

EXTENDING FMC TEST FOR FLIGHT SIMULATION AND FLIGHT EXPERIMENTS

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Abstract

By means of a simulator we could expand the test research scope which could not be reached with flight tests, and recover and repeat some special domain of the test course, and make many kinds of experiments about FMS properties, functions and with embedded failures by combining simulation tests with practical structure. The reliability and creditability of simulation results could be increased under real FMS in conjunction with semi-entity simulation. Simulators combining a real FMS with digital simulation have been used extensively for evaluating the large matrix of FMS contents.

1 Introduction

The FMS airworthiness flight test technology is an important part of civil aircraft airworthiness flight tests, because FMS penetrates nearly most avionics systems, flight control systems, engine control systems and etc. For civil aircraft FMS, America FAA promulgated the advisory circulars which expound the flight tests and draw up the relative flight test technology norms. But for airworthiness flight tests about specific FMS, FAA did not provide concrete and detailed items or indications for how to design the test program, plan flight test airways, and how to make the demonstration tests for airworthiness correspondences, which need to study. In our study programme, the semi-body FMS flight simulator was built to restore the all flight procedures. Also the flight circumstances model for FMS, FMS guidance mathematical

simulation model and its relative software were designed and developed. Also the flight test project for civil aircraft airworthiness approval was provided in our study. With the CITATION- II test airplane and advanced airborne FMS, we finished the verification flight test methods for FMS airworthiness approval project. In conjunction with both the airworthiness verification flight tests and semi-entity simulation tests for FMS, we studied the navigation/guidance correspondence items for FMS, and made the researches on FMS failure modality and combination influence by use of flight tests. The simulation experiment researches on FMS performance management and vertical navigation indicated that the performance data calculated by FMCS were all for the three flight stages, climbing, cruising and descending, so as to optimize the vertical flight profile at the restricted condition initialized by flight programme.

Our studies in this paper involve the semi-entity simulation design for FMS, primary flight simulation system structuring, FMS performance management and VNAV experiments (such as VNAV climbing, VNAV descending, cruising stage), failure imbedding or switching over simulation, simulation experiment results (such as engine failure simulation, flight track influenced by upper-level winds, comparison between actual flight tests and flight simulation experiments), real flight verification tests in air and their results (for example, Quincunx flight, Amplified rectangular flight, and etc.). A semi-entity simulation experiment system based on FMS could accurately recover and carry out three

dimensions guide and navigating calculation, guaranteeing the reliability and creditability of simulation tests with FMS, so the flight simulation test course and test results based upon FMS being directly served as evaluation basis for airworthiness approval^[1].

2 Semi-entity simulation System

In the semi-entity simulation system with FMS, the most functions of UNS-1A (including its CDU) manufactured by Universal Navigation Corporation were exploited and used for real-time simulation. External data information produced by airplane sensors (e.g. digital air computer, IRS, DME, VOR and so on) could be simulated by means of software modules, and transferred to UNS-1A through ARINC429, ARINC561 buses. And then the output signals produced by UNS-1A are transferred to each subsystem through ARINC429, ARINC561 buses. With the help of A/S, D/A, DI, DO sampling boards, the analogue and separated signals produced by UNS-1A are transferred to other subsystems while the other subsystem output signals are also transferred to UNS-1A computer. Flight plans and synthetic navigation functions could be calculated and carried out by UNS-1A based on the above information and airway data in the bank.

Motion of the airplane CITATION- II on ground and in air are simulated by the primary flight simulation software which calculates airplane equations real-time based upon received control, states, and failure information, the calculated results transferring to other subsystems by Ethernet.

Navigation equipment input/output signals introduced by digital air computers, IRS, DME, VOR, and etc, are chiefly simulated by the avionics simulation software, and transferred into UNS-1A computer.

Input/output signal, including ARINC429 BUS, ARINC561 BUS signals, and other analogue/digital signals, sampling and pre-processing of UNS-1A navigation computer are mainly completed by the interface computer which transfers the navigation data derived by simulation software to UNS-1A navigation

computer in accordance with the output format of the navigation equipment in a real airplane.

