AerospaceEurope Conference2021
WARSAW, POLAND | 23 -26 NOVEMBER 2021
PSAA
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# CONTROL IN CURVILINEAR APPROACH TO LANDING

Jacek Pieniazek[1] & Piotr Ciecinski[1]

[1]Department of Avionics and Control, Rzeszow University of Technology, Poland

## Abstract

The presented paper addresses the use of non-linear trajectory in the process of approach and landing of an aircraft. A non-linear part of the trajectory of the approach, during which the altitude decrease with circling, reduces the range of air traffic influence, e.g. by noise, in the airport environment and shortens the approach area.

Effective implementation of such kind of control method, depends on the proper development of a trajectory, enabling the aircraft to be brought safely to a touchdown point. It also depends on and the design of control algorithms, which takes into account the possibility of go around in the case of the event of adverse conditions preventing safe touchdown. Achieving a repeatable trajectory of a non-linear approach, as it is obtained in the standard straight line approach procedure, is a more difficult task. The proposed solution is an automatic control system. It controls the flight along the approach trajectory segments by position and attitude control, with the assumed flight speed maintaining. Automation ensures predictability of the behaviour of the landing aircraft.

Results of the simulation in the interception of approach trajectory, approach control, final landing procedure and runway motion show the effectiveness of the designed procedure. The possibility of suppressing wind interference and the implementation of missed approach decision is presented in the test results.

**Keywords:** fixed wing aircraft, curvilinear trajectory, approach and landing, automatic control

## 1. Introduction

Increasing use of transport and various air services, including the inclusion of unmanned aircraft in controlled traffic, poses new challenges in the organisation of air traffic, especially around airports, and airport network. At the same time, modern navigation systems and automatic control systems provide opportunities for the development of new flight, take-off, and landing procedures. Some new concepts of air traffic organisation are invented as a response to various challenges [1]. The use of curvilinear rather than straight line trajectories in certain situations can increase an airspace capacity and create new opportunities of an airport localization. The longitudinal flight path modification is proposed in [2, 3].

Landing, which is the most demanding and safety critical part of an aircraft's flight. Commonly applied procedures takes into consideration the safety. In the standard procedure, several phases of approach and then manoeuvres finishing the flight safely bring the aircraft on the ground. In this procedure, the approach to landing itself is a straight line with the 3 deg slope. Only the specific topographical conditions of some airports require a trajectory other than the standard one. The straight-line approach before runway threshold has the advantage that the pilot or automatic control system has long time to achieve the steady flight in the actual conditions. The corrective actions in the steady state are necessary only if there are disturbances resulting from turbulence of wind variability. In this way, the pilot's piloting task-load is reduced, which is important for other tasks, for example communication and analysis of the situation. No less important is the ability to assess the actual level of disturbances and to decide about the possibility of the safe landing.

Despite these advantages, the straight-line approach has a fundamental drawback, a long trajectory, which makes it impossible to use over hilly terrain or between tall buildings. It also creates noise problems in urban areas [4]. The reduction of the area of environmental impact can be achieved by shortening the approach by introducing a section of circling with descend. Hence, the concept of implementing the curvilinear approach in the lateral motion appears in the literature[5, 6, 7]. The most common configuration is to use a helix as the phase of altitude reduction and the final short straight-line section. It is also the proposition of the emergency nonlinear approach procedure in the case of the propulsion failure [8]. However, another idea is proposed recently, that the airport itself should have the shape of a circle[1]. For such shape of the runway whole approach could be carried out using a helix trajectory.

At this point, it is worth noting that the unmanned aircraft systems becomes expected as air traffic participant both in controlled traffic and in the use of airports[2] and the first UAV landing at the civilian airport has become in 2020[3] . On the other hand, unmanned aircraft equipped with the possibility of curvilinear landing could use landing areas in difficult terrain. The systems envisaged as the basic navigation equipment for automatic landing are satellite navigation systems supported by mainly ground augmentation GBAS. But it is also possible that an automatic approach in visual conditions may use airfield image for the measurement of the aircraft relative position in the reference to the runway [9, 10]

This paper will present the landing procedure, the general structure of the control system and the results of simulation tests.

## 2. Approach procedure

The main goal of an aircraft approach is obtaining proper position, i.e. in the aiming area on the runway, when aircraft airspeed, vertical speed and roll angle are in the acceptable ranges just before touchdown. The last part of the approach makes possible aircraft flight stabilisation and is typically realized by a linear segment. The proposed curvilinear longitudinal approach creates difficulties for the pilot. The state monitoring and taking decision if the landing is safe during circling are more demanding. So, the last segment with constant vertical speed is assumed as crucial for safety. Its length depends on the whole system stabilisation time and the approach ground speed.

