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Article information:

To cite this document:
Zdobyslaw Jan Goraj Ewa Cichocka , (2016),"Influence of weak and strong gyroscopic effects on light aircraft dynamics ", Aircraft Engineering and Aerospace Technology, Vol. 88 Iss 5 pp. 613 - 622
Permanent link to this document:
http://dx.doi.org/10.1108/AEAT-03-2015-0076

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Influence of weak and strong gyroscopic effects on light aircraft dynamics

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Abstract

Purpose – The purpose of this study is to investigate the influence of gyroscopic effects on the dynamic stability and the response of light aircraft to manoeuvres following either a rapid deflection of the control surfaces or wind gust.

Design/methodology/approach – The analyses were conducted for several different mathematical models of aircraft motion, which allowed for the investigation of the relationship between introduced simplifying assumptions and the aircraft response, including non-linear terms in equations of motion expressing the influence of inertial coupling. The analytical and experimental methods (measurements in the wind tunnel for the scaled model and during flight tests of I-31T prototype aircraft) were used.

Findings – It was found that gyroscopic moments are induced mainly by the propeller, and their influence on dynamic stability of a light aircraft is negligible. However, these phenomena in manoeuvring flight investigation should not be excluded, although for general aviation (GA) aircraft, they are not strong. Hence, two types of gyroscopic effects depending on the level of steady flight disturbances were distinguished. The authors differentiated weak gyroscopic effects, corresponding to classical dynamic stability, and strong gyroscopic effects, corresponding to rapid manoeuvres.

Practical implications – Conclusions include some findings on the nature of gyroscopic effects (i.e. sensitivity of flight stability versus turboprop power unit parameters) and practical recommendations for aircraft designers dealing with new configurations of GA aircraft.

Originality/value – The analysis focuses on the assessment of the flight dynamics of light aircraft with a novel, compact, lightweight, fast-rotating turbopropeller engine and strong/weak gyroscopic effects.

Keywords Dynamic stability, Flying qualities, Gyroscopic moments, Light turboprop aircraft, Propeller effects

Paper type Case study

Nomenclature

Symbols

x_8 = state vector
M_8 = generalised inertia matrix
B_8 = generalised damping matrix
λ = eigenvalue, [1/s]
ξ = damping coefficient, [1/s]
η = natural frequency coefficient, [1/s]
V_A = airspeed, [m/s] or [km/h]
Mx, My, Mz = rolling, pitching and yawing moment, respectively, [N·m]
p, q, r = aircraft angular rates, [rad/s]
α = angle of attack, °
β = side slip angle, °
ε = downwash angle, °
δe, δr, δa = deflection angle of elevator, rudder and ailerons, respectively, °;
Ixx, Iyy, Izz = moment of inertia with respect to the x-, y- and z-axis, respectively, [kg·m^2]
Ip_{prop} = polar moment of inertia of the propeller, [kg·m^2]
Ixx_{prop} = moment of inertia of the propeller about its axis of rotation, [kg·m^2]
ω_o ($\overrightarrow{\omega_o} = pi + qj + rk$) = the angular velocity of the precession, [1/s]
$\omega_{x_{prop}}$ = angular velocity of the propeller; the subscript x denotes rotation about the x-axis, [1/s]
$K_{prop} = I_{xx_{prop}}\omega_{x_{prop}}$ = the magnitude of the angular momentum of the propeller, [kg·m^2/s]
n_{prop} = propeller rotational speed, [rpm]
Ude = gust velocity, [ft/s]
n_z = normal load factor, [-]

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Aircraft Engineering and Aerospace Technology: An International Journal
88/5 (2016) 613–622
© Emerald Group Publishing Limited
[ISSN 1748-8842]
[DOI 10.1108/AEAT-03-2015-0076]

Received 7 March 2015
Revised 10 March 2016
25 May 2016
Accepted 6 June 2016

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Indexes, definitions, acronyms and abbreviations

prop	=	propeller or propulsion
G.E.	=	gyroscopic effects
CFRP	=	carbon fibre-reinforced polymer
GA	=	general aviation
ESPOSA	=	efficient systems and propulsion for small aircraft

Introduction

The number of two-four-passenger light propeller-driven aircraft is constantly growing (Piwek and Wisniowski, 2016). Despite a strong position of piston-engine aircraft in the general aviation (GA) sector, increasing share of turboprops is noticed. Furthermore, recent years have brought the new trend to design highly powered propeller-driven tractor aircraft. Visible development of lean manufacture technologies, more efficient and reliable systems of propulsion units, new low-weighted materials and the reduction of gas turbine fuel consumption make currently available gas turbine engine an attractive propulsion for light aircraft. In addition, GA is getting widely accessible to common people. At the same time, all the considered issues address the question of the flight dynamic properties of light turboprop aircraft with respect to gyroscopic effects.

The prediction of correlation between different power effects and dynamic stability characteristics of single-engine propeller-driven tractor turboprops has been the object of consideration for years. The first mathematical descriptions of the propeller-related issues were published in the first decades of the twentieth century (Lanchester, 1917; Glauert, 1919, 1935). NASA reports (Ribner, 1943, 1945) have played a particularly significant role in understanding the nature of these phenomena. However, there is still a gap in investigation dedicated to gyroscopic moments of light turboprop aircraft. Presented research is focused on the assessment of importance of this phenomenon on the aircraft handling and flying qualities.

The solution to this problem includes the finding of the trim conditions (Cook, 1997; Etkin, 1982) obtained from fully non-linear equations of motions with six independent variables represented by thrust, angle of attack, deflections of elevator, rudder, ailerons and bank angle. Flight speed, path angle, sideslip and gust are considered arbitrary parameters. Numerical analysis consists of solving the eigenvalues problem of linearized set of differential equations and the integration of the full non-linear equations of motion (McCormick, 1979; Goraj, 2014).

