33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

PRELIMINARY STUDY ON A DESIGN OF A RETURN FLIGHT TRAJECTORY OF A SUBORBITAL VEHICLE

Agnieszka Kwiek, Marcin Figat & Tomasz Goetzendorf-Grabowski

Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Nowowiejska 24, 00-665 Warsaw, Poland

Abstract

This paper presents outcomes of the study into return flight trajectory parameters of the tailless rocket plane to suborbital space tourist flights, the simulations were performed using SDSA software. This study focuses on the rocket's plane response to control as well as efficiency of control surfaces for high altitudes. In addition, the impact of the rocket plane's initial orientation and initial speed on flight trajectory is analyzed. The key parameters considered in this study are Mach number and G-load.

Keywords: suborbital flight, flight simulation, response to control, rocket plane

1. Introduction

1.1 Concept of vehicle for suborbital flights

In the last few years, the private sector started playing a significant role in the development of space technology and space exploration. In 2021 the era of suborbital commercial flights began. In response to market demand for suborbital tourist vehicles, a concept of the Modular Airplane System [2],[3],[4] has been developed at the Warsaw University of Technology. The concept assumes utilizing a two-stages system that contains a rocket plane and a carrier. The project was inspired by the Ansar-X Prize winner. The feature that distinguishes the proposed concept from currently used by commercial companies is that both vehicles are designed in tailless configuration. Furthermore, when both vehicles are bonded together then the rocket plane works as an empennage of the whole system. In terms of the rocket-plane unique features, it is designed with a leading edge extension (LEX) which shape is an outcome of the optimization process. The motivation of implementation of the LEX is to utilize the vortex lift during the return phase to slow down the rocket plane. The second unusual solution is control surfaces arrangement, the rocket plane is equipped with elevons and side plates on the wingtips which can rotate.

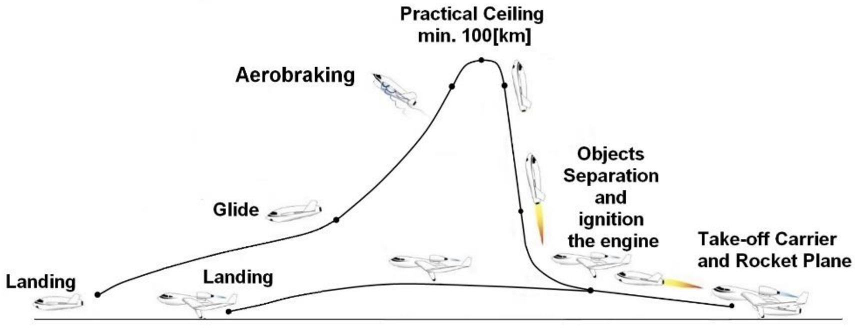

Figure 1 – Sketch of Modular Airplane System mission profile [3]

The mission profile of the Modular Airplane System is presented in Figure 1 and includes the following phases, the carrier lifts the rocket plane above Earth's thick atmosphere layer (troposphere). Next, the vehicles are separating, then the carrier turns back to the airport, in the meantime a rocket plane's hybrid engine is turned on and the vehicle begins climbing. After about 70 seconds the engine is turned off and the rocket plane continues its mission as a ballistic flight. The rocket plane crosses the boundary between Earth's atmosphere and outer space (100 km above sea level known as the Karman line and recognized by the FAA). The return flight is a gliding flight. The last part of the mission profile is the rocket plane landing (Figure 1).

The main application of the presented system is suborbital space tourism flights. The success and competitiveness of the project mainly depend on tickets price and medical recommendations for potential passengers. The cost highly depends on the weight of a vehicle, which means, that the concept of spacecraft without a heavy heat shield and only a partial thermal protection seems to be promising. The presented concept of the rocket plane assumes that the vortex flow will be used to decrease the sink rate. The rocket plane is designed with the LEX (leading edge extension, see Figure 1), which generates a vortex lift on high angles of attack. In return, the big aerodynamic force reduces the rate of descent and supports vehicle braking. Due to the small initial speed, the problem with the excessive heat of the sharp leading edge should not occur. Moreover, the LEX increased the stall angle of attack and allows flight in post-stall conditions

From a medical point of view, the G-load is one of the most important issues in suborbital flights, the FAA recommendation for commercial flights can be found in [1]. For the presented concept the higher values are expected after the rocket place separated from the carrier. The second critical point occurs during the return flight when the rocket plane needs to transit from a flight at the high angles of attack to low angles of attack. To ensure possibility of flight at high angles of attack for a wide range of speeds (subsonic and supersonic), the concept of control assumes elevons and rotational side plates (Figure 2), [7]. Both control surfaces will be deflected during the descent but in the lower part of Earth's atmosphere side plates go back to a neutral (not deflected) position and the rocket plane continues the flight at low angles of attack. The rocket plane behavior for such a transition was investigated using numerical simulations and flight tests of scaled model [9]. The preliminary results showed that the FAA recommendations regarding G-loads are met. Moreover, G-loads affect requirements regarding the stiffness of the vehicle's structure. Keeping the G-loads on a low level helps reduce the weight of the structure.