### 2.1 Standard approach procedure

The standard approach in aviation consists with several phases, but all of them are realized on the same linear trajectory. Only in specific situations, like high obstacles in the direction of the runway, there are two or more linear segments connected and turns connected in such a way to avoid obstacles. The distinguished segments of standard approach defines the initial and final conditions. The initial approach segment is intended to achieve an intermediate segment from the initial approach fix or by standard manoeuvres. In case of the windy conditions, the aircraft should achieve a stabilized configuration. At the intermediate segment, aircraft should be adjusted to prepare final approach at final aproach fix or final approach point. The final approach segment ends at the missed approach point where pilot decide if the landing is safe. The length of this segment is from 6 km to 19 km, depending on the kind of the approach and the airfield conditions. The last approach phase ends at decision point, when and where pilot decides if safe continuation of the landing is possible. If not, the missing approach procedure begins. The criteria for this decision may be stated as side position deviation, distance to aiming point (being the expected point of perfect touchdown), aircraft course, airspeed and attitude.

The long enough trajectory makes it possible to stabilise the flight state. In the case of the aircraft control surfaces trimming, no pilot control action is necessary in steady flight. This reduction of workload makes another important pilot activities possible to do. The standard procedure has been designed for the human pilot considering skills, limitations and another duties. It should be noticed, that beside aircraft stabilisation on the trajectory, pilot duties include correspondence with air traffic control (ATC) and monitoring of the aircraft state and of its systems. Pilot should also directly conduct observation of the aircraft's surroundings and landing in visual conditions, or indirectly by various instruments in instrumental conditions.

[1] https://www.nlr.org/news/the-endless-runway/

[2] https://eda.europa.eu/what-we-do/all-activities/activities-search/remotely-piloted-aircraft-systems—rpas

[3] https://www.unmannedsystemstechnology.com/2020/09/first-uav-landing-at-international-airport-in-civilian-airspace/

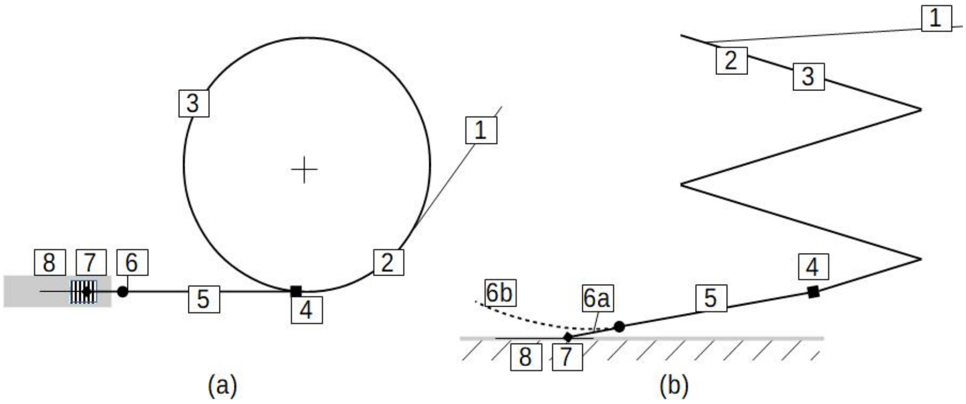



Figure 1 – Curvilinear flight trajectory a) top view, b) side view; numbering according to the phases in the procedure

But nowadays, in air transport, automatic landing is becoming a standard practice as a result of the increasingly common equipping of airports and aircraft with systems enabling unrestricted instrumental landing like ILS cat. IIIC, which enables fully automatic landing. Also probably in the future augmented GNSS systems properties will be enough to be approved for use during landing as basic instrument.

## 2.2 Approach with circling descend

Similarly to the standard procedure, in the proposed approach several phases are distinguished. Every phase has its purpose. The proposed landing approach procedure consists of the following phases (presented in the Fig. 1)

1. flight to the helix trajectory
2. stabilization of the flight on the trajectory
3. circling with a descend on the assumed trajectory
4. stabilizing the straight-line flight around the connection point
5. straight-line flight into decision point
6. a) continuation of landing or b) aborted landing and go-around procedure
7. aircraft levelling and touchdown
8. motion stabilization on the runway and braking

During the 1$^{st}$ phase, an aircraft fly in the direction of the helix segment. The 2$^{nd}$ phase is transitional, it is a time for every controller to find steady state necessary for helix trajectory realization. The 3$^{rd}$ phase is steady, or quasi steady as to be shown further, decrease in altitude with circling. The 4$^{th}$ phase is transitional, but very crucial for successful landing. As the remaining phases are the same as parts of standard procedure, the only difference is that, the stabilisation of steady flight should be achieved in shorter time. The length of this segment is limited by the required stabilisation distance. Although one missing approach is distinguished, it should be remembered that in each of the phases from 1-5 there may be a situation caused by external factors or incorrect control (for example, as a result of disruption of the measuring system operation), which require to abort the landing. The distinction of the state 6b is associated with the fact, that during the standard landing, the decision point determines the last moment after which it is impossible to interrupt the landing procedure due to the characteristics of the aircraft and of the airport.

