Paper D2-4

COMPUTER SIMULATION OF SELECTED FAILURE MODES AND OPERATIONAL CONDITIONS FOR ROTORCRAFT[1]

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Abstract

Safety is the premier goal in aviation. It is the heart of any transportation system. Without safety, the benefits of the most sophisticated aircraft or aviation technology are lost. Aircraft certification has yielded major advances in aviation safety for decades. As aircraft have become more advanced and the aviation community learns better ways of ensuring safety, additional tests and requirements have been added. The purpose of aircraft certification is to ensure that a given aircraft is initially safe to fly and will continue to be safe if certain operating and maintenance limitations and procedures are followed. Technology advances and economic pressures are rapidly transforming aviation into a fully integrated, but very complex system; thus, making it more difficult for examining complex behaviors in the “pilot - vehicle - operational conditions” system. Modeling and simulation has become one of the most efficient ways in designing and investigating new aircraft. The problem under study is how to check and evaluate flight safety or mission success standards for a new vehicle beginning from the early design and certification phases. This paper will present a technique for examining complex behaviors in the “pilot - vehicle - operational conditions” system using an autonomous situational model of flight. This approach will allow virtual testing and evaluation as an emerging method which employs mathematical modeling and computer simulation for examining vehicle dynamics and flight control under complex operational conditions. An example will be provided for a tilt rotor aircraft, using a dynamics model of the XV-15 tilt rotor research aircraft.

Introduction

Flight safety depends on the behavior of the “pilot - vehicle - operational conditions” system (the system) in complex situations. These situations normally occur as a result of unfavorable combination of several operational factors (multi-facor situations). Main contributers to flight safety are the three consituents of the system, namely [1]: the human pilot (60-70% of all fllight accidents are attributed to so called “pilot errors”), a vehicle with its systems (17%), and external operational environents (5%). This implies that the flight safety problem must be addressed at the systems level. There is a correlation between so called “chain reaction” type flight accidents with highly automated aircraft and methodologies employed in design, testing, and evaluation. The “chain reaction” is a quick and irreversible propagation of several operational factors linked by strong cause-and-effect relationships. Normally, each of these factors is not critical.

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[1] In: Proc. of Heli Japan 98 Conference, 21-23 April 1998, Gifu, Japan, 1998.

At present, the burden of test and evaluation (T&E) of the aircraft flight characteristics in complex operational conditions rests with manned simulations and flight testing. These methods are expensive and require a long time to prepare and conduct. It may also be unsafe or technically difficult to examine complex operational domains. Thus, the flight envelopes of modern aircraft may not be protected reliably enough under mutifactor situations. As a T&E methodology, manned simulations and flight testing require enhancement to address the emerging flight safety problem.

Flight Situational Model

In this section, an introduction is made to an autonomous situational model of flight. This technique is proposed to complement manned simulations and flight testing when studying complex operational domains. Basically, three formal concepts are sufficient to construct a comprehensive model of a complex flight situation. These are the *flight event* (**E**), the *flight process* (**II**), and the *flight scenario* (**S**) [2]. Using this formulation, a human pilot's control tactics and heterogeneous operational conditions of flight can be described in an integrated fashion.

The *flight event* is a characteristic state of the "pilot- vehicle - operational conditons" system. Flight events may be viewed as special "points" or nodes in a multi-dimensional flight space-structure. They are important to the pilot (or a control system designer) in terms of planning or executing flight in a particular situation.

Unlike the event, the *flight process* is a continuous component of the situational model. It represents a distinctive non-momentary aspect (action, factor, input, etc.) of the system behavior. Depending on physical background, flight processes may be divided into three main groups:

- pilot's tactical decision making and pilot errors - "piloting task" (**T**), system "state observer " (**O**), "control procedure" (**P**), and some other processes
- external operational conditions - "wind" (**W**), "rain" (**R**), "runway surface condition" (**Y**), etc.
- onboard system functioning and system failures - "function" (**B**) and "failure" (**F**).