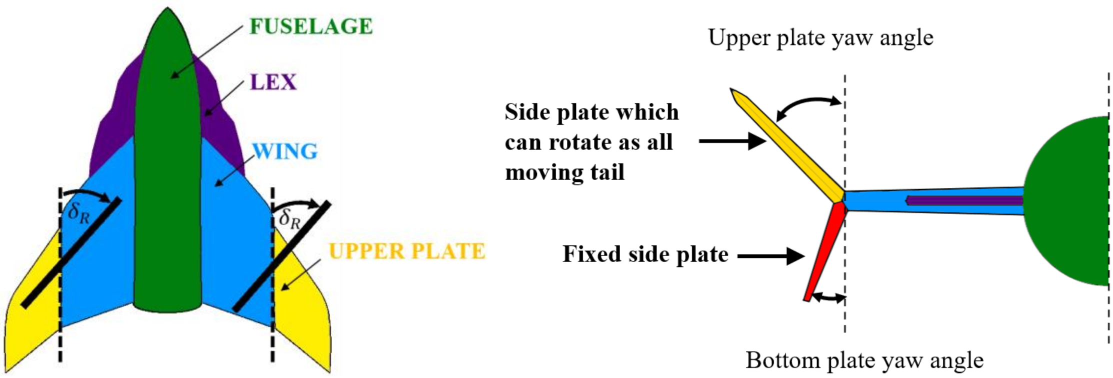

Figure 2 – Layout of the rocket plane geometry

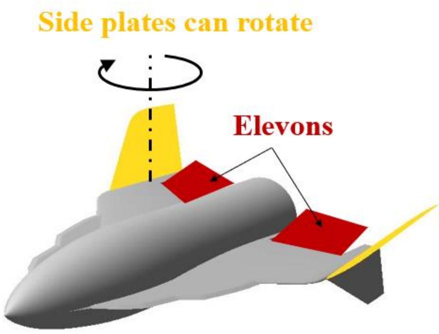

Figure 3 - Concept of the rocket plane control

1.2 Aims

The next challenge that must be addressed is a very low air density close to the boundary to outer space. Typical control surfaces are not going to be effective, therefore, the rocket plane needs small correction rocket motors to control its attitude. The first research question is where is a boundary on which the presented arrangement of control surfaces becomes efficient. And how the rocket-plane response to control at high altitudes as well as supersonic speed. The second research question is how the rocket plane's initial orientation (set-upped by the correction rocket motors) affects the rocket plane's trajectory and effectiveness of control. The last problem that is going to be addressed is the impact of the initial speed on the flight trajectory. The key parameters that are going to be investigated are Mach number and G-load in z axis.

2. Methodology

The research consists of the following stages: data preparation, simulation, and results postprocessing. The first step was CFD computations to obtain aerodynamic coefficients of forces and moments. Only the longitudinal characteristics of the rocket plane were considered. Computations were done for the clean configuration as well as with deflected control surfaces (Figure 3). Next, the results for the low Mach number were compared with data measured in the wind tunnel. Then, based on the CFD results, the necessary input data set for rocket's plane trajectory simulation was created. Including the pitch rate and control derivatives. The last stage was simulations and data analysis.

A few scenarios of simulation were considered. The first step goal was to establish altitudes on which aircraft can obtain trim conditions for supersonic speeds. Then analysis of control response for those altitudes was simulated to ensure that the maximum G-load is not excided when the rocket plane is going to obtain the trim. The next stage was the investigate into the aircraft response to control for a wider range, including very high altitudes. It was assumed that at the beginning of the simulation, the rocket-plane is not in trim condition (due to too low air density) and the elevator (which consist of elevons and side plates) is deflected. Projects assumptions state that the rocket plane re-entry flight is going to include flight close to the Karman line where the air density is so low that the aerodynamics control is not effective. During that phase the rocket plane orientation is going to be control by a set of rocket maneuvers engines. Where is the threshold between the altitude where the control surfaces starting to be effective is one of the goals of this study. The effectiveness of the control surfaces depends on speed, therefore, the next stage was to conduct simulations for different initial speeds to investigate speed distribution with the altitude as well analyze the impact of the initial speed on the maximum Mach number as well the maximum G-load. The first parameter was selected to ensure that the problem with overheating does not occur. While the G-load was analyzed due to the FAA medical requirements for suborbital commercial human flights. The next stage was to investigate the impact of the initial angle of attack and initial path angle of the rocket plane on flight parameters especially on the Mach number and the G-load. The last considered type of scenario was the simulation at relatively moderate altitudes where the control surfaces deflection is implemented to reduce the angle of attack in consequence reduce the maximum G-load.

3. Numerical model

3.1 Model of atmosphere

Simulations conducted in this paper were for altitudes that are higher than defined by the ISA model. All atmospheric data was taken from measurements done by the sounding rocket []. During all simulation the atmospheric condition was assumed as calm (no turbulence). Change of air density with altitude is presented in Figure **4**.

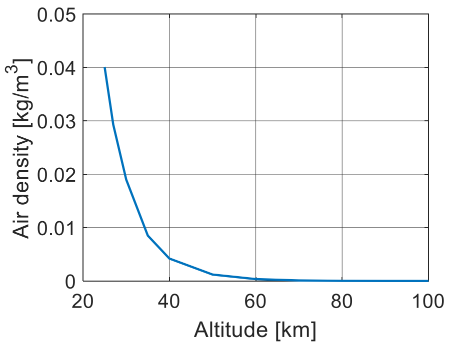

Figure 4 – Air density model for altitude above the ISA model/

3.2 Reference values

The rocket plane's geometrical data is presented in Table 1. All presented in this paper results were obtained for this reference data. It was assumed that the rocket's plane moment of inertia is not affect by the control surfaces deflection. Also, any change of the rocket mass due to use of the maneuvers rocket motors, at the beginning of the re-entry flight, was neglected as well.

Table 1 – The rocket plane's reference values

Parameter	**value**	**unit**
Mass	2342	kg
MAC	3.848	m
Wing Area (S)	18.84	m^2
Moment of Inertia (Iy)	6245	kg m

3.3 Aerodynamics

The aerodynamic forces coefficients required for simulations were obtained by the MGAERO [10] which is a commercial CFD software. The numerical model consists of 7 grid levels. An example of the pressure distribution for the model with deflected elevons and side plates is presented in Figure 5. The software based on multi-grid scheme and uses Euler's equations to flow calculations. Such type of software allows to obtain aerodynamic characteristics for supersonics speed in quite effective time of computations, but in case of inviscid flow, the vortex breakdown is not modelled. While the friction drag was estimated using the experimental data measured in the wind tunnel.

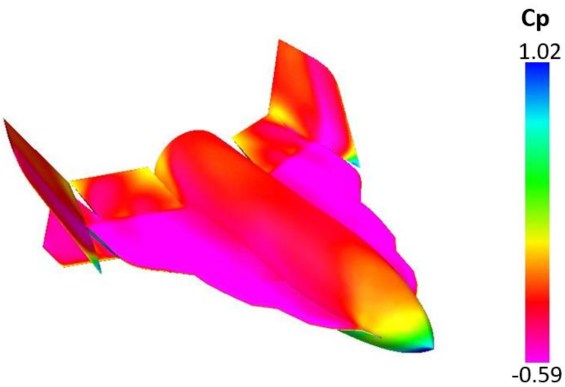

Figure 5 – Example of Cp distribution for the rocket plane with deflected both control surfaces, results computed by the MGAERO for Ma=1.5 and AoA=20 deg.