## 3. Control system

Due to the properties of the aircraft as a controlled object, the influence of control signals on the position relative to the trajectory is achieved indirectly through its orientation and speed. Hence, when implementing the control, it is necessary to determine the values of state variables that ensure that the aircraft fly on the assumed trajectory. These values can be achieved through the action of regulators, but this is associated with a long stabilization time. Direct calculation using trajectory parameters and aircraft motion model is also possible, such as presented in [6]. However, it should be noticed that these values can be determined analytically for specific conditions, including constant disturbances and accurate analytical model of the controlled object. Any inaccuracy results in an error, what require corrective action of the applicable regulator. Hence, only part of the analytical dependencies was used in the presented control system. Due to the structure of the simulation model and the wide range of operating conditions (shown in the tests), the full analytical model of the aircraft was not determined, which made it impossible to use the method of Nonlinear Dynamic Inversion, like it was used in research [11], [6]. Instead, the appropriate manoeuvres are applied as touchdown, similar to [12] and the same as used previously in straight line approach [13].
The control system consists of two main parts

(A) the master controller being state machine,

(B) the reconfigurable control system composed of regulators.

Additionally to standard measurements, the control system cooperates with the following systems:

(C) estimator of the aircraft position and deviation components from the approach trajectory,

(D) wind estimator.

The master controller decides on the correctness of execution of subsequent phases of approach and switches to the next phase appropriately to the aircraft state.
Reconfigurable control system changes structure according to the current phase of the approach to landing. It also sends commands to controllers. These commands are demanded steady state values of controlled variables, which includes airspeed, course and roll angle. The general structure is similar as used regarding linear approach [9] but modifications become necessary to achieve proper operation on the curvilinear trajectory. There are several controllers for main controlled variables. Some of them (e.g. the course controller) has two versions differing in the method of control. The first is used in the flight, the second on the ground.

## 4. Tests

Simulation tests were performed to verify the correctness of the control system operation. The simulation model has been described in earlier studies [14]. Hence only basic information will be given in this study.

### 4.1 Aircraft model

The control system presented in the article has been prepared to control the MP02A Czajka ultralight aircraft. This aircraft has the following parameters:

- wingspan – 9.72 m,
- take off gross weight – 472.5 kg,
- max. speed – 230 km/h,
- cruise speed – 170 km/h,
- stall speed – 65 km/h,
- rate climb – 6.5 m/s.

A non-linear model of aircraft motion was used during simulation. This model was prepared using first principles of aerodynamics and mechanics, with coefficients values identified and computed to be similar to the real aircraft. Main parts of the model are:

- dynamics and kinematics
- inertia,
- aerodynamics,
- propulsion,
- suspension,

The motion of the aircraft is computed by dynamics and kinematics equation of the rigid body, using actual parameters from inertia model and aerodynamic, propulsion and suspension forces and torques computed for the actual state. Auxiliary models of additional variables and measurements are used to obtain values of such variables as various speeds, actual pressures, density, and aircraft position. Besides the aircraft model, models of actuators are implemented on every control input.