The flight situation scenario (*flight scenario*) is a plan for implementing a flight situation and the associated piloting tactics during simulation or in operation. Scenarios capture cause-and-effect and other key relationships between discrete and continuous elements of flight, thus mapping its invariant logical structure.

Tilt Rotor Aircraft Example

In this section a non-standard flight situation with the XV-15 tilt-rotor aircraft is modeled as an example. This hypothetical scenario $\mathbf{S}_1$ may be called: "Transition from the airplane flight mode to the tilt-rotor mode via the helicopter mode under multiple control inputs".

The initial conditions of the maneuver are as follows. H=2,500 ft, V_{CAS}=240 kt, $\varphi=85^o$ (airplane mode), $\vartheta=0^o$, $\gamma=-10^o$, $\omega=517.6$, $\delta_F=0^o$, SCAS – on. The scenario $\mathbf{S}_1$ is briefly described below.

This flight situation starts in airborne at the event $\mathbf{E}_1$ and finishes at $\mathbf{E}_6$: "time is 60 seconds". At $\mathbf{E}_1$ three piloting tasks are initiated by the "silicon pilot", namely:

This situation starts in airborne at the event $\mathbf{E}_1$ and finishes at $\mathbf{E}_6$: “time is 60 seconds”. At $\mathbf{E}_1$ three piloting tasks are initiated by the “silicon pilot”, namely:

- $\mathbf{T}_1$: “keep pitch angle at zero” using elevator
- $\mathbf{T}_2$: “hold zero sideslip” by rudder
- $\mathbf{T}_3$: “maintain bank angle at about -10^{o}” by ailerons.

Then, at the event $\mathbf{E}_2$: ”calibrated airspeed 215 kt”, the piloting task $\mathbf{T}_3$ is modified into $\mathbf{T}_6$: ”maintain bank angle at ~+25^{o}”. One more control procedure is added at this point for execution, this is $\mathbf{P}_3$: ”change the mast angle to a helicopter mode”.

Beginning from the event $\mathbf{E}_3$: ”time is 20 seconds”, a higher command pitch is requested to maintain, so $\mathbf{T}_1$ is modified into $\mathbf{T}_4$: ”keep pitch angle at about +6^{o}”.

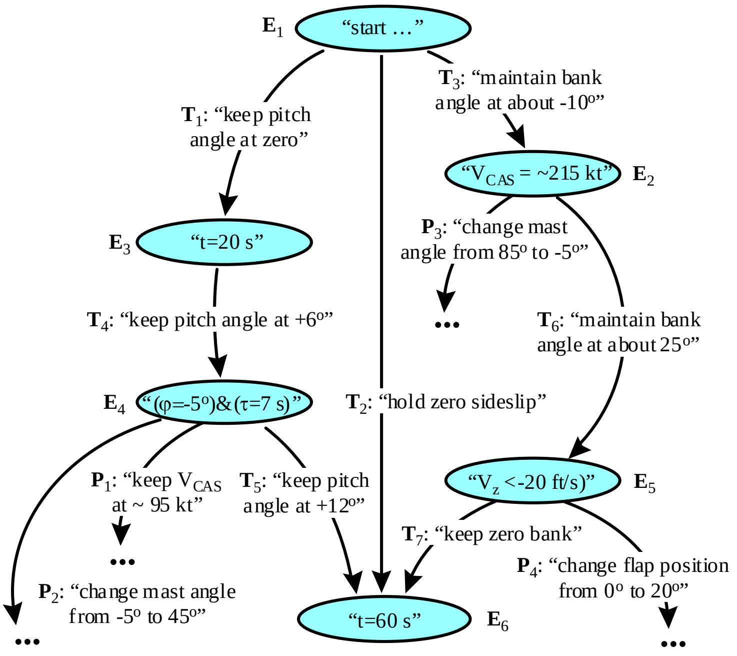

Figure 1: Hypothetical flight scenario $\mathbf{S}_1$: “Transition from the airplane mode to the tilt-rotor mode via the helicopter mode under multiple control inputs”

When the helicopter mode has been established, which is indicated by the event $\mathbf{E}_4$: ”mast angle is at a -5^{o} position for 7 seconds”, the control scenario is updated. The piloting task $\mathbf{T}_4$ in the longitudinal channel is being changed to further increase the command pitch, namely to $\mathbf{T}_5$: ”keep pitch at about +12^{o}”. Simultaneously, a control procedure is commenced to acquire a tilt-rotor flight mode, $\mathbf{P}_2$: ”change the mast angle from -5^{o} to +45^{o}”. Starting from $\mathbf{E}_4$, the “pilot” also attempts to keep the airspeed constant by applying collective inputs according to $\mathbf{P}_1$: ”keep V_{CAS} at about 95 knots”.

