DE GRUYTER OPEN
RIGA TECHNICAL UNIVERSITY

Transport and Aerospace Engineering

ISSN 2255-9876 (online)
ISSN 2255-968X (print)
December 2016, vol. 3, pp. 38–43
doi: 10.1515/tae-2016-0005
https://www.degruyter.com/view/j/tae

Dynamic Model of Aircraft Landing

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Abstract **– This manuscript presents a research method that will be used in the development process of avionics equipment. A special device predicting braking and take-off distances will help pilots and provide a complex increase of flight safety and decrease of some types of charges.**

Keywords **– Aircraft, braking, landing, rolling resistance force, runway run distance.**

I. Introduction

Aircraft landing is an important phase of the flight. One of the main tasks of this phase is to reduce the aircraft speed from a high landing speed to a low taxiing speed provided that the aircraft is not skidded off the runway. For this purpose, the pilot must perform a series of actions for breaking the aircraft movement.

II. Dynamic Model

For trouble-free braking performance of the aircraft movement the pilot should be aware of the consequences of his/her actions. The pilot's braking performance is based on his/her experience of forecasting the consequences of his/her actions during the braking movement of the aircraft [1]. However, in poor weather conditions or during the abnormal operation of any aircraft system, the probability of trouble-free performance of the aircraft braking movement can be significantly reduced [2]. In difficult operating conditions the probability of trouble-free braking maneuver can be provided by a special device that will predict the braking distance after the adoption of pilot actions [3]. Depending on the information provided by this device, the pilot will make adjustments in his/her actions by increasing or decreasing the degree of braking movement. At the Institute of Aeronautics of Riga Technical University a device providing the information about the aircraft landing roll distance after the pilot's actions is being developed. In order to optimize the structure of the device and the choice of parameters, it is necessary to simulate its operation in different aircraft landing conditions [4]. This requires the development of an aircraft movement model in landing mode. The development of the aircraft movement model in landing mode is challenging enough. This is due to the fact that the object's movement behavior varies during the landing period. In the initial landing phase, when the object is approaching the runway, there are aerodynamic forces and moments acting on it as well as the gravitational force [5]. In this situation, the object is the aircraft with its own motion laws. But as soon as the object's wheels touch the runway, there appears a new force acting on this object while other forces are changing. The wheel force of friction starts to act on the object; the aerodynamic forces start to decrease. The wheel friction force depends on the magnitude of aerodynamic lift (in respect to the weight of the object). The more time the object moves on the runway, the smaller the aerodynamic lift and the greater the wheel friction force. The aircraft in its kinematic behavior turns into a ground transport vehicle [6]. The object's longitudinal motion in the aircraft phase is described by (1)–(3) in accordance with Newton's law:

$$m\frac{\mathrm{d}V_x}{\mathrm{d}\bar{t}} + m\left(\omega_y V_z - \omega_z V_y\right) = \sum F_x; \quad (1)$$

$$m\frac{\mathrm{d}V_y}{\mathrm{d}\bar{t}} + m(\omega_z V_x - \omega_x V_z) = \sum F_y\,; \tag{2}$$

$$I_z\frac{\mathrm{d}\omega_z}{\mathrm{d}t} = \sum_{i=1}^{m} M_{z_i}\,, \tag{3}$$

where in the right side of the equations there are aerodynamic forces and moments acting on the object, i.e. the aircraft. In Fig. 1 the forces acting on the aircraft during the flight are shown as well as the motion parameters of the aircraft in the vertical plane [7], [6].

