Differential parameter method of aircraft flight simulation in aviation virtual electronic proving grounds

A R Bestugin, A D Filin and I A Kirshina
State University of Aerospace Instrumentation, Saint Petersburg, Russia

E-mail: ikirshina@mail.ru

Abstract. The study has been carried out to justify and choose an optimal method of aircraft flight simulation when designing virtual electronic proving grounds. A differential parameter method and algorithm of a set aircraft flight path simulation has been proposed based on the target status word assignment corresponding to each simulated aircraft and the joint implementation of a set of Euler's dynamical equations.

1. Introduction
The analysis of using airpower in local armed conflicts makes it clear that the successful task performance depends not only on the aircraft capabilities but also on the tactical skills of the crew and the air traffic controllers [1,2]. Therefore, there is a pressing need to create a new cognitive infrastructure for aviation personnel training: the aviation virtual electronic proving grounds (AVEPG) based on the unified complex of training measurement, simulation, and modeling instruments enabling to approach the flight tactical training (FTT) to the realistic environment due to the combination of real flight and modeling of the planned tactical setting in the predefined geographical region [3,4].

The AVEPG can be a multifunctional system combining the training flight measurement, simulation, and modeling instruments into a single complex for both individual and grouped aircraft (AC) and high-density air traffic to establish the planned tactical setting, and comprising the following functional units:

- Monitoring and Control Center (MCC).
- Ground Simulating Complex (SC).
- Data Transmission Equipment (DTE).
- Aircraft (AC) embedded Onboard Information Complex (OIC) [4,7].

The AVEPG structure is a set of interconnected components on the aircraft and on the ground within the geographical range of the aviation proving ground comprising the controlled air and ground space. The system provides for the AVEPG equipment with a set of positioning and data transmission instruments. The SC provides for simulation of an air tactical setting with subsequent transmission of a simulated model to the aircraft. All the air and ground data acquired during training are collected in the MCC, where they are displayed in various formats on computerized workstations of the training management team. The AVEPG theoretical structure is given in figure 1.

There are various MCC data display options: air situation, cabin situation with actual instrument readings, airborne system display, aircraft routes, and their tracking from any selected space point. Due to the significant increase expected in the efficacy of the flight crew members and air traffic control
officers trained with the AVEPG once it is created and introduced, the research and development in the area of the AVEPG design are of high importance.

**Figure 1.** AVEPG structure: DTE – data transmission equipment; APGMS-O – automated proving ground measurement system, operational; VEPG AIC – virtual electronic proving ground airborne information complex; ABA – airborne avionics; AS – air situation; GTS – ground tactical setting; RTFF – radio-technical flight facilities; Theater – air situation during the planned air operations; MCC – monitoring and control center.

2. Simulation Model

2.1. Setting the Problem

When developing and implementing the AVEPG, one of the most important applied problems is the generation of adequate AC movement models in compliance with their aerodynamic and technical specifics, the air traffic regulations, and the special training courses for flight management teams and air traffic controllers. The data on the current position of the simulated ACs are transmitted via the DTE to the VEPG AIC followed by mixing to the respective ABA systems of the real AC.

Generally, the mathematical model of the AC spatial motion as a solid body is described by the simultaneous 12th order nonlinear differential equations [5,6]. A number of authors present the AC movement equations, their AC spatial motion mathematical models take into account an autopilot control profile, they use simulation methods, and suggest probabilistic metric methods for assessing the simulator adequacy.

However, in the AC flight model engineering, adequate air situation simulation in the AVEPG requires solving the problems of simulating the complex AC flight paths associated with training combat maneuvers, takeoff/landing maneuvers, rounding/breaking up, simulating vertical flight profiles for different ACs, and other complex maneuvers set by an air traffic controller. Solving this problem with classic analytical techniques is rather complicated because of the multitude of varying parameters and the ambiguity of the solution since the problem is associated with the ever-changing air tactical setting.

Meanwhile, following the principles and criteria of the AVEPG SC design, it is conceivable that an AC might be considered a material object. Movement of this object is registered only by a radar position symbol and the AC crew reporting on passing the setpoints at the beginning and at the end of maneuvers, etc. A flight of an AC, both military and civil, is performed in strict compliance with the flight plan specifying the planned routes with control points [2,6]. The flight path may be changed en route when executing the commands of the air traffic control officers, or the simulated automated ground control system (AGCS), or by the AC crew (in the AVEPG SC – by the pilot operator of the simulated ACs ensuring control of the AC crews being in the same control area). Thus, to build an optimal AC movement model for the AVEPG, it is advisable to take into account the air situation display features on the AC air tactical setting indicator, the operation of an air traffic control officer, an MCC operator,
the information models of their automated workstations being the basis for their job functions performance.