Finally, if a steep descent occurs (i.e. the event $\mathbf{E}_5$: ”V_z < -20 ft/s” is recognized), two control processes will be added. These are a piloting task $\mathbf{T}_7$: ”keep bank angle zero”, and a control procedure to extend flap $\mathbf{P}_4$: ”δ_F: $0^{o} \rightarrow 20^{o}$”.

Results of computer simulation of this maneuver according to the scenario $\mathbf{S}_1$ are depicted in **Fig. 2** (see also [3]). Thus, complex interrelationships within the “pilot – vehicle – operational conditions“ system can be formalized and modeled in a rigorous yet efficient way.

Discussion

Note that only six events and 11 processes were used in the scenario $\mathbf{S}_1$ to plan and model this complex enough flight case on a PC within a few minutes.

Various modifications to this scenario can be introduced further by blocking (“freezing”) some of the events or by adding, removing, or modifying the processes as required. For example, the removal of the event $\mathbf{E}_4$ results in a modified scenario without the processes $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{T}_5$. This means that the "flight" will be executed without, respectively, the helicopter mode, airspeed control, and an interim change in command pitch.

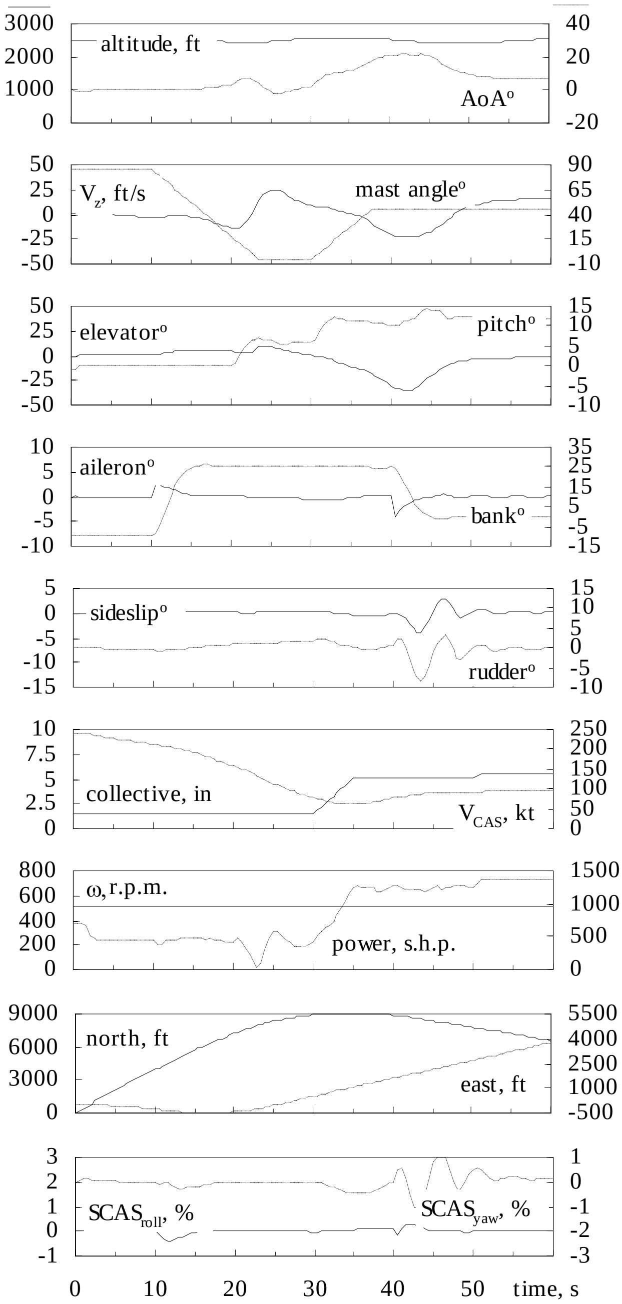

Figure 2: Simulation results (XV-15, scenario S_1)

