DOI: 10.13009/EUCASS2022-4660
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Flight Dynamics and Model Based Control for Fixed Wing UAV Demonstrator

Valentin Penev
Institute of Mechanics – Bulgarian Academy of Sciences, Sofia, Bulgaria
First Author's Address

Abstract
A novel approach for the investigation of non-minimum phase behavior of autonomous platforms has been proposed by the author. The designed LFDCD allows analysis and design of model based control at subsonic velocities.
The paper describes design of the aerodynamics and how tuning of model based control works and enumerates performance advantages. It gives an overview of previous experimental and numerical work in raising the TRL. Now NMP behavior requires examination because more and more highly non-linear platforms behave in similar way. The combination between highly non-linear systems, NMP and high precision even without hypersonic velocities is interesting present-day problem.

Abbreviations

HSV	Hypersonic vehicle
LFDCD	Low Cost Flight Dynamics and Control Demonstrator for Mini Aerial Vehicles
NMP	Non-minimum phase (behavior)
PA	Primary aerodynamics – aerodynamics of test bed airframe without secondary control surfaces
pFLCS	Primary FLCS
SA	Secondary aerodynamics – aerodynamics of test bed with secondary control surfaces
sFLCS	Secondary FLCS – responsible for reshaping the response of TAF test bed frame
TAF	Test bed air frame

1. Introduction

"The hypersonic regime introduces a number of features such as: extremely high turbulence, pressure, temperature, density, vorticity, energy, thin shock layers, viscous interactions, entropy layers, changes in vehicle stability and control; and physical-chemical gas changes such as ionization, dissociation, equilibrium effects, and other molecular phenomena. Flight control for hypersonic velocity vehicle is extremely challenging and inspiring due to the combination of nonlinear dynamics, parametric uncertainty and complex constraints. One of the general problems to be solved is flight control design and testing for autonomous hypersonic vehicles. Flight testing of hypersonic vehicles is an expensive effort and it is quite effective to verify such technologies through small-scale flight tests in practical subsonic-speed environments, prior to installation to large-scale vehicles.
The low cost requirement to LFDCD limits the following parameters:

- Size of simulated aircraft – wing span, tail span etc.
- Air speed developed by thrust propeller, lift and drag respectively.
- Angle of attack and side slip angle.
- Roll and pitch ranges

In spite of low cost requirement, the main objective of the research is to reproduce and investigate the following well-known problematic features of hypersonic flight [1,2,3,4,5,6] with reasonable average level of fidelity (higher than low cost-low fidelity):

- Uncertainty of stability and control derivatives
- Non-minimum phase behavior of flight path angle dynamics of the system
- Pulsed roll angle bank maneuver for a hypersonic glider
- Stable and controllable behavior at high AoA and low subsonic speed, which reminds the transition from ballistic descent to hypersonic gliding

The relationship between the problematic feature (set of aerodynamics parameters) of hypersonic flight and related platform response is determined with one purpose to replace the feature with artificially created response. Usage of

DOI: 10.13009/EUCASS2022-4660

that artificially created response will allow using subsonic flight and scaled down TAF to investigate flight control problems of hypersonic vehicle. The problematic features could be observed not only in hypersonic flights. It is assumed at very high degree of confidence, that with those restrictions it is not possible to reproduce the required flight conditions with TAF equipped only with pFLCS and primary control surfaces. Since, sFLCS and secondary control surfaces are used to imitate the required response. The response generated by secondary control surfaces is called modified open loop system response. The role of pFLCS or tested flight control system is to shape modified open loop system response to desired response.
NMP behavior is natural to subsonic flights as well. Moving the elevator downwards for a pitch down maneuver finally causes increased lift at the elevator. Increase lift leads to a negative pitching moment, and thus to a pitch down rotation because the center of gravity is in front of the elevator. Initially the increased lift leads to a gain of height, because your aircraft generates more lift just before the pitching moment sets in. At the instant the deflection of the elevator happens, the upward force on the tail pushes the whole aircraft up relative to the inertial reference frame. Therefore, the center of mass of the aircraft goes up initially due to the upward force on the tail before the lift on the main wing decreases, causing the center of mass to descent. That natural effect NMP is lasting for a very short time, even in some specific application it could be ignored and it is not easily explored.
Now NMP behavior requires appropriate investigation, because more and more highly non-linear platforms behave in a similar way. The combination between highly non-linear systems, non-minimal behavior and high precision even without hypersonic velocities is an interesting present-day problem. That natural effect is lasting for very short time, even in some specific application it could be ignored. The LFDCD is designed [9,10,11,12] for investigation of non-minimum phase behavior of autonomous platforms with different complexity and quality.

1.1 State of the art

A dynamically scaled model is one that responds in a scaled manner with respect to the full-scale aircraft, when subjected to inertial loads in addition to other aerodynamic loads. To do this, one must properly scale the weight or mass distribution of the aircraft. This is accomplished by scaling the mass moments of inertia about the three axes of rotation at the center of gravity. If done properly, the sub-scale aircraft should maneuver in dynamic scale of its full-scale counter-part. A good example of physical reshaping the air frame is to have a variable static stability of pitching moment or change the response of system to non-minimal phase object. The problem results from the differences in the nature of the aerodynamics at low and high speeds. The Reynold's number (Rn) is usually used as a standard of comparison here and can be used to account for differences in parameters like lift and drag on various objects. Wind tunnel models tend to have low Rn due their smaller size when compared to full-sized aircraft. The result of this difference in Rn is an increase in the drag coefficient along with a reduction in the lift coefficient. To avoid the problems with Reynold's numbers, it is important that the model to be, physically, as large as possible to keep the Rn as high as possible. Another parameter to consider when scaling is Mach number. In this research, Mach number difference is not nearly as important as Rn, as both the model and the full-scale aircraft fly at speeds well within the incompressible range. Turbulence in the air can also cause unwanted problems for a sub-scale flight-test vehicle. Since scaling an aircraft to produce a model does not reduce the scale of turbulent eddies and wind gusts in the atmosphere, the model must be built to accommodate larger g-loads.

1.2 Technical objectives and requirements

LFDCD has been developed to facilitate academic research into improving techniques for the attitude control of fixed wing aircraft basically with NMP behavior. During the initial phase of research some aerodynamics platforms (depicted in next Figure 1) have been investigated. The test beds showed good performance.

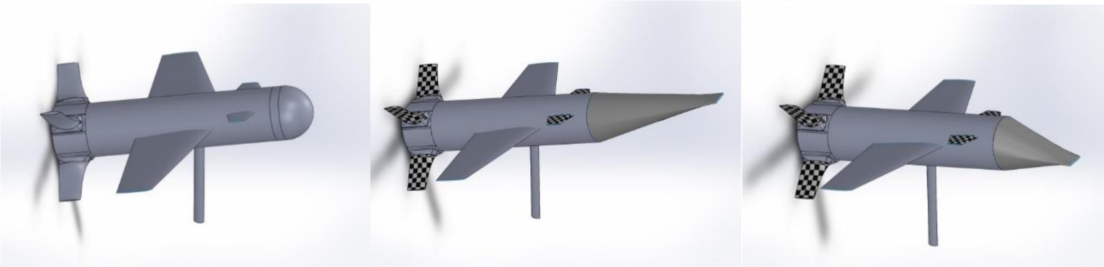

Figure 1: Some early candidates for test-bed airframe

Finally, it was decided to combine the efforts with CATLTR. CATLTR system is primarily designed to detect segment and track the cattle. The CATLTR is a small size fixed wing platform, which is hand-held launched. The introduction of system equipped with two cameras daylight and infrared into the modern husbandry has given veterinarians the ability to remotely find a physiology state of cattle. The operating range is about 15 km and flight time is about an hour. Once the target field is identified into the map, the vehicle will fly autonomously to the field and will start loitering to identify the cattle. The vehicle needs further operator input during flight to lock individual object. By its nature, CATLTR system should use precision sensors (tactical grade) and guidance, but it was decided to use low-cost sensors and try to achieve best performance from them. It was one of the goals of the research to investigate low-cost attitude reference heading system to meet the requirement for high precision guidance. The platform shows NMP behavior

The work reported here develops a six degree-of-freedom (DOF) model [1,2,3,5,7,8,15] of the CATLTR vehicle [7,8]. In addition, a guidance algorithm is developed to mimic the flying modes of the actual system. The aerodynamics of the airframe and control surfaces are modeled separately to isolate possible changes from interaction and demonstrate their effects in simulation. Partial test flights of a CATLTR are used to verify the accuracy of the proposed model and guidance algorithms. The CATLTR is roll controlled and it is also demonstrated that the orientation of the strapped-down seeker around the airframe is a significant factor in its response to damage.