The aim of this paper is to present methods which will minimise the influence of weak and strong gyroscopic moments, both, on dynamic stability around the steady-state flight and on rapid manoeuvres caused by either sadden control movements or gust upsets (Cichocka, 2015). To achieve this goal, some other important phenomena are taken into consideration. The first phenomenon corresponds to reactive moment (if moment of momentum of the propeller is changed, the remaining aircraft structure gets an opposite moment of momentum to keep the moment of momentum of the whole aircraft constant). The second phenomenon follows asymmetric aircraft flow due to vortices shedding from the propeller. The last generally undesirable propeller effect, called P-factor (Gudmundsson, 2014), is a product of asymmetry in load distribution on the moving propeller blades, especially at high angles of attack of aircraft.

As the final outcome of the conducted analysis, the possibility to predict the flying qualities and their improvement are elaborated. To present the conclusions, the last section of this paper is pertained to discuss methods to reduce or completely eliminate the influence of unfavourable gyroscopic effects of novel turboprop engines. Design guidelines for pilots on how to assess dynamic stability characteristics and manoeuvre properties of a newly designed light turboprop aircraft are presented.

Model of aircraft dynamics – gyroscopic effects

This paragraph presents briefly the flight dynamic model. The analysis is based on the non-linear model of the aircraft spatial motion, (Goraj, 2000; Goraj and Sznajder, 2002). Finally, the set of linearized integral equations of motions for small disturbances written in the stability frame of reference (Goraj, 2014) can be defined as:

$$M_8 \cdot \dot{x}_8 = B_8 \cdot x_8 \tag{1}$$

where x_8 is a state vector, M_8 is generalised inertia matrix and B_8 is generalised damping matrix. Stability analysis needs to solve the eigenvalues problem, expressed as:

$$\left[\bar{M}_8{}^{-1}\bar{B}_8 - I\lambda\right]\bar{x}_8 = 0 \tag{2}$$

where eigenvalue λ, given by:

$$\lambda = \xi + i \cdot \eta \tag{3}$$

depends on damping coefficient ξ and frequency coefficient η.

The mathematical description of aircraft spatial motion, in the form determined by equation (1), is consistent with the approach of classical mechanics of flight but is not sufficient to take into account the gyroscopic effects induced by working powerplant of each aircraft. To assess the influence of gyroscopic moments on the aircraft dynamics, additional terms for the equations of motion are required. These extra terms are called gyroscopic couples. The phenomena have a form of cross-coupling that arises from angular velocity (in pitch or yaw) associated with rotating propeller, turbines or compressor of aircraft propulsion.

Gyroscopic effects induce a strong coupling between longitudinal and lateral aircraft dynamics. Pitch rate appears after sudden elevator deflection, vertical gust or other motion of aircraft in an Oxz plane. The yaw rate is typically related to sudden deflection of rudder or corresponds to a manoeuvre around axis Oz or follows the lateral gust. Hence, depending on the reasons of disturbance from steady-state flight conditions, gyroscopic effect is considered as either induced pitching or yawing moment, labelled as M_y and M_z, respectively. Resultant displacement is always normal to the axis of propeller rotation and to the direction of aircraft angular velocity vector. However, the rotating engine parts and the propeller of the most currently produced conventional light aircraft are usually closely aligned with the longitudinal

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(lengthwise) axis. This indicates the lack of gyroscopic rolling moment as a result of aircraft rotation about axis *Ox*.

For light aircraft with the constant speed propeller and the single turbine power plant, the moment of momentum generated by all rotating components of gas turbine engine is usually negligible in comparison with the propeller moment of momentum. If we assume a constant speed propeller $\omega_{x_{prop}}$, the derivative of moment of momentum with respect to time equals zero. General expression for gyroscopic moment is specified by equation (4):

$$\vec{M}_{G.E} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \frac{\partial \vec{K}_{prop}}{\partial t} + \vec{\omega}_0 \times \vec{K}_{prop} \tag{4}$$

Ultimately, the appropriate transformation of equation (4) leads to the following definition of gyroscopic moment:

$$\vec{M}_{G.E} = \begin{bmatrix} i & j & k \\ p & q & r \\ I_{xx_{prop}}\omega_{x_{prop}} & 0 & 0 \end{bmatrix} = I_{xx_{prop}}\omega_{x_{prop}} r\vec{j} - I_{xx_{prop}}\omega_{x_{prop}} q\vec{k} \tag{5}$$

Graphical interpretation of equation (5) is shown in Figures 1 and 2.

The magnitude of the generated gyroscopic moments induced by rotating propeller is dependent on operating parameters and the type of both, the engine and propeller and the rate of pitch or yaw.

Figure 1 Pitching moment due to the yawing rate

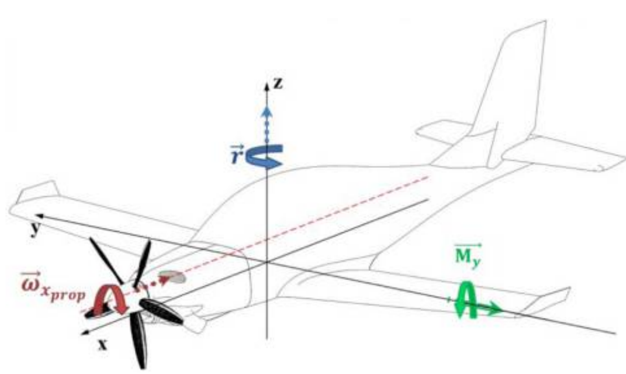
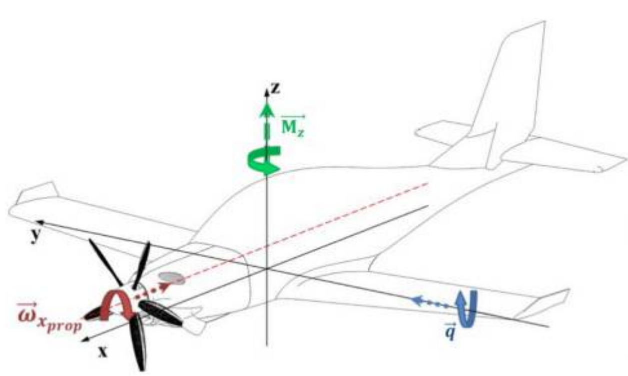


