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Role of ground and in-flight full-attitude simulation for pilot training

0. SUMMARY

- In this document, we intend to present our experience in full-attitude aircraft simulation, in particular we intend to describe criteria that we consider fundamental in the preparation of the total aerodynamic coefficients build-up functions and in the Aerodynamic Data Base development. The aim is to obtain a simulator which is fully representative of the aircraft dynamics in all flight conditions including post-stall angle of attack, loss of control, departure and spin.
- A new approach to training student pilots is proposed, based on advanced simulators and a low-cost variable-stability jet trainer able to perform specific pre-programmed aircraft responses and high-alpha manoeuvre demonstrations.

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1. INTRODUCTION

- In the 1960's, high-alpha simulation was considered impossible for two main reasons. First, a wind tunnel test methodology was not available; second, standard criteria required to measure the aerodynamic coefficients necessary to represent the high angle of attack characteristics and to build a mathematical model were not well defined.
- A standard mathematical model was not considered representative of phenomena like
- wing rock, stall, spin and autorotation.
- The investigation of high angle of attack characteristics was then performed with some empirical criteria and with a dynamically scaled free flight model in a vertical wind tunnel
- From this test it was practically impossible to investigate the stall, departure, and spin entry characteristics; consequently, only the developed spin mode and the recovery characteristics from developed spin were obtained.
- Some companies did not consider essential to investigate post-stall angle of attack characteristics of transport airplanes through wind-tunnel tests. Soft envelope protection devices like a stick shaker/pusher were considered adequate to prevent Loss of Control (LOC).

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- Due to lack of confidence many prototypes were lost during flight tests at high angle of attack.
- Since 1970 the wind-tunnel test result analyses have been based on the estimation of spin equilibrium conditions and on the evaluation of control effectiveness for the spin entry or recovery from spin equilibrium conditions.
- In the 1970’s I started to consider the possibility to simulate high-alpha behaviour too using wind-tunnel data from fixed and rotary balance.
- Since the first approach the simulation results were very close to flight test results and we became more and more confident in the preparation of a mathematical model and in performing wind-tunnel tests.
- Application of high-alpha dedicated wind-tunnel and flight test plans in several civil and military projects of the 1970’s demonstrated the reliability and fidelity of the aerodynamic models developed following high-alpha aircraft characterization criteria and test methods. This proved that performing six DOF simulations at high angle of attack does not present particular difficulties, mainly on account of the good accuracy of wind-tunnel data.

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- The wide experience acquired in performing wind-tunnel tests with a static and rotary balance enabled to evaluate the reliability of the results with a remarkable degree of familiarity and to organize wind-tunnel test programs to identify the most important coefficients and to prepare the data base for the complete simulations.
- In 1980's I participated to the AGARD WG 11 in order to define criteria to be proposed for the preparation of the Aerodynamic Data Base and the methodologies to be applied in order to establish a reliable aerodynamic characterization of the aircraft, aimed to high-fidelity simulation.

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2. AERODYNAMIC DATA BASE PREPARATION

- The technical approach is based on static and dynamic wind-tunnel tests, which include rotary and oscillatory balance.
- The concept is that the aircraft aerodynamic characteristics at high angle of attack (AoA) and angle of sideslip (AoS) can be measured and modelled following the same methods and criteria applied in the low AoA and AoS regime.
- This provides a standard testing program throughout the full aircraft envelope, with the same aerodynamic model structure at all flight conditions/regimes.

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In particular, in order to have all the necessary data we can consider the following wind-tunnel test activities:

1- **Wind-Tunnel Tests with Static Balance**

Stability and control characteristics are obtained from wind-tunnel static balance tests. These tests can be carried out by varying the model both in the angle of attack and angle of sideslip. Usually an alpha range should be as wide as ±90° and beta range ±30° to properly evaluate an HAOA behaviour .

2- Wind-Tunnel Tests with Rotary Balance

Stability and control and damping characteristics are obtained from wind-tunnel rotary balance tests. These tests can be carried out for a given apha and beta at different values of wb/2V.