2.2. Mathematical simulation modeling
Proceeding from the assessment of the real air traffic control based on using the radar data, the AC flight path generation can be presented in the AVEPG SC as a set of interconnected route sections between the control points (CPs) [8]. In each current CP, a full set of parameters for AC straight or nonlinear spatial motion is specified up to the next CP, where the AC movement parameters will be specified anew.

Using Euler's dynamical equations, the AC movement model between the CPs is implemented based on the parameters set in the current CP. The use of Euler's dynamical equations to simulate the AC flights in the VEPG SC is justified by the need to balance out the adequacy and complexity, proved in practice.

The structure of the algorithm implementing the differential parameter method of the AC flight path simulation is given in figure 2.

One of the main advantages of this algorithm is its implementation capability, i.e. an ability to provide automatic acceptance and implementation of an event affecting the simulated AC flight path.

![Figure 2. Structure of the algorithm implementing the differential parameter method of the AC flight path simulation.](image)

The current status of each AC is described with a target status word (TSW) designed to incorporate the predefined and updated set of AC parameters in its structure. The large-scale structure of TSW is a set of data fields containing the following information:

- AC identification: target number, flight number, AC number, AC type, takeoff/landing table row number, and maneuver;
- order of the CPs in the trajectory tables: takeoff, routes, landing approach, execution of ground commands, maneuvers;
- order of the current coordinates and AC parameters: heading, azimuth, length, altitude, remaining fuel, flight pattern;
- crew reports: flight level reporting altitude, calculated descent altitude, transition flight level;
• flight plan parameters: departure airfield, destination airfield, reserve airfields, landing approach method, AC pilot-in-command minimum, transponder code, takeoff time.

In addition to the AC identification information, the TSW stores sequences of points defining the planned AC flight path (or numbers of sequences), various attributes, current coordinates and movement parameters, next point data, cells for designing the trajectories based on the commands being received, maneuvers set, and a provision for restoring the planned path after the specified maneuver completion.

Operating result of the programs of command decoding and set path selection from the maneuver table data array is the change in the respective TSW fields.

The movement of different ACs on the ground and in-flight is simulated in the VEPG SC in real time based on their mission, technical, and aerodynamic features. Wind is taken into consideration when simulating the AC movement. The changes in the aerodynamic features are set out based on the real flight conditions.

When this method is applied, the AC movement in the VEPG is simulated by the application of two techniques: movement simulation by fixed trajectories at setpoints and movement simulation on the basis of Euler's dynamical equations between the control points. In addition, the AC path in the VEPG SC has functional relation to the altitude and directional commands from the command post issued by the airtraffic controllers or the commands issued by the simulated AGCS (figure 2).

When this method is applied, the AC movement along the predefined paths is simulated using the control points, CPs. The AC movement path is visualized as a set of CPs. Moreover, the CP is defined as a predetermined condition of the aircraft movement, and when it is fulfilled the AC passes to the next CP selected according to the maneuver trajectory table. During the preparation of the AVEPG SC database, any trajectory and any maneuver can be defined using this set of CPs.

The aircraft position is determined at the discrete instants of time and is described in the TSW. The AC coordinates can be requested both intermittently — once every cycle of air situation model calculation — and upon an event, at floating time intervals.

An event means achieving a CP or any parameter set out (velocity, altitude, direction, time, etc.) as a result of an air traffic controller's command entered from the instructor's control panel.

3. Analyzing the studies of differential parameter method application in aircraft flight simulation on VEPG

Let us consider the differential parameter method actual application in AC movement simulation based on Euler’s equations as suggested above. In this case, the model of AC movement between the points or after the air traffic controller’s command is built using the aircraft aerodynamic specifics. The model is based on the set of Euler's dynamical equations in the aircraft coordinates. Moments affecting the aircraft movement are considered balanced by the respective deflections of controls. In addition, all the forces influencing the aircraft are taken as applied to its center of gravity. The aircraft movement influenced by aerodynamics and thrust in the aircraft coordinates is described by a set of equations (1). The engine thrust direction is along the roll axis, while the gliding angle is small and can be neglected.