The wind tunnel test camping was carried out at Warsaw University of Technology aerodynamics laboratory (Faculty of Power and Aeronautical Engineering). The wind tunnel tests were carried out in a closed-circuit subsonic tunnel, the experimental section diameter is 1.16m. The rocket plane model was hanged at open measure section by means of wires which passed through muffs in the fuselage (Figure 6). The tunnel is equipped with the Witoszyński type balance [12] with a digital data acquisition system. During the test only a lift, drag, and pitching moment were measured. The rocket plane model for wind tunnel tests was built in 1:15 scale. The data was collected at a free stream velocity of 40 m/s, which corresponds to the Reynolds number of about Re= $0.7*10^6$ (calculated based on the MAC of the wing). The measurements were taken in aerodynamic coordinate system for the reference point, which was 21% of the wing MAC, the assumed center of gravity position of the rocket plane. The longitudinal characteristics were measured for the range of angles of attack from -5^o to $+40^o$ [8]. Due to the facility constrain, the experiment with a higher AoA or higher Mach number was not possible.

Figure 6 – Models of the rocket plane during the wind tunnel campaign

The numerical results were compared with data measured during the wind tunnel tests, see Figure 7. A good compatibility of results was obtained. The drag coefficient for numerical results is lower due to lack of the friction drag (MGAERO simulates the flow as inviscid). Therefore, the experimental results were used to estimate the friction drag that was added to the numerical results to obtain final results for flight simulations. The biggest discrepancy was obtained for pitching moment which was related to the method of setting the reference point in the wind tunnel and the pitching moment sensor big sensitivity for vibrations (that was impossible to avoid or mitigate due to the localization of the facility in the middle of the big city).

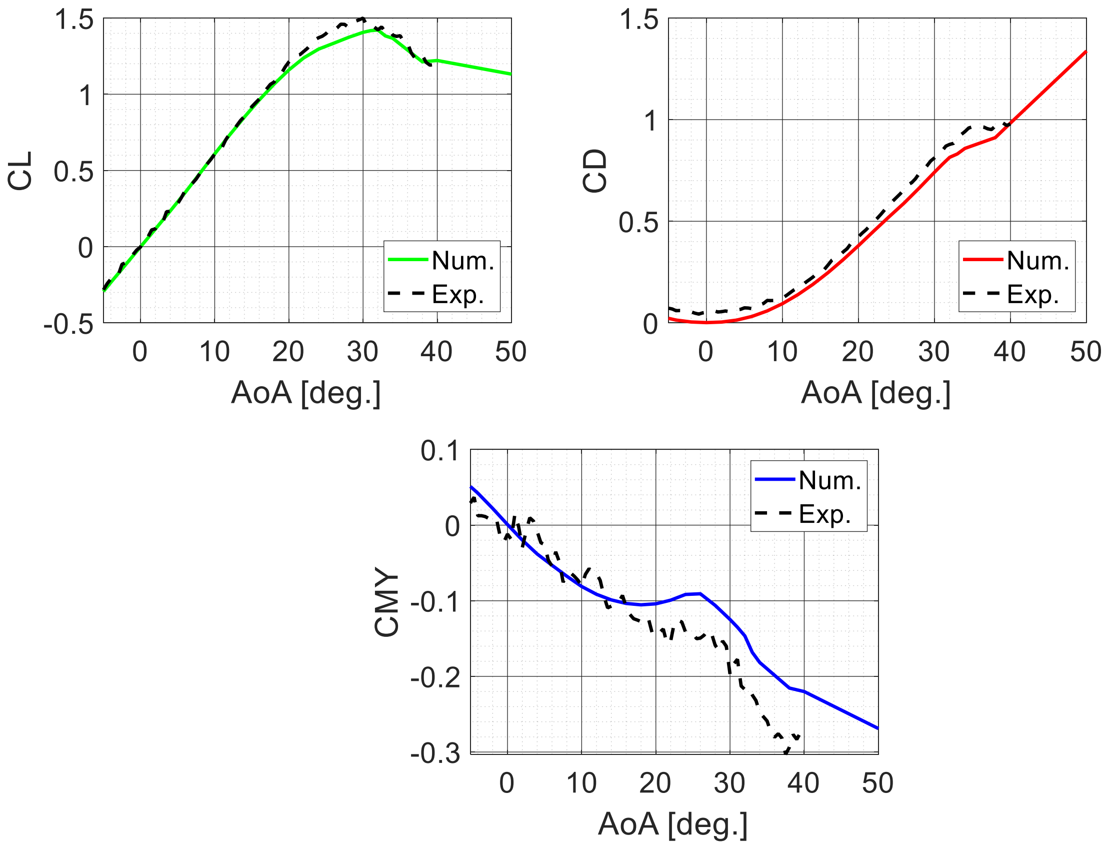

Figure 7 - Comparison of numerical results with the experimental data

3.4 Flight simulations

The flight simulations were performed using the SDSA software [4], [5], [13], one of the functionalities of which is 6DoF simulation (Figure 8) of the aircraft motion. The flight parameters can be recorded for further postprocessing. The input data consist of aerodynamic characteristic, stability and control derivatives as well as geometry and inertia properties. The SDSA 6DoF simulation allows the analysis of the response to control with the unit step function or impulse function. Because the software assumes one control surface (device) per axis (one for pitch control, one for yaw control, and one for roll control) therefore, to take into account impact of both elevons and side plate the elevator characteristics are equivalent to sum of both controls characteristics and simulated by one deflection angle. For example, the deflection of elevator by -10 degrees means that both elevons and side plates are deflected by -10 degrees. The simulation in the SDSA can be performed for initial condition which does not correspond to the trim condition and state parameters like angle of attack or path angle can be set up by the user. This functionalities were used to perform simulations presented in this paper.

The SDSA software was used in other projects where the software outcomes were compared with data recorded in a flight campaign [6] also, for case of aircraft designed in the flying wing configuration [11]. A good consistency of results was obtained.