In the course of climb, cruise and descending, both horizontal navigation and guiding could be realized, and both a great circle track and uniform angle track could be completed, and automatic or man flight could be activated, and both a flight according to a flight plan and flight according to revised waypoints could be all fulfilled by the UNS-1A navigation computer and its CDU. In the stages of cruise and descending, VNAV and vertical guide could be accomplished. According to the established descending velocity and current ground velocity, the TOP point could be calculated, and the remainder distance to the TOD point. And the vertical deviation may be provided after the TOD point.

According to the vertical deviation, wheel angles might be calculated, and then the airplane might fly along the established flight plan and vertical profile.

The UNS-1A navigation computer may provide fuel management. It could calculate current fuel flow, and calculate the required fuel volume for the flight plan according to the current consumed fuel rate and ground velocity. Tune function may be used for radio frequency management while a radio tune unit (RTU) is installed in the system.

The semi-body simulation system structure with FMS is showed in Fig.1, and the configuration of sensors connected with FMS is schematically showed in Fig.2.

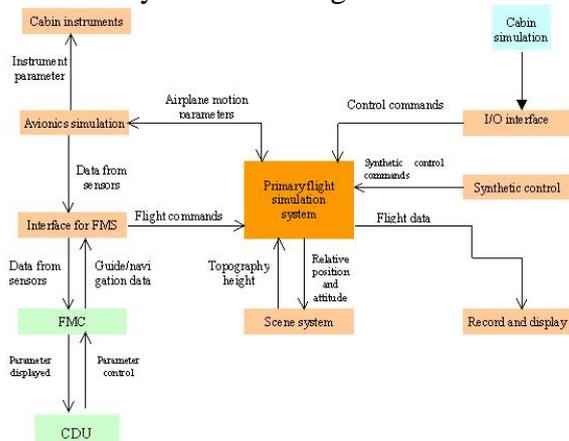


Fig.1 semi-entity simulation system structure for the civil airplane FMS

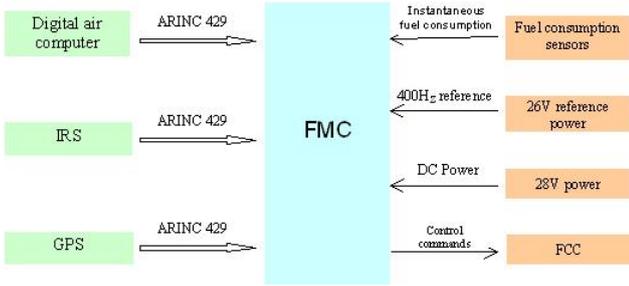


Fig.2 configuration of sensors connected with FMS

3 Primary flight simulation system

The primary flight simulation software is the core of the semi-body simulation system, and its main function is the realization of flight course simulation in the whole flight enveloping curve covering the typical stages such as taking off, cruising, approaching, landing and running. If necessary risky flight jobs should be also simulated about the flight tests on enveloping curve profile and airworthiness approval, and in the meantime failures often encountered in an airplane system could be also quantitatively or qualitatively simulated.

The mathematical model of the primary simulation software consists of several parts,

a) Nonlinear six dimension full variables equations have been applied in flight dynamics modeling. Aerodynamic elasticity effect may be improved by increasing elastic freedom degrees in motion equations, and also by introducing the coefficient correction method in aerodynamic coefficients. Flight dynamics models have the characteristics such as high order, multi-variables, nonlinear, and time-variable.

b) Airplane system simulation modeling covers the contents of engine system, control system, navigation system, A/P, instruments, fuel system, power system and etc. In airplane system models, there is a lot of multi-control logic which may connected with switches and indicators.

c) To increase fidelity and efficiency in simulation, mathematical models such as flight freeze, crash about airplanes have also been built.

The primary flight simulation modeling is composed of many mathematical modules involving aerodynamic coefficients calculation,

aerodynamic parameters, D-value calculation, motion equations, landing gears, mass characteristic, engine system, hydraulic system, turbulent current and wind, atmosphere and freezing, all these 12 modules schematically showed in Fig.3.

