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AUTOMATIC TAXI DIRECTIONAL CONTROL SYSTEM FOR GENERAL AVIATION AIRCRAFT

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Abstract

The article presents a concept of an automatic directional control system for a General Aviation class aircraft during the taxiing phase. In particular, it shows the concept of the system and the control laws synthesis – mathematical model and simulation of taxiing aircraft. Several reasons have emerged in recent years that make the automation of taxiing an important design challenge including decreased safety, performance and pilot workload. The adapted methodology follows the model based design approach in which the control system and the aircraft are mathematically modelled to allow control laws synthesis using the Adaptive Disturbance Rejection Control method. The computer simulations are carried out to analyze the control system behavior. Chosen methodology and modelling technique, especially tire-ground contact model, resulted in a taxing aircraft model that can be used for directional control law synthesis. Aerodynamic forces and moments were identified in the wind tunnel tests for the full range of the slip angle. The results can be used for the preliminary performance assessment of the ADRC method applied in the taxi directional control system. Such system has not been introduced to General Aviation yet. Therefore, the model of taxiing aircraft including aerodynamic characteristics for the full range of the slip angle and a directional control system have a big value in the process of design and implementation of the future automatic taxi systems.

Keywords: *General Aviation, taxiing, automatic control, mechanics of flight, aerodynamic tests*

1. Introduction

According to statistics of aviation accidents, a group of accidents taking part during taxiing motion makes, with respect to the number, the second group, after accidents taking part during landing manoeuvres [1]. This state of affairs leads to necessity of investigations including projects aimed at effective system for controlling the aircraft's traffic on airport's taxi tracks and runways. The current state with human-operator controlling this traffic is assessed to be not optimal, either in respect of safety, or in respect of potential increase of aircraft's motion intensity: raising numbers of take-offs and taxi operations after landing manoeuvre [2-4]. Safety, however, is not the only one factor proving the purposefulness of investigations within the area of organisation of taxiing. The analysis of trends of passenger streams in air transport shows expectations of air traffic increase in all airports: HUBs, international and local in the near future [5-7]. The expected process of including Remotely Piloted Aerial Systems (RPAS) into the non-segregated airspace constitutes the additional argument making such a forecast reliable. Automation of taxi phase of aircraft's motion can be noticed as a way towards intensification of aircraft's traffic on ground – this should result in both effectiveness and safety of performed operations. Such a system should be capable to assure an appropriate level of safety when operating taxiing aircrafts with lower separation distances and increased speed of taxiing motion. Now this speed seems to be too low, which results, depending on airport's size, in 10 minutes average time period of taxi motion to reach the runway.

The structure of automatic control system of taxi motion should be composed of two layers:

one the high level Taxi Management System (TMS), responsible for Taxiing Plan elaboration and supervision over this Plan execution, and the second one, the low level layer Taxi Control System (TCS), aimed at stabilisation of taxiing speed and heading along the required time regime [8]. The work is focused on the attempt aimed at integration of TCS sub system, which is responsible for keeping the referenced heading of motion. The problem is new in worldwide scale, as the autopilot for taxiing phase of motion has not been proposed yet. In the process of such a system design, some useful guidelines are coming from experience collected in automotive area [9, 10], however, from the perspective of mechanics, steering a car is far more effective than steering an airplane during taxi phase of motion. This comes from obvious differences between car and airplane functionalities, however in any case of driving/taxiing motion, a key role belongs to adhesion to the surface, defined as a function of summarised pressure resulting from distribution of weight on elements of undercarriage and aerodynamic forces acting along this direction. So:

– in the car, spoilers are defined as aerodynamic surfaces used for increasing the normal tire forces as the speed increases, while in the aircraft, the increased speed of taxi motion results in appearing a lift force, which decreases normal tire forces,
– the structure of airplane's undercarriage is affecting adversely on characteristics and parameters of airplane's taxi motion; this structure, usually is arranged with three landing wheels: two main wheels located on both sides of the central part of fuselage and one nose steerable landing, wheel making the airplane capable to perform turns while taxiing, with about 80% of weight on main landing gear. Such an irregular distribution of weight load makes the nose gear more susceptible to skidding in turns (especially in case of wet runway/taxi track or covered by snow/ice),
– big lifting surfaces of the airplane generate aerodynamic forces and torques disturbing airplane's taxi motion. In case of strong wind of transversal direction, the vertical tail surface exerts a destabilising effect on taxi motion via yawing moment appeared,
– owing to fuel tanks location in airplane's wings, the inertia component with respect to vertical axis increases, which results in significant and adverse effect on turning performance.