Figure 2 Yawing moment due to the pitching rate



The highest precession is achieved at the maximum angular velocity of the propeller and the lowest at idle conditions. These facts mean that the most significant flight phase is the early stage of aircraft take-off. Because of low speed of aircraft, the aerodynamic forces are also quite low, and, thus, the ability of the aircraft to counteract against the generated gyroscopic side effect is much smaller than under cruise conditions. Especially, for an unexperienced pilot, this yawing tendency appearing during the pitch-up manoeuvre at take-off is often unanticipated. To control an aircraft in rapid manoeuvres, the use of a control stick to deflect elevator in yaw or pedals to deflect rudder in pitching movement is necessary.

Gyroscopic effects

Dynamic stability analysis is based on the assumption of small disturbances of steady-state flight parameters. This theory also applies to perturbations of components of aircraft angular velocity. Because of small changes in pitch and yaw rates, the induced phenomena of precession are relatively not strong and are called weak gyroscopic effects. In contrast, during very rapid manoeuvres, especially when pitching or yawing rates are substantial, coupling between longitudinal and lateral degrees of freedom plays a significant role. Therefore, generated gyroscopic moments are named as strong gyroscopic effects. In extreme cases, disturbed motion may be large enough to cause loss of control or even structural failure. For this reason, gyroscopic effects are particularly important.

Among different types of manoeuvres which induce gyroscopic effects, two types can be distinguished – pull-up from the steady-state level flight and lateral displacement of aircraft from straight trajectory. In case of the first one, the manoeuvre corresponds to pitching following after either sudden elevator deflection or vertical gust. Conversely, yawing can occur after either a sudden rudder deflection or a horizontal lateral gust. Deflections of control surfaces versus time and the change in the wind gust might either be of the step change type, Figures 13 (a) to (c), or of the sinusoidal type. Oscillatory shape of the wind gust is compatible with the requirements of Certification Specifications for Light Aircraft (CS-23, 2012). Moreover, the gust may act on the whole aircraft body, on the main wing only or on the tailplane only. To assess the propeller gyroscopic effects, different cases are taken into account, and then all the achieved results are analysed in detail.

Thus, the issue of dynamic stability consists of solving the set of eight equations. By contrast, considering the strong gyroscopic moments generated in manoeuvres requires 12 first-order differential equations describing the motion of a rigid body aircraft. Gyroscopic effects terms are included in the generalised inertia matrix **M** (the sum of products of two factors: the moment of inertia I_{xx_i} and the angular velocity ω_{x_i}, where index i indicates the rotating parts of power unit including the propeller).

Assessment of influence of gyroscopic effects

Aircraft selected to analysis

As an exemplary aircraft representing the GA single turboprops, I-31T, shown in Figure 3, is chosen. This is a

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Figure 3 The first flight of a single-engine four-seat light aircraft I-31T from Institute of Aviation in Warsaw

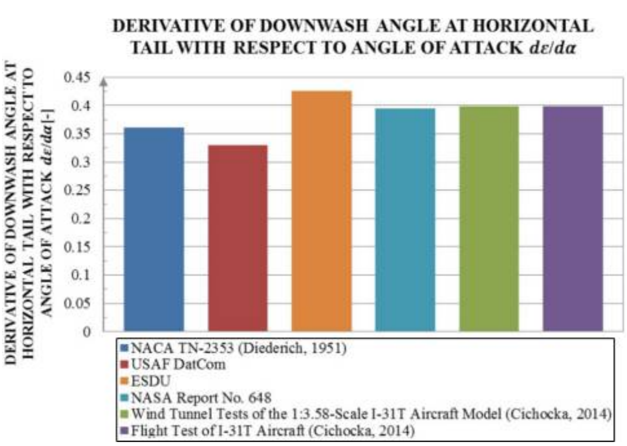
Polish, four-seat light turbopropeller aircraft based on the design of piston aircraft I-23 Manager, certified in Normal Category. At the same time, I-31T is one of the three flying technology demonstrators used to validate in flight a newly designed, compact, highly effective propulsion, realised in ESPOSA international project (Piwek and Wisniowski, 2016). The influence of gyroscopic effects on flight dynamics is scrutinised and assessed for this upgraded version of flying prototype.

Comparison of methods to determine non-dimensional derivatives

A full set of stability and control derivatives is used to linearize (simplify) the equations of motion. To find a credible solution of this system, different methods to define aerodynamic model (the complete collection of stability and control derivatives) are investigated and teamed with experimental data.

A single value of change in downwash angle with respect to the angle of attack, shown in Figure 4, corresponds to the linear-lift-region derivative. Regardless of the analytical method chosen, the calculated results are in accordance with in-flight, and wind tunnel measurements are determined through experiments.

Figure 4 Comparison of methods to determine the $d\varepsilon/d\alpha$ derivative



Other examples of comparison of the experimental results with data based on theoretical and semi-empirical mathematical formulas or numerically determined output data (3D panel method and computational fluid dynamic methods) are presented in Figures 5-7. Both longitudinal,

Figure 5 Comparison of several methods to estimate low-speed stability derivative Cl_p

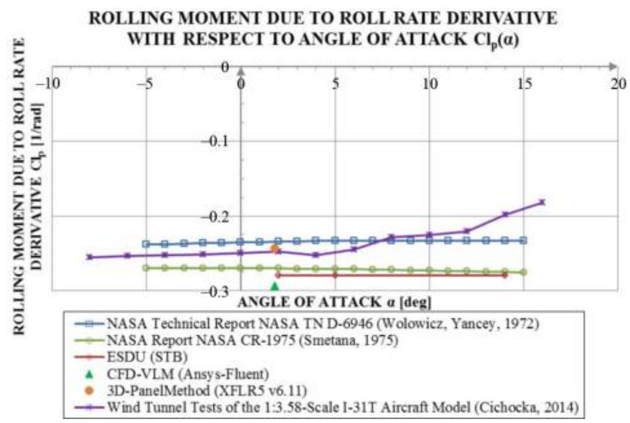


Figure 6 Comparison of several methods to estimate low-speed stability derivative Cl_r

