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MODELING AND SIMULATION OF AIRWORTHINESS REQUIREMENTS FOR AN HSCT PROTOTYPE IN EARLY DESIGN

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ABSTRACT

In this paper an attempt is made to map some of the airworthiness requirements (FAR, Part 25) into computational algorithms, data structures and flight modeling experiments for a high speed civil transport airplane (HSCT). The objective is to develop and test a method for virtual flight testing and certification of an HSCT prototype in the earlier design phases. An autonomous situational model of flight is employed as a substitute for a flight test article. Formal test flight scenarios, which map the airworthiness requirements for takeoff are described. Examples of autonomous modeling and simulation of two takeoff situations are presented.

PROBLEM

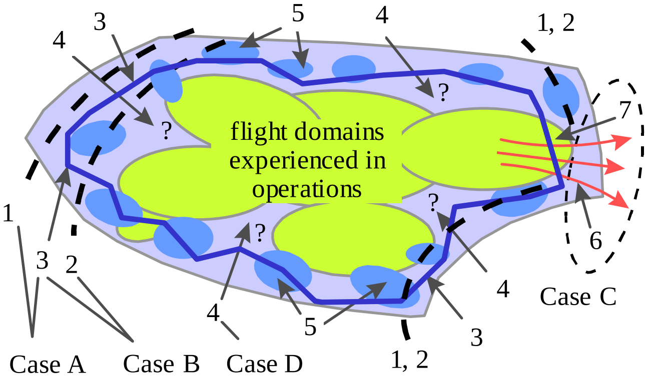
The problem addressed in this paper is as follows. How to assess the compliance of the flight safety characteristics of an HSCT prototype with the airworthiness requirements in the earlier design phases?

In the current approach the airworthiness requirements for a new airplane are mapped into a flight test program, which implements a specified set of potentially critical cases. This program is executed in manned simulations and, after a test article is built, in flight tests. However, shortcomings revealed at these stages may require substantial redesign work, which leads to cost and schedule overruns.

Using these methods, it is also difficult to check all potentially critical cases at the edge of the vehicle's flight envelope. This is because the list of possible demanding conditions and their combinations, which constitute a complex operational domain, is too long to permit their thorough examination. As a result, the edge of the flight envelope can be only exemplified at certain points. Some of these critical situations are revealed later in operation as flight accidents or incidents of a 'chain reaction' type [3].

Thus, as flight research methods, flight testing and manned flight simulation require enhancement [2]. The shortcomings include a slow experimentation capability (limited by the flight time scale), inability to reconstruct many of demanding conditions and scenarios, necessity to have a pilot in the test loop, instability of the pilot's performance from flight to flight, a growing cost of testing equipment and processes, and other. As a result, the edge of the vehicle's flight envelope may not be identified and thus protected.

Basically, there are three main cases of misidentification of the vehicle's flight envelope (**Fig. 1**): underestimated danger, overestimated danger, artificially created danger, and unknown danger.



Legend: 1, 2 - assigned flight constraints
3 - actual flight constraints
4 - non-examined (unknown) domains
5 - tested/simulated flight modes
6 - "chain reaction" flight paths
7 - "hole" in the flight envelope
Case A - underestimated danger
Case B - overestimated danger
Case C - artificially created danger
Case D - unknown danger

Fig. 1. Main cases of misidentification of the flight envelope

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The underestimated danger (see Case A in **Fig. 1**) may be defined as an unsafe flight situation when actual operational limits are closer than expected (i.e. than the assigned constraints). The overestimated danger (Case B) is a safe situation occurred when the actual flight limit is found farer than one assigned. The artificially created danger (Case C) is a "chain reaction" type emergency situation which is created spontaneously due to the complexity of the "pilot vehicle – operational condition" system dynamics. Finally, the unknown danger (Case D) is a critical situation with unknown consequences.

Often, such cases occur under multiple conditions, when several operational factors overlap, forming a multi-factor flight situation. Thus, there is a need for new flight research methods, which would complement the existing methods, be more affordable and more capable of testing and assessment of the vehicle's flight performance under such conditions.

SOLUTION METHOD

A solution to the problem of more reliable identification of the vehicle's flight envelope under such conditions is seen in performing a model-based T&C process. Unlike the present practice, this process is done with the intention of gaining as much knowledge of the system behavior as possible before the vehicle is built. For this purpose, autonomous flight simulation is linked to conceptual and preliminary design [2].

The principle idea is use a comprehensive mathematical model of the "pilot - vehicle - operational conditions" system behavior and a computer as a testbed for virtual testing and certification of the vehicle flight performance. Then the airworthiness requirements can be modeled in autonomous flight simulation experiments by means of a situational human pilot model [4] and a library of test scenarios. Through this process, an early assessment of the vehicle's flight safety standards can be made.

This integration allows necessary redesign work to be carried out virtually due to an earlier feedback from autonomous simulation. The amount and the quality of knowledge of the system behavior will also increase. This will help better focus manned simulations and physical test programs. As a result, the flight envelope border can be examined more systematically.

Virtual flight experiments can be conducted uniformly and quickly for a series of viable designs [5], all "flying" on a computer according to the same test scenarios. However, the availability of a comprehensive input database for the vehicle (aerodynamic, propulsion, mass, geometric, inertial and other characteristics) is a pre-requisite.