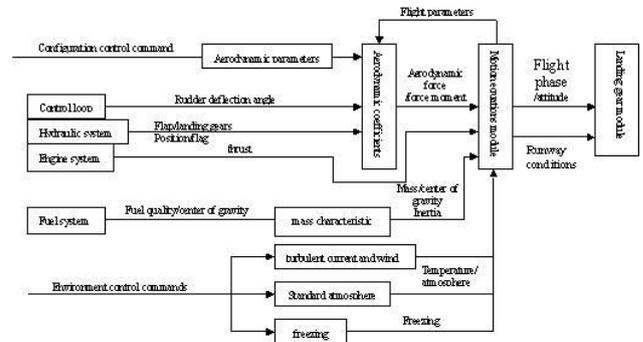


Fig.3 primary flight simulation modules

The quality and precision of FMS guide could be influenced greatly by turbulent current and wind modules which are set up as follows.

Input signals:

- a) airplane motion parameters from motion equation modules;
- b) steady constant winds switches, wind speeds, wind directions set by a synthetical control desk;
- c) turbulent current intensity set by a synthetical desk.

Output signals:

- a) three direction wind values forced upon motion equation modules;
- b) three direction turbulent current values forced upon motion equation modules.

Function:

- a) steady constant winds at any direction;
- b) the four kinds of wind shear specified by FAA;
- c) atmospheric turbulent currents.

Principle:

- a) constant wind modeling
- Three component wind velocities along the earth axes as follows.

$$\begin{cases} u = const \\ v = const \\ w = const \end{cases} \quad (1)$$

Three component velocity rates along the earth axes as follows.

$$\dot{u} = \dot{v} = \dot{w} = 0 \quad (2)$$

b) 1-cos abrupt wind model (semi-wave length)

$$u, v, w = \begin{cases} 0 \\ \frac{v_m}{2} (1 - \cos(\frac{\pi x}{d_m})) \\ v_m \end{cases} \quad (3)$$

where d_m —abrupt wind size v_m —abrupt wind strength.

c) wind shear model. Fig.4 shows one of the four wind shear models supplied by FAA.

d) Atmospheric turbulence utilization of the Dryden model of atmospheric turbulence, the parameters of a profiled filter may be determined as follows:

$$G_w(S) = \frac{K_w}{1 + T_w \cdot S} \quad (4)$$

$$K_w = \sigma \sqrt{\frac{L_w}{\pi V}}, T_w = \frac{2L_w}{\sqrt{3}V} \quad (5)$$

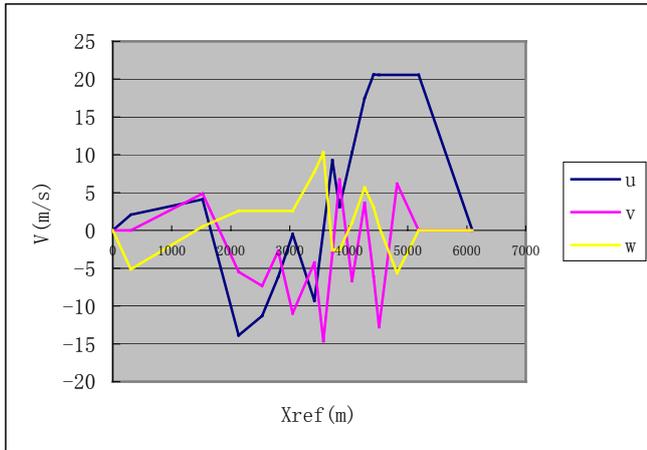


Fig.4 the fourth wind shear model

4 Simulation tests for navigation and guiding

4.1 Three kinds of basic navigation modes

There are three navigation modes in flight, and which navigation mode to be selected depends on ground navigation stations status in use and the receivers' effectiveness. The following are the three navigation modes respectively.

a) DME/ DME /IRS;

b) DME/VOR/IRS;

c) IRS/GPS.

The sensors such as VOR, DME, IRS, DACD and GPS are all digitally simulated in the semi-entity simulator.

4.2 Contents for simulation test

a) great circle flights;

b) equal track angle flights;

c) navigation stations manual/auto-tuning demonstration (outside FMC);

d) manually and autopilot flights;

e) flights autothrottle on/off.

4.3 Simulation tests for performance management and vertical guiding

The performance signals calculated by FMCS are all for the three flight phases climbing, cruising and descending, which optimizes the vertical flight profile under the limited section given by flight planning.

