13th International Conference on
AEROSPACE SCIENCES & AVIATION TECHNOLOGY,
ASAT- 13, May 26 – 28, 2009, E-Mail: asat@mtc.edu.eg
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Prediction of Handling Qualities for a Jet Training Aircraft Using Dynamic Flight Model and Pilot Rating

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Abstract: A dynamic flight model of a jet trainer aircraft (Aero L-39) is developed in MATLAB-SIMULINK. Using a six degree of freedom mathematical model, non-linear simulation is used to observe the longitudinal and lateral-directional motions of the aircraft following a pilot input. The mathematical model is in state-space form and uses aircraft stability and control derivatives calculated from the aircraft geometric and aerodynamic characteristics. The validated results from the simulation of aircraft mathematical model are used to estimate flying handling qualities of Aero L-39. This estimation is carried out for the stick fixed longitudinal and lateral characteristics. The handling qualities are rated based on both computational method and practical method. The damping and frequency of both short and phugoid period modes were determined in terms of aerodynamic stability derivatives [3] for both longitudinal and lateral stabilities and based on pilot's opinion rating by means of using Cooper-Harper rating scale. The handling qualities of the aircraft can be estimated according to its class and flight phase, and then it can be specified in terms of flying qualities levels.

Keywords: Flight dynamics, Handling qualities, Dynamic model, Longitudinal stability, Lateral stability, Mathematical model, Simulation.

Introduction

It is mandatory that an aircraft shall be capable of being flown throughout its intended flight envelope, and in all but the severest of weather conditions by an average pilot. The pilot must be able to maneuver and to retain control of the aircraft at all times. In the rare event that the pilot loses control, for example in a stall or spin case, a safe recovery must be possible [1].

In order to examine the handling qualities of the aircraft, the simulation of a dynamic flight model results are used to calculate damping ratios and natural frequencies of aircraft dynamic responses.

Simulation of flight is one of the most acceptable techniques in the aircraft flight test programs used by aviation industry. In order to use simulation as a useful tool to reduce the time and cost of designing and testing aircraft [6], a mathematical model is derived from the six degree of freedom equations of motion describing the dynamic behavior of an aircraft [3]. The accuracy of the simulation results depends on the accuracy of the mathematical model used in the simulation.

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In this study, simulation of aircraft motion is developed in MATLAB and SIMULINK. The mathematical model developed is applied to an advanced jet training aircraft Aero L-39. Stability and control derivatives of L-39 are obtained based on set of formulas and methods presented in several references [3, 6, 7, 9] related to aircraft stability and control.

As a result of a considerable research, target values for damping ratios and frequencies have been set for all the flight levels and flight phase categories of aircraft classes [7].

Aircraft or flight phases with damping ratios and frequencies deviating from the target values are considered unsatisfactory.

Handling qualities estimated based on computational method are functions of damping and frequency, and these are functions of stability derivatives and therefore, are functions of aircraft geometric and aerodynamic characteristics. However, geometry of aircraft can not be changed without effective consequence like increasing weight or reducing the performance. The designers are faced with the challenge of providing an aircraft with optimum performance that is both safe and easy to fly. One of those challenges is to design an aircraft with high stability and high maneuverability at the same time, which is almost not possible because of the fact that both of them are opposite of each other. To achieve this, the designers need to know what degree of stability and maneuverability is required for the pilot to consider the aircraft safe and flyable. In addition to computational way of estimation, pilot ratings are considered in which the pilot is enabled to award a level to the aircraft to show compliance with a specifications based on pilot experience and opinion. This rating is scaled in ten points where 1 indicates excellent and 10 the worst.

Finally, both methods of flying qualities estimation are discussed to compare the results. Such results can be used as a tool for flight test missions or designing suitable autopilot and stability augmentation systems for this aircraft. The method can be used for other airplanes as well, provided that their stability and control derivatives are introduced into the model.

Technical Approach

One of the most useful and acceptable techniques used for aircraft performance evaluation is simulation, where the motion of the aircraft is expressed in a mathematical model. Simulation of aircraft dynamics allows the designers to study the dynamic characteristics of the aircraft before carrying out any actual flight tests. This significantly reduces the risk, cost and the time needed for automatic flight control system design and development and evaluation of new airplanes. In order to examine the handling qualities of the aircraft, the simulation results are used to calculate damping ratios and natural frequencies which are used as an index for estimation of aircraft dynamic response.

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This estimation is done for the stick fixed longitudinal and lateral characteristics. The damping and frequency of both short and phugoid period modes were determined in terms of aerodynamic stability derivatives [5]. Moreover, there is additional estimation for the rating of handling qualities based on pilots opinion by means of using Cooper – Harper rating model, in this rating the pilot give a rate out of ten called Pilot Rating in addition to flying quality level.