All calculations are made in the Cartesian system relative to the reference point, with X axis directed northward, thus

\[
\begin{align*}
\dot{V} &= g \left( \frac{P - X}{G} - \sin \theta \right) \\
\dot{\theta} &= g \left( \frac{Y}{V} \cos y \pm \cos \theta \right) \\
\dot{\varphi} &= \pm \frac{Y}{G} \cdot \frac{g}{V \cdot \cos \theta} \cdot \sin y
\end{align*}
\]
where $g$ - gravity acceleration; $\theta$ - path inclination in the vertical plane; $\gamma$ - roll; $\varphi$ - heading; $V$ - true airspeed; $P$ - aircraft thrust; $Y$ - lift; $X$ - drag; $G$ - gravity (AC weight); $\alpha$ - angle of incidence.

All the forces are considered applied to the aircraft center of gravity.

The range of aerodynamic parameters depends on the used aerodynamic parameter curves for each chosen AC type, which is selected from the AVEPG SC database, and the simulated AC flight mode. Thus, to account for the drag, an aerodynamic curve of airspeed and AC type is used with zero lift. Airspeed can be selected from the range of operating speeds and altitudes for the specified AC type. The lift coefficient vs. induced drag coefficient curves at different flight speeds taken from the TSC database are used. We also use the allowable lift coefficient vs. speed curves.

The set (1) is a basis for AC movement parameters, and the sets of kinematic equations are used to calculate the aircraft position (2):

$$
\begin{align*}
\frac{dx}{dt} &= V \cdot \cos(\theta) \cdot \cos(\varphi) \\
\frac{dy}{dt} &= \frac{dh}{dt} = V \cdot \sin(\theta) \\
\frac{dz}{dt} &= -V \cdot \cos(\theta) \cdot \sin(\varphi)
\end{align*}
$$

In the discrete application, the current parameters may be presented as expressions (3), (4):

$$
\begin{align*}
v[i+1] &= v[i] + \frac{dv[i+1]}{dt} \cdot \Delta t \\
\varphi[i+1] &= \varphi[i] + \frac{d\varphi[i+1]}{dt} \cdot \Delta t \\
\theta[i+1] &= \theta[i] + \frac{d\theta[i+1]}{dt} \cdot \Delta t \\
x[i+1] &= x[i] + \frac{dx}{dt} \cdot \Delta t \\
z[i+1] &= z[i] + \frac{dz}{dt} \cdot \Delta t \\
h[i+1] &= h[i] + \frac{dy}{dt} \cdot \Delta t
\end{align*}
$$

A set of equations (1÷4) fully describe the AC spatial motion, providing for calculation of all its motion characteristics and their change over time once the engine operating mode, thrust, and aerodynamics of the chosen AC type are specified. The track speed and flight path angle are determined by the formulas (5 ÷7):

$$
W = \sqrt{V^2 + U^2 + 2 \cdot V \cdot U \cdot \cos(\psi)}
$$

$$
\varphi_c = \arcsin\left(\frac{U \cdot \sin(\psi)}{W^2}\right)
$$

$$
\varphi^* = \varphi + \varphi_c
$$

where $\varphi$ - initial heading; $V$ - true airspeed; $U$ - wind speed; $W$ - track speed; $\psi$ - heading angle between the vectors $V$ and $U$; $\varphi_c$ - drift angle; $\varphi^*$ - flight path angle.
The benefit of this method simulating the AC movement in the AVEPG is that it makes the simulation significantly more adequate compared to the real flight. It takes into account the interrelation of forward and sideways motions, the speed dependence on altitude, weight, and AC maneuvers. The wind speed is also considered when simulating the AC flight. The motion dynamics simulation using this method makes allowance for a wide range of speed and altitude changes specific for modern AC types, as well as the AC engine limit load operation.

Fuel consumption is one of the important parameters monitored during flight. The air traffic control officers shall plan a flight taking fuel consumption into account. For this reason, the flight models shall comprise the fuel consumption simulation. The analysis of existing models shows that the use of complex analytical models is inexpedient for the AVEPG. We propose the simplest and sufficiently adequate method based on the known dependance diagrams of consumption for different AC types with their linear-spline approximation [2,9]. As a basis, the method uses fuel consumption vs. altitude and flight speed curves for maximal and afterburning modes.