On other hand, by adding, between $\mathbf{E}_1$ and $\mathbf{E}_6$, a new process-arrow to the initial scenario-graph, for example $\mathbf{W}_1$: "strong windshear identified from an accident dated xx/xx/xx", the vehicle behavior specified in $\mathbf{S}_1$ can be tested under demanding weather conditions encountered in some accident.

The proposed "events-processes" formulation of flight scenarios provides a practical tool for quick and flexible planning of various tilt rotor test cases on a computer. The modeling experience demonstrates that the content and logic of a flight situation of any complexity can be mapped into a compact set of data structures, simulated and retained on a computer for future reuse. Piloting or programming skills are not required. The complexity of the scenario planning and simulation task does not increase with the complexity of the flight situation under study.

Thus, using the flight scenario concept, complex flights situations can be represented in the form of directed graphs. This formulation allows capturing cause-and-effect and other invariant relationships between discrete and continuous elements of flight. Flight situations of practically any complexity can be coded into compact input data structures for autonomous simulation. Modeled cases may range from test certification programs to flight accidents and special maneuvers. Piloting or programming skills are not mandatory for the experimenter.

Autonomous flight simulation

Autonomous flight simulation is an engineering technique for reconstructing complex behaviors of the entire "pilot - vehicle - operational conditions" system using the described situational model of flight and a computer. The overall purpose of this technique is to keep the number of flight test and manned simulation hours for a new vehicle within the reasonable bounds. This can be achieved through a more comprehensive coverage of complex operational domains where the traditional T&E approaches fail.

This technique combines complementary properties of several theoretical, experimental and computational disciplines. This list includes flight mechanics, aerodynamics, flight control, propulsion, human pilot decision making and situational (tactical) control, flight dynamics simulation, numerical methods, graph theory, and computing. Through such integration, complex behaviors of the “pilot – vehicle – operational conditions” system can be simulated. The objective is to examine potentially critical situations in the system behavior, including a “chain reaction” type phenomena [3], before the vehicle is built and flown. During “what-if” experimentation with the situational model on a computer, various test scenarios can be applied to thread the vehicle’s operational domain.

In general, two components contribute to the vehicle’s operational domain: (1) specified phases or modes of flight, and (2) anticipated operational factors of flight, their combinations and levels. The operational factors may be presented as flight processes and flight events and grouped accordingly, i.e.: pilot errors and piloting methods (delays, objectives, gains, patterns, etc.), onboard system failures (engines, primary and secondary controls, undercarriage, autopilots, etc.), and demanding weather conditions (wind gusts, wind-shear, crosswind, rain, icing, runway, atmosphere, etc.). The flight scenario formulation introduced in previous sections allows uniform representation and processing of these factors. A concise and meaningful “events-processes” data structure implementable on a computer can be associated with any multi-factor flight situation.

A pre-requisite for successful application of autonomous flight simulation to the virtual T&E processes, however, is the availability of a non-linear mathematical model of vehicle flight dynamics. The fidelity of autonomous modeling and simulation is determined by the quality and completeness of vehicle input characteristics. These input characteristics and their arguments must cover the flight modes and operational factors under examination. Some “exotic” characteristics may also be needed to account for special regimes and conditions of flight. Also required is a general (verbal, qualitative) description of test cases under study.

The autonomous flight situational model has been used to study the flight performance for 17 aircraft types and two design projects. This list includes turbojet and turboprop transport airplanes, helicopters, a tilt-rotor aircraft, a high-speed civil transport project, and trans-atmospheric vehicles. Over 30 practical problems were studied in the sectors of flight safety, flight control, and practical aerodynamics. These include the following groups of tasks:

- studying combined effects of failure modes, pilot errors and weather conditions on vehicle dynamics and control
- validation of new piloting methods and automatic control systems under multi-factor conditions
- virtual testing and certification of an aircraft flight performance in early design
- rehearsal of complex test programs and reconstruction of recorded flight test modes
- reconstruction of flight accidents; examination of operational domains around a flight accident/incident
- implementation of a “silicon pilot” model in a training flight simulator for an aerospace vehicle.