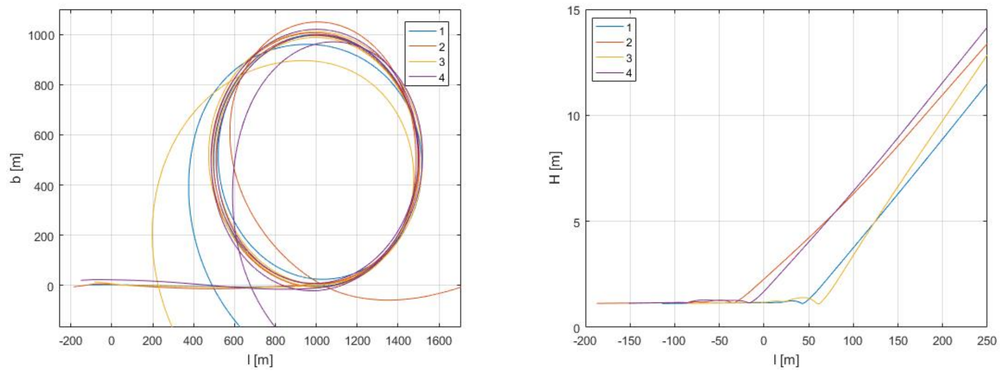
### 4.2 Approach trajectory

The trajectory of an aircraft approach to landing consists of the sections resulting from the presented procedure. The first section is a helix, which is located on the right side of the runway centreline. The second section is a straight line ending on the ground at the aiming point. The distance of the central line of the helix, around which the aircraft orbits, from the aiming point, results from the assumed radius (here 500 m) and the length of the rectilinear section (here 1000 m). The size of both segments depends on the aircraft class [15]. The ones used in tests are assumed for small aircraft (class A). Considering limitations of roll angle, bigger and faster aircraft needs greater radius and also more time to stabilize the state on the line segment. For example, the approach presented in the [5] includes a trajectory with two circling segments, one for small and second for large aircraft. Trajectory in two projections is presented in the Fig. 1. The slope of the final section was adopted as in the standard approach procedure, i.e. 3 deg. But, when determining the slope of the helix, a larger angle of inclination was assumed. The properties of an aircraft, which have been taken into account, is that, during circling a aircraft with non-zero roll angle requires a higher value of the lift coefficientto obtain a steady state comparing to this necessary for a straight line flight as the lift force equals the aircraft weight in both cases and the same airspeed is assumed.

Hence, after roll angle change at the transition between the sections of the trajectory, there will be a natural tendency to reduce the flightpath slope. Changing the trajectory becomes a disturbance that the controller would have to compensate. Another effect is increasing distance between successive turns. For the assumed circling radius, this distance is 165 m for 3 deg flight slope, but 220 m for 4 deg flight slope. With a standard vertical separation of 1000 ft, the second value means a separation of about 1.5 turns, i.e. subsequent planes are on opposite sides of the helix. It seems to be more beneficial than the orbiting of aircraft above each other, as it would happen with a trajectory slope of 3 deg. The decision point D is distinguished on the linear section. Its location is determined as adopted in aviation by the height above the threshold of the runway. The value of the decision height for the tested aircraft was determined as such the altitude for which the aircraft, after deciding to abort the landing and activating the missing approach procedure, performs this procedure without violating the minimum altitude.

### 4.3 Test results

To illustrate the operation of the control system, simulated test flights were conducted. During four simulations full functionality of the control system was tested, but during three next simulations wind estimation was turned off. The expected effect of the lack of information about the disturbance value is a delayed response of the control system. The integrating part of the trajectory regulator needs a time to corrects the aircraft side drift. Hence, the tests examined the operation of the system under




(a) Top view (b) Altitude

Figure 2 – Flight trajectories during tests of cases 1-4

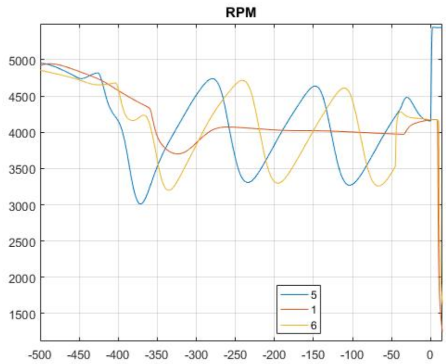



Figure 3 – RPM vs time (test cases 5, 1, 6)

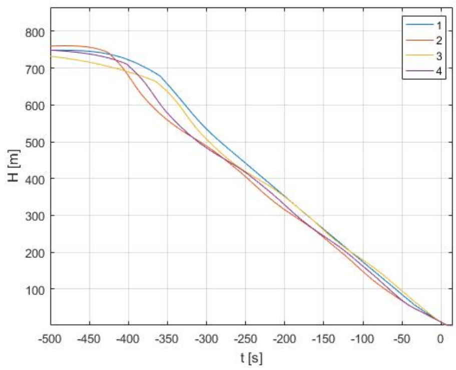
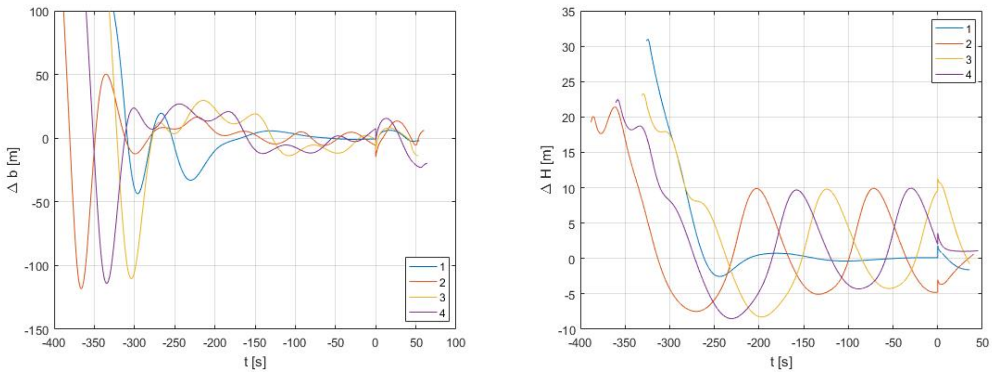