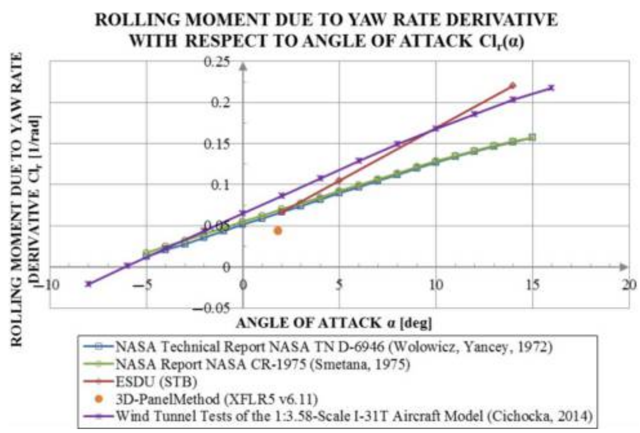
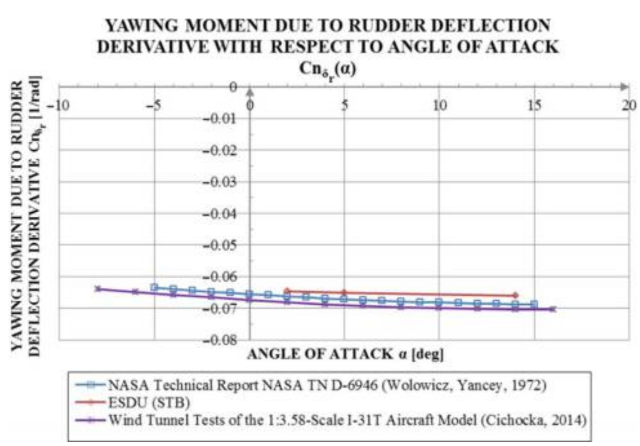


Figure 7 Comparison of several methods to estimate low-speed control derivative $Cn_{\delta r}$



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lateral-directional and control derivatives, based on classical approach, yield similar values in the range of small angles of attack.

Many different methods are used to estimate the low-speed stability and the control derivatives of conventional turbopropeller light aircraft. The outputs of the computation are compared with each other and with the existing wind tunnel data for aircraft model and with flight test measurements to assess relative suitability of employed methods to determine the aerodynamic derivatives and then evaluate dynamic stability of each aircraft at low subsonic speeds. The studies confirm that in general, a classical approach (ESDU, 1954; Smetana *et al.*, 1984) is entirely reasonable and absolutely credible to set the necessary aerodynamic data, based on analytical and empirical formulas. Numerical calculations (Dziubiński, 2013) also give reliable results. However, the estimation of dimensionless aerodynamic coefficients and derivatives using computer software is a complex and time-consuming task, especially, the calculation of derivatives, because of angular speed or control surface deflection. Ultimately, within the range of small angles of attack, none of the methods appeared consistent and appropriate for estimating all non-dimensional derivatives, in particular.

Results of dynamic stability analysis

Dynamic stability analysis was performed in a number of computational cases. We considered not only the level flight but also non-horizontal flight conditions (both, steady climbing and descending) at different altitudes, airspeeds, take-off weights and positions of centre of gravity (Goraj, 2014; Goetzendorf-Grabowski *et al.*, 2010). The outcomes of all calculations show a negligible influence of gyroscopic effects induced by small disturbances of steady-state flight. Therefore, a question was addressed on how changes in rotational speed of a turbine and a propeller and value of moment of inertia influence gyroscopic effects and, further, aircraft dynamic stability. Influence of the propeller rotational speed η_{prop} on dynamic stability was investigated for I-31T turboprop aircraft in the whole range of airspeeds at altitude H = 0 and excluding the ground effect on aerodynamic characteristics for the following sets of rotational speeds and moments of inertia: $\mathbf{n}$ = {n.prop.$_1$, n.prop.$_2$, n.prop.$_3$} = {2,158, 40,000, 60,000} [rpm] and $\mathbf{I_{xx}}$ = {I_{xx1}, I_{xx2}, I_{xx3}} = {1.5, 7.5, 10.0} [$kg \cdot m^2$], respectively. Moreover, all these results are compared with the case of gyroscopic effects negligence.

The permissible propeller diameter of conventional lightweight GA aircraft limits its rotational speed. The maximum value of revolutions per 1 min usually cannot be greater than approximately 3,200-3,400 [rpm] to not exceed the maximum performance reached at tips of the propeller blades (i.e. the value between 0.8 and 0.92 Mach). The latter (n.prop.$_3$) corresponds to the whole powerplant. If the direction of rotation of the engine components is not opposed and is the same as for the propeller, then the angular momentum induced by engine parts is not to neglect. Assuming in the calculation that each engine part has the same moment of inertia, i.e. $lxx_{propeller} = lxx_{engine\_part_1} = lxx_{prop}$, it is possible to determine a substitute rotational speed for the entire power unit so that the resultant angular momentum meets the following requirement:

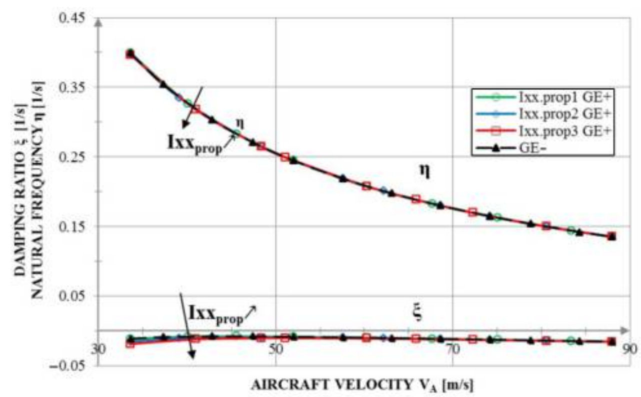
$$\sum_{i=1}^{n} I_{xx_1} \cdot \omega_{x_1} = I_{xx_{prop}} \cdot \omega_{x_{prop}} \tag{6}$$

where index i corresponds to a propeller and each rotating component of an engine.

