08368	0.08432
		$\overline{M}_z^{\alpha}$	0.072	0.043832	39.12		K_{act2}	-0.0755	-0.0802
		$\overline{M}_z^{\alpha}$	31.7	33.607	6.02		K_{wz}	-0.0023	-0.0026
		$\overline{M}_z^{\delta}$	23.87	23.557	1.33		K_{ny}	0.22634	0.28096
		$\overline{Y}_a^{\delta}$	0.0782	0.076923	1.63				

As shown in table 3 time of 2-6 parameters of model adjusting during each identification cycle for step and sine wave input signals is 1-2 sec. (it's necessary to take into account that this is just computational time of PC program run that will be obviously less at hardware realization). For 2, 3 unknown parameters in the most cases time of 1 sec. is enough for identification to a high accuracy (0-5.5%). Identification of 4-6 unknown parameters is less accurate for maintaining desired time but it's enough for qualitative control because of satisfactory accuracy of values of controller gains. In some experiments disturbances were considered as additional unknown parameters for identification. Obtained results demonstrates that the proposed identification will be sensible to any AdC changes and will provide stability of flight control system.

6. Conclusion

The new method of identification of aircraft parameters is proposed. This method is based on using global multiparametric optimization – Halton method - in the identificator of indirect adaptive flight control system. On conditions that angle of attack, angular pitch velocity and normal acceleration are measured by sensors, in system it is realized procedure of search of model parameters that will provide a global minimum of quadratic estimated function with respect to deviations of angle of attack, pitch rate and normal acceleration values from those in model.

This method guarantees stability of control system with enough high accuracy of identification, contrastingly, the development of convenient adaptive procedure in flight control systems with both explicit and implicit reference models don't guarantee stability of the system: optimization is carried out on functioning object that in some cases can cause instability of even stable system. Algorithm has confirmed efficiency of its use on example of flight control system design for F-101B with identification 2-6 unknown coefficients with and without additive and multiplicative disturbances.

For using of the method it is required to have full and correct information about allowable range of each parameter to be identified.

It should be mentioned that the proposed method can be successfully applied not only in longitudinal control, but also in any system with unknown parameters for identification and optimization.

Investigations should be conducted in direct of improving the method by its combination with existed gradient methods for obtaining the best compromise between accuracy and time of identification. It is of particular interest to extend the method to the aircraft with significant nonlinearities such as actuator saturation.

References

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Table 1

F-101B dynamic coefficients depending on flight condition

H	M	$\bar{M}_z^{\omega_z}$	$\bar{M}_z^{\alpha}$	$\bar{M}_z^{\alpha}$	$\bar{Y}_a^{\alpha}$	$\bar{M}_z^{\delta}$	$\bar{Y}_a^{\delta}$	V	$V/(g\cdot 57.3)$
0	0,2	0,56	0,096	1,6	0,392	2,792	0,0529	340,3	0,121202
0	0,3	0,838	0,146	3,6	0,578	6,216	0,0794	340,3	0,181804
…									
0	0,9	2,704	0,506	40,86	2,041	59,522	0,2535	340,3	0,545411
0	1	2,808	0,294	68,04	2,017	58,932	0,2228	340,3	0,606012
3	0,32	0,638	0,112	2,82	0,43	4,894	0,0598	328,6	0,187256
3	0,4	0,792	0,144	4,4	0,544	7,57	0,0747	328,6	0,234071
3	0,5	0,998	0,184	6,8	0,677	11,834	0,0944	328,6	0,292588
…									
10.5	1,8	0,888	0,024	46,48	0,669	29,702	0,0727	297	0,952025
…									
13.5	1,5	0,53	0,006	26,06	0,469	17,068	0,0492	295	0,788012
13.5	1,6	0,538	0,006	28,34	0,472	18	0,0486	295	0,840546
13.5	1,7	0,554	0,014	30,18	0,47	18,898	0,0475	295	0,89308
13.5	1,8	0,574	0,016	31,42	0,465	19,706	0,0474	295	0,945614

Table 4

Allowable ranges of parameters

range	$\bar{M}_z^{\omega_z}$	$\bar{Y}_a^{\alpha}$	$\bar{Y}_a^{\delta}$	$\bar{M}_z^{\alpha}$	$\bar{M}_z^{\delta}$	$\bar{M}_z^{\alpha}$
min	0.3	0.2	0.035	2.4	4	0
max	1	0.7	0.081	47	30	0.2

Table 2

Controller gains calculation after identification cycle is completed

$$W_{ny}(s)=\frac{D}{s^4+F\cdot s^3+G\cdot s^2+H\cdot s+I} - \textit{transfer function from } n_{yt} \textit{ to } n_y$$

where

$$D=K_{st}\cdot\bar{M}_z^{\delta}\cdot b\cdot\bar{Y}_a^{\alpha}\cdot V\cdot g/57.3;$$

$$F=\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha'}+\bar{M}_z^{\omega z}+a_1^{c};$$

$$G=\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha}+a_1^{c}\cdot(\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha'}+\bar{M}_z^{\omega z})+a_0^{c};$$

$$H=a_1^{c}\cdot(\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha})-\bar{M}_z^{\delta}\cdot b\cdot K_{\omega z}+a_0^{c}\cdot(\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha'}+\bar{M}_z^{\omega z});$$

$$I=a_0^{c}\cdot(\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha})-\bar{M}_z^{\delta}\cdot b\cdot K_{\omega z}\cdot\bar{Y}_a^{\alpha}-K_{ny}\cdot\bar{M}_z^{\delta}\cdot b\cdot\bar{Y}_a^{\alpha}\cdot V\cdot g/57.3.$$

$$a_0^{c}=a_0\cdot K_{act2};\ -\ \textit{actuator gains}$$

$$a_1^{c}=a_1\cdot K_{act1};$$

$$W_{ny}^{d}(s)=\frac{D}{s^4+F_d\cdot s^3+G_d\cdot s^2+H_d\cdot s+I_d}, \text{where } F_d,\ G_d,\ H_d,\ I_d \ \textit{- desired characteristics of stability}$$

$$W_{ny}^{d}(s)=W_{ny}(s)\Rightarrow\begin{cases}D=D_d;\\ F=F_d;\\ G=G_d;\\ H=H_d;\\ I=I_d.\end{cases}\Rightarrow\begin{cases}K_{st}=\dfrac{D_d}{\bar{M}_z^{\delta}\cdot b\cdot\bar{Y}_a^{\alpha}\cdot V\cdot g/57.3};\\ K_{act1}=\dfrac{F_d-\bar{Y}_a^{\alpha}-\bar{M}_z^{\alpha'}-\bar{M}_z^{\omega z}}{a_1};\\ K_{act2}=\dfrac{G_d-\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}-\bar{M}_z^{\alpha}-a_1^{c}\cdot(\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha'}+\bar{M}_z^{\omega z})}{a_0};\\ K_{\omega z}=\dfrac{a_0^{c}\cdot(\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha'}+\bar{M}_z^{\omega z})+a_1^{c}\cdot(\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha})-H_d}{\bar{M}_z^{\delta}\cdot b};\\ K_{ny}=\dfrac{a_0^{c}\cdot(\bar{M}_z^{\omega z}\cdot\bar{Y}_a^{\alpha}+\bar{M}_z^{\alpha})-\bar{M}_z^{\delta}\cdot b\cdot K_{\omega z}\cdot\bar{Y}_a^{\alpha}-I_d}{\bar{M}_z^{\delta}\cdot b\cdot\bar{Y}_a^{\alpha}\cdot V\cdot g/57.3}.\end{cases}$$