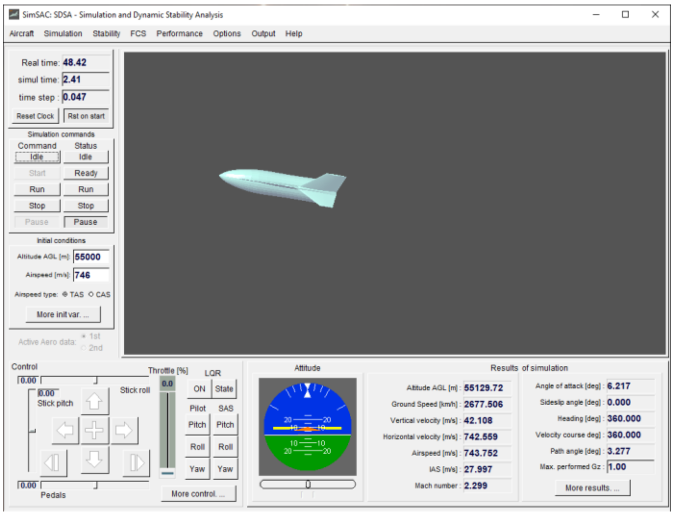

Figure 8 – SDSA simulation window

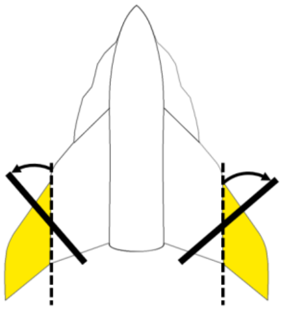

Figure 9 – Definition of the negative side plates deflection, when the plates working to control the pitch motion.

3.5 Control derivatives

The rocket plane is equipped with side plates and elevons. In all simulations, presented in this paper, it was assumed that both side plates and elevons are deflected simultaneously by the same angle. The derivative of the pitching moment in respect to angle of attack for selected Mach numbers is presented in Figure 10. For low AoA, the reduction between subsonic and supersonic speed is more severe than for high AoA. During the simulation the change of the pitching moment and lift coefficient due to elevator deflection were taken into account while the impact of the drag force was neglected.

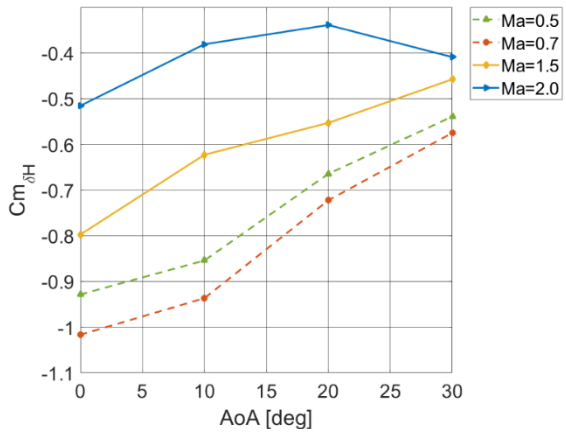

Figure 10 - Example of derivative of the pitching moment in respect to elevator (sum of the elevons and side plates deflection). Comparison of the derivatives of selected subsonic and supersonic Mach numbers.

4. Results

This section presenting results obtained by the SDSA software for different scenarios. Including how the change of the rocket plane initial orientation affected the trajectory. The impact of the initial speed on the maximum flight parameters and the rocket plane response to control. As well as results for case when the rocket plane travel with supersonic speed but the density of the air is sufficient to obtain the trim condition.

4.1 Trim results

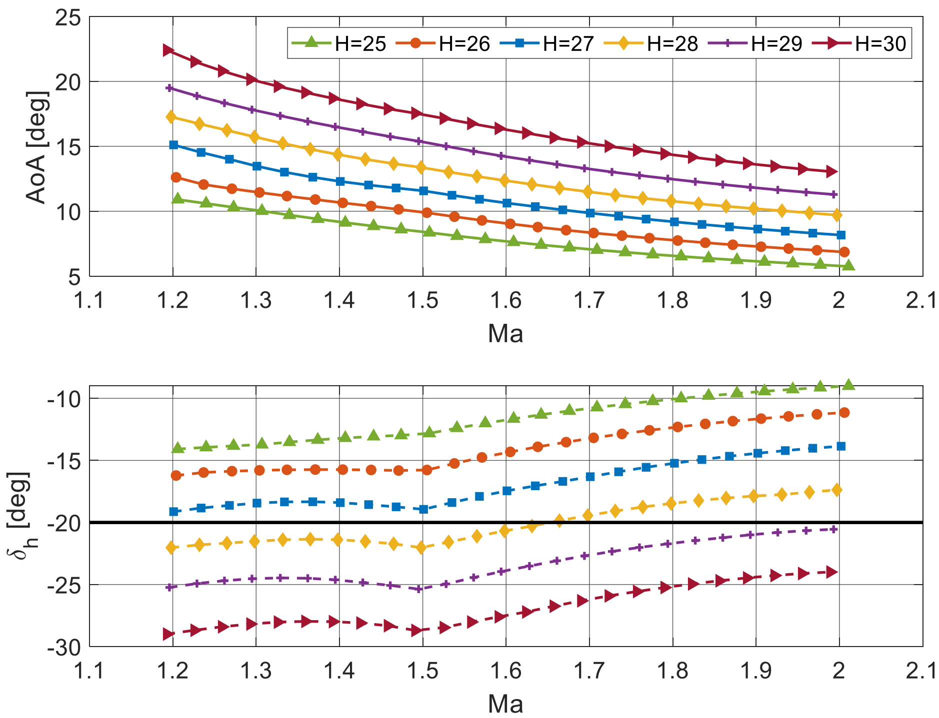

Figure 11 – Results of SDSA trim computation for the supersonic speed range and altitude range of 25 to 30 kilometers. The black solid line represents the maximum possible deflection of the elevator.

The first step was to establish where a threshold is that the rocket plane can achieve trim conditions for the supersonic speed regime, in terms of flight on high altitudes. The results are presented in Figure 11 and were calculated by the SDSA software which solved the problem of equilibrium of forces and moments. At the altitude about 27 kilometers, the required angle of the elevator deflection in whole range of considered Mach numbers is within the acceptable border (see Figure 11, the black solid line represents the maximum possible elevator deflection). Also, the required angles of attack are reasonable. Therefore, to confirm that the control surfaces are efficient at this altitude as well as their deflection do not cause exceeding the maximum allowed G-load (according to FAA the recommendation is less than G_z=3), the simulation of the rocket plane response to impulse deflection was performed. The results presented in Figure 12 confirmed that the rapid deflection is relatively safe on altitude of 25 km. The presented results were computed for Ma=1.5, in case of flight at higher speed, the expected angle of attack is going to be lower as well as change of the elevator deflection is going to be lower too.