3- Wind-Tunnel Tests with Oscillatory Balance

Give us the possibility to know the characteristics due to acceleration.

4- Flying Models

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The tests with flying models are often performed for high AOA behaviour studies. Theoretically these tests are hightly effective because, by means of these flights it is possible to carry out all the aircraft maneuvers, evaluating possible danger conditions. In case of instrumented models, it is possible to obtain all dynamic derivatives through parameter identification programs, as well as to obtain a mathematical model for a flight simulator.
Should we get a good shot of the tests, we would have a qualified result as to the behaviour and in many cases this is more than sufficient for our scope. A good video gives indications on the spin typical attitude, rotation speed, entry control effects, during-the-spin maneuver, and on the recovery transient. Mostly, this is more than enough to face flight tests with the utmost safety conditions.

In our experience the most important aerodynamic data in order to identify the high-alpha characteristics are the data from static and rotary balances.

Flying models can be an effective and low-cost approach for a small general aviation aeroplane.

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2. SIMULATIONS

- Simulation is the innovative criterion to approach HAOA behaviour estimation.
- With simulation it is possible to evaluate the effects of the different coefficients on high-alpha behaviour and consider all the conditions of mass and inertia of the aircraft.
- Carrying out such a task usually involves several specialists and pilots. A traditional flight simulator is expensive to run, therefore the work can usually be carried out only within a sizeable budget environment, and where a simulator is already available.
- With new-generation personal computers it is possible to perform real time simulation as well, and a PC can be a low-cost substitute of a classic simulator for the first evaluation of the HAOA behaviour.
- For this purpose a dedicated simulation program, AIRSIM, was developed by our company. The program runs on a PC with Windows 95 operating system.

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Thanks to the outstanding accuracy of the algorithm used to obtain the solution of the equations of motion, AIRSIM is able to perform a simulation in all the situations including stall, departure, spin entry, developed spin and recovery.

The most important characteristics of the program are:

- PC-based high-accuracy simulation;
- Implements reliable precision aircraft simulation with six degrees of freedom;
- Able to simulate even critical situations such as stall, spin and autorotation and in general in high angle of attack flight conditions:
- Effective help for:
  - New aircraft design;
  - Analysis of aircraft behavior in all conditions including HAOA situation;
  - Reconstruction and study of aircraft accidents;
- User-friendly interface to prepare, manage and use different aircraft databases;
- Graphical and tabulated Time History display and print.

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3. PILOT TRAINING

- As regard pilot training we are aware that there is potential for current simulators to be not completely representative of the dynamics of the target aircraft in full envelope manoeuvring. This can be due to limited validity envelope, partial motion, visual cues representation and different pilot gain/technique when flying the simulator. In order to improve the training standard, development of higher fidelity simulators and integration of in-flight simulation training within the pilots training syllabus is proposed. .
- NTSB reported that "*Inadequate programming of flight simulators has contributed to more than half of all airline fatalities in the past decade*". We consider this statement a significant technical motivation to propose an approach in order to better formalize baseline standards for the development of higher-fidelity simulators.

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3.1 FLIGHT SIMULATOR

- Fixed based Flight Simulator Training Devices (FSTDs) extensively used for pilots training are in general very well representative of normal flight but unable to simulate unusual and emergency conditions such as those associated to aircraft stalls, loss of control, spin departure and spin recovery. Pilots do not receive sufficient training in jet upsets and aerodynamic stalls because simulators currently in use cannot accurately reproduce such conditions and provide necessary motion/g force cues.
- It is our opinion that heavy swept-wing transport aircraft pilot training only in the low angle of attack regions does not address the growing number of loss of control accidents.

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- We have published many reports describing the criteria used and the good results obtained performing the simulation, and as airline pilots are trained using this kind of devices, the training they receive is good enough if they do not encounter emergency conditions, but absolutely unfit in case they have to cope with a loss of control event. Simulating these situations is possible on the basis of wind-tunnel data, and in this case the simulator can be an effective training device.
- After a brief investigation within airline pilots' environment it became evident that, in general, only those with previous Air Force experience were well prepared with the necessary awareness, recognition and recovery skills needed to resolve emergency loss of control conditions due to their expertise and training.