In the following sections this method will be introduced in more detail for an HSCT prototype. A general algorithm for translating airworthiness requirements into a series of 'flight experiments' on a computer will be described. A formalized model of a complex (multi-factor) operational domain will be introduced. A realistic example of construction and simulation of two flight test certification scenarios will be demonstrated for the takeoff phase of flight.

WORK DEFINITIONS

The system under examination is the "pilot - vehicle - operational conditions" system (**Fig. 2**). Main factors contributing to the problem of flight safety with modern transport airplanes are associated with the three constituents of this system. Therefore, the flight safety standards of a future vehicle should be assessed and secured at the system level.

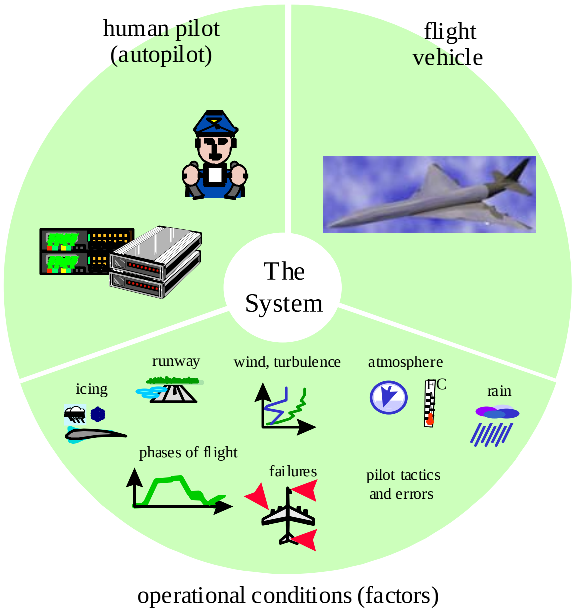

Fig.2. The system under examination

Virtual testing and certification (VT&C [2]) is a process of examination of the vehicle flight safety standards during the R&D cycle, using (**Fig. 3**): an autonomous situational model of the behavior of the "pilot - vehicle - operational conditions" system, the airworthiness requirements, e.g.: FARs [1], and a computer (e.g.: a PC).

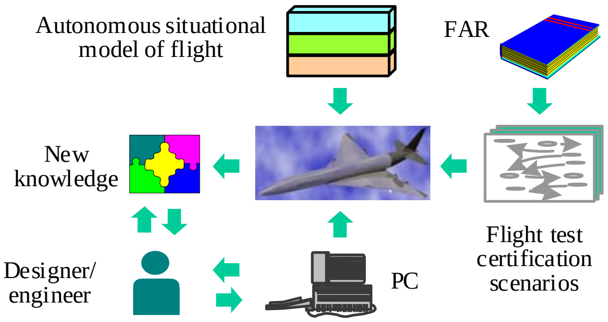

Fig. 3. Virtual flight testing and certification process

PRESENT DESIGN AND CERTIFICATION PRACTICE

The vehicle's R&D cycle includes the following four stages: design, manned simulations, flight testing, and certification. The purpose of this process is to obtain knowledge, with respect to the system behavior in complex flight situations, which is necessary and sufficient to build and certify a flight vehicle for operations. At present, flight testing and certification are performed after a test article is built, i.e. at the very end of the R&D cycle (**Fig. 4**).

If the performance of a new vehicle demonstrated in flight tests satisfies the airworthiness requirements, it goes into volume production. However, an expensive redesign or modification effort is required in the event the vehicle fails to meet the specified standards.

In this scheme the earlier stages of the R&D cycle, i.e. conceptual and preliminary design, are "switched off" from the T&C loop. Thus, little design freedom is left for radical changes of the vehicle's flight performance if a problem is discovered during testing and certification. The reason, of course, why the T&C stage cannot be pushed forward is due to the necessity to have a test article for physical experimentation. This process is long and expensive.

DESIRED DESIGN AND CERTIFICATION PRACTICE

In the proposed approach, the autonomous flight modeling and simulation techniques allow the testing and certification procedures to be emulated closer to the beginning of the R&D cycle (**Fig. 5**). This helps identify and address in advance possible mismatches between the vehicle's performance and the airworthiness requirements.