Tandem aerodynamics satisfies very well requirements for PA, SA, pFLCS and sFLCS. There are 3 core elements in the research: secondary control surfaces – position, orientation, dimensions and shape. Those parameters depend on the test bed airframe aerodynamics and requirements for response of system. Primary FLCS Secondary FLCS

The reference model of non-minimum phase behavior should be chosen very carefully, because they are some physical limitations, which could not be implemented.

Table 1: Requirements

No.	Req.	Description
Req 1	TAF aerodynamics should provide as close as possible to features of hypersonic flight	In spite of low cost requirement the following well known problematic features of hypersonic flight with reasonable average level of fidelity will be reproduced.
Req 2	The sFLCS reshapes the response of TAF to the required open system loop	The control algorithms of sFLCS are capable to provide 0.002 seconds control response time. Two reliable algorithms for AHRS should be executed simultaneously in the same time step. The response of open loop system should be as close as possible to problematic features of hypersonic flight responses
Req 3	The pFLCS and its control algorithms are responsible for the overall closed loop system response of the TAF	The control algorithms of pFLCS should be capable to provide 0.002 sec control response time. Two reliable algorithms for AHRS should be executed simultaneously in the same time step. Aerodynamics model of the test bed with different levels of details, which will be used as reference model in the control loop: Adaptive Model based control; Inverse dynamics control; Gain Scheduled; Three loop structure; Sliding mode control

Novel model based control and its algorithm for tuning are proposed and tested in the simulation and real flights. Partial flight log data is compared to that of the proposed model and it is shown that the model accurately replicates the true flight dynamics. The strapped-down seeker model passes the deflections of the target from Line-of-Sight to the autopilot. The results predict that the vehicle’s performance in response to excessive roll, pitch and yaw is extremely sensitive to the quality of guidance. The joint simulation model demonstrated was highly dependent on failure of the seeker used for guidance due to oscillation at some degree of the roll, pitch and yawing of the airframe.

The above problems (issues) restrict the flight dynamics of tested air platform and keep the test price high. One of the way to keep the cost of demonstrator low is to deploy secondary Flight Control System. sFLCS has its own control surfaces, which will increase substantially the variety of tested flight dynamics and control laws, in spite the low air velocity and small size of test bed.

2. Aerodynamics of demonstrator

According to mission requirements, previous experience and analysis of contemporary achievements, the tandem fixed wing configuration was selected – Figure 1. Tandem aerodynamic configuration has fewer oscillations in roll, pitch and azimuth and good controllability.

DOI: 10.13009/EUCASS2022-4660

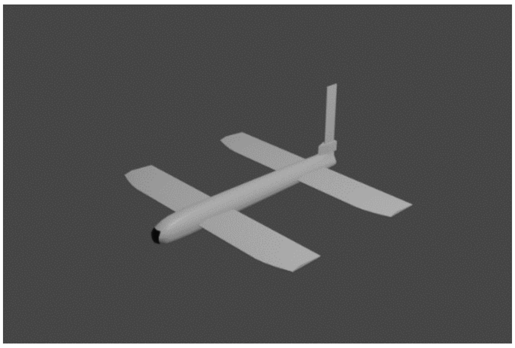

Figure 2. Tandem aerodynamics configuration

2.1. Defining vehicle geometry

Relationship between the problematic feature (set of aerodynamics parameters) of hypersonic flight and related platform response is determined with one purpose to replace the feature with artificially created response. Usage of that artificially created response will allow using subsonic flight and scaled-down vehicle to investigate flight control problems of hypersonic platforms and subsonic flights with NMP behavior.
The 3 core elements in the design of flight control system are:

- Secondary control surfaces – position, orientation, dimensions and shape. Those parameters depend on the test bed airframe, aerodynamics and requirements for response of system.
- Primary FLCS (pFLCS)
- Secondary FLCS (sFLCS)

As it said, it is assumed at very high degree of confidence, that with those restrictions the test bed will not be able to reproduce the required flight conditions with only one pFLCS and primary control surfaces. The response generated by secondary control surfaces is called modified open loop system response. The role of pFLCS or tested flight control system is to shape modified open loop system response to desired closed system loop. The proposed sFLCS will be able to reproduce the NMP behavior problematic feature of hypersonic and/or subsonic flight using adaptive model based control law.
Relevant geometry model was developed in the environment of Fluent (ANSYS). The demonstrator of atmospheric entry vehicles presumes that flight path profile is often determined a priori. The geometry of this tandem fixed-wing platform is described below. The original design objective for this geometry was a general aviation UAV that was safe, simple to fly, and easily maintainable with specific mission and performance constraints. Potential performance requirements for this aircraft include: level cruise speed; acceptable rate of descent and climb; acceptable stall speed; controllable low level velocity flight. The incomplete input set for calculating the forces, moments, aerodynamic coefficients and derivatives is given in Table 2.

Table 2: LFDCD UAV geometry

LFDCD UAV Specifications	
Wingspan (one wing)	0.6 m
Fuselage Length	0.725 m
Max Speed	170 Km/h
Cruise Speed	40 Km/h
Min Speed	10 Km/h
Max Takeoff Weight	2 Kg
FPA during terminal stage	-3°

2.2. Determining vehicle aerodynamics and flight dynamics equation

Analytical prediction is a quicker and less expensive way to estimate aerodynamic characteristics in the early stages of design. The airframe model incorporates several key assumptions and limitations: The airframe is rigid body and has constant mass, center of gravity, and inertia; CATLETR is laterally symmetric vehicle; Control effectiveness varies nonlinearly with angle of attack and linearly with angle of deflection and air velocity. Control effectiveness is not dependent on sideslip angle.
Two flight dynamics models have been developed [1,2,7]. The first one was precisely describing behavior model or proposed aerodynamics configuration. The second one is real time one, which does not allow lost in performance during the defined flight envelope. The core of the simulation model is a non-linear model of the aircraft dynamics, consisting of twelve ordinary differential equations, and a large number of output equations. This model can be

broken down into a number of different modules, most of which are independent of the kind of moving vehicle under consideration.
u, v, w - Body fixed linear velocity components in forward, side, and vertical directions, m/s;
$\dot{u}, \dot{v}, \dot{w}$ - Linear accelerations, m/s^2;
Xa, Ya, Za - body forces per unit mass, N/kg;
p, q, r - Body fixed roll, pitch, and yaw rates;
g - Acceleration due to gravity, m/s^2;
Linear accelerations equations

$$\dot{u} = rv - qw - g\sin\theta + X_a$$
$$\dot{v} = pw - ru + g\sin\varphi\cos\theta + Y_a$$
$$\dot{w} = qu - pv + g\cos\varphi\cos\theta + Z_a$$