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3.2 FLIGHT EXPERIENCE

- We also consider fundamental, for the new training system we are proposing, to include flight experience of Upset Recovery Training.
- The present training market reality shows that it is grossly outdated, time-consuming and unnecessarily expensive. Is very clear that the new emerging economies (China, India) cannot afford using existing training system developed over the past 50 years due to availability, economical and (more important) timing considerations.
- To train the required number of pilots to supply the ever increasing needs to support rapidly growing economies would take too much time and the results would be of much lower quality.
- We suggest to use for training pilots a small propeller-driven trainer for the early approach to flight, and a jet trainer with variable stability for the complete training.

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- As regard the small propeller-driven trainer we suggest to use a VLA- certified airplane. An aircraft in the class of the SD 27 can be a good candidate mainly because it was tested in order to perform high-alpha maneuvers (spin and departure) although this is not required by CS-VLA requirements.
- As regard the jet trainer, presently there is no civil-certified aerobatic jet training aircraft on the world market. In these latest several years, airlines started to seriously address this issue with limited success due to the lack of suitable hardware.
- The existing surplus military airplanes, that are also capable of aerobatic flight, are not economical and their use is severely limited. Another difficulty is that no certification exists for their commercial operations.
- A good candidate can be the new PHOENIX FANJET (PFJ), as that aircraft can be equipped with the existing technology, computer-controlled electro-hydraulic system, and thus become capable to imitate the flying characteristics of several airliners.

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3.2.1 PROJECT ASSUMPTIONS

Design specifications of the PFJ aircraft:

- \- Simplicity (cost-effectiveness) of manufacturing process;
- \- Known gap in the market for this type of aircraft;
- \- Not a “blank sheet” design, as cost of design and a substantial part of testing cost was absorbed by previous project owners;
- \- Sound basic design – over 700 hours flown;
- \- Very well defined market with no known competitor;
- \- Current training systems are very costly, time consuming and inefficient;
- \- New training system developed in co-operation with Calspan Corporation of Buffalo, NY

3.2.2 CAPABILITIES

- In-flight simulation of flying characteristics of any airplane in operation programmed into system
- Ability to simulate any emergency with preset limits to ensure that parameters are not exceeded
- Advanced manoeuvre and upset recovery training
- Alternate controls recovery ACR training to deal with abnormal or unknown aircraft behaviour
- Ability to safely re-fly known "accident patterns" to the critical point of recovery.

3.2.3 ADVANTAGES

- Single, economical platform for the entire training program
- No need for re-training in different aircraft as training progresses (piston, turboprop, jet)
- Student pilot brought to the needed skill level – not achievable with classic systems.
- Cost and time advantages
- End product, **Higher Quality Pilot.**

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3.3 GENERAL CONSIDERATIONS

- Independently from the type of aircraft that is to be simulated, a characteristic which should be included is the capability to reproduce high alpha/post stall dynamics. This can be effectively coupled with all Upset Recovery Training (URT) and In-Flight Simulation activities to provide characteristics that cannot be provided by the ground based FSTDs, including those with full-motion systems.
- The approach of some certification agencies, and new requirements that do not consider necessary high-alpha characteristics evaluation as mandatory for the certification of new aeroplanes is surprising.

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- In 1994 I was the responsible for the certification of the first Italian VLA aeroplane, the SIVEL SD-27. On the basis of VLA requirements it was not necessary to show recovery from developed spin, but I choose a different approach and we performed all the spin tests in order to offer a really safe aeroplane. It seems that the new approach is to rely just on the installation of a ballistic parachute, and several general aviation aeroplanes obtained their certification without spin tests.
- A pilot trained in such aeroplane, in my personal opinion, is not well trained, as far as I know we are still far from installing a ballistic parachute in an airliner.

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4. CONCLUSIONS

We have presented a new and integrated approach to pilot training systems using new solutions which can help in saving time and money.

The use of the simulator can help a lot and our experience tells us that:

- It is not a problem to simulate loss of control and, in general, all the manoeuvres associated with high alpha.
- The simulator responses are very representative and allow a true advanced pilot training.