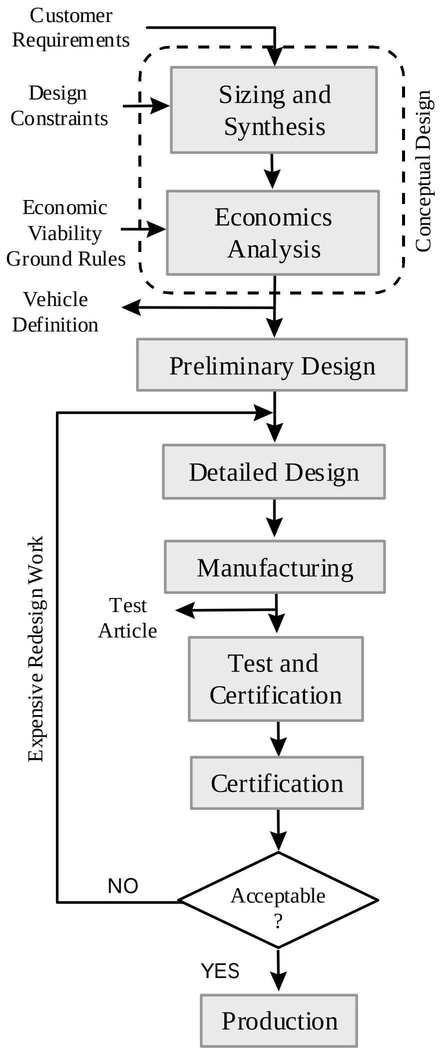

Fig. 4. Present design and certification practice

Compared with the present scheme shown in **Fig. 4**, the following two changes are made. First, a traditional object of T&C, the "test article", is substituted by a mathematical model of the system behavior. Input characteristics for the model are already available from conceptual and preliminary design (a "vehicle definition" database). Second, experimentation with the model can be carried out on computer in a much quicker and more systematic way than in flight tests.

In VT&C, autonomous flight modeling experiments may also be complemented with manned simulations on an engineering flight simulator to study problems which require the human pilot in the flight control loop. A comprehensive failure modes and effects analysis is performed as well to check the system behavior under multi-factor conditions. This virtual procedure is based on the same input as physical

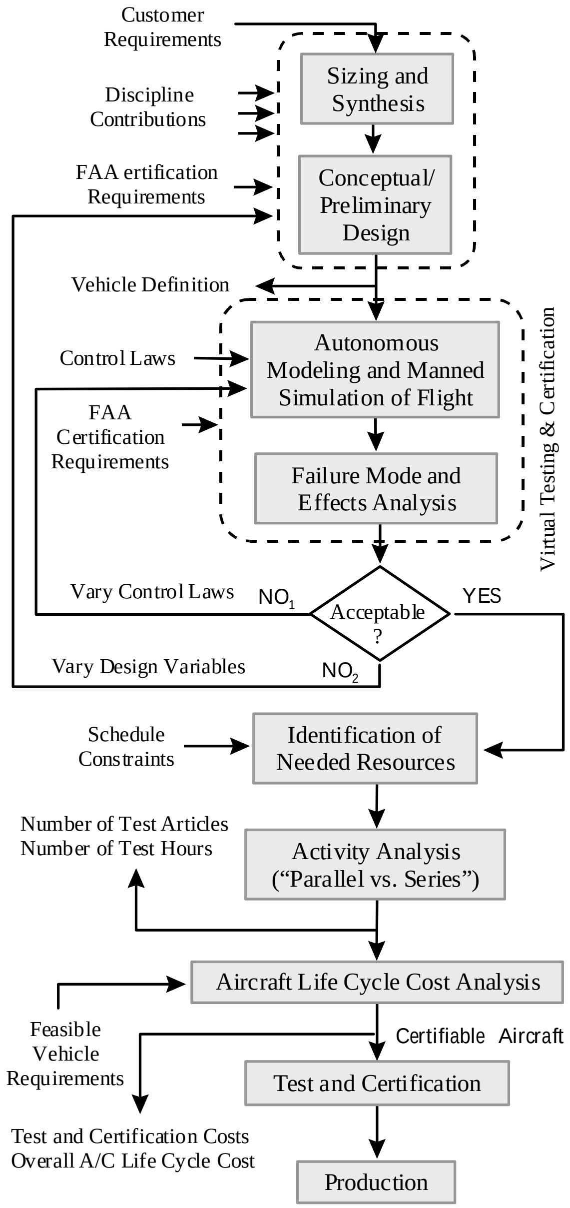

Fig. 5. Desired design and certification practice

testing (airworthiness requirements, control laws, failure modes scenarios, etc.).

There are two contours of "virtual redesign" envisioned in case of failure to meet the airworthiness standards: the inner loop and the outer loop. The inner loop is employed when the problem can be rectified by redesigning the automatic control laws or/and piloting tactics and flight patterns. In the event the effect of these improvements is insufficient (e.g.: the "test vehicle" does not meet certification standards), deeper changes are to be made by redefining basic design variables (the outer virtual redesign loop).

If, finally, the output of VT&C is acceptable, the following stages and activities are performed (see **Fig. 5**):

- identification of needed resources, given R&D cycle schedule constraints
- activity analysis ("parallel vs. series")
- aircraft life cycle cost analysis (based on the number of flight test articles and test hours identified in VT&C and given feasible vehicle requirements)
- physical testing and certification optimized in terms of the associated costs and flight regimes to be addressed, and
- production.

The output of the life cycle cost analysis is a certifiable vehicle. This is possible to achieve because the major burden of T&C experiments is carried out earlier, during the virtual phase. Once an optimum certifiable vehicle is determined, then the actual flight test program may be initiated to verify modeling and simulation results. If the FAA accepts these results, then T&C costs will be reduced greatly.

In general, the source of savings due to VT&C is seen in the following directions: reduced probability of accident/failure in operation owing to a more thorough identification of the flight envelope, no redesign work, better focused and structured T&C programs, and reduced amount of total T&C flight hours.