A. VERTICAL GUIDED CLIMB

The demonstration for Vertical guided climbing performance should be carried in the course of the velocity calculated by FMCS and the introduced velocity by a pilot. While climbing velocity changes should be also introduced. Climbing should be kept until a level flight so as to demonstrate altitude capture performance. The altitude capture for both FMC and mode control panel should be all demonstrated. Generally the autopilot, F/D and autothrottle should be connected together during simulation tests^[2].

a) Vertical guiding mode is on after taking off. Flaps are retracted normally and climbing is continuing until the altitude 10,000 feet;

b) Vertical guiding mode is on after taking off. The flaps should be retracted after verification of flaps limitation is performed^[3];

c) The autopilot guides a vertical economical climbing. A medium altitude capture on the mode control panel should be demonstrated during a climbing, and then continues to reach a cruising altitude on FMC;

d) The autopilot guides a vertical maximum climbing rate while the autothrottle is off;

e) The autopilot guides a vertical maximum climbing angle;

f) The autopilot guides a vertical selected velocity climbing. The target velocity should be changed during climbing.

B. VERTICAL GUIDED DESCENT

The simulation demonstration for a vertical guided descending is carried at the speed of elevators in the course of a descending track. The descending velocity is demonstrated upon the selected economical speed and selected manual control speed. The descending tracks will include an economical track and a manual control track. The transition from a sort of descent to another one should be demonstrated. Descents before or after TOD should be all demonstrated. Altitude captures for both a mode control panel selection and FMC should be demonstrated in simulation tests. Different cost index values and the range for total airplane weight should be also simulated and demonstrated.

The autopilot guides a vertical descending speed, economical speed;

The autopilot guides a vertical descending speed, manual speed;

The autopilot guides a vertical descending speed, and selects a track descending while the speed beginning with descent;

The F/D guides a vertical descending speed, an economical speed;

The F/D guides a vertical descending speed, a manual speed with the autopilot is off;

The autopilot guides a vertical descending track, an economical track. Continuing descending until the altitude 10,000 feet, and then ILS capture;

The autopilot guides a vertical descending track. An economical track, demonstrating discontinuous in a vertical direction with the autothrottle off;

The autopilot guides a vertical descending track. A manual track, an altitude level off and altitude capture for a medium mode control panel. Recapturing the original track;

The autopilot guides a vertical descending track, and selects speed descent after the track descent occurs;

The autopilot guides a vertical descending track, and does a TOD descent ahead from the

entrance of a cruise, and then the capture of an altitude;

The autopilot guides a vertical descending track, and does a hysteretic TOD descent from the entrance of a cruise;

The autopilot guides a vertical descending track, and demonstrates the minimum speed command limitation at the positions of flaps 0° , 1° , 5° and 15° relative to the autothrottle on / off;

The pilot does a track descent flight in accordance with the track deviation displayed on HIS, while the autopilot and F/D are all off.

C. CRUISE^[4]

The autopilot, F/D and autothrottle are all switched on in the flight simulation test at a cruise condition.

a) climbing during cruising sections;

b) descending while cruising;

c) an altitude holds while cruising;

d) a minimum speed protection while cruising.

At a cruising stage, the VNAV function will enter the Cruise mode when the "TO" waypoint and the vertical flight path have been defined, the aircraft is not more than 200 feet below the reference altitude of the "TO" waypoint, and the vertical flight path will be intercepted ahead of the aircraft, as is showed in Fig.5. The Cruise mode shows the distance to the Top-Of-Descent (TOD) point in nautical miles, that is, the distance along the flight plan until the current altitude intersects the vertical flight path. In some installations, aircraft deviation from the Vertical Flight Path will be displayed.

The TOD location is based upon present groundspeed, present altitude, the altitude for the TO vertical waypoint location, and the "target vertical speed" (TGT V/S) the pilot has entered for the descent.