The analysis results presented in Figures 8 and 9 show that the moment of inertia of the propeller does not have a significant influence on Phugoid, Short Period and Dutch Roll, independent of flight speed. This conclusion, however, is not a surprise. The present-day propellers, usually made of carbon fibre-reinforced polymer (CFRP), are very light, so its overall moment of inertia is quite small. In addition to that, most modern turboprop compressors and turbines rotate in opposite directions, yielding a very low value of gyroscope moments.

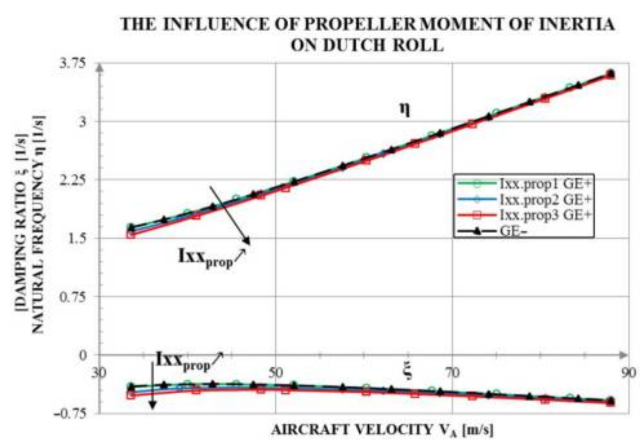
On the contrary, the propeller rotational speed affects the modes of dynamic motion. Increasing the constant speed of rotation results in an increase in Short Period frequency η_{SP},

Figure 8 Phugoid of aircraft with and without gyroscopic coupling taken into analysis



Note: The influence of propeller moment of inertia on Phugoid stability

Figure 9 The influence of propeller moment of inertia on Dutch Roll stability with (GE+) and without (GE−)



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(Figure 10), decrease in Dutch Roll frequency η_{DR}, (Figure 11), slight improvement of Dutch Roll damping ξ_{DR}, (Figure 11) and negligible worsening of Short Period damping ξ_{SP}, (Figure 10). As is shown in Figure 12, alongside speed-up

Figure 10 The influence of moment of inertia on stability of Short Period with (GE+) and without (GE−)

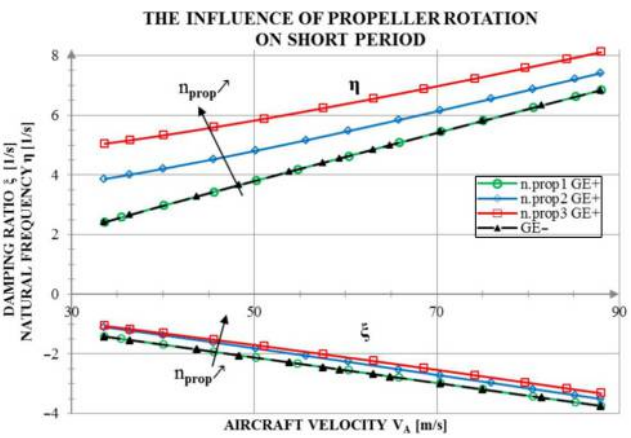


Figure 11 The influence of propeller speed of rotation on stability of Dutch Roll with (GE+) and without (GE−)

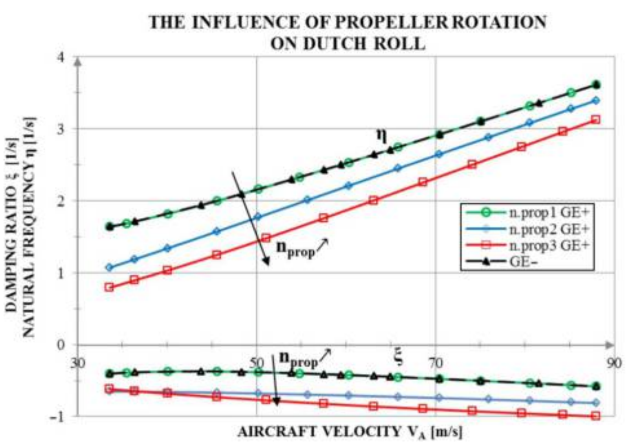
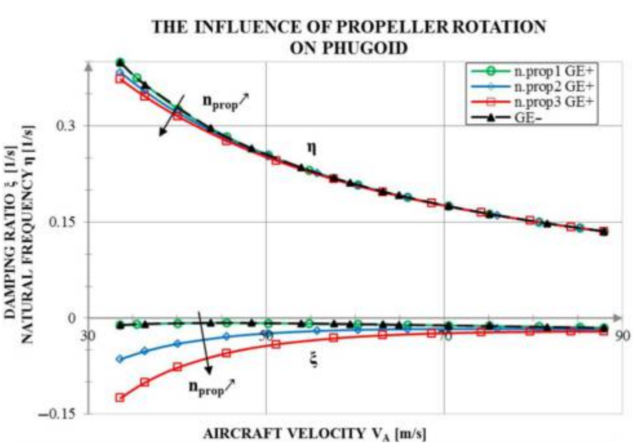


Figure 12 The influence of propeller moment of inertia on stability of Phugoid, with (GE+) and without (GE−)



of n_{prop}, damping of Phugoid ξ_{PH} rises, especially at low airspeeds of flight, and there is hardly any change in natural oscillation frequency η_{PH} (Figure 12).