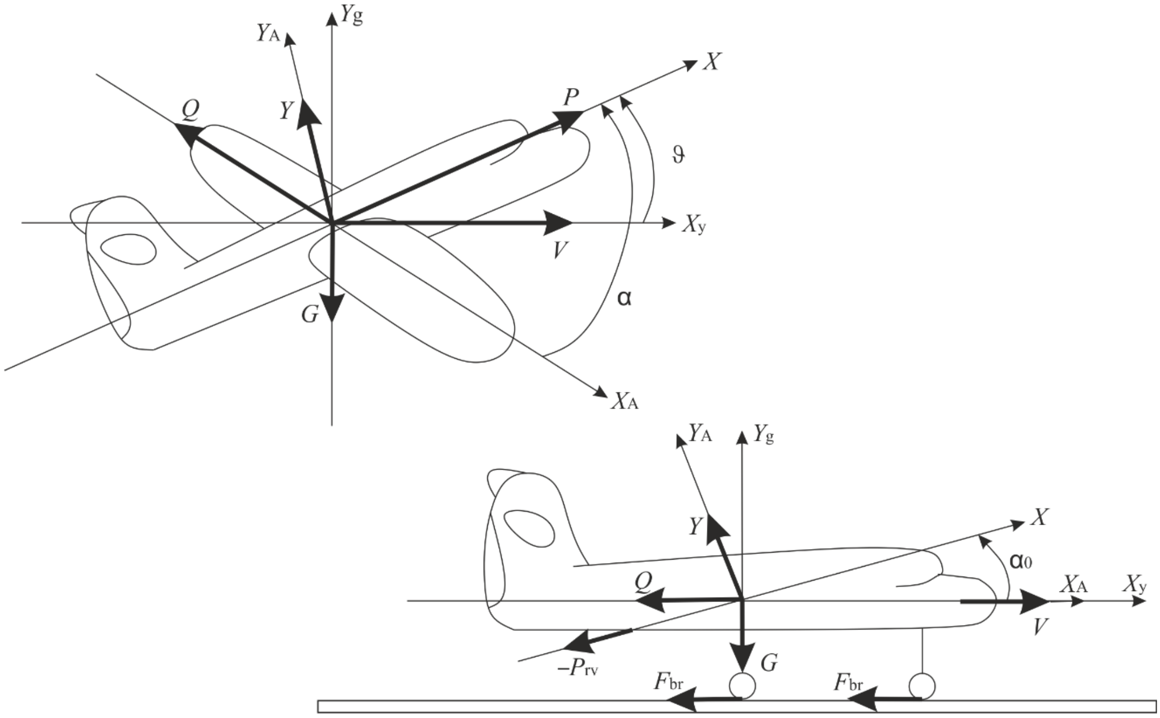

Fig. 1. Forces acting on the aircraft during the flight.

Aerodynamic forces such as lift Y and drag X are acting on the aircraft during the flight process [8]:

$$Y = C_y S\frac{\rho v^2}{2}; \tag{4}$$

$$X = C_x S\frac{\rho v^2}{2}, \tag{5}$$

where

- C_y, C_x aerodynamic force coefficients;
- S wing area;
- ρ air density;
- v air speed.

Gravity force G and aircraft engine thrust P are acting on the aircraft during the flight process. Then the equation describing the linear motion of the aircraft is written in the form:

$$m\left(\frac{\mathrm{d}v_x}{\mathrm{d}t} + \omega_y v_z - \omega_z v_y\right) = P_X - X - G\sin\theta; \tag{6}$$

$$m\left(\frac{\mathrm{d}v_y}{\mathrm{d}t} + \omega_z v_x - \omega_x v_z\right) = Y - G\cos\theta. \tag{7}$$

Kinematic equations should be added to these equations:

$$v_y = \frac{\mathrm{d}H}{\mathrm{d}t} = v_0 \sin\theta; \tag{8}$$

$$v_x = \frac{\mathrm{d}L}{\mathrm{d}t} = v_0 \cos\theta, \tag{9}$$

where

v_x, v_y relative velocity components along the earth coordinate system axes.