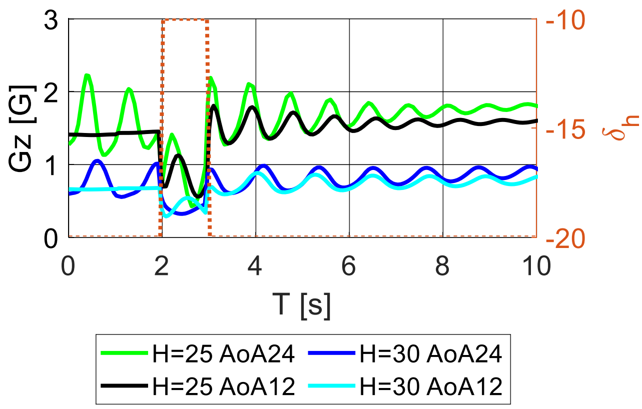

Figure 12 – Rocket plane response to control in case of the impulse deflection. The simulation was conducted for initial speed which correspond to Ma=1.5.

4.2 Response to control

The next step was to investigate the rocket plane response to impulse deflection for a more wide range of altitudes including those on which obtaining the trim condition by elevator deflection is not possible (due to the low density). The results are presented in Figure 13, the change of the angle of attack due to elevator deflection does no explicit answer where the impact of elevator deflection on change of the trajectory can be neglected. To better judge this phenomenon the analysis of the G-load was made, see Figure 14. Based on the obtained results it was concluded that deflecting the elevator above 50 kilometers is not effective. The effectiveness is going to related with the speed of the rocket plane. Therefore, the next problem that must be addressed is what is the expected speed on the altitude about 50 kilometers. And how this speed depends on the initial flight conditions. Results of such simulations are presented in the next section of this paper.

In Figure 13, the rocket plane oscillations can be observed but for all altitudes the oscillations are damped, the damping is the stronger on the lowest altitude which is associated with the biggest air density – the biggest forces.

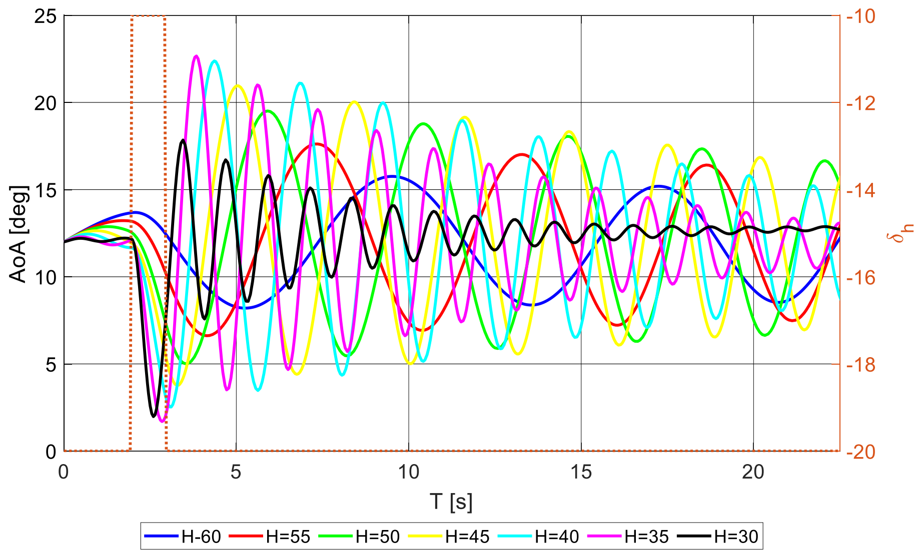

Figure 13 – SDSA results of the rocket plane response to control. The simulations were conducted for initial Ma=1.5 and AoA=12°.

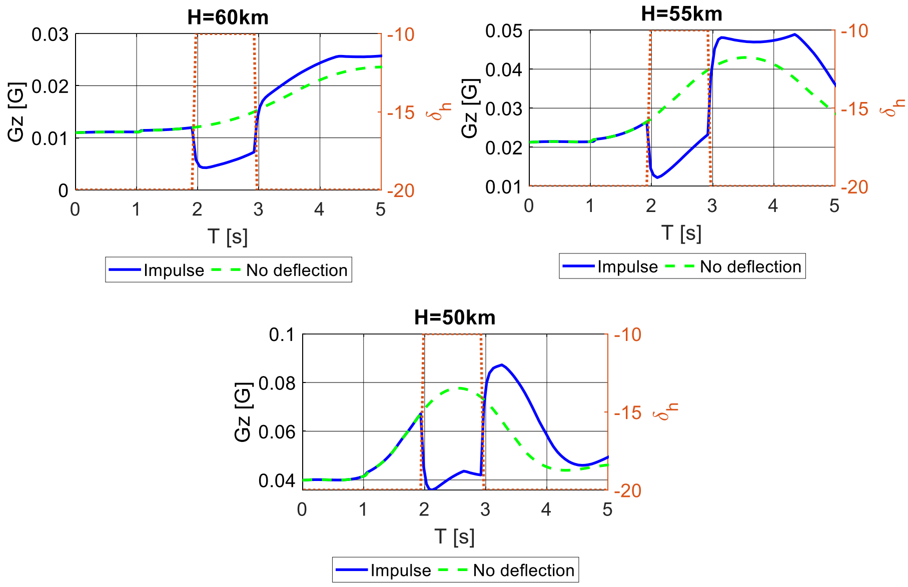

Figure 14 – SDSA results for two scenarios: impulse deflection of the elevator and no deflection. Simulation were conducted for initial Mach number of Ma=1.5 and different altitudes.

4.3 Results of flights simulations

The next set of simulations were done for the initial altitude of H=80km and different initial speeds, the rocket plane's elevator was deflected by -20 degrees. Previous simulations showed that beginning the return flight without deflected elevator is not recommended because after a few second of flight the rocket plane starting to dive. The deflection of the elevons and side plates significantly affect the aerodynamic characteristics especially the pitching moment. The pitching moment equal to zero of the rocket plane in case of the deflected elevator occurs for the higher angle of attack which is associated with the higher lift and drag forces as well as is closed to the angle of attack that corresponds to the maximum L/D. During the simulation, the deflection of the elevator was constant and equal to δ_H=-20 degrees. The aim of this analysis was to investigate the impact of the initial speed on the maximum Mach number and the maximum G-load. And to estimate the initial condition (speed) for simulation at lower attitudes. The obtained results are presented in Figure 15, as it was expected higher initial speed causes higher maximum Mach number but lower maximum load factor. To reduce both of parameters the change of the elevator deflection must be implemented.