In addition, having a basic trainer like the SD-27, and a jet trainer like The Phoenix Fanjet (PFJ), able to perform all the manoeuvres in flight, this allows producing a really complete training system.

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FIG.1 THE SIVEL SD-27

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FIG. 2   The SIVEL SD-27

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FIG. 3 THE PFJ

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FIG. 4 THE PFJ

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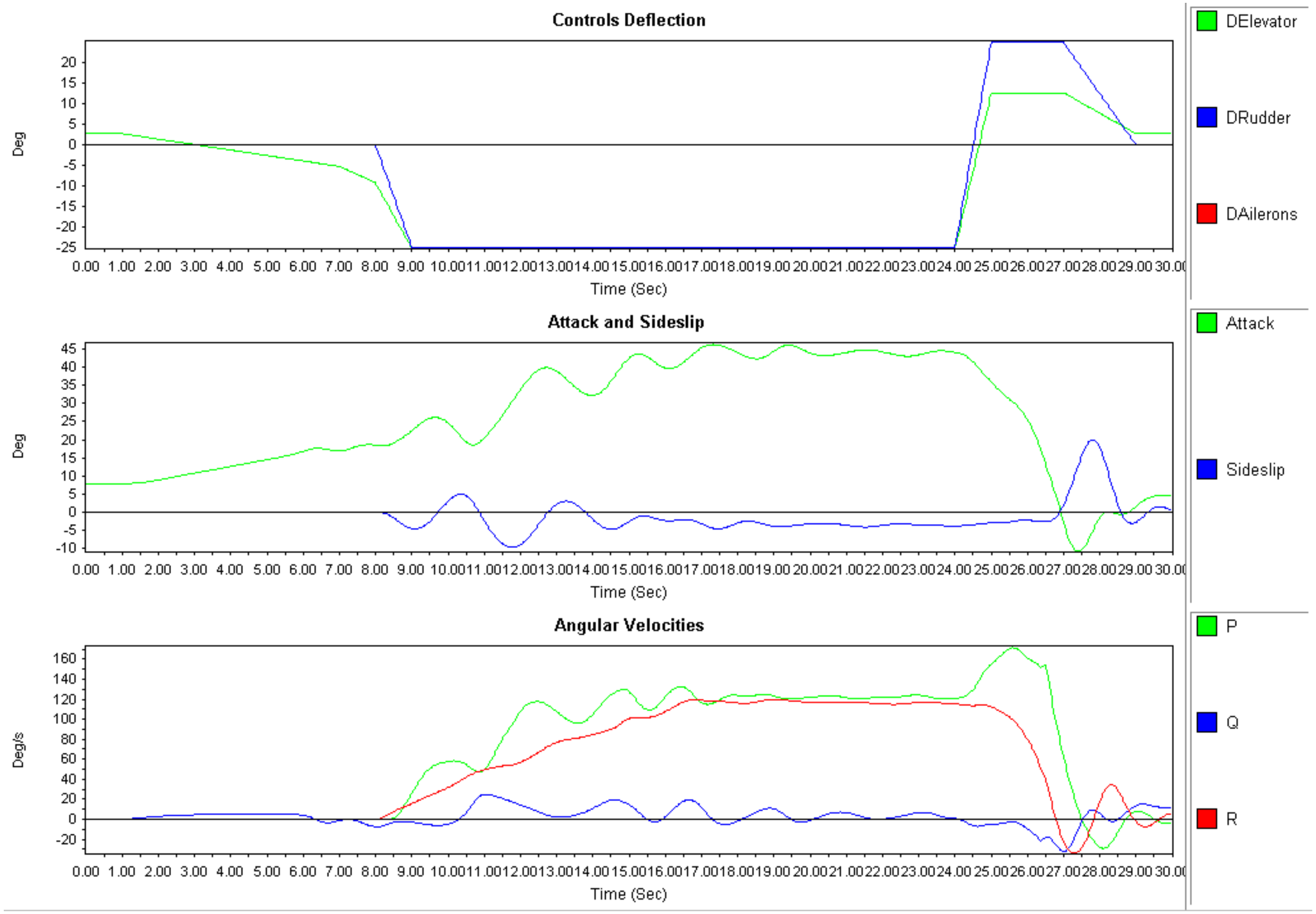