Angular accelerations equations

$$\dot{p} = C_3L + C_4N + C_2pq + C_1qr$$
$$\dot{q} = C_7M + C_6(p^2 - r^2) + C_5pr$$
$$\dot{r} = C_4L + C_9N + C_8pq - C_2rq$$

where,

$$C_1 = \left((I_{yy} - I_{zz})I_{zz} - I_{xz}^2\right) / (I_{xx}I_{zz} - I_{xz}^2)$$
$$C_2 = (I_{xx} - I_{yy} + I_{zz})I_{zz} / (I_{xx}I_{zz} - I_{xz}^2)$$
$$C_3 = I_{zz} / (I_{xx}I_{zz} - I_{xz}^2)$$
$$C_4 = I_{xz} / (I_{xx}I_{zz} - I_{xz}^2)$$
$$C_5 = (I_{zz} - I_{xx}) / I_{yy}$$
$$C_6 = I_{xz} / I_{yy}$$
$$C_7 = 1 / I_{yy}$$
$$C_8 = (I_{xx} - I_{yy})1_{xx} + I_{xz}^2 / (I_{xx}I_{zz} - I_{xz}^2)$$
$$C_9 = I_{xx} / (I_{xx}I_{zz} - I_{xz}^2)$$

$\dot{p}, \dot{q}, \dot{r}$ - roll, pitch and yaw angular acceleration
I_{xx}, I_{yy}, I_{zz}- Moments of inertia about x, y, and z axis, kg.m^2
L, M, N - Roll, pitch, and yaw moments about body axis, N. m;
First derivatives of roll, pitch and yaw are listed below:

$$\dot{\theta} = q\cos\varphi - r\sin\varphi$$
$$\dot{\varphi} = p + q\sin\varphi\tan\theta + r\cos\varphi\tan\theta$$
$$\dot{\psi} = q\sin\varphi\sec\theta + r\cos\varphi\sec\psi\,\theta$$
$$[X_aY_aZ_a] = \frac{\overline{q}\,S}{\overline{m}}\left[C_X\ C_Y\ C_Z\right]$$
$$[L\ M\ N] = \overline{q}\,S\left[b\,C_l\ c\,C_m\ b\,C_n\right]$$

The general set of aerodynamics coefficients equations (1) could be rewritten in specific way of terms of ANSYS FLUENT

$$C_x = -CX + CX_P - CX_Q\,(C_{X_q}\frac{q\bar{c}}{V}) + CX_R + CX_{ailP} + CX_{ailS} + CX_{elS} - CX_{elP} + CX_{rud} \quad \textbf{(1)}$$
$$C_y = CY + CY_P(C_{Y_p}\frac{p\bar{c}}{V}) + CY_Q - CY_R(C_{Y_r}\frac{r\bar{c}}{V}) + CY_{ailP} + CY_{ailS} + CY_{elP} - CY_{els} + CY_{rud}$$
$$C_z = -CZ + CZ_P - CZ_Q(C_{Z_q}\frac{q\bar{c}}{V}) + CZ_R + CZ_{ailP} + CZ_{ailS} + CZ_{elP} - CZ_{elS} + CZ_{rud}$$
$$C_l = -Cl + Cl_P(C_{l_p}\frac{q\bar{c}}{V}) + Cl_Q + Cl_R(C_{l_r}\frac{q\bar{c}}{V}) - Cl_{ailP} - Cl_{ailS} + Cl_{elP} - Cl_{elS} + Cl_{rud}$$
$$C_m = -Cm - Cm_P + Cm_Q(C_{m_q}\frac{q\bar{c}}{V}) - Cm_R + Cm_{ailP} + Cm_{ailS} + Cm_{elP} - Cm_{elS} + Cm_{rud}$$
$$C_n = -Cn - Cn_P(C_{n_p}\frac{q\bar{c}}{V}) + Cn_Q + Cn_R(C_{n_r}\frac{q\bar{c}}{V}) - Cn_{ailP} - Cn_{ailS} + Cn_{elP} - Cn_{elS} + Cn_{rud}$$

DOI: 10.13009/EUCASS2022-4660

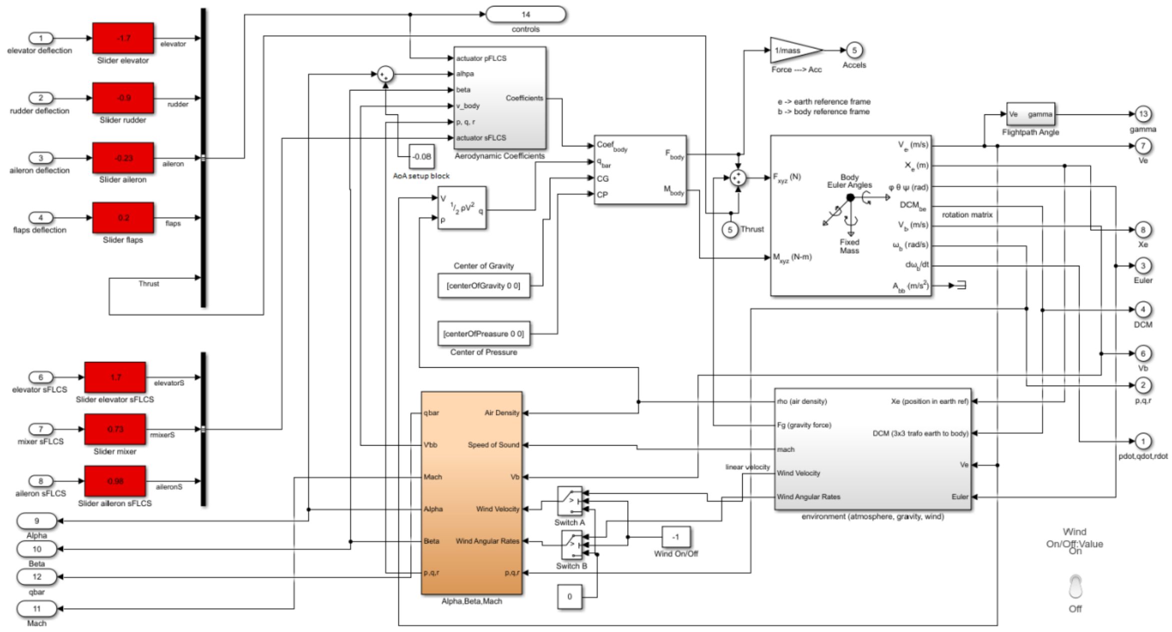

Figure 3: General flight dynamics block diagram

AoA setup block creates an artificial angle of attack here and its role will be defined in next chapter. Front and aft wings of tandem has elevons, but here two separate signals of aileron and elevators are used because of the way of calculations of coefficients of control surfaces. FLCS calculate separately aileron and elevator commands and mix them in one joint elevons command.

2.3. Aerodynamics coefficients for constructing forces and moments

Tandem aircraft is a typical fixed-wing UAV with geometry and control surfaces [2,4,6,11]. The typical airframe model consists of a number of subsystems, such as: equations of motion; environmental models; calculation of aerodynamic coefficients, forces, and moments; environmental models; alpha, beta, Mach; aerodynamic coefficients; forces and moments. All look-up tables calculated by Fluent (ANSYS) are implemented in the flight model. Body-fixed reference frame is used, to specify forces, moments and angles. Primary control surfaces are primary elevons and primary rudder. Secondary control surfaces are secondary elevons and secondary mixer (specific usage).