Figure 4 – Altitude vs time (cases 1-4)

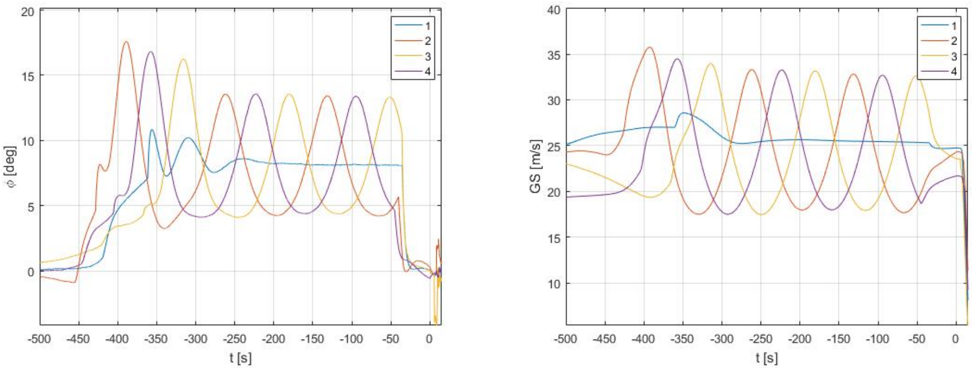



(a) Side deviation (b) Altitude deviation

Figure 5 – Deviations from the approachideal trajectory during tests of cases 1-4

Table 1 – Test cases

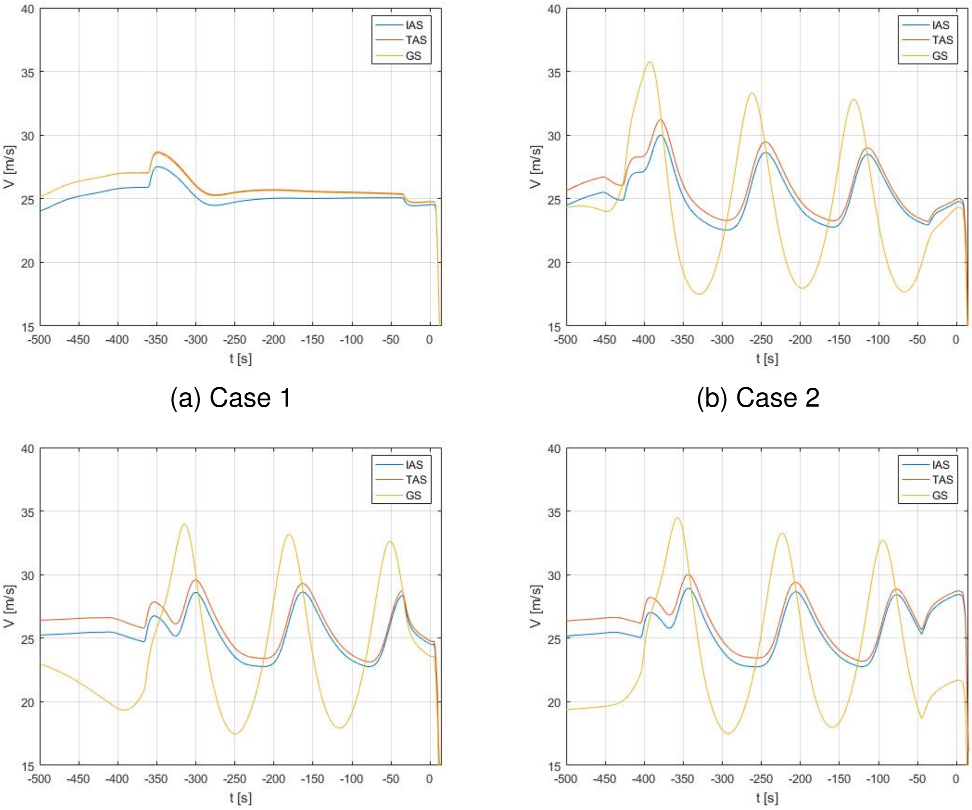
| Test case | Side wind [m/s] | Headwind [m/s] | Wind estimator | Comments |
|---|---|---|---|---|
| 1 | 0 | 0 | no/yes | without wind no difference |
| 2 | +7 | 0 | yes | - |
| 3 | -7 | 0 | yes | - |
| 4 | 0 | 7 | yes | - |
| 5 | 7 | 0 | no | landing aborted |
| 6 | 0 | 7 | no | - |