2. Physical model of the control object

The MP-02 Czajka A/C two-seater construction, presented in Fig. 1, which was adopted as a control object is a high-wing aircraft with a wing equipped with a double-slotted flap, a T tail configuration, and a three-point landing gear with a front swivel wheel. The main wheels are equipped with disc brakes. The maximum take-off weight is $m = 472.5$ kg, inertia moment $I_z = 990.5$ kg·m^2, the wingspan is $l = 9.72$ m, their lift area is $S = 10.2$ m^2, and the mean aerodynamic chord is $c_a = 1.08$ m.

Fig. 1. Experimental aircraft MP-02 Czajka

It was assumed that the aircraft during the taxiing phase is treated as a rigid body with three degrees of freedom. Such a model makes it possible to formulate equations that specify its:

– progressive movement at u speed compatible with the rotations of the wheels,
– lateral movement at v speed, being the result of their slip,
– change in the driving direction as an effect of coordinated deflection of the front wheel not dependent on the yaw moment which is the result of assymetric rolling friction.

The adopted assumptions, in particular, result in omitting the aircraft pitch and roll movements being an effect of both radial and lateral deflection of tires of the landing gear wheels, and also deformation of its struts. The results obtained during the performed tests show that the maximum deflection of struts in the actual conditions is approximately 100 mm, which is about 10 times greater than the recorded deformation of each landing gear tire. Therefore, it is important to assume that both factors together result in the maximum pitch and roll angular movements within the limits of ±5°, which should not have a significant impact on the process of selecting a regulator of the aircraft driving direction control system.

The distance between the front wheel and the aircraft centre of gravity $a = 1.0$ m was assumed, the distance from main wheels $b = 0.36$ m, the track of which is $c = 2.06$ m. The vertical distance of a contact point of all the landing gear wheels with the ground from the aircraft centre of gravity, is the same for each of them, and it is $h = 1.1$ m.

3. Mathematic model of the control object

For such a defined model, choosing three local coordinate systems $Ox_ny_nz_n$ for $n = 1...3$, with axes parallel to the body coordinate system $Oxyz$ attach ed in contact points with the ground of each landing gear wheel, the equations of motion of an aircraft take the following matrix form:

$$\begin{aligned} \dot{u} - rv &= 0, \\ \dot{v} + ru &= Y/m, \\ \dot{r} &= n/I_z, \end{aligned} \tag{1}$$

in which the state variables include two linear velocities, u longitudinal and v lateral, and r yaw rate. Their integration allows for determination of the current position and yaw angle of the controlled object. For the purposes of testing of an isolated system for controlling the taxiing course, it was assumed that the longitudinal velocity will be constant u = const. By eliminating the necessity of balancing the forces resulting from rolling resistance and aerodynamic drag by an appropriate selection of the drive unit thrust, such an approach clearly allows to focus on testing the control system. Finally, the aircraft with the weight of m and I_z moment of inertia determined in relation to Oz axis of the body system, is directly affected only by Y lateral force and N yaw moment in the examined case.