$C_X = C_X(\alpha,\beta,\delta_{ap},\delta_{ep},\delta_{as},\delta_{es},\delta_r);\quad C_{l_a} = C_l(\alpha,\beta,p,r,\delta_u,\delta_r,\delta_{ap},\delta_{ep},\delta_{as},\delta_{es});$
$C_Y = C_Y(\alpha,\beta,p,r,\delta_{ap},\delta_{ep},\delta_{as},\delta_{es},\delta_r);\quad C_m = C_m(\alpha,q,\delta_{ep},\delta_{es});$
$C_Z = C_Z(\alpha,q,\delta_{ep},\delta_{es});\quad C_n = C_n(\alpha,\beta,p,r,\delta_u,\delta_r);$

The result of calculation of aerodynamic coefficients is split in three standard categories: Datum coefficients; Damping coefficients and Control surface deflection coefficients (See Figure 4)

DOI: 10.13009/EUCASS2022-4660

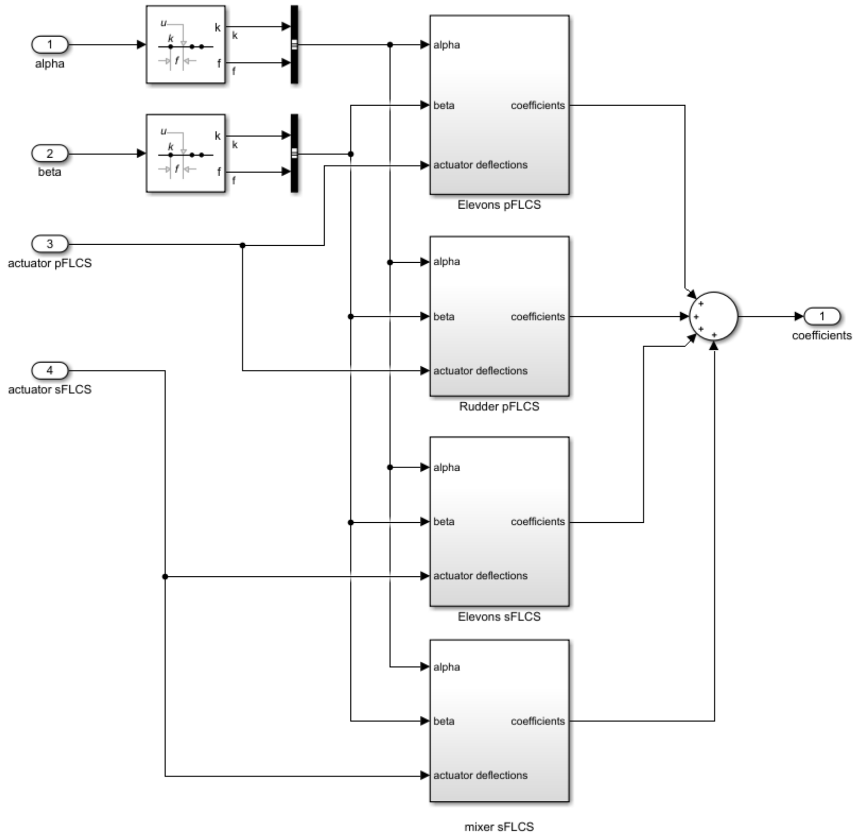

Figure 4: Block diagram of control surfaces coefficients in simulation

3. Model based control

Novel approach is proposed to create NMP behavior of the platform. The same approach is used to control the same platform. The primary aerodynamics PA, which describe the platform has some short period non-minimum phase behavior during entire flight envelope especially at high AoA and low speeds. Successful real-time implementation of trajectory guidance algorithms has employed approximate methods that either assume some knowledge of the flight mechanics and/or make assumptions to reduce the dimensionality of the dynamical system.

Instead, intuitive and robust MB control is used. Proposed MBC approach could be used for: azimuth, bank or pitch control. The concept of proposed MBC [7, 8] includes two basic steps: design the reference trajectory or required response and design the model following controller. The model based control concept works well with proposed approach of using sFLCS and pFLCS. If the primary aerodynamics is minimum phase (or zero dynamics for nonlinear), it could be converted to non-minimum phase response, adding non-minimum phase response to sFLCS, which will be generated by secondary control surface directly. During the simulation azimuth demand is changed from 0 to 10 °. The advantages of proposed algorithm are:

- Two-loops MBC autopilot with angular position and angular velocity (Figure 6, Figure 7a and Figure 7b).
- Off-line procedure for tuning the parameters of control – complete search for optimal solution.
- Robust control to the changes of flight parameters and environment

Many different forms of autopilot had been studied in some literatures [6,7,10,11,12,13,14].

Position and velocity reference models for NMP behavior are defined as follow:

$$F_{posRM} = \frac{(s-t_1)(s+t_2)}{(s^2+p_1 s+p_2)} \; ; \; F_{velRM} = \left[\frac{(s-t_1)(s+t_2)}{(s^2+p_1 s+p_2)}\right] s$$

Proposed scheme is two-loops control law, where the position is calculated first. Velocity reference model is determined as differentiation in appropriate way of position reference model. Transient response of typical position response model is shown in Figure 5, NMP behavior is obvious. Interesting cases are observed when the static gain of reference NMP model is relatively small and when the velocity reference model is slightly different than differentiated position model. The relatively small static gain could be used for having NMP behavior just in the beginning of transition process.

DOI: 10.13009/EUCASS2022-4660

The input to the reference model is elevator demand. Some of examined transfer functions for reference models are given below:

$$NMP(s) = \frac{(s-68.8)(s+0.6)}{(s^2+0.00466s+0.0053)(s^2+0.806s+1.311)} \quad (8)$$

$$NMP(s) = \frac{(s-68.8)(s+0.6)}{(s^2+0.81s+1.311)}; \; NMP(s) = \frac{(s-27.3)}{(s^2+0.61s+1.311)}; \; NMP(s) = \frac{(s-12.3)}{(s^2+0.61s+1.311)}$$

$$\mathrm{NMP(s)} = \frac{(\mathrm{s}-11.3)(\mathrm{s}+0.6)}{(\mathrm{s}^2+0.61\mathrm{s}+1.31)} = 4\,\frac{\mathrm{s}^2-13.56\mathrm{s}+0.36}{\mathrm{s}^2+0.61\mathrm{s}+1.31}$$

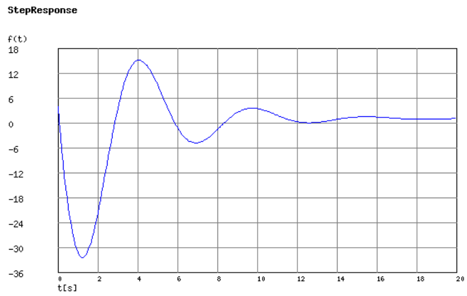

Figure 5: Typical NMP transition process to step input

The reference model has two feedback signals proportional (pitch) and velocity (pitch rate), shown in the Figure 6. Consequently, the proposed MBC has also two simple gains: proportional and velocity.

$$K_p = (P_{min}, P_{max});\ K_v = (V_{min}, V_{max})$$

The ranges of feedback gains describing the influence of position and velocity reference models are defined in the following way:

$$K_{rp} = (RP_{min}, RP_{max});\ K_{rv} = (RV_{min}, RV_{max});\ K_{ar} = (AR_{min}, AR_{max}) \text{ if needed}$$

The steps of gain changes are determined as d_p, d_v, d_{rp} and d_{rv}.

