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Power optimization of a single propeller airplane take-off run on the basis of lateral maneuver limitations

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A B S T R A C T

The problem of selecting optimal take-off run power of a single propeller airplane on the basis of the lateral maneuver limitations is analyzed in this paper. The single propeller reactive torque as the function of engine power and speed generates non-aerodynamic asymmetric load disturbance. The capability of lateral flight control surfaces to compensate for this asymmetric load and perform the required maneuver defines the safe flight envelope boundaries in the form of engine power setting – airspeed relation. The take-off run length consisting of acceleration, decision making, brake activation and airplane stopping length distances is calculated for engine power settings along the safe flight boundaries defined by the lateral flight control capabilities. The minimum of take-off run along thus defined safe flight boundary determines the engine optimal power setting. The results are presented for the example of the single propeller airplane on concrete runway surface.

1. Introduction

Regardless of the type, the primary analysis of airplane performances is based upon the assumption of the airplane geometric, inertial and aerodynamic symmetry. Furthermore, from the flight dynamics point of view, airplane performances are analyzed as the pseudo-stationary process, reducing the airplane dynamics model to the one of material point, as presented by classical examples [1,2]. The problem of airplane performance improvement is an ever-present subject in the analysis of the optimal airplane configuration selection [3].

In practice, the airplane is, to some degree, always asymmetric and must be treated as such. The asymmetry analysis is based upon flight dynamics textbooks [4–7] and papers [8], using the guidelines of historic importance presented in [9]. The airplane asymmetry classification relative to the asymmetric loads is the most common one. The capability to generate the required aerodynamic control forces and moments can be defined as the flight control authority, the flight controls being used to control the airplane and compensate for its loads. The asymmetric airplane loads can be classified into those that are aerodynamic related or aerodynamic unrelated, i.e. non-aerodynamic asymmetries. Aerodynamic related asymmetric loads are scalable to the compensating capabilities in the form of the flight control authority throughout the range of airplane airspeed use. The decrease of the flight control authority with airspeed reduces their compensating capabilities, increasing the impact of the non-aerodynamic asymmetric loads within the lower dynamic pressure range.

Current down-sizing tendencies reintroduced medium to high-power single propeller airplanes in the role of the training and close combat support airplanes. Within the terminal flight phases, this power range emphasizes inherent asymmetric properties of the single propeller airplanes arising from the non-aerodynamic asymmetric load of the propeller reactive torque. The general problem of the asymmetrically loaded airplane stability is given in [10]. The problem of the asymmetrically loaded airplane within the terminal and low level flight phases previously used two approaches. The first is from the stability and control point of view. General analysis of the damaged asymmetric airplane stability evaluation is given in [11], some examples of adaptive control cases being [12,13]. The second is from the aerodynamic and flight dynamics point of view, the examples being perching maneuver [14] and low level turn analysis [15].

Any airplane controlled motion depends on the capability of control surfaces to generate adequate aerodynamic control forces and moments, and therefore the concept of the flight control authority has been introduced [16,17]. The concept stemmed out from the reduction of the general airplane rotation analysis [18] to the case of the asymmetrically loaded airplane. This served as the basis for determination of the safe flight boundary conditions