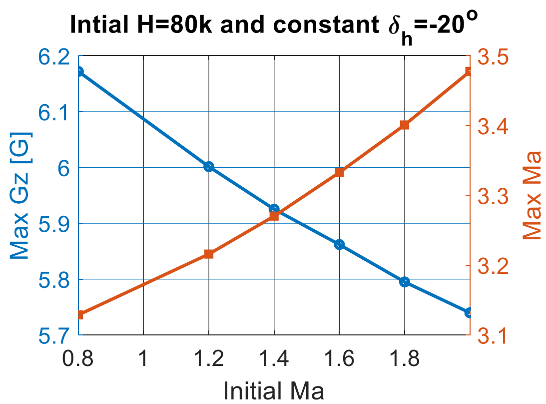

Figure 15 – Results of the SDSA simulation with initial condition H=80km, δ_H=-20 deg and different initial Mach numbers.

The next set of simulations considered the impact of the initial angle of attack and path angle on the flight trajectory. It was assumed that on altitude 80 km the rocket-plane orientation can be set-upped by the correction rocket engines. The results are presented in Figure 17, it can be concluded that the impact of both angles on the trajectory is negligible. A similar analysis was conducted for altitude of 55 kilometers. Results of simulations are presented in Figure 18 - Figure 20. Simulations revile that difference of Mach number and G-load is bigger than for case of 80 kilometers but the relative change between cases of flight at altitude of 55 is also negligible. In case of flight on higher angle of attack, the flight parameters fluctuations are bigger, and the Mach number is lower.

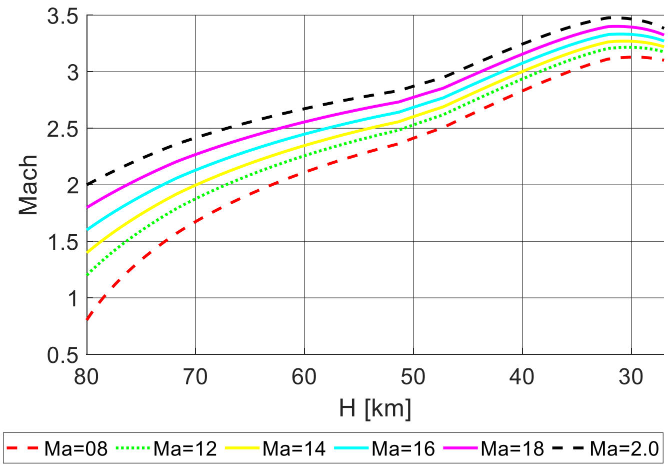

Figure 16 – Results of SDSA simulation with initial altitude of H=80km, AoA=12°, and fixed elevator deflected by -20 degrees and different initial speeds.

The last of the simulation set was the investigation on how the change of the angle of attack on moderate altitudes caused by the impulse elevator deflection affect the maximum Mach number and maximum G-load. The simulations were conducted for initial Mach number of Ma=1.5, angle of attack AoA=12 degrees, and the initial elevator deflection of δ_H=-20. After 20 second, the elevator deflection was reduced to -10 degrees. The results are presented in Figure 21 and Figure 22, it can be concluded that use of control to reduce the angle of attack on lower altitude affect the maximum G-load which is lower for lower altitude.

In this research, in all considered scenarios, regardless of initial conditions the maximum Mach number was achieved around the altitude of 30 kilometres, after this point the rocket plane begins to slow down. In case of the elevator deflection, the rocket plane slow down around 25 kilometres.

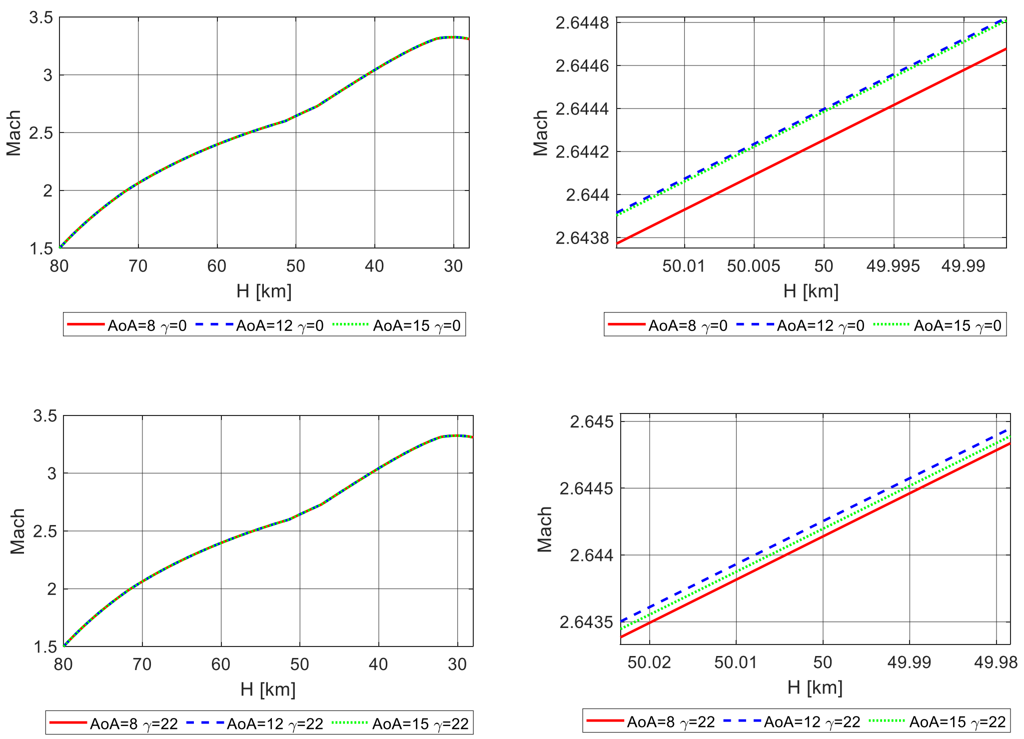

Figure 17 – Results of SDSA simulation with initial altitude of H=80km, fixed elevator deflected by -20 degrees, Ma=1.5, and different initial angles of attack (AoA) and path angle (γ).