(a) Roll angle (b) Ground speed

Figure 6 – Selected state variables during tests of cases 1-4

different conditions. Table 1 contains values of the wind components and information whether a wind estimator was active during the test.
The simulation study consisted of performing a flight to the trajectory of the approach starting at a certain point. Initially, the flight took place at a constant altitude, while the final interception of the helix trajectory was carried out by tightening the bend simultaneously with the commanded altitude corresponding to the altitude of the helix at the angular position of the aircraft in the reference to the helix. The following drawings present the waveforms of the values of the selected quantities. Time scaling is adopted in a way that the value of 0 corresponds to the decision point $D$. It makes easier the comparison of landing processes in different conditions. The distance $l$ in Fig. 2 and 9 is determined as an aircraft distance to the aiming point in the direction of the runway.
The flight trajectories of the first four cases are presented in the Fig. 2. The aircraft position is determined by $l$ and $b$, being a distance to the runway centreline, and $H$, being altitude above the runway (or more detail aiming point). The intake trajectories (approach phase 1) differ as the effect of the wind. But finally, after stabilisation, an aircraft flies on the assumed helix. After circling with descend (phase 3), there is a manoeuvre (phase 4) of taking a rectilinear section.
Altitude over time is presented in the Fig. 4. The visible convergence of the trajectory under different conditions before point 0 indicates that the selected length of the rectilinear segment is sufficient. More detailed image of control accuracy is presented in the Fig. 5 as side deviation and altitude deviation. The timescale is modified to distinguish the point where controller's mode changes from 3 on helix to 5 on the straight line through intermediate phase 4.
Fig. 2b shows the trajectory in the final phases of the landing (segments from 6 to 8). The differences in the position of the first contact of the wheels of the aeroplane with the surface of the runway shall be within 70 m in front of and 50 m behind this point. Regardless of the possibility of improving the control quality, these test results show how long the touchdown area should be.
The values of the roll angle ($\phi$ in the Fig. 6a) and ground speed (GS in the Fig. 6b) are presented in the next figure. In windless conditions, a transitional process of stabilisation on the trajectory is visible, while the constant wind, which for orbiting becomes a periodic disturbance, causes the control




(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

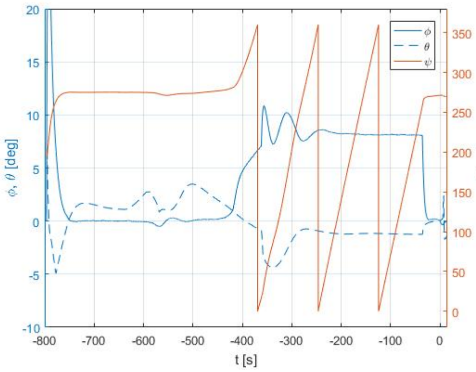
Figure 7 – Velocities (IAS, TAS, GS) vs time

system to change the roll angle accordingly. Changes in ground speed are also mainly related to this disturbance.

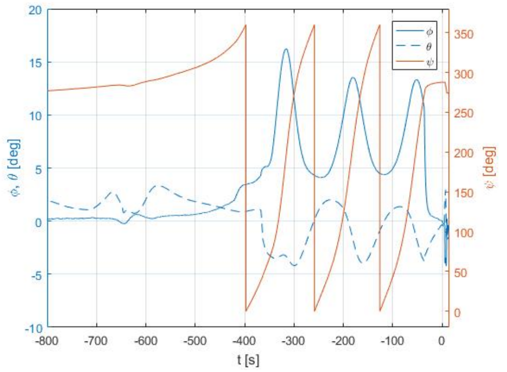
The values of instrumental airspeed (IAS), true airspeed (TAS), which is relative to air and ground speed (GS) are presented in the Fig. 7. The decreasing difference of IAS and TAS, when an aircraft descend, illustrates the effect of static pressure changes with altitude. In windless conditions, the TAS and GS values are identical, although it should be remembered that in a real aircraft these values are measured by different methods and so differences in values resulting from the metrological properties of the measurement systems should be expected. Under wind conditions, there are periodic disturbances in the value of every speed. Therefore, despite the airspeed control, which is visible on the graph of the engine RPM (Fig. 3), the IAS value is not constant. Changes are in the range of about +3/-2 m/s, in the disturbance strength $\pm 7$ m/s. The speed values are important before and in phase 4 (it is about time -50 s) as the aircraft should have assumed airspeed on the final approach. Noticed changes in IAS depend on the direction of the wind, it increases in case 2 (Fig. 7b) but decreases in case 3 (Fig. 7c). The case 4 is different. When landing with a headwind (Fig. 7d) in phase 5, the final approach IAS was increased for the effect of shortening the landing time.