The object's dynamics in the ground transport phase will change significantly in comparison with the object movement in the aircraft phase, which is described in (6)–(9), because the object movement on the surface of the runway will impose certain restrictions on the object's kinematics and dynamics. The object's movement on the surface of the runway will lead to many changes in the object's kinematic parameters. There will be no angular velocity of the object ($\omega_x = 0$, $\omega_y = 0$, $\omega_z = 0$), as there will be no angular movements of the object. The angle of trajectory movement inclination θ will be equal to zero. The angles of attack α and pitch ϑ will be constant and equal to ($\alpha = \vartheta$). The forces acting on the object during its movement along the runway will change as well in comparison with the forces acting in the phase of flight (Fig. 1) [9]. The objective of this flight phase is to reduce the speed of the aircraft. Therefore, there will be no aircraft engine thrust (P). Force acting on the aircraft in the direction opposite to its speed will be created. After the aircraft wheels touch the runway the direction of aircraft engine thrust P is reversed ($-P_{\mathrm{rv}}$) as compared to the flight phase. It has to be done by the crew by means of a special reverse device at the initial stage of movement along the runway when the speed is very high. Reducing the aircraft wheel speed by wheel braking leads to intensive tire wear. Therefore, this method of braking in the first phase of aircraft movement on the runway is not applicable. The reverse device at the initial stage of movement along the runway is used only during a relatively small period of time to intensively reduce the aircraft's speed at the initial stage of its movement along the runway. So during the braking process aircraft engine thrust will be acting in a negative direction only at a certain time interval ($-P_{\mathrm{rv}}(\Delta t)$). Aerodynamic forces acting on the aircraft in flight will also affect the movement of the aircraft on the runway. Drag X will continue to act opposite to the speed of the aircraft exerting a breaking effect on it (reducing its speed). The magnitude of drag X will be reduced in time as it will decrease the speed of the aircraft (5). There will be created one more aerodynamic resistance force at the stage of aircraft movement along the runway – the force of spoiler resistance X_{sp}. The force of spoiler resistance X_{sp} is created by special wing flaps exposed against the flow. There is a new braking force typical of the aircraft movement along the runway. This is the wheel shaft rotation braking force $R_{\mathrm{br.}}$ This force consists of two components. The first component F_{fr1} arises from the existence of force interaction between the surfaces of the runway and the aircraft wheels. It is a rolling resistance force. The magnitude of the rolling resistance force is determined (in literature) as [10]:

$$F_{\mathrm{fr1}} = k_{\mathrm{fr1}} G, \tag{10}$$

where

k_{fr1} rolling resistance coefficient;

G vehicle weight.

Rolling resistance coefficient k_{fr1} depends on the aircraft movement speed V and runway condition coefficient C_{st} (humidity, icing, etc.):

$$k_{\mathrm{fr1}} = \left(0.0041 + 0.000041V\right) C_{\mathrm{st}}. \tag{11}$$

Runway condition coefficient C_{st} (11) can vary widely. In particular dry smooth concrete C_{st} will be 1.0.

Rolling resistance force F_{fr1} (10) for the case of aircraft movement braking process takes the form of:

$$F_{\text{fr1}} = k_{\text{fr1}}(G - Y) \ , \tag{12}$$

where

Y lift magnitude.

Lift Y will decrease over time (4), since the braking of the object's movement leads to the decrease of its speed (V). The weight of the object (G) will remain the same as in the last moment of the flight (when the object's wheels touch the runway). That is, the magnitude of rolling resistance force F_{fr1} (12) is minimal in the aircraft wheels touching point on the runway. When the aircraft is moving on the runway, rolling resistance force F_{fr1} magnitude will increase in time. The second component of rolling resistance force $F_{\text{fr2(pd)}}$ arises due the object's wheel shaft rotation braking facility used by the pilot pressing the brake pedal. This is the driving force of the aircraft's movement braking process. By intuitively creating a wheel braking force value, the pilot reduces the aircraft's speed to a predetermined value within the time period of the aircraft's movement on the runway thereby avoiding the aircraft overrunning the runway [6], [11]. In this process it is also important (especially for civil aviation) to implement the optimal selection of the wheel braking force value so that the tire wear would be the lowest possible. In order to implement the optimal braking process the pilot should anticipate the consequences of braking force towards the aircraft kinematics. This is a very difficult task [12]. A special device which after each pilot's braking action will show the length of the subsequent run after the creation of a specific braking force can help qualitatively solve this problem. In order to optimize the structure and evaluate the instrument errors with respect to various design parameter choices it is necessary to analyze the work of the special predictive tool. This can be done on a dynamic model of aircraft landing. The analysis of landing dynamics and kinematics makes it possible to create the aircraft landing model [13]. From (6)–(9) we obtain the dynamic model of aircraft landing:

$$m\frac{\mathrm{d}V}{\mathrm{d}t} = -P_{\text{rv}}(\Delta t) - X - F_{\text{fr1}} - F_{\text{fr2(pd)}} - K_{1Ux}U_x - K_{2Uy}U_x; \tag{13}$$

$$L_{xz}\left(t\right) = Vt, \tag{14}$$

where

$L_{xz}(t)$ aircraft landing run distance on the runway;

$K_{1Ux}U_x$, $K_{2Uy}U_x$ wind disturbances from horizontal wind speed component U_x.

In the dynamic model of aircraft landing all forces should be set in a certain way depending on landing conditions [14]. Aircraft engine reverse force P_{rv} should be taken from the specific aircraft engine landing mode characteristics. Aerodynamic forces such as lift Y and drag X are very easy to be calculated as these force values depend only on the aircraft movement speed (4), (5). It is necessary to enter the C_y, C_x coefficient dependence on the aircraft speed in the aerodynamic forces and apply the aircraft speed on their inputs. This will give rise to feedback loops in the model. In order to calculate rolling resistance force F_{fr1} it is necessary to reduce the aircraft weight constantly in time by the amount of lift. Wind disturbances $K_{1Ux}U_x$, $K_{2Uy}U_x$ from horizontal wind speed component U_x will be determined from the expression for aerodynamic forces (4), (5). When U_x occurs, the magnitude of aerodynamic forces X and Y (ΔX and ΔY) will vary as well and become disturbing factors for the aircraft motion. The disturbing factor magnitude is determined as the aerodynamic forces X and Y components expand according to U_x parameter:

$$K_{1Ux}U_x = \Delta X = \left(C_x^{\ V} S\frac{\rho V^2}{2}\right)U_x + \left(C_x S\frac{\rho 2V}{2}\right)U_x = \frac{S\rho V^2}{2}\left(\frac{C_x^M}{a_H} + \frac{2C_x}{V}\right)U_x; \tag{15}$$

$$K_{2Uy}U_x = \Delta Y = \left(C_y^{\ V} S \frac{\rho V^2}{2} \right) U_x + \left(C_y S \frac{\rho 2V}{2} \right) U_x = \frac{S\rho V^2}{2} \left(\frac{C_y^M}{a_H} + \frac{2C_y}{V} \right) U_x. \quad (16)$$

Then coefficients K_{1Ux}, K_{2Uy} (15), (16) in the aircraft landing dynamic model are defined as (17), (18):

$$K_{1Ux} = \frac{S\rho V^2}{2} \left(\frac{C_x^M}{a_H} + \frac{2C_x}{V} \right); \quad (17)$$

$$K_{2Uy} = \frac{S\rho V^2}{2} \left(\frac{C_y^M}{a_H} + \frac{2C_y}{V} \right). \quad (18)$$

Control braking force of aircraft $F_{\text{fr2(pd)}}$ (13) due to the aircraft wheel shaft rotation braking process when the pilot is pressing the brake pedals should be modeled by applying the permanent signals corresponding to the pilot's effort to the model at different time moments [15]. Values $F_{\text{fr2(pd)}}$ can be fed into the model of the experimenter reproducing a pilot action during the landing stage.

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