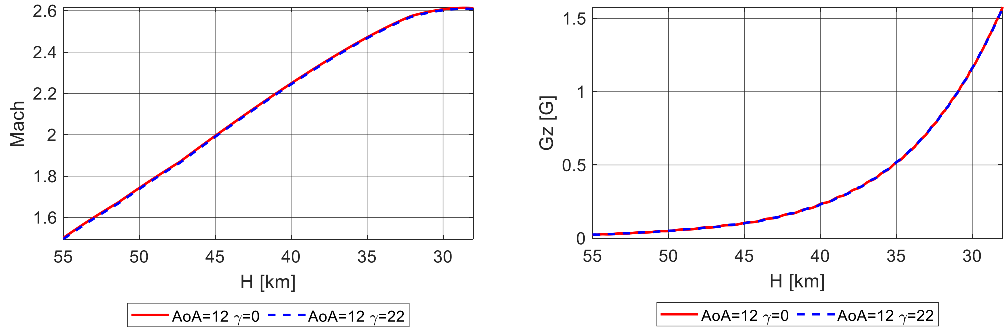

Figure 18- – Results of SDSA simulation with initial altitude of H=55km, fixed elevator deflected by -20 degrees, Ma=1.5, and different initial path angle (γ).

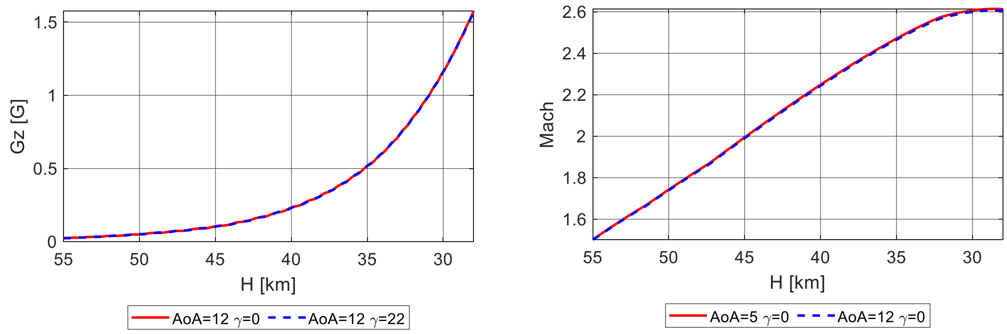

Figure 19 – Results of SDSA simulation with initial altitude of H=55km, fixed elevator deflected by -20 degrees, Ma=1.5, and different initial angle of attack.

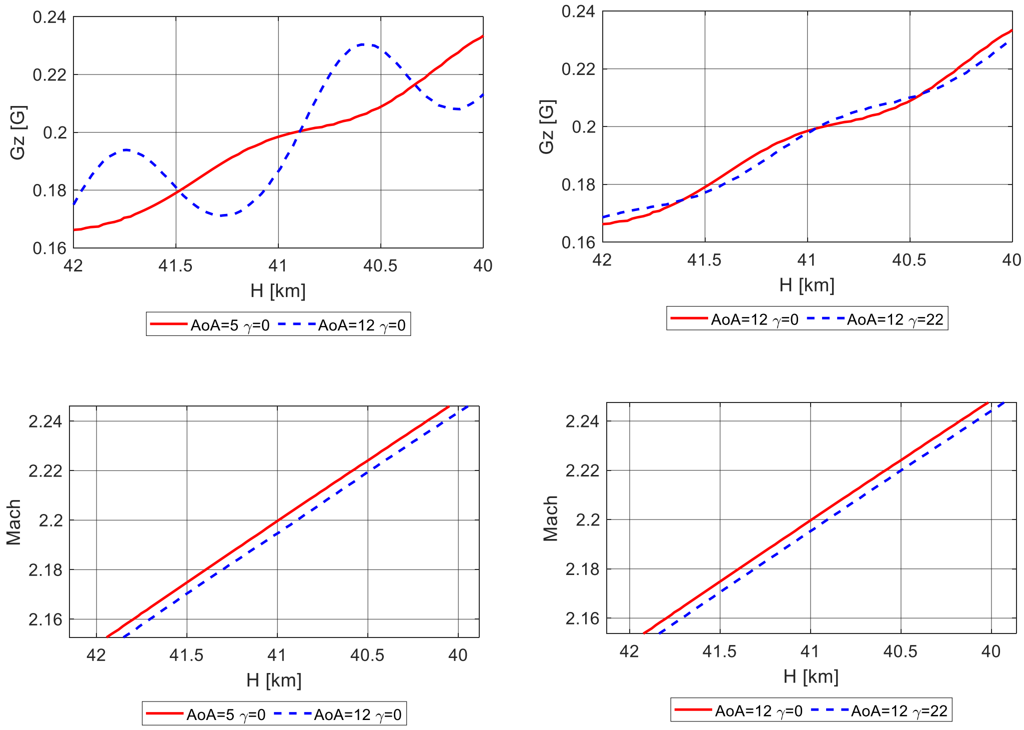

Figure 20 – Zoom in on the results presented in Figure 18 and Figure 19.

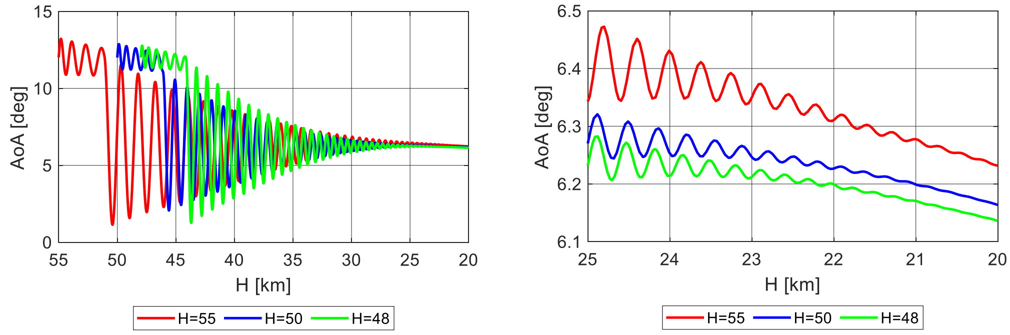

Figure 21 – Results of SDSA simulation with initial Ma=1.5 and initial angle of attack AoA=12 degrees for different initial altitudes. The initial deflection of the elevator is -20 degrees, after 20 second of simulation the elevator was reduced to 10 degrees.