Aircraft or flight phases with damping ratios and frequencies deviating from the target values are considered unsatisfactory.

The handling qualities of the aircraft can be estimated according to its class and flight phase, and then it can be specified in terms of one of three levels.

Aircraft Specification and Geometry

The specifications of the L-39 are presented in Table 1, and its geometry in Figure 1.

Table 1 Characteristics of the L-39 airplane.

Manufacturer	Aero Vodochody - The Czech Republic
Type	Double seater – advanced jet training aircraft and ground supporter.
Length	12.13 m
Height	4.77 m
Wing span	9.12 m
Wing area	18.8 m^2
Wing profile	NACA 64A012
Empty weight	3467 kg
Max. take-off weight	5600 kg
Engine	Ivtchenko AI-25 TL
Thrust	1720 kg at sea level.
Rate of climb at sea level.	22 m/s
Max. speed	910 km/hr
Service ceiling	11,500 m
Range with internal fuel	1000 km.

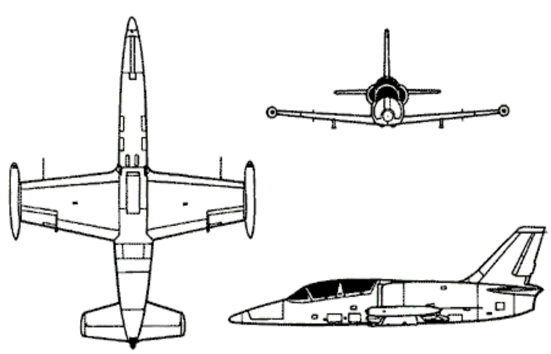

Fig. 1 Aero L-39 Geometry

According to classifications table L-39 is considered as:

Class: IV
Flight Phase: A

All results flight tests and simulation were carried out at altitude of 3,000 m and speed of 500 km/hr which are considered as the optimum speed and altitude for this trainer regarding to its controllability.

Results

Longitudinal Flying Qualities

Damping and frequency limits for longitudinal flying qualities are presented in both phugoid mode and short period mode in the following tables [1]

Table 2 Phugoid Damping Ratio (ζ_p) Limits

LEVEL	1	2	3
Characteristics	ζ_p at least 0.04	ζ_p at least 0.02	An un-damped oscillatory mode with $t_{1/2}$ of at least 55 seconds.

Table 3 Short Period Damping Ratio (ζ_{sp}) Limits

FLIGHT PHASE CATEGORY	LEVEL 1		LEVEL 2		LEVEL 3	
	Min ζ_{sp}	Max ζ_{sp}	Min ζ_{sp}	Max ζ_{sp}	Min ζ_{sp}	Max ζ_{sp}
A	0.35	1.3	0.25	2.0	0.1	-
B	0.30	2.0	0.20	2.0	0.1	-
C	0.50	1.3	0.30	2.0	0.25	-

Aero L-39 longitudinal handling qualities can be calculated using (damp) command in MATLAB code, by finding damping ratio and frequency for the matrix of longitudinal stability derivatives. According to previous tables handling qualities is summarized in the following table:

Table 4 Handling Qualities of Longitudinal Motion

Flight Condition	Speed = 500 km/hr (139 m/s), Altitude = 3000 m, Mass = 4200kg	
Phugoid Mode	ζ_p = 0.139	LEVEL 1
Short Period Mode	ζ_{sp} = 0.23	LEVEL 3

It can be seen from previous table that the handling quality of short period mode is LEVEL 3 however, and as tabulated in table 4 , the rate can be level 2 because it much closer to the value 0.25 than 0.10 , especially when we take into consideration the fact that ,this value may decrease with increasing altitude [1,3].

Lateral-Directional Flying Qualities

Lateral flying qualities requirement are listed in Tables 5, 6 and 7. The definition of aircraft class and category are the same for longitudinal consideration and with the same flight conditions. The lateral motion mode requirements are presented as following:

Roll Mode Flying Qualities

Acceptable values of the roll mode time constant, t_R , are given in Table 5.