The physics of this phenomenon obviously results in the necessity of taking into account the effects of Y_{t_i} transverse friction with the direction consistent with the axis of rotation of the landing gear wheels, where i numbers respectively refer to the front wheel, the main right and left ones. The mentioned forces occur in the contact point of each landing gear wheel with the ground, and their value depends on λ_i slip angle, and also on Z_{n_i} pressure force, as well as a type and a state of the ground, on which taxiing takes place,

$$Y_{t_i} = Y_{t_i}(\lambda_i, Z_{n_i}) \;\; i = \{1, 2, 3\}. \tag{2}$$

Including the impact of the yaw angle of the front wheel δ_1:

$$\lambda_1 = \tan^{-1}\left(\frac{v + r \cdot \mathrm{a}}{u}\right) - \delta_1, \quad \lambda_2 = \tan^{-1}\left(\frac{v - r \cdot b}{u - r \cdot c/2}\right), \quad \lambda_3 = \tan^{-1}\left(\frac{v - r \cdot b}{u - r \cdot c/2}\right), \tag{3}$$

and the pressure force Z_{n_i} on the wheels, which include the impact of inertia forces, and aerodynamic forces: lateral Y_a, lift Z_a, and also roll L_a and pitch M_a aerodynamic moments:

$$
\begin{aligned}
Z_{n_1} &= \frac{b(-m\,g - Z_a) + M_a}{a+b}, \\
Z_{n_2} &= \frac{a(-m\,g - Z_a)aM_a}{2(a+b)} + \frac{h[-m(\dot{v} + ru) + Y_a] + L_a}{c}, \\
Z_{n_3} &= \frac{a(-m\,g - Z_a)aM_a}{2(a+b)} - \frac{h[-m(\dot{v} + ru) + Y_a] + L_a}{c}.
\end{aligned} \tag{4}
$$

The lateral force Y_{t_i} determined in such a way and the yaw moment that is affected by it:

$$N_t = Y_{t_1}\, a \cos\delta - b(Y_{t_2} + Y_{t_3})\,. \tag{5}$$

Finally, Y lateral force and N yaw moment that occur in the equations of motion (1) can be determined as:

$$
\begin{aligned}
Y &= Y_{t_1} \cos\delta_1 + Y_{t_2} + Y_{t_3}, \\
N &= N_t + N_a,
\end{aligned} \tag{6}
$$

where N_a is aerodynamics yaw moment [11].

Figure 2 presents the selected coefficients of aerodynamic forces and moments, which affect aircraft while taxiing, determined during the aerodynamic tunnel and water tunnel tests and with the use of CFD calculations.