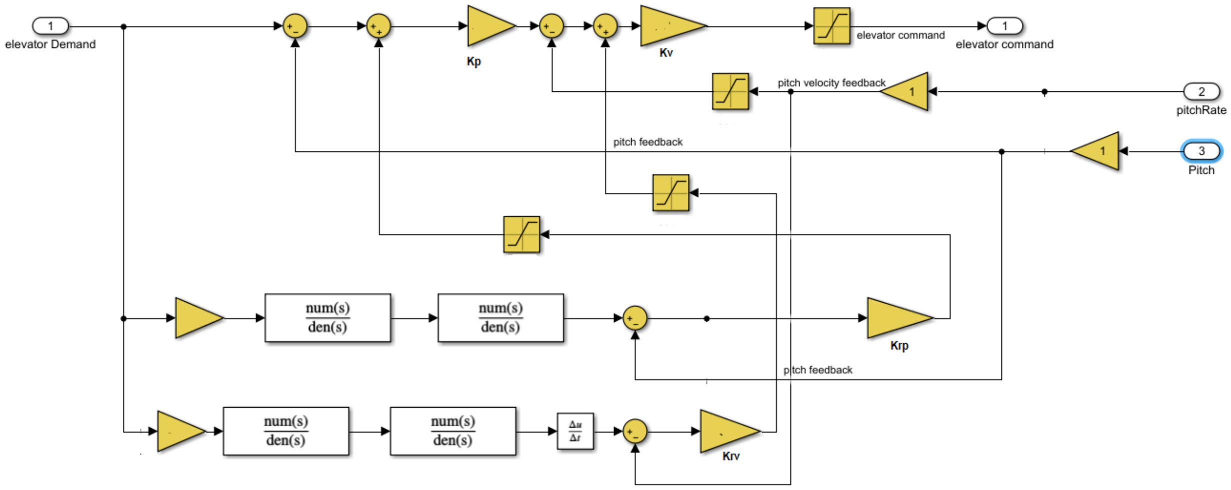

Figure 6: NMP behavior model based control

The ranges of control surfaces deflections of pFLCS and sFLCS are defined in the following way and that is important because it is the way to manage the influence of pFLCS and sFLCS.

$$\delta_{ep} = (\delta_{ep\,\mathrm{min}}, \delta_{ep\,\mathrm{max}});\ \delta_{ap} = (\delta_{ap\,\mathrm{min}}, \delta_{ap\,\mathrm{max}});$$
$$\delta_{es} = (\delta_{es\,\mathrm{min}}, \delta_{es\,\mathrm{max}});\ \delta_{as} = (\delta_{as\,\mathrm{min}}, \delta_{as\,\mathrm{max}});$$
$$\delta_{r} = (\delta_{r\,\mathrm{min}}, \delta_{r\,\mathrm{max}});\ \delta_{f} = (\delta_{f\,\mathrm{min}}, \delta_{f\,\mathrm{max}})$$

DOI: 10.13009/EUCASS2022-4660

In addition, for each range is defined a step d_{pp} and d_{vp}. In general case shown in Figure 8, four MBC are used:

- primary MBC for pitch - part of pFLCS
- primary MBC for azimuth - part of pFLCS
- secondary MBC and NMP for pitch - part of sFLCS
- secondary MBC and NMP for azimuth - part of sFLCS

The core of current tuning procedure consists of four nested loops, which move the current values of the gains: K_p, K_v, $K_{rp,}$ and K_{rv} with appropriate steps d_p, d_v, d_{rp} and d_{rv}.
This determines the simple algorithm doing full-scale search through the ranges of the gains and parameters. During the run-time parameters of each transition-time process or frequency domain characteristics are stored and the best solution according to proper criteria is chosen. Each loop corresponds to the specific gain or parameter (could be the limits for saturations for example) of the MBC. The number of loops is equivalent to the number of gains and/or parameters determined by the structure of MBC.
There are several saturations in the position, velocity and accelerations loops. They could be defined in the same way and could be added to search algorithm if needed. The same approach is used either transfer function which describe the roll or pitch dynamics or complete 6DoF flight dynamics model. The algorithm was implemented in Matlab file, which opens the SIMULINK model and start the four nested loops for all secondary MBC (pitch and azimuth) for each step change. Definitely, first the NMP behavior with MBC for sFLCS are shaped. The parameters of time domain and frequency domain responses are stored and evaluated for best values of. That is a numerical solution for complex problem of analytical tuning of gains of model based control. It avoids stopping at local extremum. The time required for calculations depends on complexity of flight dynamics models. To adjust the pFLCS we should repeat the same procedure, having already NMP behavior by tuned sFLCS. Procedure for tuning the NMP behavior consist of the following steps is shown in Table 3.

Table 3 Steps of tuning procedure for secondary MBC

STEP 1: DETERMINE THE BOUNDARY CONDITIONS AND STEPS OF ALL TUNED PARAMETERS – TWO SETS OF (K_{RP}, K_{RV})
STEP 2: DETERMINE THE INITIAL CONDITIONS FOR ALL TUNED PARAMETERS
STEP 3: DETERMINE FLIGHT CONDITIONS AND NEED ANGLE OF ATTACK TO BE INCLUDED IN TUNING AS PARAMETER
STEP 4: RUN MATLAB FILE WITH THE ALGORITHM
STEP 5: **RUN THE NESTED LOOPS WHICH CHANGES STEP BY STEP THE TUNED PARAMETERS OF SECONDARY AND PRIMARY FLCS**
STEP 6: CALCULATE THE TRANSITION PROCESS FOR EACH SET OF TUNED PARAMETERS. REMEMBER THE BEST THREE SOLUTIONS ACCORDING TO CHOSEN CRITERIA

The main step in the procedure is Step 5 and consumes most of the calculation time. Sometimes the order of nested loops (or input parameters) could affect the final result. It is not frequently happened, but should be mentioned. The same effect could happen in the next more complex case determined in Chapter 3.1.

3.1. Adaptive and gain-scheduled model based control

Two options in gain-scheduled reference model were investigated:

- Gain-scheduling for reference model parameters
- Gain-scheduling for gains or parameters MBC

Reference model assuring NMP behavior could also be gain-scheduled [8] as it is shown in the next equation.

$$F_{gNMP}(s) = \frac{(s - z_1(t))(s + z_2(t))}{(s^2 + A(t)s + B(t))}$$

It is a decent manner to use gain scheduling for some of the gains of sFLCS along with air velocity and AoA. Briefly, time variant parameters of reference model should be included in the loop of procedure as inputs with their ranges or look-up tables, but it is not included in the current article. In this case, the gain will be a look-up table with the inputs of AoA and/or total air velocity. The selection criteria and parameters of transition process are multifaceted. For that reason, AoA setup block (see Figure 3) is added to simulation solution with 6DoF. During the tuning procedure that block could easily change the current AoA. Diagram of adaptive model based control for pitch is illustrated in Figure 7. Additional nested loop should be added for AoA and its step of change to the procedure. To assure almost entire range of change that artificial AoA setup block is used.