FIG. 5 AIRSIM Time History

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TEST Rollio
LGAA

Aircraft : LGAA   Test : TONNEAU

Points : 300,00
Integration Step : 0,02
Printing Step : 15,00

Angular Accelerations and Velocities, Attitude

Time (s)	P. (dg/s2)	Q. (dg/s2)	R. (dg/s2)	P (dg/s)	Q (dg/s)	R (dg/s)	PHI (dg)	THETA (dg)	PSI (dg)
0,00	0,00	30,42	0,00	0,00	0,00	0,00	0,00	5,57	0,00
0,30	0,00	-0,17	0,00	0,00	0,04	0,00	0,00	5,60	0,00
0,60	-76,39	-0,07	-0,37	-4,09	0,01	-0,02	-0,14	5,60	0,00
0,90	-178,23	0,27	-1,94	-45,60	0,02	-0,32	-6,85	5,60	-0,04
1,20	-77,53	2,16	-4,43	-89,47	0,32	-1,24	-28,08	5,57	-0,26
1,50	-17,81	5,37	-5,85	-101,89	1,42	-2,81	-57,28	5,32	-0,85
1,80	-6,00	7,65	-3,22	-104,85	3,37	-4,28	-88,46	4,47	-1,82
2,10	-6,40	5,85	2,34	-106,54	5,50	-4,48	-120,23	2,82	-2,77
2,40	-7,11	0,87	7,20	-108,47	6,54	-3,07	-152,49	0,69	-3,19
2,70	-6,30	-3,80	9,53	-110,39	6,06	-0,55	-185,33	-1,32	-3,03
3,00	-4,24	-6,68	9,17	-111,92	4,44	2,28	-218,70	-2,92	-2,69
3,30	-0,99	-7,47	6,16	-112,71	2,26	4,63	-252,44	-4,39	-2,44
3,60	2,78	-5,74	0,95	-112,51	0,21	5,77	-286,28	-6,00	-2,09
3,90	84,60	4,28	-4,44	-107,12	-0,65	5,26	-319,83	-7,49	-1,28

1 of 1 Cancel Close 20 of 20 Total:20 100%

FIG. 6 AIRSIM Tabular Report

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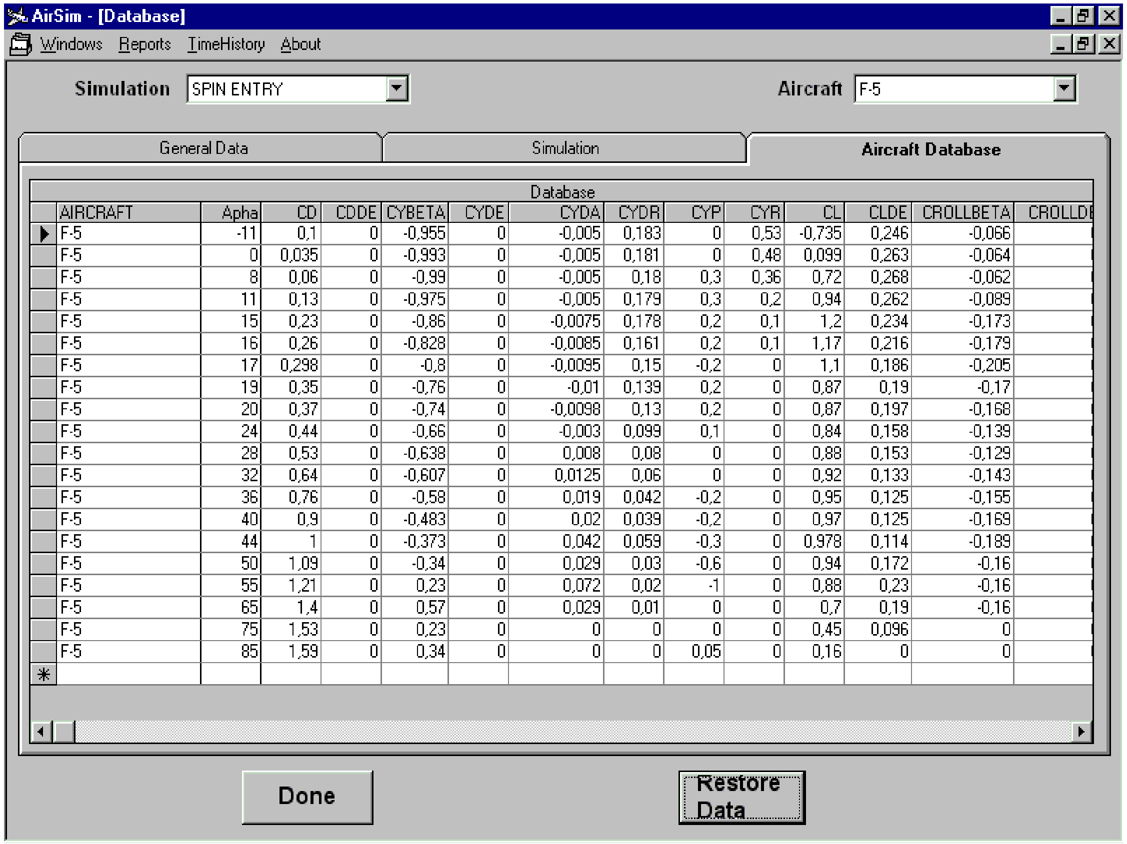