The moment of inertia of a propeller depends strongly on the distribution of mass along its blades, geometry of a propeller and the materials of which the propeller is made. These factors lead to the conclusion that it is rather impossible to markedly influence the magnitude $lxx_{propeller}$. Similarly, modern engines dedicated to GA usage are nowadays compact and lightweight. Therefore, designers are deprived of the possibility to influence the gyroscopic effects through the changes in power unit properties. By contrast, a pilot adjusts a power setting to the specific flight phase. At the same time, the working parameter, i.e. rotational speed of engine components, and the propeller are not constant during the whole flight mission. Affecting gyroscopic precession by decreasing or increasing of the frequency of rotation is feasible.

Gyroscopic effects in rapid manoeuvres

A general approach to the simulation of rapid manoeuvres is based on the mathematical model with six degrees of freedom. This means that the aircraft motion is described by a set of 12 dynamic equations (Cichocka and Goraj, 2016). In the analysis, it was assumed that only one control surface (elevator or rudder or ailerons) was deflected at a prescribed moment of time from the state of equilibrium [Figures 13(a) to (c)]. Three different possibilities of control surfaces deflection were determined. After time ΔT, defined as: $\Delta T = T_{\partial 1} - T_{\partial 0}$, the control stick (or pedals) can be either reverted to initial position [Figure 13(a)] or in the opposite direction just to speed up the return to trim conditions, Figure 13(b), or the pilot may retain control column or rudder pedals in a non-trimmed position until the end of the simulation time T_{END}, as is shown in Figure 13(c).

Each computational case was calculated for four different mathematical models:

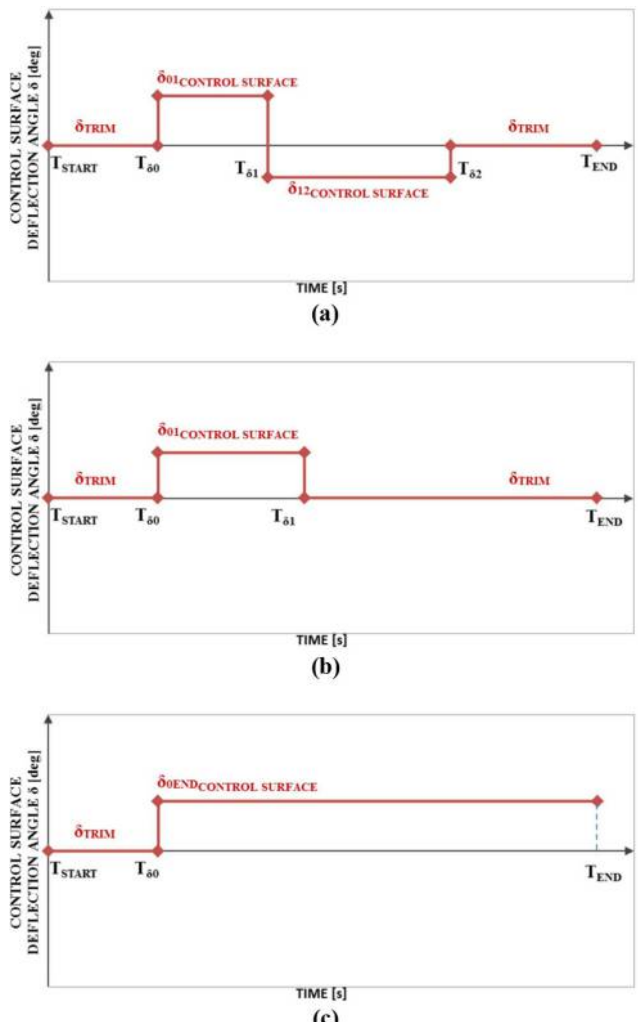
1 linear model excluding gyroscopic effects;
2 linear model with gyroscopic effects;
3 non-linear model including the products of inertial forces and the moments and gyroscopic effects; and
4 the non-linear model including the products of inertial forces and moments and excluding gyroscopic effects.

Figure 14 presents the following three flight parameters: Q (pitch rate), Y (lateral translation) and β_0 (sideslip angle).

All the results, summarised in Figure 14, correspond to double-step deflection of elevator: first at angle $\delta_H = -10^\circ$ (TE goes up at $T_{\partial 0} = 1[s]$) and then on $\delta_H = +10^\circ$ (trailing edge goes down at $T_{\partial 1} = 2.5[s]$). Finally, elevator is deflected back to trim conditions at $T_{\partial z} = 4[s]$. Comparison of all the graphs (Figure 14) confirms that any disturbance in vertical plane of motion (aircraft plane of symmetry) caused by deflection of the horizontal control surface excites a gyroscopic precession of aircraft. This effect, which is a yawing moment, is stronger for the mathematical linear model of aircraft spatial motion.

Non-linearities increase the dumping of aircraft motion because of aircraft inertia. Moreover, for linear model with gyroscopic effects, one can observe a slight change in flight direction when elevator deflection returns back to the initial

Figure 13 Three types of control surface deflection



Notes: (a) Double-step rapid deflection of aircraft control surface; (b) single-step rapid deflection of aircraft control surface; and (c) step rapid deflection of aircraft control surface

condition. Aircraft starts to move slowly left, just as if the pilot has applied rudder. Results of simulations for other mathematical models show that when elevator returns to trim conditions, the aircraft regains its initial steady state immediately.

An analogous effect is obtained after rudder deflection. As the aircraft starts to yaw, gyroscopic pitching moment is generated. The response of the aircraft after entering vertical or horizontal gust was also investigated. It was assumed that the gust is of unit jump, can act either on the whole aircraft, on the main wing or on the empennage only. For the case when the vertical gust acts on the whole aircraft, the harmonic gust distribution was assumed (CS-23, 2012; FAR-23, 1953). On the contrary, the lateral gust can act on the whole aircraft. In all the simulations, it was assumed that maximum gust velocity was equal to U_{de} = 50 ft/s.