DOI: 10.13009/EUCASS2022-4660

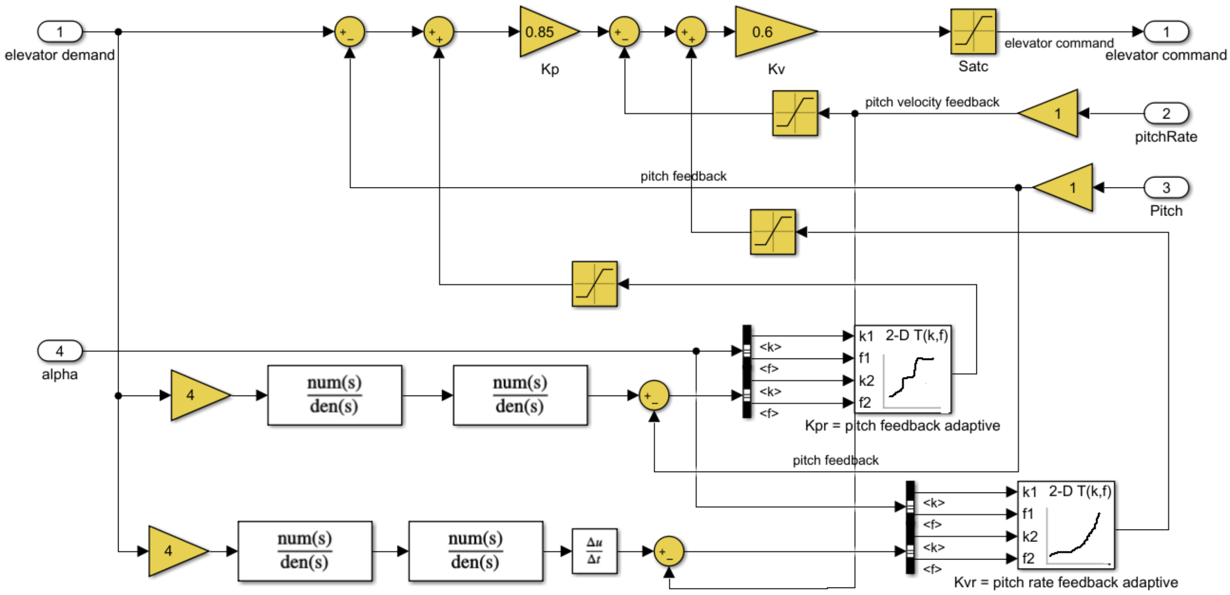

Figure 7a: NMP behavior gain scheduled model based control

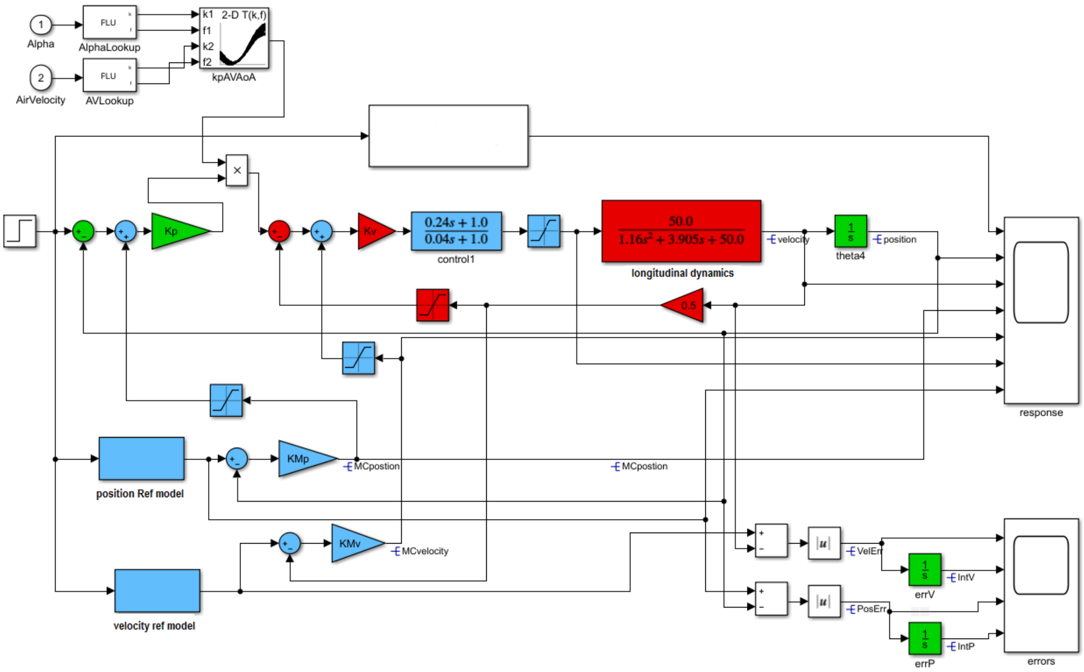

Figure 7b: Simplified version of NMP behavior gain scheduled model based control

The simplified version of NMP behavior gain scheduled model based control depicted in Figure 7b, where only two lookup tables have been used, respectively for Kp and Kv forward gains was created and tested in simulation and in real flights. The time for tuning the parameters is much shorter. Development of real-time aerodynamics model with different level of details used for reference systems in flight control systems.

There is an extensive set of algorithms for aircraft trimming and linearization as well as automatic tuning three loop autopilots, inverse dynamic control, model based control or one example for specialized algorithms for trimming and linearization of fixed wing aircraft. The algorithms are developed in the environment of MATLAB and Simulink.

Here, main steps in shaping procedure are the same as previously stated in Table 3. The new parameters should be added as inputs and nested loops.
The main feature of that self-tuning procedure is that it will calculate for global extremum and will not stop at some local extremum. The procedure is time consuming, and for more complex flight dynamics it will take more than 24 hours to calculate optimal set of control law parameters. The rewards are obvious when the flight dynamics is non-linear, and look-up tables are used instead of formulas. The same procedure could be applied to sliding mode control and inverse dynamic control with nonlinear dynamics [8].
Of course, that extends the time for finding complete solution, but avoids the case where you find a local extremum.
The MBC provides similar behaviors as those found with the more complex algorithms lake LQG, but has the benefits of a simplified and more intuitive scheme, even when the saturation parameters are added to dynamic parameters of position, velocity and acceleration references systems. The process of tuning of a MBC reduces to adjusting a simple reference 'bandwidth' in order to achieve the desired performance for the specific vehicle. The design of the controller has two key elements: finding performance-relevant reference system dynamics; tuning the parameters of controller.
Concurrently with simulation environment, the first version of really flying LFDCD was build conferring the geometry parameters given in Table 2. Once a control-relevant model is derived, tuning of the MBC is quite straightforward. Some preliminary flights were done with flying demonstrator with visual homing, where the input to model based control could be either the azimuth and elevation distances or their derivatives, which are somewhat angular velocities of LOS.
The AHRS and FLCS were built on ESP32 and some performance tests are listed in Table 4.

Table 4: Performance of AHRS/FLCS processor

Flight dynamics model (mid level of accuracy, 32 look-up tables) appropriate	0.4 ms
Model based control with reference model (position, velocity and acceleration), and removing the Gravity (steep turns)	0.23 ms

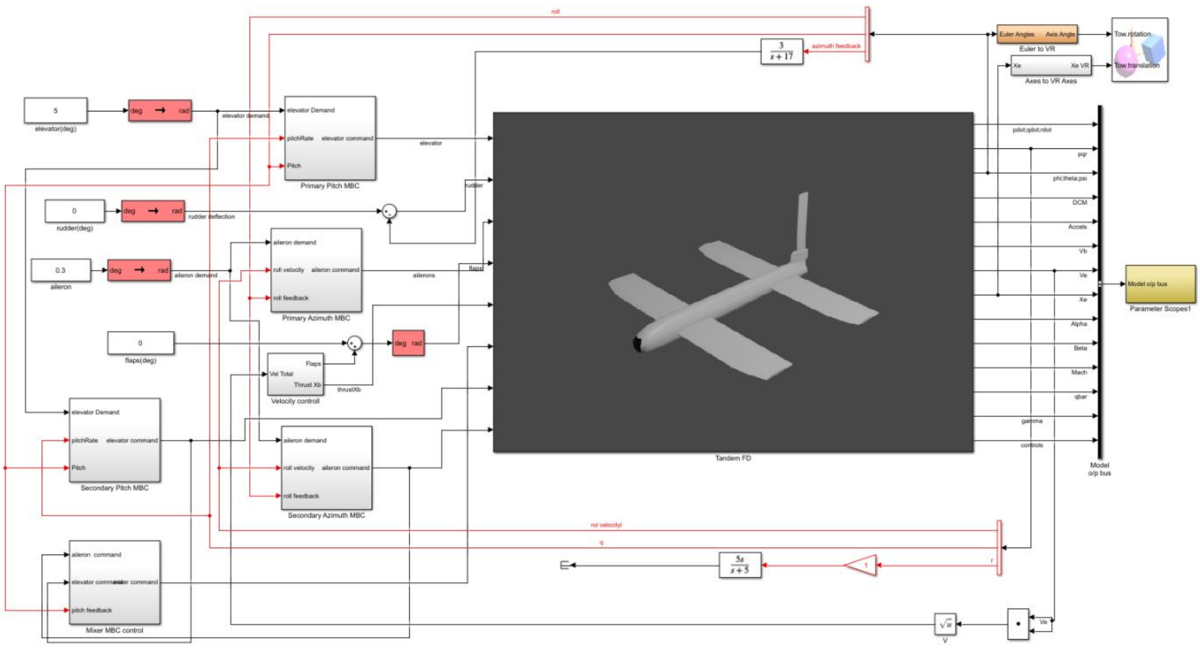

Figure 8: Overall simulation solution

When considering reasonable accuracy assumptions in number of gains, gain steps and total time of transition process (in average 60 sec.) the tuning procedure for only secondary pitch MBC will last about 12 hours. Including the gain scheduled procedure with AoA or air velocity dependency only will double the time at least.