AIRCRAFT	Apha	CD	CDDE	CYBETA	CYDE	CYDA	CYDR	CYP	CYR	CL	CLDE	CROLLBETA	CROLLDE
F-5	-11	0,1	0	-0,955	0	-0,005	0,183	0	0,53	-0,735	0,246	-0,066	
F-5	0	0,035	0	-0,993	0	-0,005	0,181	0	0,48	0,099	0,263	-0,064	
F-5	8	0,06	0	-0,99	0	-0,005	0,18	0,3	0,36	0,72	0,268	-0,062	
F-5	11	0,13	0	-0,975	0	-0,005	0,179	0,3	0,2	0,94	0,262	-0,089	
F-5	15	0,23	0	-0,86	0	-0,0075	0,178	0,2	0,1	1,2	0,234	-0,173	
F-5	16	0,26	0	-0,828	0	-0,0085	0,161	0,2	0,1	1,17	0,216	-0,179	
F-5	17	0,298	0	-0,8	0	-0,0095	0,15	-0,2	0	1,1	0,186	-0,205	
F-5	19	0,35	0	-0,76	0	-0,01	0,139	0,2	0	0,87	0,19	-0,17	
F-5	20	0,37	0	-0,74	0	-0,0098	0,13	0,2	0	0,87	0,197	-0,168	
F-5	24	0,44	0	-0,66	0	-0,003	0,099	0,1	0	0,84	0,158	-0,139	
F-5	28	0,53	0	-0,638	0	0,008	0,08	0	0	0,88	0,153	-0,129	
F-5	32	0,64	0	-0,607	0	0,0125	0,06	0	0	0,92	0,133	-0,143	
F-5	36	0,76	0	-0,58	0	0,019	0,042	-0,2	0	0,95	0,125	-0,155	
F-5	40	0,9	0	-0,483	0	0,02	0,039	-0,2	0	0,97	0,125	-0,169	
F-5	44	1	0	-0,373	0	0,042	0,059	-0,3	0	0,978	0,114	-0,189	
F-5	50	1,09	0	-0,34	0	0,029	0,03	-0,6	0	0,94	0,172	-0,16	
F-5	55	1,21	0	0,23	0	0,072	0,02	-1	0	0,88	0,23	-0,16	
F-5	65	1,4	0	0,57	0	0,029	0,01	0	0	0,7	0,19	-0,16	
F-5	75	1,53	0	0,23	0	0	0	0	0	0,45	0,096	0	
F-5	85	1,59	0	0,34	0	0	0	0,05	0	0,16	0	0	