Table 5 Maximum Values of Roll Mode Time Constant, t_R

CLASS	FLIGHT PHASE CATEGORY	t_R (sec)		
		LEVEL 1	LEVEL 2	LEVEL 3
I, IV	A	1.0	1.4	Insufficient evidence to define an upper limit. Limited evidence suggests a value of 6 to 8 seconds for all flight phases and aircraft classes.
II, III	A	1.4	3.0	
All Classes	B	1.4	3.0	
I, IV	C	1.0	1.4	
II , III	C	1.4	3.0	

Spiral Mode Flying Qualities

Spiral mode acceptability is assessed in terms of the minimum time to double the bank angle for an airplane initially in trimmed level flight with zero yaw and stick free but following a disturbance in bank of up to 20°. Minimum values are given in Table 6

Table 6 Minimum Time to Double Bank Angle, t_2 (sec)

FLIGHT PHASE CATEGORY	LEVEL 1	LEVEL 2	LEVEL 3
A, C	12	8	5
B	20	8	5

Dutch Roll Mode Flying Qualities

Minimum Dutch Roll frequency and damping requirements are given in Table 7

As for longitudinal motion, L-39 lateral-directional handling qualities can be calculated using (damp) command in MATLAB code, by finding damping ratio and frequency for the matrix of lateral stability derivatives. According to previous tables handling qualities is summarized in Table 8.

Table 7 Minimum Values of Natural Frequency and Damping Ratio for the Dutch Roll Oscillation

CLASS FLIGHT PHASR CATEGORY		Minimum values								
		LEVEL 1			LEVEL 2			LEVEL 3		
		ζ_D	$\zeta_D \omega_D$ (rad/s)	ω_D (rad/s)	ζ_D	$\zeta_D \omega_D$ (rad/s)	ω_D (rad/s)	ζ_D	$\zeta_D \omega_D$ (rad/s)	ω_D (rad/s)
IV	A	0.4	-	1.0	0.02	0.05	0.5	0.0	-	0.4
I,IV	A	0.19	0.35	1.0	0.02	0.05	0.5	0.0	-	0.4
II,III	A	0.19	0.35	0.5	0.02	0.05	0.5	0.0	-	0.4
All Classes	B	0.08	0.15	0.5	0.02	0.05	0.5	0.0	-	0.4
I, IV	C	0.08	0.15	1.0	0.02	0.05	0.5	0.0	-	0.4
II, III	C	0.08	0.10	0.5	0.02	0.05	0.5	0.0	-	0.4

Table 8 Handling Qualities of Lateral-Directional Motion

Flight Condition	Speed = 500 km/hr (139 m/s), Altitude = 3000 m, Mass = 4200kg	
Roll Mode	t_R = 0.329	LEVEL 1
Spiral mode	t_2 = 58.97 sec	LEVEL 1
Dutch Roll Mode	ζ_D =0.14, ω_D =2.93(red/s), $\zeta_D \omega_D$ =0.41 (red/s).	LEVEL 2

Flying qualities based on pilot rating

In order to use wide prospective estimation based on more than one technical approach, and as human/machine inter face becomes one of essential element in aircraft design, the pilot opinion have been taken as an extra source of flying qualities. In this task more than 10 expert pilots with average flying hours of 1500 hours on type.

The results build up based on Cooper-Harpor flow chart filled by pilots individually after understanding the way of rating according to deferent flying phases.

Flight Condition	Speed = 500 km/hr (139 m/s), Altitude = 3000 m, Mass = 4200kg	LEVEL
Longitudinal stability	Phugoid Mode	1
Lateral Stability	Roll Mode	2
	Spiral mode	1
	Dutch Roll Mode	-

It can be seen from the comparison of the result that some of the handling quality modes cant not be predicted by the pilot like longitudinal shot period mode and dutch roll mode because they depend on a very short time of response that can not be easily felt the pilot. And the differences in the levels rated to the aircraft was acceptable once it was close from the simulation results especially after gathering the results and show them to the pilots some of them tend to agree with the simulation results after reviewing their ratings.

Conclusion

A six degree of freedom simulation of aircraft motion is developed to predict the flying qualities for both longitudinal and the lateral-directional motion following a pilot input. The simulation is capable of simulating aircraft dynamic response over the entire defined flight envelope. The MATLAB - SIMULINK tools have been used to simulate the motion of the model developed.

The ability to perform a simulation of aircraft motion has significantly reduced the time, cost and risk involved with aircraft control system design. The mathematical model is not always precisely representing the aircraft motion. The model developed for the aircraft longitudinal and lateral-directional motion is not free from some inaccuracies. The mathematical model primarily consists of aircraft stability derivatives and control coefficients.

In general, the handling qualities mainly depend on the aircraft geometry, and having some improvement in the aircraft handling qualities requires an increase in the area of horizontal stabilizer to improve longitudinal handling qualities and increase area of vertical stabilizers to improve lateral handling qualities in addition to other things. However, increasing the area results in more drag, the result is that the aircraft performance will worsen and the airplane will be heavier. Therefore, some sort of stability augmentation system that will enhance the aircraft handling qualities at all altitudes and speeds could be implemented [6].

Finally, pilot opinion can be used as support tool for prediction of any aircraft handling qualities in addition to computational tool once the pilot was expert on type and evaluate as a pilot not as a native subject.

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