Usually, the lateral gust has a smaller influence on aircraft dynamics than the vertical gust. The highest disturbance of aircraft dynamics is caused by the gust acting on the main

Figure 14 Aircraft dynamic response to manoeuvre following sudden elevator deflection

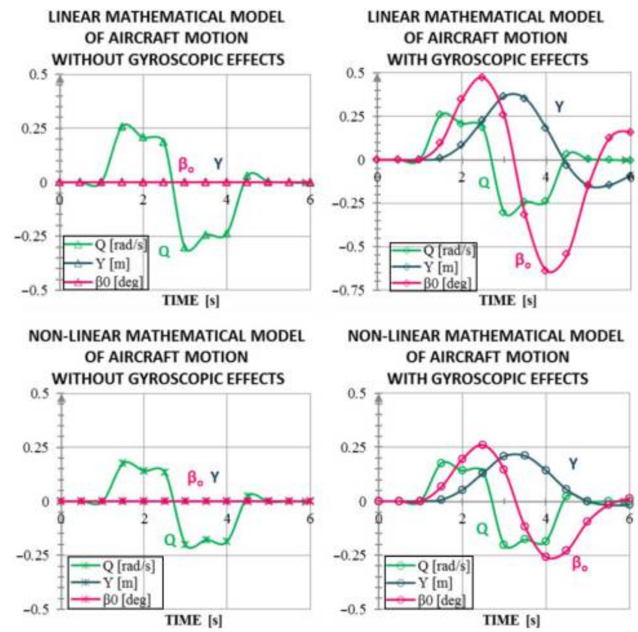
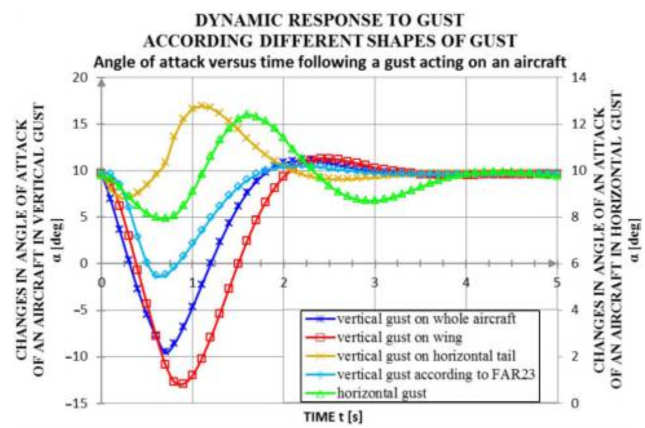


Figure 15 Aircraft dynamic response (change in angle of attack) to horizontal gust and vertical gust acting on the whole body, on wing section only or only on horizontal tail



wing only (Figure 15). However, flight asymmetry resulting from the gyroscopic effect is still relatively low – an extreme sideslip angle is equal to -1.38° (Figure 16). It must be underlined that among five different models of gust and simulation output, shown in Figures 15 and 16, the case corresponding to "vertical gust on horizontal tail" is qualitatively different from all four other cases, because the frequency of oscillation for model "vertical gust on horizontal tail" is essentially shorter, and the positive increase in angle of attack is much higher than in other cases (Figure 15). Changes in angle of attack for "vertical gust on wing" and "vertical gust on whole aircraft" are also high, but in these cases, one can observe negative increase in the angle of attack, first.

Each case of the gust simulations deals with a dynamic phenomenon. The first study on the nature of dynamic lift and an aerodynamic hysteresis problem was carried out by Farren

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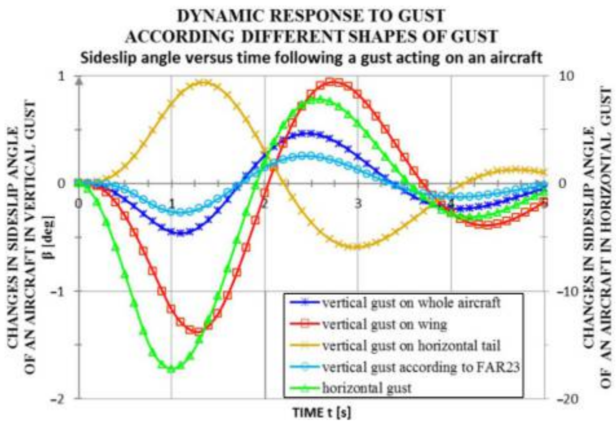
Figure 16 Aircraft dynamic response (change in sideslip) to horizontal gust and vertical gust acting on the whole body, on wing section only or only on horizontal tail



(1935). The delay of flow separation impedes dynamic stalling. This means that the extreme value of a momentary angle of attack may reach or even overtake a critical angle of attack. Instead of stalling and then dropping sharply, an aircraft immediately returns to a steady-state flight. As is shown in Figure 16, the disturbance of flight parameters caused by rapid vertical wind is well and instantly damped. A vertical gust acting only on aircraft horizontal tail is the reason for exceeding the stall angle of attack. However, the maximum angle of attack is defined for static flight conditions. Hence, when dynamic stability of an aircraft is appropriately strong, then the aircraft damps the high perturbation of flight without stalling.

It is also worth noting that in the case of a lightweight aircraft, the distance between wings and the horizontal tail is normally quite small. Therefore, the vertical gust of wind influencing only the horizontal tail will rather not occur. At the same time, because of extreme values of key flight parameters obtained for an aircraft under simulation, these variants should always be considered thoroughly. For this reason, this computational variant was defined deliberately to emphasise on its crucial importance, especially for significantly larger aircraft being subject to analysis.

The results of simulations (Cichocka, 2015) show that for gust models, defined by Airworthiness Standards (CS-23, 2012; FAR-23, 1967), the reaction of an aircraft to gust is more moderate than in case of the gust of unit jump type, presented in Figures 15 and 16. It means that the response of aircraft after unit jump gust is not representative for the requirements of Airworthiness Standards, both, in terms of velocity distribution and the duration of time in which the gust is acting.