MAPPING ALGORITHM

INTRODUCTION. Following is an algorithm for mapping selected airworthiness requirements (see [1], Part 25, Subpart B, General/Flight/Performance) into formal scenarios and a plan of experimentation using the autonomous flight model. Based on this algorithm, an example of assessment of the vehicle's takeoff path (ref. Section 25.111 [1] and other) under multiple operational conditions will be given.

PURPOSE. The purpose of this example is to demonstrate that: (1) flight test cases specified in FAR can be formalized as flight scenarios for autonomous simulation, (2) such a mapping process helps decrease the ambiguity in interpreting the airworthiness requirements, and (3) the VT&C process on the model can be automated.

Benefits expected from this process are as follows:

- a unique formal cause-and-effect structure (a flight scenario) can be associated with each of the certification requirements, capturing their meaning

- after formalization these requirements can be modeled on a computer in a rigorous yet efficient way to check the vehicle's flight safety standards
- through this process, the VT&C method gains features of physical experimentation, as it can be repeated in exact detail or modified in the future for the same or other designs.

DISCLAIMER. The material presented in this and following sections is for illustration only. It should not be used as a citation of or reference to any aviation regulatory document or in conjunction with any particular vehicle type or test certification program.

ALGORITHM. The mapping algorithm combines flight scenario planning and simulation steps. It is described as a sequence of implications of the following kind: [*source specification of an airworthiness requirement (reference to FAR)* $\Rightarrow$ sequence of steps] , …, [*airworthiness requirement (reference to FAR)* $\Rightarrow$ sequence of steps]. The algorithm is described below.

[*All tests must be accomplished for each weight-CG combination over the entire ranges expected in operation (Section 25.21, a)* $\Rightarrow$

1. Define a list of airplane weights for the selected phase of flight (in our example a superscript T stands for takeoff): $\Omega^T(W) = \{W_{min}, W_{max}\}$;

2. Define a set of center of gravity locations for testing: $\Omega^T(CG) = \{CG_{fwd}, CG_{mid}, CG_{aft}\}$;

[*Tests must be accomplished at all weights, starting altitudes and ambient temperatures expected in operation (Section 25.105a)* $\Rightarrow$

3. Define a set of aerodrome altitudes for testing: $\Omega^T(H_0) = \{ H_{0\ min}, H_{0\ min} + \Delta H, \dots, H_{0\ max} \}$;

4. Define a range of extreme ambient temperatures for testing: $\Omega^T(t_{atm}) = \{t_{min}, \dots, t_{max}\}$]

[*… the airworthiness standards for transport category airplanes must be checked for wet runways (Section 25.101)* $\Rightarrow$

5. Define a range of the tire-runway adhesion (coupling) factor measured by decelerometer for testing: $\Omega^T(\mu) = \{ \mu_{min}, \dots, \mu_{max} \}$]

[*For any given set of conditions … a single value of VR must be used to show compliance with both the one-engine-inoperative and the all-engines-operative provisions (Section 25.107)* $\Rightarrow$

6. Specify a range of VR speeds for testing (a VR estimate can be obtained by other methods): $\Omega^T(VR) = \{ VR_{min}, \dots, VR_{max} \}$;

7. Specify a range of VEF speeds for testing: $\Omega^T(VEF) = \{ VEF_{min}, \dots, VEF_{max} \}$;

8. Specify two levels of the operational factor-condition Φ^{EF}: "critical engine failure" for testing: $\Omega^T(\Phi^{EF}) = \{\Phi_0^{EF}, \Phi_1^{EF}\}$, where:

- Φ_0^{EF} is the all-engines-operative condition (it is modeled by not including event $\mathbf{E}_{11}$: *"speed VEF"* into the scenario, i.e. $\mathbf{E}_{11} \notin \Omega(\mathbf{E})$ [2, 4]);
- Φ_1^{EF} is the one-engine-inoperative condition (it is modeled as a failure type process $\mathbf{F}_1$: *"engine #1 failure"* [2, 4] added to the scenario at event $\mathbf{E}_{11}$;

9. Construct a set of operational conditions (factors) for testing in autonomous simulation as a Cartesian product of the most critical combinations Φ_i of factors from the operational sets defined above, i.e.: $\Omega^T(\Phi) \equiv \Omega^T(W, CG, H_0, t_{atm}, \mu, VR, VEF, \Phi^{EF}, \dots) = \Omega^T(W)\times\Omega^T(CG)\times\Omega^T(H_0)\times\Omega^T(t_{atm})\times\Omega^T(\mu)\times\Omega^T(VR)\times \Omega^T(VEF)\times\Omega^T(\Phi^{EF})\dots$

Alternatively, the set $\Omega^T(\Phi)$ can be written as follows: $\Omega^T(\Phi) = \{\Phi_1, \dots, \Phi_i, \dots, \Phi_{N(\Phi)}\}$, where $\Phi_i = (W, CG, H_0, t_{atm}, \mu, VR, VEF, \Phi^{EF}, \dots)_i$ is one combination of operational conditions for testing;

10. Based on subjective assessments of the criticality of each of the factors constituting Φ_i, evaluate the complexity (criticality) level of the combined test condition Φ_i, $\chi_i(\Phi_i)$]