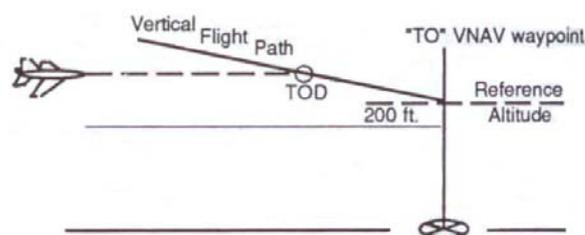


Fig.5 VNAV in cruise section

The TGT V/S is a manual entry of desired descent rate, in feet per minute, is used for computing the vertical flight path to the “TO” VNAV waypoint. VNAV will remain in the inactive mode until the TO vertical waypoint is defined and either a valid Target Vertical Speed (0 to 8000 fpm) is entered or automatic sequencing occurs to the NX vertical waypoint (which activates the Descent mode and the VNAV Descent page).

The FROM waypoint is always PPOS (present position). An offset distance, defaulted to +10NM, is displayed relative to PPOS. This offset represents the distance ahead of the FMS present position to the position used for calculating the Vertical Speed Required to reach the TO VNAV waypoint at the specified altitude. For example, the pilot may wish to enter zero value. Zero would then become the default value until next altered. Entry of a TGT V/S value will delete the offset distance. Fig.6 shows the FR PPOS +xx NM.

The great circle distance, expressed in nautical miles, between the aircraft’s present position and the TO VNAV waypoint.

The Vertical Speed Required (VSR) to descend (or climb) is from the aircraft’s present position (plus offset distance) and altitude to cross the TO VNAV waypoint at the target altitude. If the vertical flight path exceeds 6° (fixed wing) or 9° (rotary wing), the VSR will be displayed in yellow.

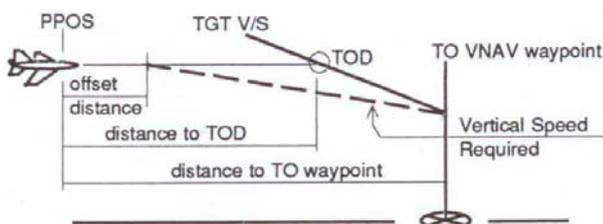


Fig.6 the FR PPOS +xx NM

Each TO and NX VNAV waypoint is defined by a flight plan waypoint and the offset distance prior to (-) or beyond (+) that flight plan waypoint. Next to the VNAV waypoint location is the target altitude for that vertical waypoint. VNAV waypoint altitudes must be in level or descending sequence in the range from

0 to +64034 ft. An altitude out of range will be invalid.

If the vertical flight profile between two VNAV waypoints is steeper than 6° (fixed wing) or 9° (rotary wing) the result will be a vertical step in the VNAV flight profile. FMS will use the limit descent angle (6° or 9°) through the more distant waypoint target altitude for computing the TGT V/S and vertical deviation for that leg, as is showed in Fig.7.

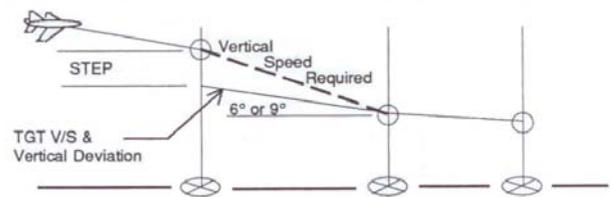


Fig.7 vertical step profile

The Target Vertical Speed, indicating a descent rate, in feet per minute, is used for computing the vertical flight path to the “TO” VNAV waypoint. Whenever VNAV waypoints are sequenced, the TGT V/S is initialized to the VSR (Vertical Speed Required) for the new vertical nav leg or to the VSR that maintains a 6° (fixed wing) or 9° (rotary wing) flight path, whichever is less. Target Vertical Speeds from 0 to 8000 fpm not exceeding a vertical flight path angle of 9° (fixed wing) or 12° (rotary wing) are valid. Once the Descent mode is activated, the FROM waypoint is always PPOS (present position).

D. APPROACH

Approaches are defined in the Data mode and stored in the pilot data base. Up to 100 approaches may be defined and stored. Each approach includes a final approach fix (FAF) and an end-of-approach point. The end-of-approach point can be a runway threshold, touchdown point, or a missed approach point (MAP). One or two additional waypoints may be defined along the approach path. Only one of the optional waypoints may be located outside the FAF, and only one may be between the FAF and the end-of-approach point.

The difference between VFR, VOR, and RNV approaches are the Q factor and the nav facility requirements. Should the Q factor or nav

input requirements not be met, the HSINAV flags will come into view.