Compared with flight testing and manned simulation (**Table 1**), this technique offers an inexpensive and accessible source of knowledge about complex behaviors of the “pilot - vehicle - operational conditions” system. It allows quick examination of multi-factor operational domains for new vehicles in a more systematic and manageable way.

Table 1: Flight testing and manned flight simulation vs. autonomous flight simulation

Comparison criterion	1	2	3
Studying complex (extreme) operational domains	$+^{**}$	$+^{*}$	$+^{*}$
Systematic examination of flight envelope	-	$+^{**}$	+
Inexpensive to establish and run	-	-	+
Flexibility and sensitivity of experimentation	$+^{**}$	$+^{**}$	$+^{*}$
Accessibility in research and education	-	-	+
Accuracy and fidelity of results	+	$+^{*}$	$+^{*}$
“What-if” experimentation capability	$+^{**}$	+	+
Autonomy (independence of the human pilot)	-	-	+
Retention and automation of test scenarios	-	$+^{**}$	+
Faster-than-real-time flight experimentation	-	-	+
Safety of experimentation	$+^{**}$	+	+
Suitability for pilot training	+	$+^{*}$	$+^{**}$

Notes:

1	Flight testing
2	Manned flight simulation
3	Autonomous flight modeling and simulation
+/-	“Yes” or “no” in matching the criterion
*	Depends on the fidelity of a dynamic model
**	Limited capability

Thus, provided that a dynamic model of the vehicle exists, the autonomous modeling and simulation technique may complement the present T&E practice, namely:

- increase the volume and improve the quality of knowledge about complex operational domains of flight
- reduce the volume (or prevent excessive growth) of required flight tests and manned flight simulations
- accelerate and virtualize the overall T&E process.

Thus, autonomous flight simulation is an inexpensive and accessible source of knowledge about the “pilot – vehicle – operational conditions” system behavior in multi-factor flight situations. This technique can be used for systematic examination of the flight envelopes of new aircraft to identify potential problems, which may affect flight safety. Thus, autonomous flight modeling and simulation may complement and reduce the volume of flight testing and manned flight simulations when studying complex operational domains for advanced aerospace vehicles.

Conclusions

1. A technique has been developed for virtual testing and evaluation of a tilt rotor’s flight characteristics using autonomous situational modeling of flight. This technique may be used from the earlier design to operational phases of the vehicle’s life cycle. The model integrates a human

pilot's tactical decision making processes and anticipated operational conditions of flight. Various operational factors may be combined and their effects upon the six-degree-of-freedom controlled motion of a tilt rotor aircraft can be examined.

2. A concept of the flight situation scenario in the form of a directed graph is proposed to formalize complex flight cases. It may be used to map the airworthiness requirements and other qualitative specifications of flight into compact data structures for computer simulation. Both hypothetical and actual flight cases can be studied. A library of flight scenarios can be constructed and retained in electronic format. Given a new design input, this allows the virtual T&E process to be quickly repeated for the same or other vehicles.

3. A pre-requisite for successful application of the method is the availability of a comprehensive mathematical model of the vehicle flight dynamics. Physics-based models of new technologies, which are employed in a new vehicle, are required as well. Input characteristics of the vehicle dynamic model must encapsulate the operational domain under examination.

4. The situational model demonstrates its performance as a practical, affordable tool for generating systematic knowledge about the behavior of the "pilot – tilt-rotor - operational conditions" system in complex situations. The autonomous flight simulation technique is complementary to flight tests and manned flight simulations. By applying this methodology, flight test programs can be better focused. As a result, the number of test and certification hours required for a new vehicle may be significantly saved with a simultaneous increase in the quality and amount of knowledge about complex flight domains.

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