11. Sort test conditions in $\Omega^T(\Phi)$ to put more complex or critical combinations Φ_i at the beginning: $\Omega^T(\Phi) = \{\Phi_{(1)}, \dots, \Phi_{(i)}, \dots, \Phi_{(N(\Phi))}\}$, where $\chi(\Phi_{(i)}) \geq \chi(\Phi_{(j)})$ $(\forall i, j)$ $(i, j = 1, \dots, N(\Phi)$ $(i < j)$]

[*in Appendix 1 an example of verbal specification of two generic types of test scenario is given, a normal takeoff (**S**$_0$) and a continued takeoff (**S**$_1$); these scenarios are required to use for assessing the airplane's flight path according to Section 25.111)* $\Rightarrow$

12. Construct a scenario for normal takeoff, $\mathbf{S}_0$, using the method described in [2].

13. Construct a scenario for continued takeoff with a left hand (critical) engine failure, $\mathbf{S}_1$;

Scenarios $\mathbf{S}_0$ and $\mathbf{S}_1$ are described below.

14. Associate with each of these scenario types a combination $\Phi_{(i)}$ of the operational conditions from the prioritized set $\Omega^T(\Phi)$. The result is two virtual flight testing and certification programs: $\Omega^T(\mathbf{S}_0,\Phi) = \{(S_0, \Phi_{(1)}), (S_0, \Phi_{(2)}), (S_0, \Phi_{(3)}), \ldots\}$ and $\Omega^T(\mathbf{S}_1,\Phi) = \{(S_0, \Phi_{(1)}), (S_0, \Phi_{(2)}), (S_0, \Phi_{(3)}), \ldots\}$;

15. Conduct a series of autonomous flight simulation experiments on a computer according to the programs $\Omega^T(\mathbf{S}_0,\Phi)$ and $\Omega^T(\mathbf{S}_1,\Phi)$. In addition to factor prioritization in $\Omega^T(\Phi)$, other methods can be used to rationalize the process;

16. Evaluate the compliance of the vehicle's flight safety standards and other characteristics using the airworthiness criteria specified in Part 25 (**Fig. 6**)]

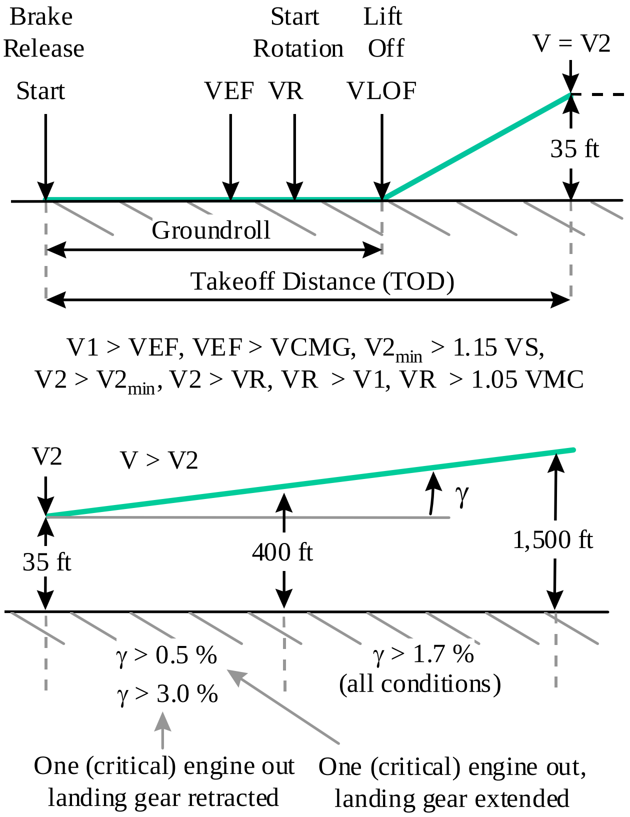

Fig. 6. Selected FAR requirements for takeoff

TAKEOFF SCENARIOS

Both normal ($\mathbf{S}_0$) and continued ($\mathbf{S}_1$) takeoff scenarios are presented in **Fig. 7**.

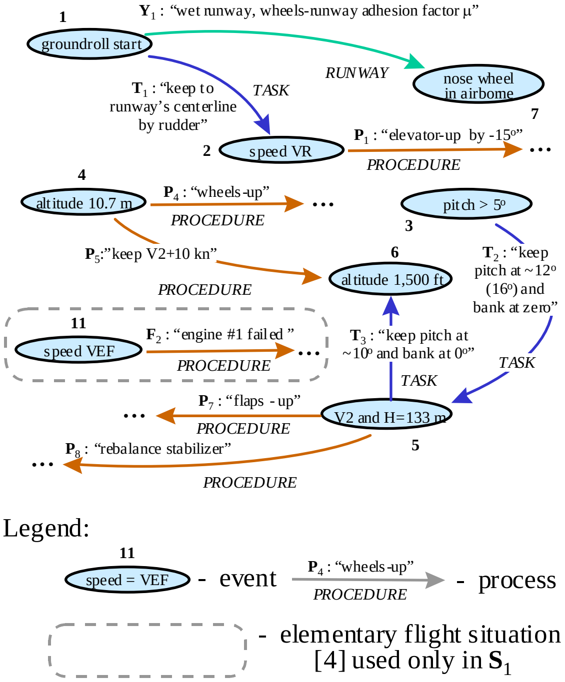

Fig. 7. Normal $\mathbf{S}_0$ and continued $\mathbf{S}_1$ takeoff scenarios for an HSCT (example)

These scenarios are based on the airworthiness requirements from FAR's Part 25 and have very similar logical structure. The only difference between them is that event $\mathbf{E}_{11}$ together with process $\mathbf{F}_2$ are not used in $\mathbf{S}_0$. It is important that many of the operational conditions from $\Omega^T(\Phi)$ can be implemented through parametric adjustment of flight events and flight processes while logical structure of the scenario remains invariant. Programming is not required to construct and modify scenarios.