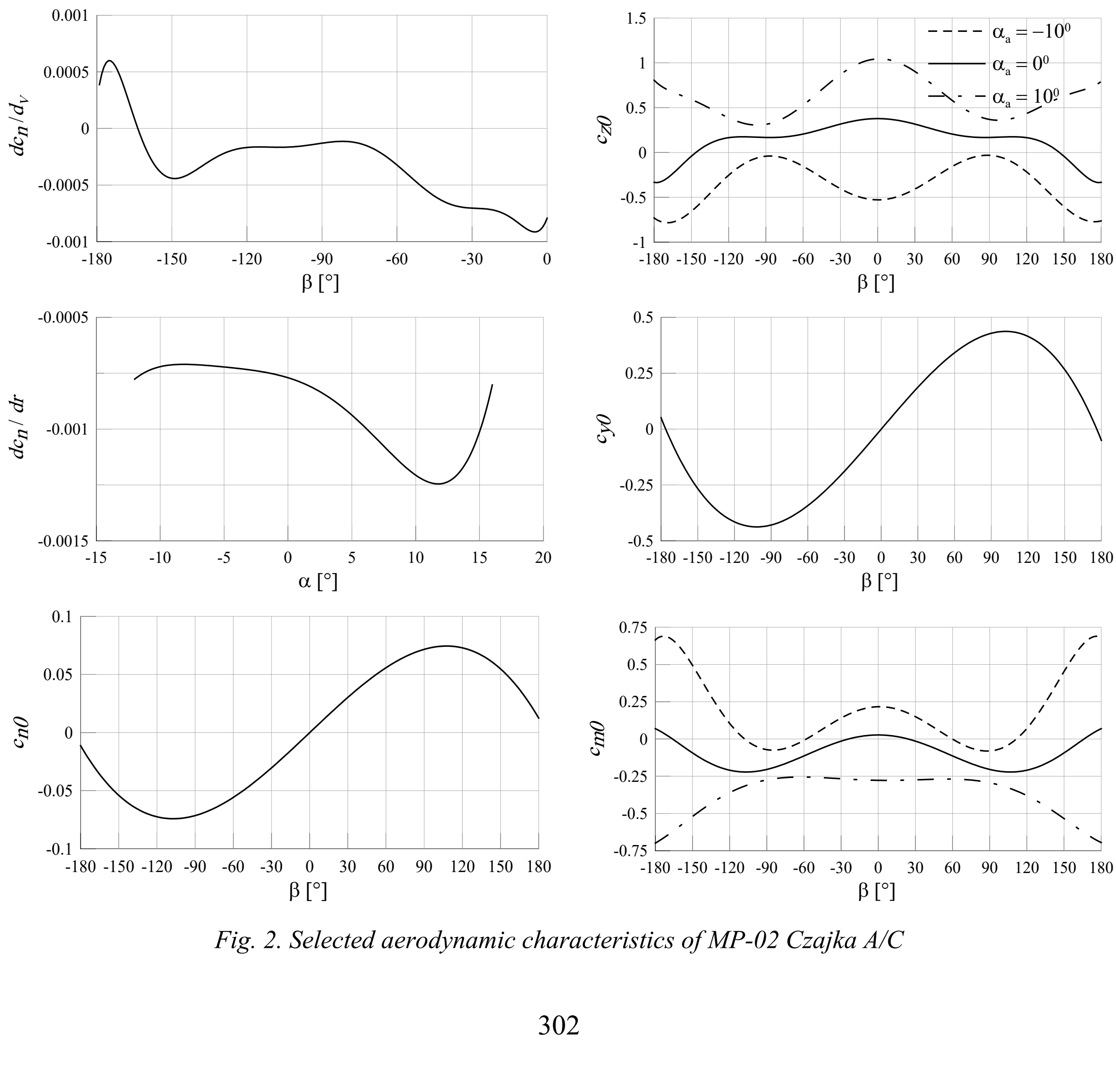

Fig. 2. Selected aerodynamic characteristics of MP-02 Czajka A/C

3. Directional system control algorithm

The choice of the control algorithm must take into account specific features of the taxiing aircraft motion. Firstly, uncertainties in the aircraft model parameters and variations of the taxiway condition are present with the latter strongly affecting the tire grip. Secondly, nonlinearities exist mainly in tire and aerodynamic characteristics. Therefore the directional taxi control algorithm must be robust, applicable for a nonlinear plant model and must not need full state feedback. Several control algorithms were analyzed according to defined requirements. The results are presented in Tab. 1.

Table. 1. Results of control algorithm analysis

Control algorithm	Robust (does not need a very accurate model)	Can be synthetized with nonlinear model	Does not need full state feedback
PID with gain scheduling	Yes	No	Yes
LQR	Yes	No	No
NDI (feedback linearization)	No	Yes	No
$\mathcal{H}_\infty$	Yes	Nie	Yes
MRAC, MIAC	No	Yes	Yes
MPC	No	Yes	Yes
LPV	Yes	No (LPV model)	Yes
Backstepping	No	Yes (triangular form)	No
Sliding Mode Controller	Yes (chattering)	Yes	Yes
Fuzzy Controller	Yes	Yes	Yes
Neural Network Controller	Yes (need accurate data for training)	Yes	Yes
ADRC	Yes	Yes	Yes

The ADRC algorithm does not suffer from problems like chattering related to sliding mode control, neural network training process and lack of rules for formulating fuzzy sets [12, 13]. Therefore the ADRC was chosen as the algorithm for the automatic taxi directional control system.

The idea of the ADRC algorithm is to compensate disturbances acting on a aircraft. The total disturbance causes the plant output to deviate from the reference input. It is estimated by the Extended State Observer (ESO) and used in the internal feedback loop to compensate effects caused by it. The total disturbance consist of external disturbances and both structural and parametric uncertainties of the model [14-17]. This compensation finally allows to design the robust feedback controller.

