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Single propeller airplane minimal flight speed based upon the lateral maneuver condition

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A B S T R A C T

This paper presents the application of the previously presented general analysis method to determine the safe flight boundaries of the asymmetrically loaded airplane within the terminal flight phases as applied to the case of inherently asymmetric single propeller airplane. As the lateral control surface design is done for the flight conditions out of the terminal flight phases, the key objective is to improve the flight safety of the asymmetrically loaded airplane by introducing the lateral flight controls verification at the low flight speeds. The concept of the authority of control surfaces presenting their capability to generate the forces and moments needed by the airplane to perform required maneuvers is the basis of the analysis. Control surface authority is the function of the control surface aerodynamic properties, structurally available flight control displacements and dynamic pressure. The analysis method scope is based upon the requirement to supplement the safe flight boundaries of symmetrically loaded airplane within the terminal flight phases, with the lift coefficient observed as the function of the angle of attack being at the linear limit. Control surface demands are lateral maneuver execution and asymmetric load and lateral wind compensation, the method scope permitting them to be addictive. Thus defined, the method is based upon the comparison of the available control surface authority and demands. For the defined flight conditions, the analysis is reduced to the comparison of the demanded and structurally available flight control displacement. The method combines the simple roll dynamics model, the stationary equations of the airplane lateral-directional motion and several numeric analysis procedures to obtain the results. This new combination possesses synergy properties and is implemented as the computer program. The method is applicable for any combination of airplane asymmetric loads and can be used throughout entire airplane life cycle. The contemporary trend of downsizing training and light combat airplane types with the rising number of the introduced medium and high power single propeller airplane types increases the significance of the method application in the design procedure.

1. Introduction

Mathematical model used in the analysis of the airplane dynamics is generated by the process of the abstraction, the basic form presenting the airplane in its nominal configuration possessing the plane of geometric and inertial symmetry, resulting in the symmetric load. In most of the cases, the abstraction modeling process to the symmetric airplane form goes too far, as the existence of the airplane with the symmetric geometric, inertial and load properties is extremely rare.

Propulsive and aerodynamic forces and moments are used to control the airplane motion. Within the aerodynamic based part of the control system, the capability of control surfaces to generate the control moments can be defined as the control surface authority. The control surface authority is the function of airplane structure properties, form and available deflection of the control surfaces, and flight conditions, the dynamic pressure being dominant. The concept of the control surface authority is used as the basis for the analysis presented herein.

Airplane properties relative to flight behavior are defined by design procedure that is cyclic in nature and related to the aerodynamic and inertial properties. The design procedure is complex and contains the definition of the aerodynamic form, dynamic system analysis and all of the disciplines related to the control system design. The standard guidelines for design and testing procedures are contained in books [1–4] and papers [5–13]. The problem of flight

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Nomenclature

b_w	wing span	m
C_L	lift 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_m	engine angular velocity unit vector direction	
$C_{l\delta n}$	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	
$C_{y\beta}$	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	
C_z	dynamic system Z-axis force coefficient	
F	roll angle sine function	
F_φ	shooting function in determining maneuver roll control angle	
g	Earth gravity acceleration	$\mathrm{m/s^2}$
H	flight height	m
I_x	moment of inertia about X-axis, general	$\mathrm{kg\,m^2}$
k	flight control structural limit reduction factor	
$k_{\delta l}$	factor of aileron effectiveness reduction for deflections over 10°	
k_l	roll control reduction due to flight control elasticity	
k_n	yaw control reduction due to flight control elasticity	
m	airplane mass, general	kg
Q	dynamic pressure	Pa
S_w	wing surface	$\mathrm{m^2}$
t	time	s
T_{ac}	time to acquire bank angle required in maneuver	s
V_K	airplane speed relative to the ground	m/s
V	airplane speed relative to surrounding air	m/s
v_{aw}	lateral wind airspeed	m/s
V_c	landing speed	m/s
$V_{\min(s)}$	minimal airspeed of symmetrically loaded airplane	m/s
$V_{K(\min)}$	lift defined minimal airspeed	m/s
V_l	landing speed	m/s
V_S	stalling speed, clean airplane	m/s
V_{Sl}	stalling speed, airplane in the landing configuration	m/s
V_{St}	stalling speed, airplane in the take-off configuration	m/s

Greeks

α	angle of attack, general airplane and symmetric airplane	rad
β	sideslip angle	rad
β_{aw}	sideslip angle due to lateral wind, disturbance sideslip angle	rad
$\delta_{ar,l}$	right, left aileron deflection	rad
δ_{fl}	flaps deflection	rad
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
$\delta_{l(\lim)}$	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
$\delta_{n(\lim)}$	limiting yaw control	rad
$\delta_{n(s)}$	structural limit of yaw control	rad
δ_r	rudder deflection	rad
φ	roll angle	rad
$\varphi_{(b)}$	roll angle at the end (T_{ac}) of commanded maneuver	rad
φ_{rq}	roll angle required in maneuver	rad
ρ	air density	$\mathrm{kg/m^3}$
ψ	course angle	rad

Acronyms

AI	Air force Institute
BCAR	British Civil Airworthiness Requirements
MTI	Military Technical Institute
NASA	National Aeronautical and Space Administration
VTI	Vojnotehnicki Institut (Serbian name of MTI)

mechanics in the proximity of the ground is for the propeller airplane addressed by Rasuo [10], and for the hang glider by Cook [14]. The characteristic of the design procedure is that the classic form wing airplanes are with local performance and dynamic properties optima at the design point. Regarding the airplane dynamics and controllability, the result of the airplane form design at the design point, produces control surface geometry and limiting deflections that are for the given dynamic pressure defining univocally the control surface authority. In all of the other flight phases within the flight envelope, including the terminal ones, the airplane characteristics must be within the pre-defined boundaries.

By genesis, asymmetric loads are either inherent properties of airplane regular use or a consequence of some failure state. Those asymmetries that can be considered as the disturbances can be classified in two groups, the first one being of aerodynamic nature. The control surface authority is scalable to these type of asymmetric loads, with measurable capability to compensate them throughout the airplane dynamic pressure range. The second group comprises non-aerodynamic asymmetric loads such as propulsive group moment or under-wing stores. The second group of asymmetric loads requires particular analysis in the terminal flight phases, as the control surface authority is reduced due to low airspeed. Relative to the significance to the airplane dynamics, asymmetries have been previously relatively rarely analyzed, some early examples being [15,16], while the recent examples of the analysis are [17,18].

Sophisticated fly-by-wire control systems containing digital computers with sufficient capabilities to implement various forms of failure adaptable and/or propulsion based flight control laws are one solution to the general problem of the asymmetrically loaded airplane, the examples being [19,20]. In the absence of the sophisticated, digital computer-based flight control system, the solution of the problem of the airplane loaded by non-aerodynamic asymmetric load reverts to the classical approach, that is, to define the safe flight envelope and include it into the pilot notes.

The classical approach to the general solution of the problem of the airplane loaded by non-aerodynamic asymmetric load is treated by Stojakovic [21], the results for the case of the asym-