More detailed description of a multi-factor takeoff situation similar to $\mathbf{S}_0$ and $\mathbf{S}_1$ is given in Paper No. AIAA-98-4937.

SIMULATION EXAMPLES

Examples of simulation results for two flight test cases belonging to the programs $\Omega(\mathbf{S}_0,\Phi)$ and $\Omega(\mathbf{S}_1,\Phi)$ are demonstrated in **Fig. 8** and **9**, respectively (see Appendix 2). These include:

- normal takeoff, including groundroll on a wet runway, performed according to scenario $\mathbf{S}_0$, and
- continued takeoff with left (critical) engine inoperative at VEF under the same runway conditions, performed according to $\mathbf{S}_1$.

Main initial conditions for these takeoffs are summarized in **Table 1**.

Table 1. HSCT initial takeoff conditions

total weight	MTOW	kg
fuel weight	180,000	kg
instrumental speed	0.5	km/h
CG location on MAC	34	%
altitude (with respect to wheels)	0.0	m
pitch angle	1.0	degr
AoA	1.0	degr
flaps	15.0	degr
horizontal stabilizer	-15.0	degr
elevator	10.0	degr
throttle 1	100.0	%
throttle 2	100.0	%
throttle 3	100.0	%
throttle 4	100.0	%
wheels	1.0 (on)	-
tire-runway adhesion factor	0.3	-

A takeoff test mode shown in **Fig. 8** meets the airworthiness requirements for the rate of climb and V2. The best initial climb is achieved at the command pitch angle of 12^o.

In the second scenario a critical engine failure is introduced at VEF = 200 km/h. Note that after this event the airplane is directionally controllable on a wet runway. Rudder consumption temporarily increases to its maximum limit at lift-off (to counter the loss of nose wheel contact with the runway), but lateral excursions of the airplane during groundroll remain appropriate.

However, in the scenario $\mathbf{S}_1$ it is difficult to secure a lift force at VR sufficient for initial climb: the increased command pitch (16^o compared with 12^o in the normal scenario) is not sufficient.

As a result, a continued takeoff for the airplane is problematic under given conditions. The airworthiness criteria are not met: the initial rate of climb is about 0.2-0.5% and the indicated airspeed is below V2.

CONCLUSION

A method has been developed for mapping the airworthiness requirements into formalized test scenarios for autonomous simulation experiments with a situational model of flight. This method allows to automate and virtualize the flight testing and certification process for a subset of flight requirements specified in FAR, Part 25. A library of such scenarios can be developed and retained on a computer for future reuse for the same or other vehicles.

The distinguishing feature of this method is that various multi-factor test flight situations can be formalized and examined on a computer by a non-pilot in a rigorous, yet efficient way. As a result, flight test certification programs can be modeled in the earlier design phases based on FARs and a database of vehicle's input characteristics. More systematic knowledge of the "pilot – vehicle – operational system" behavior under complex flight situations can be obtained in design and flight test programs can be better focused.

ACKNOWLEDGEMENT

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NOMENCLATURE

SYMBOLS

$\forall$	"each", "every"
$\Rightarrow$	logical implication
$\times$	Cartesian product symbol
$\chi_i(\Phi_i)$	level of complexity of factor Φ_i

ASDL	Aerospace Systems Design Laboratory
CG	center of gravity
F	‘failure’ type flight process [2, 4]
HSCT	High Speed Civil Transport
K	landing gear control switch
MAC	mean aerodynamic chord
P	‘control procedure’ type process [2, 4]
S	flight scenario
S	shocker displacement
t	ambient air temperature; time
T	‘piloting task’ type process [2, 4]
T&C	testing and certification
V1	takeoff decision speed [1]
VCMG	minimum control speed on the ground [1]
VEF	engine failure speed [1]
VLOF	lift-off speed [1]
VMC	minimum control speed [1]
VR	rotation speed [1]
VS	stalling speed [1]
VT&C	virtual testing and certification
W	airplane weight
Y	‘runway condition’ type process
ΔH	aerodrome altitude increment
Φ	operational condition (factor)
$N(\Phi)$	number of levels in factor-set $\Omega^T(\Phi)$
$\Omega(\square)$	set of elements of type $\square$
μ	tire-runway adhesion (coupling) factor

SUBSCRIPTS

(i)	code of factor in a prioritized set, $i \in \{1, ...\}$
0	at sea level; normal takeoff; normal condition
1	‘one engine failed’ condition
atm	atmospheric
fwd	forward
i, j	code of event/process/factor, $i, j \in \{1, \dots\}$
mid	middle (average)
R	right (for aileron)
shock	shocker (in undercarriage)

SUPERSCRIPTS

EF	engine failure
T	takeoff

APPENDIX 1. SPECIFICATION OF NORMAL AND CONTINUED TAKEOFF SCENARIOS [1]

(a) The takeoff path extends from a standing start to a point in the takeoff at which the airplane is 1,500 feet above the takeoff surface, or at which the transition from the takeoff to the en route configuration is completed and a speed is reached at which compliance with Sec. 25.121(c) is shown, whichever point is higher.