4. Simulation results

The concept of Model Based Control includes two basic steps design the reference trajectory or response and design the model following controller. The MBC works well with proposed approach of using sFLCS and pFLCS.

DOI: 10.13009/EUCASS2022-4660

The reference model of non-minimum phase behavior should be chosen very carefully, because they are some physical limitations, which could not be implemented. The aerodynamics of frame and the proposed reference model of NMP behavior have been simulated in several situations:

- Straight level flight of demonstrator with NMP behavior and related air speed – only sFLCS works
- Straight level flight of demonstrator with NMP behavior and related air speed – pFLCS and sFLCS work
- Descent flight of demonstrator (-2° to -7° elevator down demand) with NMP behavior and related air speed – only sFLCS works
- Descent flight of demonstrator (-2° to -7° elevator down demand) with NMP behavior and related air speed – pFLCS and sFLCS work
- Ascent flight of demonstrator (5° to 9° elevator down demand) with NMP behavior and related air speed – only sFLCS works
- Ascent flight of demonstrator (5° to 9° elevator down demand) with NMP behavior and related air speed – pFLCS and sFLCS work

Some of the simulation results are shown in the next figures. Again, the desired natural behavior of NMP system is observed in all transition processes. It is long enough to be investigate and compensated

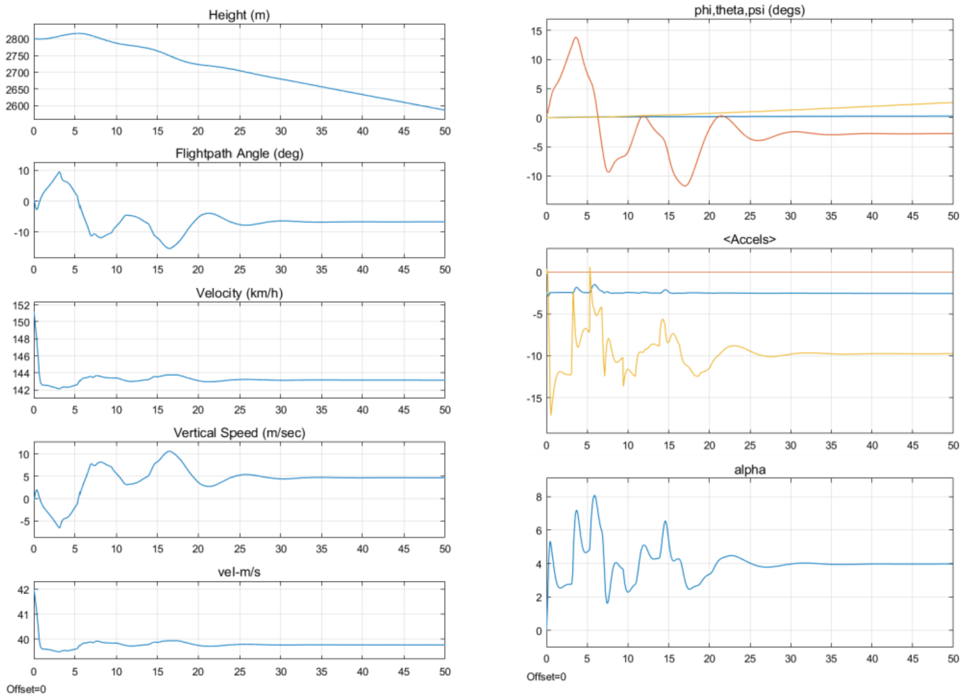

Figure 9: The response of MBC control systems with non-minimum phase object in reference loop descent

The sFLCS response shows an initial “wrong” way reaction of the non-minimum phase system. Tested pFLCS improves the behavior and completely reimburses the NMP behavior – see Figure 11. The vehicle with estimated guidance signal has noisy acceleration command. That needs the robust and reliable FLCS. Many different forms of autopilot had been studied. The design of pFLCS is well described in previous work [7,8] and it was not exposed here.

DOI: 10.13009/EUCASS2022-4660

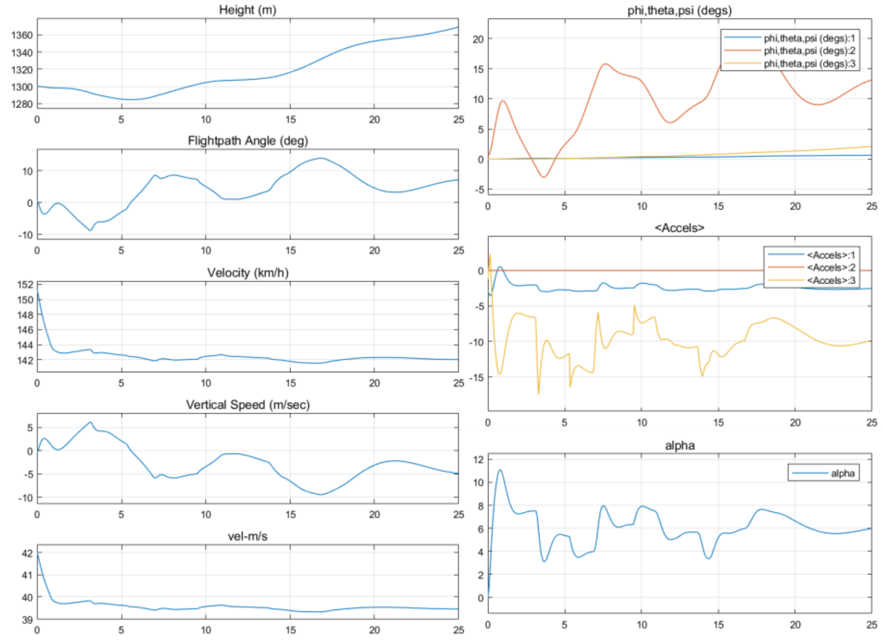

Figure 10: The response of MBC control systems with non-minimum phase behavior during ascent