For any approach in visual conditions, definition and reception of a primary VOR facility is optional. Quality factor requirements are less stringent for valid navigation (28 or less) than for other approach options. This can also be used when runway coordinates have been manually entered by the pilot and the inbound course and distance will not be entered.

For VOR approaches, a collocated DME will be used when available, but its reception is not required for valid navigation. VOR signals must be received from the reference facility and DME signals must be received from any available facility. The Q factor must be less than 10 while 50 to 15 NM from the end-of-approach point. The Q must be less than 5 while within 15 NM of the end-of-approach point.

If an approach is being created from a VOR Approach when the reference VOR facility has DME, it is recommended that the TYPE selection be RNV. The DME tunes the 15 closest stations once every minute. By selecting RNV, the reference facility DME will be one of every 2 DMEs tuned (instead of only once for every 15 DMEs tuned). The pilot will thus be warned more quickly if there is a loss of DME from the reference facility.

It is noticed that there may be a slight difference between the UNS computed coordinates for the end-of-approach point and the coordinates found on the approach chart. These minor variations are considered normal. Minor variations (if any) do not compromise the approach accuracies as set forth in AC90-45A^[5]. However, it is the pilot's responsibility to verify that these variations are within the accuracies as set forth in AC90-45A.

5 Simulation tests for failure embedded and Switched over

Based upon the failure modeling on the FMS and its relative systems, and the requirements on failure simulation in the semi-body simulation system, a mathematical statistic method and a maintenance handbook for Boeing 737 series are used to construct the failure

modes for the FMS and its relative systems. The failure modes are divided according to the FMS and its relative systems. In the semi-body FMC simulation system, FMC and CDU being entities, the failure simulation is activated and carried. The synthetic control station is used to set various failure modes and failure types, and the failure signals excited are reacted upon the primary flight simulation system. The methods to create failures are as follows:

- a) switch off the power for FMC, create A01 failure;
- b) switch off the inputs for ADC, VOR/DME, create A02 failure;
- c) switch off the FMC outputs for autopilot, create A03 failure;
- d) switch off the FMC outputs for EFIS, create A04 failure;
- e) switch off the FMC inputs from ADC, VOR/DME, and then recover normally after 5 seconds, create A07 failure;
- f) switch off the power for CDU, create A10 failure.

Notes: A01 = failures for the CPU and memory of FMC;

A02 = failures for the output interfaces of FMC, phase 1;

A03 = failures for the output interfaces of FMC, phase 2;

A04 = failures for the output interfaces of FMC, phase 3;

A07 = generally occurs while the program is disturbed;

A10 = CDU failures.

6 Simulation tests

As is showed in Fig.8 that the yaw distance at one engine cutout condition is larger than normal, where the red curve represents the normal, and the blue the failure section.

Given a 15m/s steady wind along x direction, the airplane will fly first in the north direction for 10 minutes.

Given a 5m/s steady wind along y direction, the airplane will fly first in the north direction for 10 minutes.

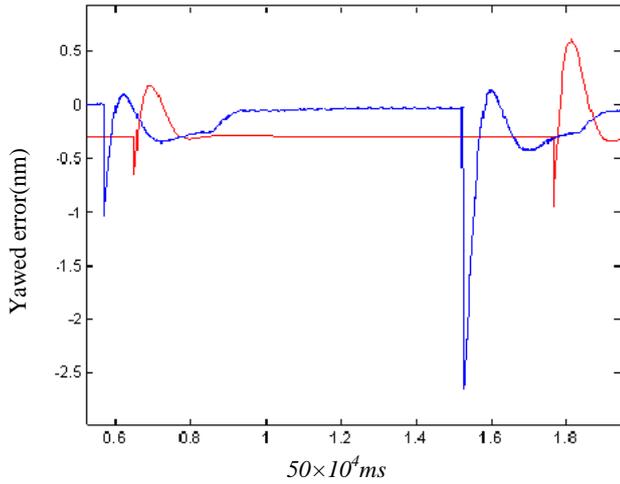


Fig.8 an engine failure simulation

Given a 5m/s steady wind along z direction, the airplane will fly in the north direction for 10 minutes with a FMC navigation, which indicates that the yaw acted by winds could be overcome by the FMC, and the airplane would fly along the preset desired track. As is showed in Fig.9.