In addition:

(1) The takeoff path must be based on the procedures prescribed in Sec. 25.101(f);
(2) The airplane must be accelerated on the ground to VEF, at which point the critical engine must be made inoperative and remain inoperative for the rest of the takeoff; and
(3) After reaching VEF, the airplane must be accelerated to V2.

(b) During the acceleration to speed V2, the nose gear may be raised off the ground at a speed not less than VR. However, landing gear retraction may not be begun until the airplane is airborne.

(c) During the takeoff path determination in accordance with paragraphs **(a)** and **(b)** of this section:

(1) The slope of the airborne part of the takeoff path must be positive at each point;
(2) The airplane must reach V2 before it is 35 feet above the takeoff surface and must continue at a speed as close as practical to, but not less than V2, until it is 400 feet above the takeoff surface;
(3) At each point along the takeoff path, starting at the point at which the airplane reaches 400 feet above the takeoff surface, the available gradient of climb may not be less than: … (iii) 1.7 percent for four-engine airplanes; and
(4) Except for gear retraction …, the airplane configuration may not be changed, and no change in power or thrust that requires action by the pilot may be made, until the airplane is 400 feet above the takeoff surface.

(d) The takeoff path must be determined by a continuous demonstrated takeoff or by synthesis from segments. If the takeoff path is determined by the segmental method:

(1) The segments must be clearly defined and must be related to the distinct changes in the configuration, power or thrust, and speed;
(2) The weight of the airplane, the configuration, and the power or thrust must be constant throughout each segment and must correspond to the most critical condition prevailing in the segment;
(3) The flight path must be based on the airplane's performance without ground effect; and
(4) The takeoff path data must be checked by continuous demonstrated takeoffs up to the point at which the airplane is out of ground effect and its speed is stabilized, to ensure that the path is conservative relative to the continuous path.

APPENDIX 2. TAKEOFF SIMULATION

Scenario $\mathbf{S}_0$: All engines operative, command pitch at initial climb = 12^0, VR = 320 km/h, V2 = 380 km/h. FAR's requirements are met for the rate of climb (γ= ~2.5 %) and V2