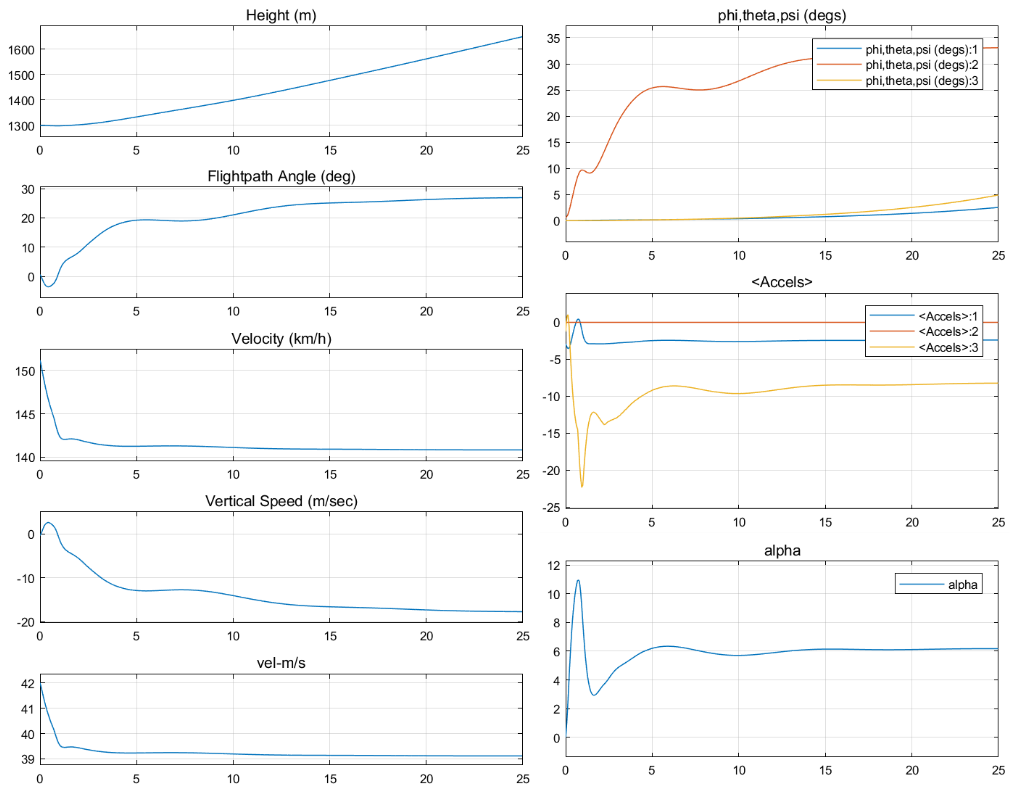

Figure 11: The response of compensated MBC control systems with non-minimum phase behavior during the ascent

DOI: 10.13009/EUCASS2022-4660

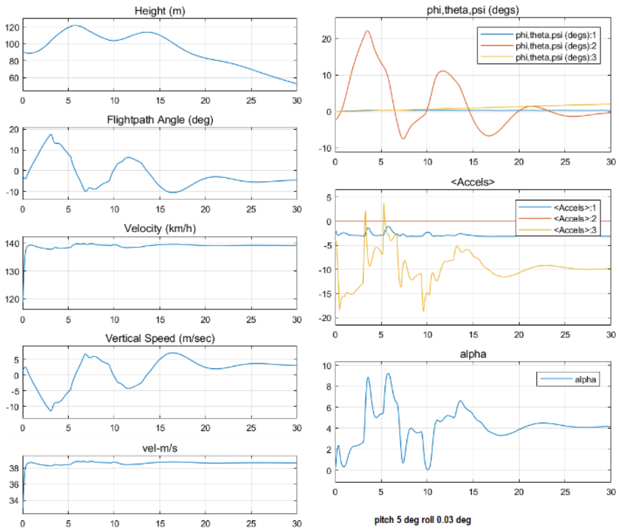

Figure 12: Non-fully compensated NMP behavior with small static gain

MBC disclosed high robustness. The procedures for tuning the pFLCS and sFLCS have been run many times to examine the difference between the specific sets of gains at different altitudes and velocities. Difference is in the range of 5%, but here more important is quality of transition process. If a set of calculated for high altitude and high velocity is used for low altitudes and low velocity, the quality of transition process remains similar.
The article is concentrated on 2-loops MBC, but 3-loop MBC was tested as well. Of course the time required for shaping the gains is longer and that approach gives more possibilities – increases the accuracy and complexity of required behavior.

5. Conclusion

The innovative method of deploying the MBC and two FLCSs allows developing subsonic test bed platform and investigating the NMP behavior. The research will continue with implementing new features: pulsed roll angle bank maneuver for a hypersonic glider and stable and controllable behavior at high AoA and low subsonic speed, which reminds the transition from ballistic descent to hypersonic gliding. As it was mentioned some real flights were completed. The flight parameters of interest were recorded and they were similar to the simulation results. The outcomes were very promising and rewarding, allowing complex behaviors to be considered.

Acknowledgement

The part of research leading to these results has received funding from the Ministry of education and science under the National science program INTELLIGENT ANIMAL HUSBANDRY, grant agreement n°Д01-62/18.03.2021

References

[1] Dietrick, R. A., Hypersonic Flight: Time To Go Operational, DOI:10.21236/ad1018856, Corpus ID: 117637631, 2013
[2] Fiorentini, L., Serrani, A., Doman, D., Nonlinear control of non-minimum phase hypersonic vehicle models, DOI:10.1109/ACC.2009.5160211, Corpus ID: 33136791, 2009
[3] Oppenheimer, M., Doman D., Control of an unstable, Non-minimum phase hypersonic vehicle model *Mathematics, 2006 IEEE Aerospace Conference*, DOI:10.1109/AERO.2006.1655985, Corpus ID: 2467024 2006
[4] Caughey, David A. (2011) Introduction to Aircraft Stability and Control, Course Notes for Mechanical & Aerospace Engineering, Cornell University, New York, USA, 2011
[5] Jackson, E. B., and C. L. Cruz (1992) Preliminary Subsonic Aerodynamic Model for Simulation Studies of the HL-20 Lifting Body," *NASA TM4302* (August 1992).
[6] O. Karas (2012) UAV Simulation Environment for Autonomous Flight Control Algorithms, West Virginia University, 2012.

[7] Penev, V., Tandem UAV with inverse dynamics control, *JOURNAL OF INFORMATICS AND INNOVATIVE TECHNOLOGIES (JIIT)* , 2022, vol 1, 27-40

[8] Penev, V., Design and Performance of Demonstrator of Autonomous Fixed Wing UAV CATLTR, *Journal of Theoretical and Applied Mechanics*, Vol 52(3), Print ISSN: 0861-6663

[9] Penev, V., Rowlands, G., Georgiev G., Kavardjikov, V., Integrated Fixed Wing UAV Design with MATLAB, Scientific Conference „*50 Years Unmanned Aviation in Bulgaria*",Technical University, Plovid, 2018

[10] Penev, V., Rowlands,, G., Georgiev, G., Novel Aproach for Multi-Layered and Redundant AHRS in Spin Stabilized Munition, *13th National Congress on Theoretical and Applied Mechanics* Sofia, Bulgaria, 6-10th September 2017

[11] Penev, V., Rowlands, G. R., Georgiev, G. L., Low-Cost Robust High Performance Remotely Piloted Autonomous Fixed-Wing System, *International Journal of Unmanned Systems Engineering (IJUSEng)*, Volume 4 Number 1,, Number 1,, 2016, ISSN:2052-112X, 23-36

[12] Penev, V., Zlateva, P., Rowlands, G., Georgiev, G.. Gyro Stabilized Roll and Pitch Gimbal Controller with Sliding Mode Control, *International Journal of Unmanned Systems Engineering (IJUSEng)*, 2016, ISSN:2052-112X

[13] Ali, J., Salman, S. A., Sreenatha, A. G., and Choi, J. Y. (2006) Attitude Dynamics Identification of Unmanned Aircraft Vehicle, *Int. J. Control. Autom. ans Syst.*, no. 1, pp. 782–787, 2006.

[14] Arifianto, O. and Farhood, M., (2015) Development and Modeling of a Low-Cost Unmanned Aerial Vehicle Research Platform," vol. 80, pp. 139–164, 2015.

[15] Stengel, R. F. (2004) *Flight Dynamics*, Princeton University Press, Princeton, 2004