Then the fuel flow rate can be calculated as per the formula:

\[
GS = g_0 + g_1h + g_2h^2 + g_3v + g_4v^2 + g_5vh,
\]

where \(GS\) - fuel flow rate, kg/s; \(h\) - flight altitude, m; \(v\) - current speed, Mach; \(g\) - coefficients depending on the type of AC and the engine operating mode.

Six points are selected on the curves. These points must include zero altitude and maximum altitude. Four other points shall be randomly picked at intermediate altitudes. To ensure more accurate calculation of consumption at lower altitudes, the points shall be chosen accordingly at low altitudes. To ensure a more accurate calculation of consumption at higher altitudes, the points shall be chosen accordingly at high altitudes. The fuel flow rate depending on the speed, altitude, for each type of AC is generated upon the air situation model display.

The current AC position coordinates on the airfield are generated based on the kinematic equations of its center of gravity movement. The coordinates are calculated according to the predefined calculation cycle or upon the specific events (receiving the air-traffic controller's commands or achieving parameters set out for the point). The aircraft moves along the set paths from point to point, while the path is a consecutive set of CPs describing the airfield structure.

The shortest path problem from the theory of graphs is used for the automatic generation of moving object paths on the airfield. For this, at the stage of preparing the training exercises, a database of taxiways, aprons, and ramps is created [10,11].

Taxiway data comprise a set of CPs in the Cartesian system with the attributes of the corresponding report, if at this point a radio exchange with the start/taxiing manager is provided, and with a radius, if at this point a turn with a certain radius is provided.

4. Conclusions

The presented method of applying the differential parameter method for simulating AC flight paths in the AVEPG's mathematical information software allows for modeling the air tactical setting and the airfield ground situation based on the required degree of complexity of the air tactical setting according to the curriculum, with a high level of adequacy and a sufficient level of validity.

Practical testing of this method demonstrates its potential in the construction of AVEPGs and training facilities for air traffic controllers.

Due to the replenishment of the initial database, the AVEPG acquiring the implementation capability can be constantly improved in the process of its use during the flight tactical training.

Aknowledgement

The study was funded by the Russian Foundation for Basic Research, grant No. 20-07-00437A.
References

[1] Krasovskiy A A 2005 Fundamentals of the Theory of Flight Simulators (Moscow, USSR: Mashinostroyeniye) p 383

[2] Filin A D, Bestugin A R and Sannikov V A 2018 Fundamentals of Air Traffic Control (Moscow, Russia: Urait) p 515

[3] Bestugin A R, Kirshina I A, Filin A D and Shatrakov Yu G 2015 Flight Safety and Directions for the Development of Training Simulators for Air Traffic Control Officers (St. Petersburg, Russia: SUAI) p 516

[4] Bestugin A R, Kirshina I A, Filin A D and Rachkov V P 2020 Organization of airspace operation (Moscow, Russia: INFRA-M) p 344

[5] Filin A D, Rachkov V P and Shatrakov Yu G 2018 Virtual aviation electronic proving grounds – status and development trends Aerospace Defense Annals 4 109-22

[6] Bestugin A.R, Eshenko A.A., Filin A.D. 2020 Air Traffic Control Automated Systems Springer 271 p

[7] Bestugin A R, Shatrakov Y G, Filin A D and Volodyagin A V 2014 The complex automated system of flight and tactical preparation and its estimates Proc. 2nd Int. Conf. on Eurasian scientific development (GmbH, Vienna: East West Association for Advanced Studies and Higher Education) pp112-7

[8] Filin A D, Bestugin A R and Rachkov V P 2019 Studies on the methodological support of the operation of automated flight tactical training systems – electronic proving grounds Aerospace Defense Annals 4 51-8

[9] Brunsch T, Raisch J, Hardouin L and Boutin O 2013 Discrete-Event Systems in a Diod Framework: Modeling and Analysis Control of Discrete-Event Systems 433 431-50

[10] Chriette A, Plestan F, Castañeda H,Pal M, Guill F, Odelga M, Rajappa S and Chandra R 2016 Adaptive robust attitude control for UAVs – Design and experimental validation International Journal of Adaptive Control and Signal Processing 30 1478-93

[11] Lekkas A M, Dahl A R, Breivik M and Fossen T I 2013 Continuous-Curvature Path Generation Using Fermat’s Spiral Modeling, Identification and Control 34(4) 183-98