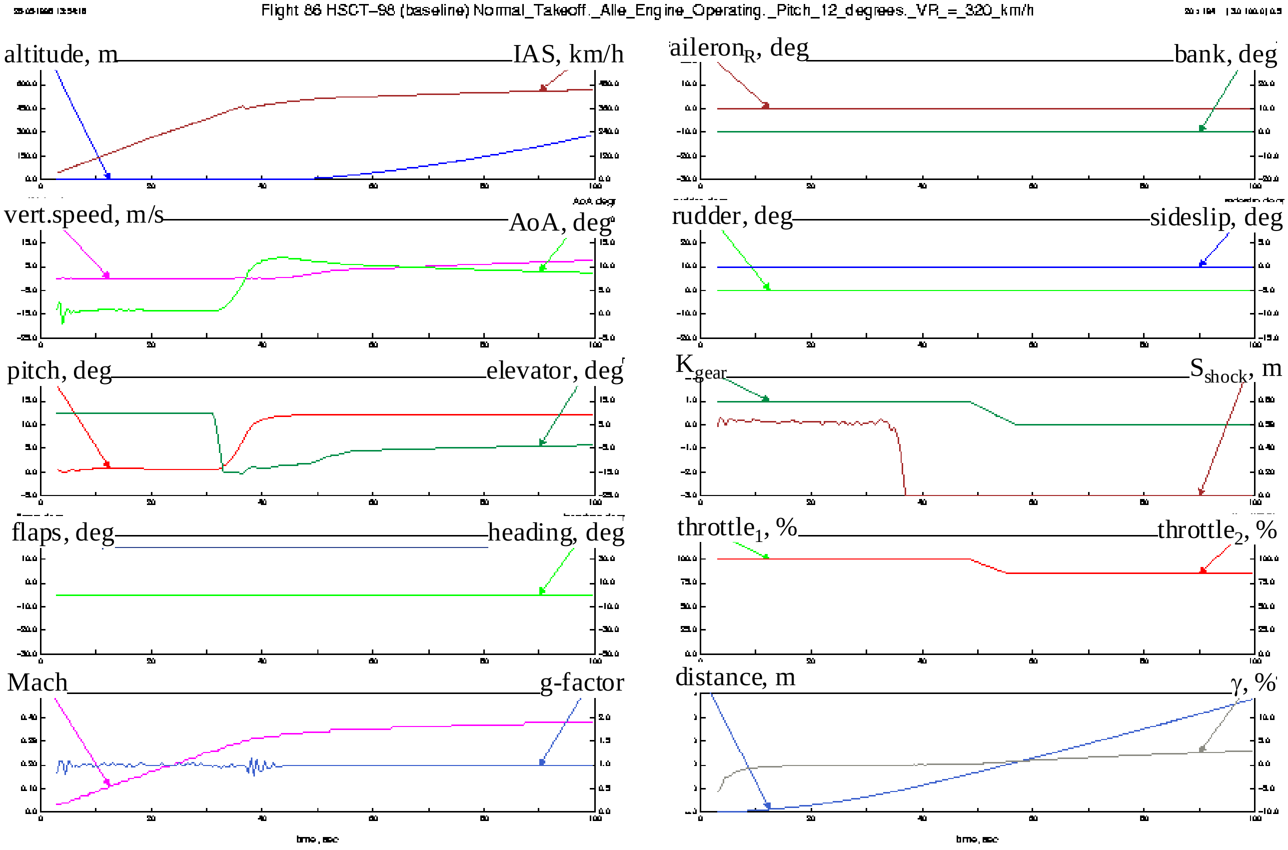

Fig. 8. Normal takeoff

Test scenario $\mathbf{S}_1$: One (outer left hand) engine inoperative, command pitch at initial climb = ~16^0, VEF = 200 km/h, VR = 320 km/h, and V2 = 380 km/h. FAR's requirements are not met for the rate of climb (γ = ~0.2 %) and V < V2

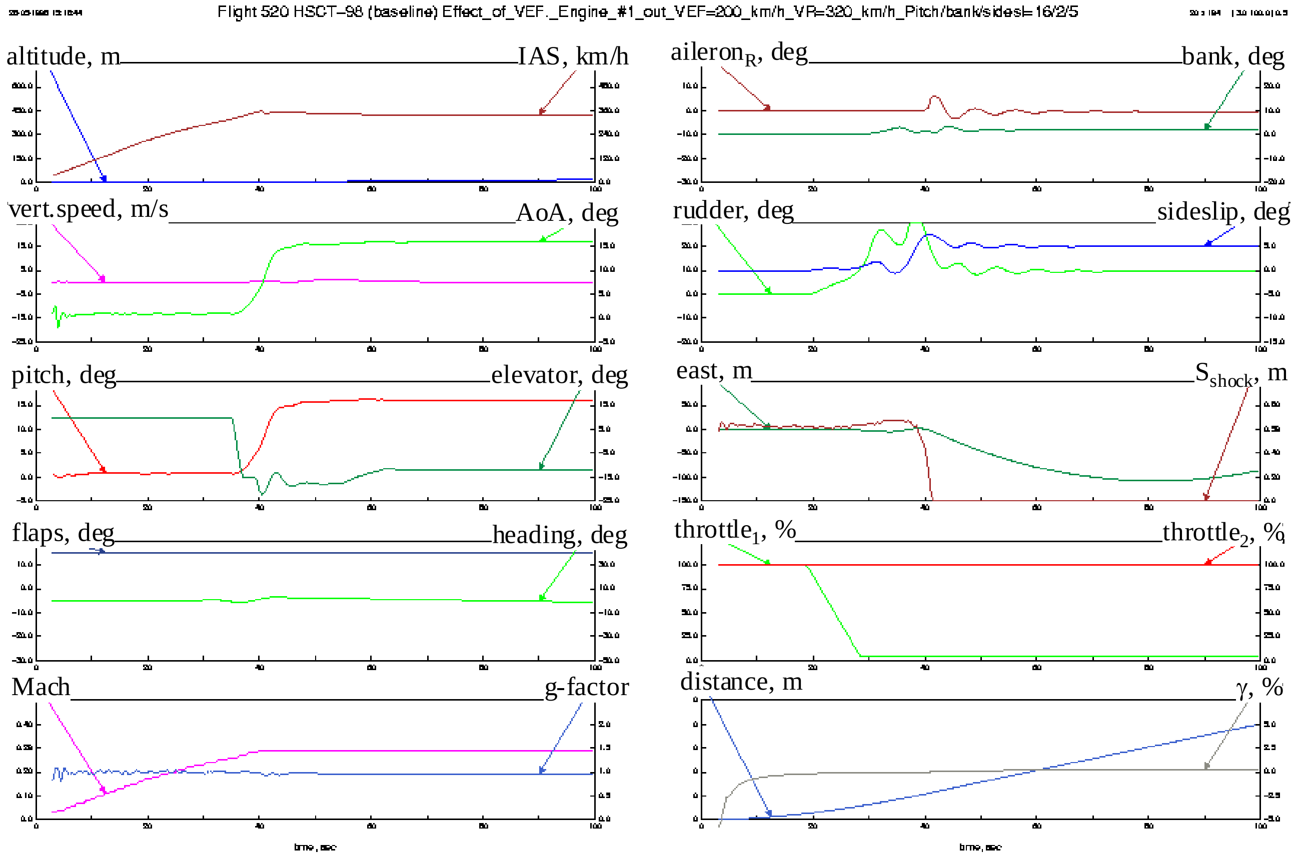

Fig. 9. Continued takeoff