The ESO parameters were tuned so that its bandwidth is 33 rad/s. The rest of the parameters which are proportional and derivative gains, output scaling parameter and nonlinear gain scaling function parameter were tuned using the gradient descent optimization method. The method iteratively searched for the minimum of the cost function. The cost function was based on the difference between the step response requirements and the aircraft step response. The computed parameters are used in the ADRC algorithm.

4. Simulation results

The ADRC controller was tested in computer simulations. The experiment presented in this article aimed to test the behavior of automatically controlled aircraft subjected to side wind disturbance modeled using Dryden's theory. In the presented test case the aircraft is tracking a constant 0º heading reference signal. After 5 seconds it is affected by the 10 m/s or 5 m/s wind from the right side. The initial disturbance of the aircraft heading is rejected in about 4 s for the

10 m/s wind and 3 s for 5 m/s wind. The controller reaction allowed for 0.1º deviation from heading reference for 10 m/s wind and 0.03º for 5 m/s wind (Fig. 3). Fig. 4 and 5 show the resulting cross track error for both cases.

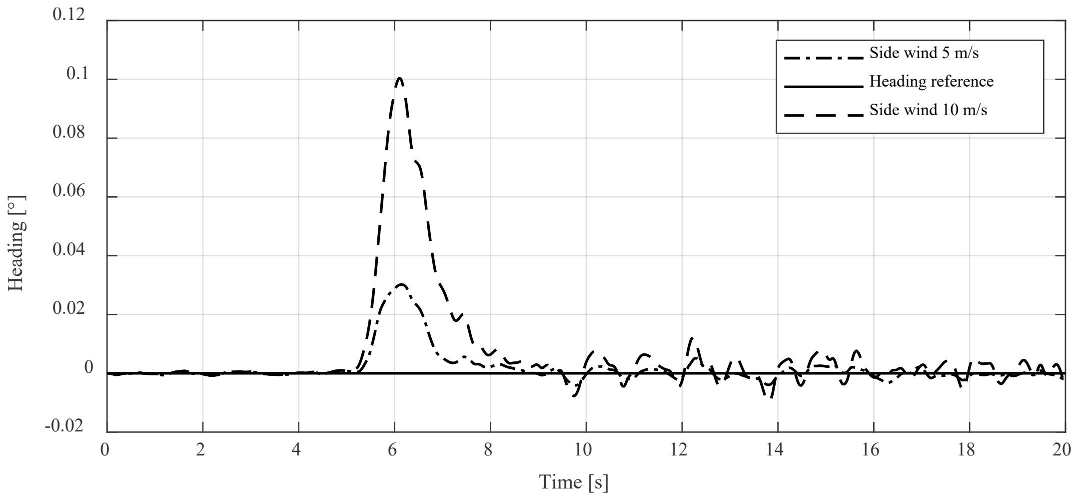

Fig. 3. Aircraft heading

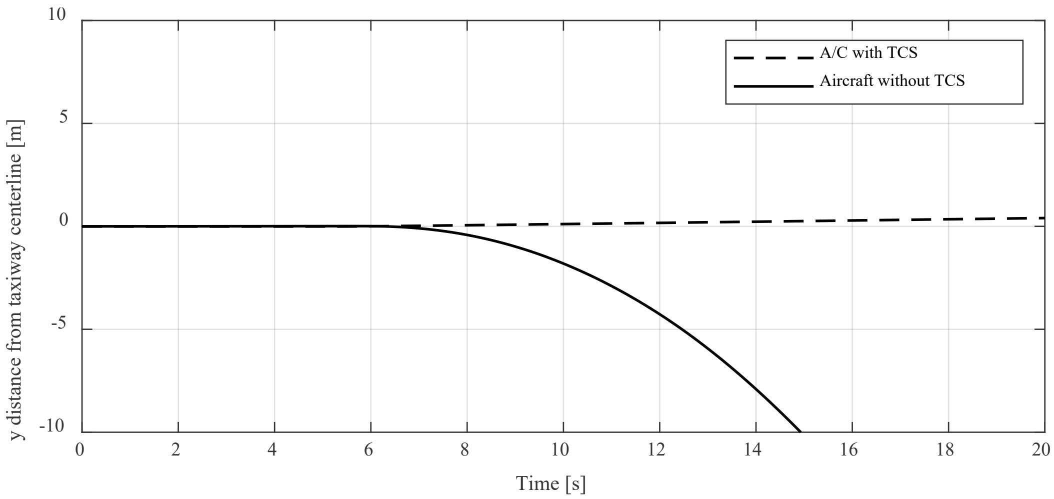

Fig. 4. Cross track error, side wind 5 m/s starting at 5 s

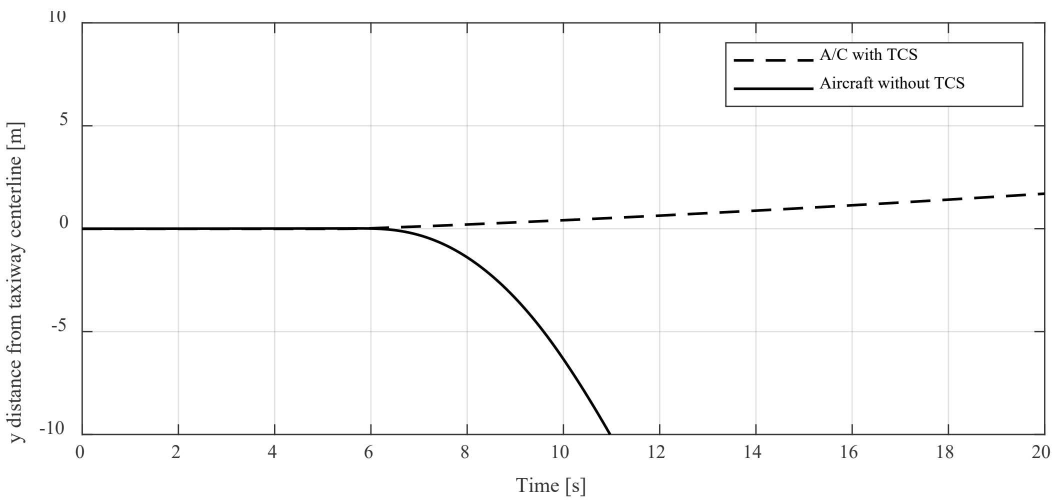

Fig. 5. Cross track error, side wind 10 m/s starting at 5 s