Requirements in Certification Specifications for Light Aircraft versus gyroscopic couple

Regulations for Light Aircraft Certification Specifications (CS-23, 2012) provide the procedure for calculating gyroscopic loads. The purpose of that is to determine the magnitude of gyroscopic loads acting on engine mount and its supporting structure for each light aircraft, regardless of the engine type.

Depending on the number of propeller blades having the diameter not bigger than 2.74 [m], the method of evaluation of gyroscopic moments is given by:

- for two-blade propeller:

$$M_{G.E.} = 2 \cdot I_{p_{prop}} \cdot \omega_1 \cdot \omega_2 \tag{7}$$

- for more than two-blade propeller:

$$M_{G.E.} = I_{p_{prop}} \cdot \omega_1 \cdot \omega_2 \tag{8}$$

where I_{pprop}, I_{pprop} and $I_{p_{prop}}$ are the polar moments of inertia of the propeller [$\text{kg} \cdot \text{m}^2$]; $\omega_1 = \omega_{x_{prop}}$ is the propeller rotation [rad/s]; and ω_2 is the pitch or yaw rate [rad/s].

The conditions necessary for the checking involve the following combinations:

- the maximum continuous rotational velocity of the engine and propeller;
- a yaw velocity $r = 2.5$ [rad/s];
- a pitch velocity $q = 1$ [rad/s];
- a normal load factor $n_z = 2.5$; and
- the maximum continuous thrust $\text{T} = \text{Tmax}_c$.

Discussion and conclusion

The main objective of this paper was to describe and present the methods to minimise the influence of the weak and strong gyroscopic moments, both, on dynamic stability around the steady-state flight and dynamic properties in rapid manoeuvres.

Nevertheless, it was first found that all the methods used to estimate the low speed stability and to control dimensionless derivatives give reasonably accurate predictions for those derivatives which are obtained from experiments and are the reference data. These results suggest that for each light turbopropeller aircraft in conventional configuration, classical approach is sufficiently accurate to determine the input set for further analysis of dynamic stability.

There is also no doubt about the current progress of the state of the art in the GA. For this reason, the consideration of gyroscopic effects has to be taken into account, especially when switching from piston to turbopropeller propulsion of the light aircraft.

The obtained results of the study nonetheless indicate that for light aircraft, gyroscopic effects are generated predominantly by the propeller. Gas turbine engine has a negligible influence on dynamic response of the aircraft. This results from the opposite direction of rotation of its main components, i.e. compressor and turbine. Thus, the total gyroscopic moments induced by gas turbine are not significant, especially in dynamic stability analysis. Finally, we can assume that the resultant gyroscopic moment is equal to the propeller gyroscopic moment only. Rotating composite blade of the propeller, in case of small perturbation of the steady-state flight parameters, also causes non-influential gyroscopic precession. Therefore, we distinguish two types of gyroscopic effects: weak and strong, depending on the level of steady flight condition disturbances. The first one exacerbates itself in case of small perturbation of flight parameters, and, on the contrary, the second phenomenon type excites in rapid

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manoeuvring flights. The strong precession may have significant influence on the aircraft. The general rule can be expressed as:

- the higher power-to-weight ratio;
- the stronger gyroscopic moments; and
- simultaneously, the faster and greater the reaction of the aircraft.

Furthermore, the reduction of an unfavourable gyroscopic effects magnitude is investigated. Aircraft designers implement devices, such as "yaw killer" (e.g. in light turboprop aircraft PZL-130 TC-II Orlik). It is used to counteract against the loss of a straight flight path through the compensation of an undesirable tendency to yaw and roll generated by the propeller. Consequently, a corrective control input from the pilot is definitely minimised, reducing his/her workload.

The reset of gyroscopic moments means that no additional corrective pilot action is needed. First idea to eliminate these side effects consists of fitting to the engine the two well-designed contra-rotating ducted propellers (i.e. two props rotating in opposite directions on the same axis). This solution allows to eliminate not only gyroscopic precession but also the effect of the engine and propeller torque moment and, finally, because of this, to facilitate the handling of the aircraft. Unfortunately, this innovative approach has serious drawbacks – the design of such entire power unit is very heavy and too complicated. The other idea relies on a proper use of the other side effects of rotating propeller to compensate for gyroscopic moments.

Trying to eliminate power effects generated by each conventional single-engine aircraft, the idea of designing asymmetrical aircraft has appeared. Among the first of such aircraft is the propeller-driven reconnaissance aircraft Blohm & Voss BV 141. The structural asymmetry is a configuration with a non-central fuselage and an engine nacelle with a propeller well mounted on wings. Through an asymmetric design with a carefully shaped aircraft geometry, designers have tried to suppress or even totally eliminate all power effects, especially the tendency to yaw because of a highly rotating propeller. Many obstacles and arguments against the aircraft configuration without the plane of symmetry make these aircraft uncompetitive and uncommon to be ordered into full-scale production.

Propeller effects are especially relevant for taildraggers (tailwheel aircraft). The most unfavourable flight phase is an initial climb after take-off or a balked landing manoeuvre. Then, because of the nose incidence angle on the ground, high power generated at low speed and the high angle of attack of tailwheel aircraft, the lift distribution over the propeller disc is highly asymmetric. Consequently, for clockwise propeller rotation, the left area of the disc generated less thrust than the right one. The pilot deals with the propeller effect, named usually as P-factor, which tends to turn the aircraft nose to the left. However, the asymmetric moment depends strongly on the working parameters of the power unit and may be significant. For this reason, designers have to properly size the vertical tail to ensure the directional stability strong enough, especially in the case of the aircraft with taildragger landing gear configuration.

The most important conclusion is that the induced gyroscopic moments of modern GA aircraft do not diminish the flight safety level and are quite easy to control by the pilot, even in rapid manoeuvres. The small turboprop power units do not cause dynamic properties deterioration of light aircraft, either. Highly satisfactory features of the newly designed compact turboprop engines dedicated to power light aircraft are certainly an attractive alternative to the currently dominating piston engines.

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