The waveforms of the attitude angles (roll $\phi$, pitch $\theta$ and yaw $\psi$) are presented in the Fig. 8. Comparing the motion in a windless atmosphere (Fig. 8a) with other cases, significant differences in the shape of the waveforms depending on the direction of the wind are visible. As the GS changes due to wind and IAS stabilisation the shape of the helix trajectory is preserved by roll control. Switching off the wind estimator in crosswind (Fig. 8e) results in a different course of the roll angle in phase 4 (comparison with 8e, from time of about -50 s), which results in a different course waveform in both cases and a large deviation from the runway axis (Fig. 9a). With the headwind, the problem does not occur (Fig. 8f and 8d). Comparing the view of the trajectory in Fig. 9a before the connection point of the helix with the straight line, there are no significant differences. But the drift, caused by side wind after this point, makes it impossible to land.

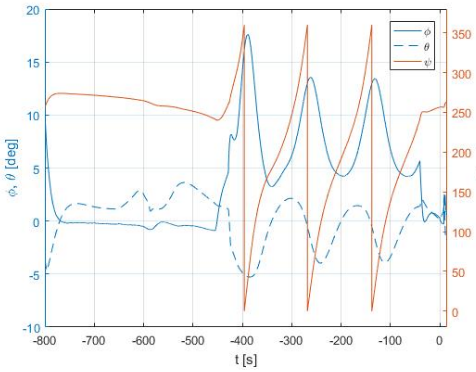
Excessive deviation from the axis of the runway at the decision point $D$ results in the abort of the