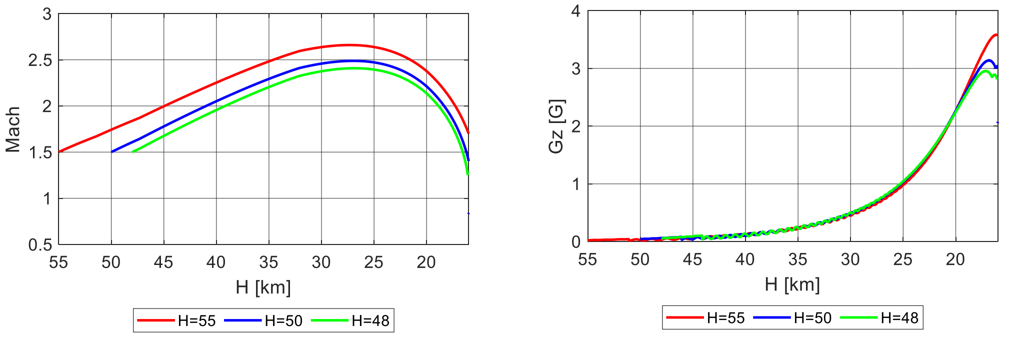

Figure 22 – Results of SDSA simulation with initial Ma=1.5 and initial angle of attack AoA=12 degrees for different initial altitudes. The initial deflection of the elevator is -20 degrees, after 20 second of simulation the elevator was reduced to 10 degrees.

5. Conclusions

The paper presents preliminary results of the return flight simulation of the rocket plane for different initial vehicle's orientation and different initial speed. Also, analysis of the efficiency of control surfaces for high altitudes as well as rocket plane response to control. The main purpose was the analysis of the rocket plane trajectory parameters to gain necessary information for more detailed design of the trajectory which satisfies the control and stability constraints as well as the G-load recommendation. The obtained results allow for assessing the presented project of the rocket plane as a promising configuration of the vehicle for space tourism flights. Based on the presented results the following conclusions can be draw:

- Higher initial speed results in higher maximum Mach number
- Higher initial speed of the vehicles results in lower maximum value of the G-load
- The maximum G-load can be affected by the change of the elevator deflection, but this must be implemented below 55km to significantly affect the value of G-load
- For altitude around 25-30 km the rocket plane starting significantly slowing down
- Initial orientation on high and moderate altitudes has a negligence impact on the trajectory
- Aircraft oscillating but all oscillations are damped, the stronger damping occurs on lower altitudes

6. Further work

The next step of the research is to create a simulation with a more sophisticated model of elevator deflection to design the trajectory that satisfies the control and stability constraints as well as G-load recommendation. Designing the control approach that allow to ensure that the maximum G-load is not exceeded is key factor from the passenger's medical requirements point of view.

7. Contact Author Email Address

Corresponding author Agnieszka Kwiek, mailto: agnieszka.kwiek@pw.edu.pl

8. Copyright Statement

References

[1] Antuñano M J, Baisden DL, Davis J, Hastings J, Jennings R, Jones D, Jordan J.L., Mohler, S., Ruehle, C., Salazar, G.J., Silberman, W.S., Scarpa, P., Tilton, F.E., Whinnery, J.E., 2006 „Guidance for Medical Screening of Commercial Aerospace Passengers", FAA report DOT/FAA/AM-06/1, available at https://libraryonline.erau.edu/online-full-text/faa-aviation-medicine-reports/AM06-01.pdf (accessed 10.01.2021)

[2] Figat M, Galiński C, and Kwiek A. Aeroplane Coupled System to space tourism. *Progress in Astronautics*, Vol. 32, No. 1, pp.24-37, 2011

[3] Figat M, Galiński C, and Kwiek A. Modular Aeroplane System. A Concpet and Initial Investigation, *Proceeding of the 28th Congress of the International Council of the Aeronautical Sciences*, Brisbane 2012, Paper ICAS 2012-1.3.2

[4] Galiński C, Goetzendorf-Grabowski T, Mieszalski D, and Stefanek Ł. A concept of two-staged spaceplane for suborbital tourism. *Transactions of the Institute of Aviation*, No. 4/2007 (191), pp.33-42, 2007

[5] Goetzendorf-Grabowski T., Mieszalski D., Marcinkiewicz E.: Stability analysis using SDSA tool, Progress in Aerospace Sciences, Volume 47, Issue 8, November 2011, Pages 636–646

[6] Goetzendorf-Grabowski T, Marcinkiewicz E and Galiński C. Comparison of traditionally calculated stability characteristics with flight test data of PW-6U sailplane, *Proceedings of the CEAS conference, Linköping*, Sweden, 15-19.09.2013, Linköping University Electronic Press, Linköping, pp. 536-543.

[7] Kwiek A. Study on Control and Stability of the Rocket Plane to Space Tourism, *29th Congress of the International Council of the Aeronautical Sciences*, St. Petersburg, Russia, Paper No 2014_0893

[8] Kwiek A, Figat M. LEX and wing tip plates interaction on the Rocket Plane in tailless configuration, *The Aeronautical Journal,* Vol. 120, Issue 1224, pp.255-270, 2016

[9] Kwiek, A., Galinski, C., Bogdański, K., Hajduk, J. and Tarnowski, A. 2021, "Results of simulation and scaled flight tests performed on a rocket-plane at high angles of attack", Aircraft Engineering and Aerospace Technology, Vol. 93 No. 9, pp. 1445-1459. https://doi.org/10.1108/AEAT-11-2020-0276

[10]MGAERO user's manual Version 3.1.4

[11]Mieloszyk J, Tarnowski A, Tomaszewski A, Goetzendorf-Grabowski T. Validation of flight dynamic stability optimization constraints with flight tests, *Aerospace Science and Technology*, Vol. 106, 2020, https://doi.org/10.1016/j.ast.2020.106193

[12]Witoszyński C.: Travaux de L'Institut Aerodynamique de Varsovie. Fascicule V, Warsaw 1932, http://bcpw.bg.pw.edu.pl/dlibra/docmetadata?id=3157&from=&dirids=1&ver_id=49254&lp=4&QI=!EFCF9417B69770894E5914376646D2BD-59 a document in Polish and French, (Accessed 01.06.2022)

[13] Simulation and Dynamic Stability Analysis: https://www.meil.pw.edu.pl/add/ADD/Teaching/Software/SDSA , (Accessed 01.06.2022)