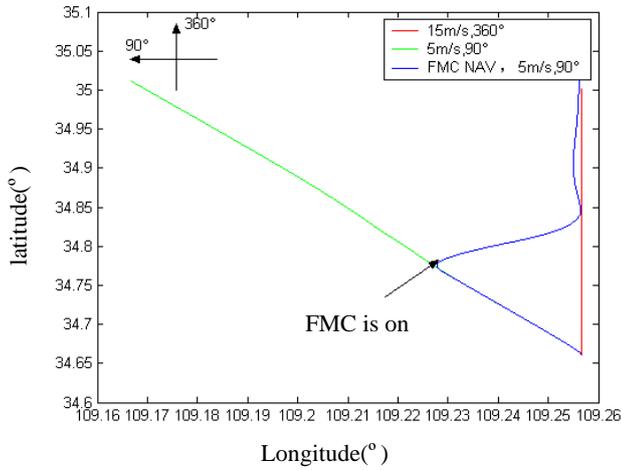


Fig.9 flight track affected by high level winds

The flight track created in a flight simulation test is the blue curve, and the real flight track for CITATION - II is the green curve. From Fig.10 we know both curves have nearly the same one track. It can be seen that these simulation tests on FMS have the identity.

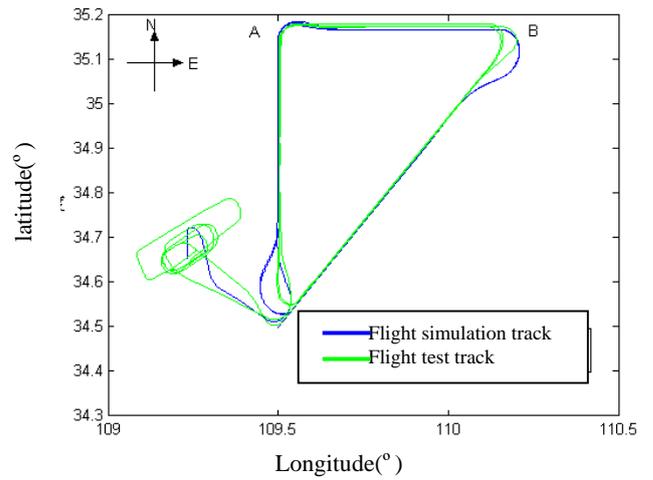


Fig.10 the comparison between the real flight test and the flight simulation

7 Flight verification tests

7.1 Quincunx flight

Keeping the altitude $H_P=4000m$ and velocity $V_i=350km/h \sim 450 km/h$, the FMS guided the aeroplane first horizontally flying 30km then quincuncially flying at magnetic azimuths $45^\circ, 180^\circ, 315^\circ, 90^\circ, 225^\circ, 0^\circ, 135^\circ, 270^\circ$ centered round a town. Fig.11 shows the second quincunx flight guided by the FMS.

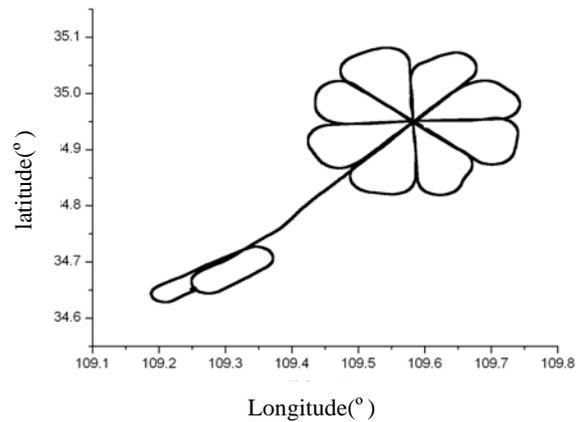


Fig.11 the second quincunx flight guided by the FMS

7.2 Amplified rectangular flight

The amplified rectangular flight started from a town and turned left, at 10km intervals. Fig.12 shows the amplified rectangular flight track.