Although aircraft tracks 0º heading reference, small side movement of the aircraft in the direction of wind can be observed. This phenomena is caused by the tires elastic properties included in the model. Under the side wind force the tires contact patch deforms and a side slip angle appears. As a result the aircraft has a side velocity component. Nevertheless, the nose of the aircraft tracks the reference heading. The system is stable under the limit maximum taxi speed limit which is getting lower as the taxiway becomes more slippery when it is wet or there is snow on it.

5. Conclusion

Results of numerical simulations, completed on the basis of MP – Czajka aircraft's mathematical model are leading to the following final conclusions:

– Presented ADRC controller of TCS system has turned out to be the appropriate one for steering the airplane's taxi phase of motion, for different steady states.
– During a taxi phase of airplane's motion, an envelope of exploitation parameters exists, defined by wind-induced disturbances, parameters of technical state and surface adhesion.
– Presented ADRC controller can be equipped with Stability Augmentation System, which is aimed at performing the following tasks: adjustment of taxiing velocity up to current weather conditions, affecting the state of taxi tracks and runways, and velocity correction, when the motion is performed in gusty wind conditions.
– Possibility for expanding the taxi motion exploitation parameters envelope should be noticed in implementation on aircrafts' boards systems currently used in automotive vehicles, like: Anti-Lock Braking System, Electronic Stability Program, Adaptive Cruise Control, Electronic Brake Force Distribution.
– The TCS just prepared should be supplemented by TMS.

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