FIG. 7 AIRSIM Aircraft Database Management sample

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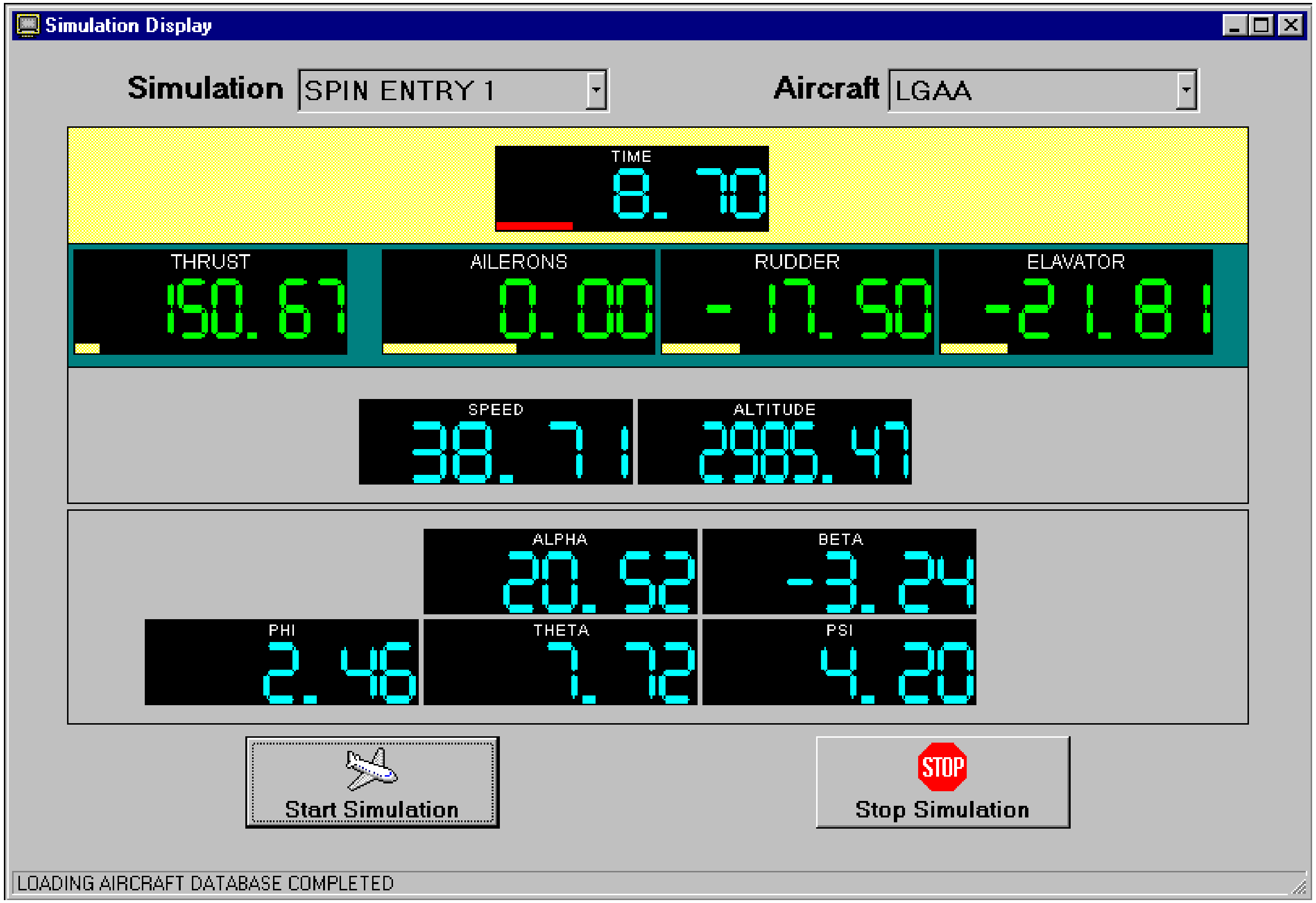

FIG. 8 Airsim Control Panel