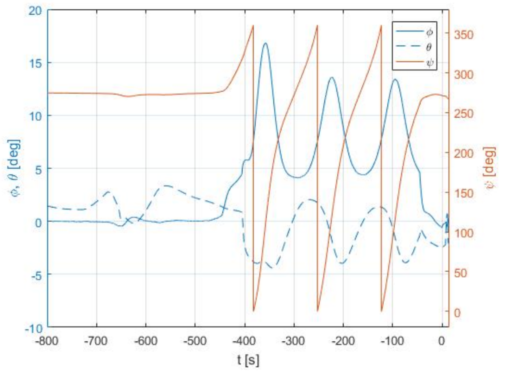

(a) Case 1



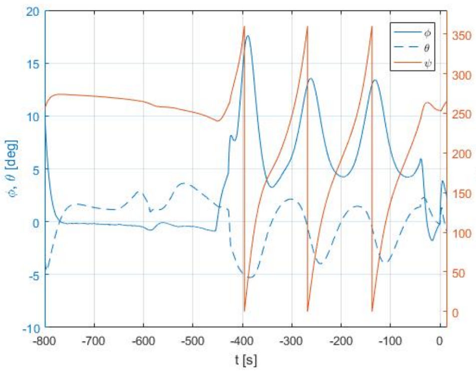

(b) Case 3



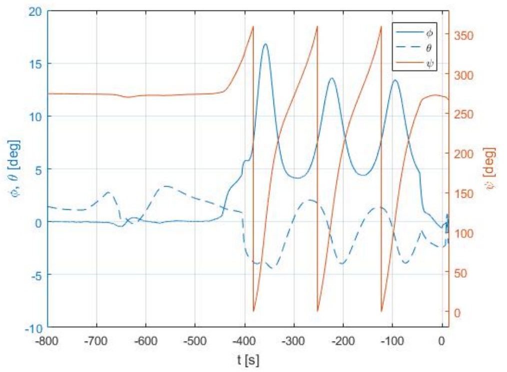

(c) Case 2




(d) Case 4

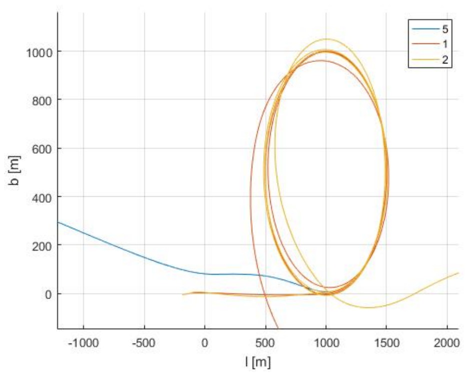



(e) Case 5

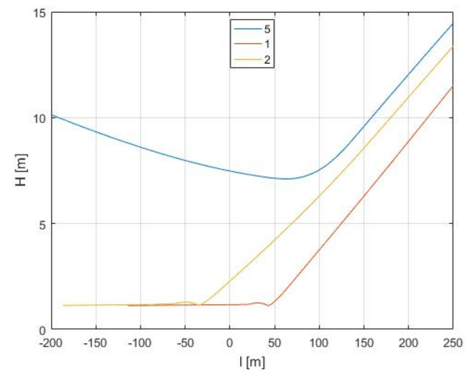



(f) Case 6

Figure 8 – Attitude (roll, pitch, yaw) vs time

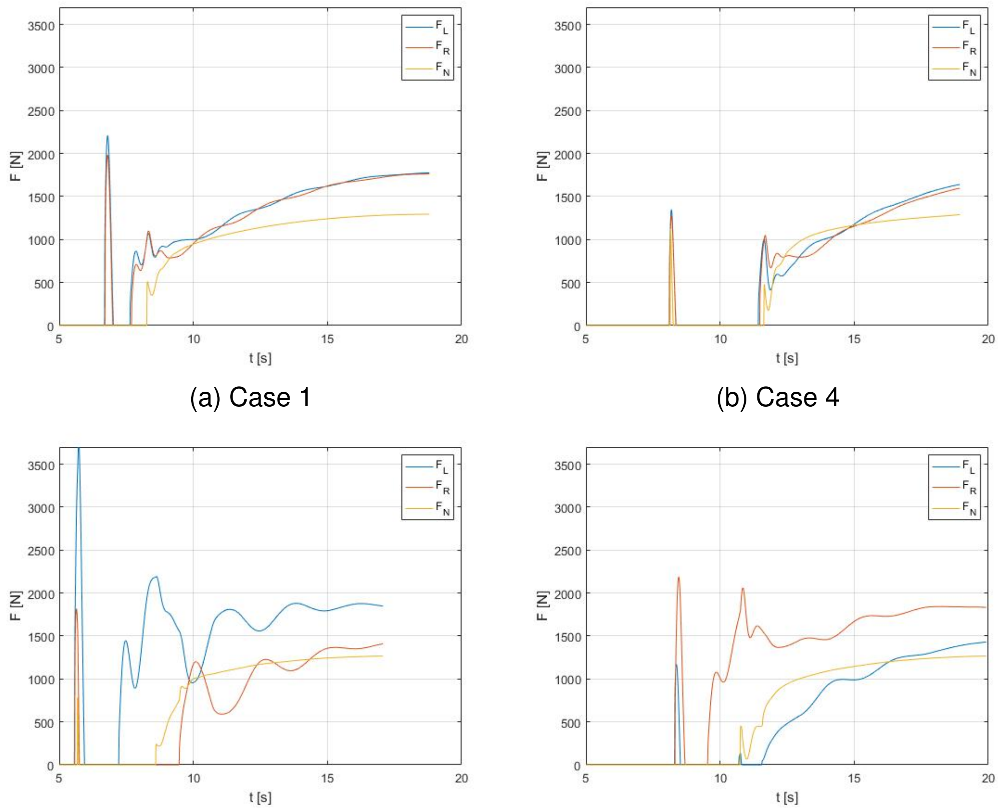



(a) Top view




(b) Altitude

Figure 9 – Flight trajectory during missed approach 5 with comparision to case 1 and 2




(a) Case 1

(b) Case 4

(c) Case 3

(d) Case 2

Figure 10 – Forces vs time

landing. There is an increase in the power, which in Fig. 3 is visible as an increase in motor RPM, and the transition of the control system to the climb mode. The altitude changes shown in Fig. 9b can be compared with the correct landings (cases 1 and 2).

The values of the vertical component of the force acting on the individual wheels of the aircraft are presented in the following figure (Fig. 10). The force designations are as follows: $F_R$ – the force acting on the right wheel, $F_L$ – the force acting on the left wheel, $F_N$ – the force acting on the front wheel. In all cases, the first touch of the runway appears as the pulse and then after a short time from 1 s to 3 s the aircraft begins a motion on the runway. When landing without wind and with headwind, the first ground touch is symmetrical on the main wheels. Crosswind landings vary depending on the wind direction. This is due to the effect of reducing the power of the engine before the touchdown, which also causes torque. The first ground touch is asymmetrical because of a temporary drive on one wheel and a delayed ground touch of the second main wheel, which appears after the front wheel. Regardless of these effects, the force values are on the acceptable level.

## 5. Conclusions

Proposed new approach procedure compared to the standard procedure is more demanding for a control system. The combination of the helix section with the straight line is in itself a disturbance which, when combined with other possible disturbances, can be critical to the success of the landing. Fully automatic implementation of this phase of flight along with automatic touchdown and on-the-ground motion control, seem to be a solution that in the current state of technology of control and measurement systems is realizable. However, a fully operational control system requires testing the behaviour of the system under various conditions. Developed control system has functions of state assessment and activation of the missed approach procedure if necessary. Thanks to the use of simulation methods and an advanced simulation model of the aircraft, it is possible to study the entire process from the beginning of the flight trajectory, through the approach trajectory to the aircraft braking on the runway.

However, it should be noted, that the assessment of correctness must consider the influence of other disturbances than a few examples presented in this study. Therefore, further experiments and refinement of control algorithms are planned to ensure their robustness to aircraft model changes that reflect possible deviations in the characteristics of the real aircraft.

## 6. Contact Author Email Address

mailto: jp@prz.edu.pl

## 7. Copyright Statement



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