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Nomenclature

a	airplane ground run acceleration	m/s^2
b_w	wing span	m
C_D	airplane drag force coefficient	
C_L	airplane lift force coefficient	
C_{lp}	roll moment coefficient damping derivative	
$C_{l\beta}$	roll moment coefficient derivative due to sideslip angle	
$C_{l\delta l}$	roll moment coefficient derivative due to roll command	
$C_{l\delta n}$	roll moment coefficient derivative due to yaw command	
$C_{n\beta}$	yaw moment coefficient derivative due to sideslip angle	
$C_{n\delta l}$	yaw moment coefficient derivative due to roll command	
$C_{n\delta n}$	yaw moment coefficient derivative due to yaw command	
C_T	propeller traction force coefficient	
$C_{y\beta}$	lateral force coefficient derivative due to sideslip angle	
$C_{y\delta l}$	lateral force coefficient derivative due to roll command	
$C_{y\delta n}$	lateral force coefficient derivative due to yaw command	
D_e	propeller diameter	m
F	roll angle sine function	
F_φ	shooting function in determining maneuver roll control angle	
g	Earth gravity acceleration	m/s^2
H	flight height	m
I_x	moment of inertia about X-axis	$kg\,m^2$
k_l	roll control reduction due to flight control elasticity	
k_n	yaw control reduction due to flight control elasticity	
k_r	engine-propeller reduction ratio	
$k_{\delta l}$	factor of aileron effectiveness reduction for deflections over 10°	
m	airplane mass, general	kg
M_{ac}	active engine torqueintensity	Nm
M_{re}	reactive engine torqueintensity	Nm
n_e	engine angular speed in rounds per minute	rpm
$n_{e(\max)}$	maximal engine angular speed in rounds per minute	rpm
$n_{e(\min)}$	minimal engine angular speed in rounds per minute	rpm
n_p	propeller angular speed in rounds per minute	rpm
$n_{p(a)}$	propeller angular speed during acceleration run	rpm
$n_{p(b)}$	propeller angular speed during breaking run	rpm
n_r	relative engine angular speed in rounds per minute	rpm
p	roll angular speed	rad/s
P_s	engine propeller shaft power	kW
Q	dynamic pressure	Pa
R_D	airplane drag force	N
R_L	airplane lift force	N
s_{ac}	airplane abandoned take-off ground run acceleration path length	m
s_{dm}	airplane aband. take-off ground run decision making path length	m
s_{br}	airplane abandoned take-off braking ground run path length	m
s_t	airplane abandoned take-off total ground run path length	m
$s_{t\,\min}$	minimum of airplane abandoned take-off total ground run path length	m
S_w	wing surface	m^2
t	time	s
$\vec{T}$	propulsor (propeller) traction force	N
T_{gt}	gas turbine exhaust thrust force	N
T_p	propeller traction force	N
t_{ac}	time to acquire roll angle required in maneuver	s
v_{aw}	lateral wind airspeed	m/s
V	airplane speed relative to surrounding air	m/s
V_1	decision making airspeed	m/s
V_b	ground run safe flight boundary speed	m/s
$V_{\min}$	airplane minimal airspeed	m/s
V_s	stalling speed	m/s
V_{st}	stalling speed, airplane in the take-off configuration	m/s
V_{to}	take-off airspeed	m/s
V_{ms}	minimal maneuvering airspeed of symmetrically loaded airplane	m/s
$\vec{V}_K$	airplane velocity relative to the ground	m/s
x_1, x_2	phase state space variables	

Greeks

β_{aw}	sideslip angle due to lateral wind, disturbance sideslip angle	rad
β_K	sideslip angle relative to inertial space	rad
$\delta_{ar,l}$	right, left aileron deflection	rad
δf_l	wing flaps deflection	deg
δ_l	roll control	rad
$\delta_{l(b)}$	roll control value at the end of command movement in maneuver	rad
$\delta_{l(c)}$	compensating roll control	rad
$\delta_{l(\mathrm{lim})}$	limiting roll control	rad
$\delta_{l(m)}$	roll control required by maneuver	rad
$\delta_{l(s)}$	structural limit of roll control	rad
δ_n	yaw control	rad
$\delta_{n(c)}$	compensating yaw control	rad
$\delta_{n(\mathrm{lim})}$	limiting yaw control	rad
$\delta_{n(s)}$	structural limit of yaw control	rad
δ_r	rudder deflection	rad
φ	roll angle	rad
φ_{rq}	bank angle required in maneuver	rad
$\mu_{(a)}$	acceleration run friction coefficient between airplane wheels and ground	
$\mu_{(b)}$	brake run friction coefficient between airplane wheels and ground	
θ_e	propeller pitch angle	
ρ	air density	kg/m^3
Ψ_K	course angle	rad
$\vec{\omega}_e$	engine angular velocity	rad/s
$\vec{\omega}_p$	engine angular velocity	rad/s
ζ	throttle position	%

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