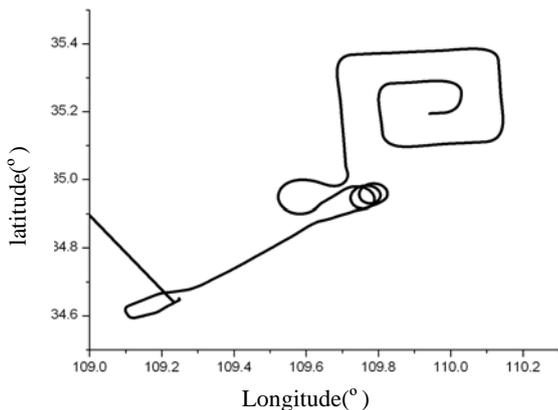


Fig.12 the amplified rectangular flight track guided by FMS

7.3 A great triangle flight

The FMS guided an airplane flying at the velocity $V_i=350\text{km/h} \sim 450 \text{ km/h}$ along the waypoints $A \rightarrow B \rightarrow C \rightarrow A$, where $A \rightarrow C$ stands for a straight latitude flight, and $B \rightarrow C$ a straight longitude flight. Fig.13 shows a great triangle flight track.

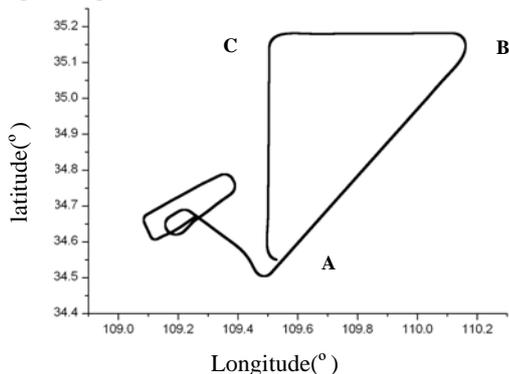


Fig.13 A great triangle flight

7.4 Turn leg and radius

If the separation between legs is less than $2R$, the SMC, an FMS computer with added special mission capability, will continue to a point $1/2R$ past the end waypoint of the leg and then turn in the direction to increase crosstrack to the new leg. At a crosstrack distance equal to the midpoint between the leg separation (LSEP) and the $2R$ separation, the SMC will reverse its turn direction and fly on a circular arc to intercept the new leg. It will intercept the new leg before the endpoint and then fly the great circle path between the leg waypoints, as is showed in fig.14.

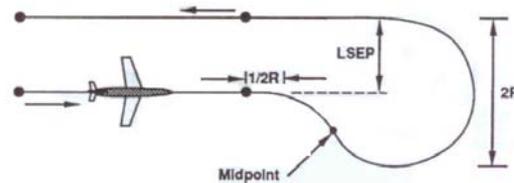


Fig.14 leg and minimum turn radius

If the separation between legs is greater than or equal to $2R$, the SMC will continue on the straight path to a point $1/2R$ beyond the end waypoint. It will then command a turn onto a track perpendicular to the new desired track. With a crosstrack of $1R$ the SMC will command steering on a circular arc to intercept the new leg. It will intercept the new leg before the end waypoint and then fly the great circle path between the leg waypoints, as is showed in fig.15.

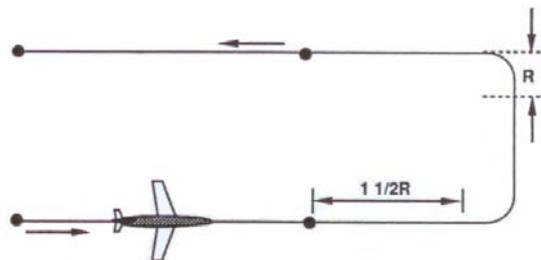


Fig.15 interval greater than or equal to $2R$

8 Conclusion

An advanced semi-entity simulation structure is applied in the design of the general scheme for an FMS simulation test platform. From engineering simulation, the semi-body simulation based upon an FMS could precisely real-time recover the whole flight test process with an FMS structure, realize the flight simulation deduction in relation to FMS, and accurately scheme flight test tasks so as to greatly increase flight tests efficiency. The based an FMS semi-entity simulation system could accurately recover and realize the computation for guidance and navigation, and make sure of the reliability and confidence of FMS simulation, so that the flight simulation process and results based an FMS could be directly applied to the evaluation for airworthiness approval. But in general a full-digital simulation couldn't reach the fidelity and reality in engineering simulation test.

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