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Virtual Flight Testing of an Experimental Tilt-Rotor Aircraft under Complex (Multi-Factor) Operational Conditions - A Case Study

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Presentation Plan

- Problem: tilt-rotor flight safety and control tactics under complex (multi-factor) conditions
- Solution approach: virtual flight testing in autonomous modeling and simulation
- Flight situation/case under study
- Modeling and simulation results. Discussion.
- Conclusions

Problem. Solution Approach. Objective

Problem

How to test and evaluate "pilot-vehicle-environment" system dynamics under complex (multi-factor) operational conditions? Specific problem: XV-15 autorotation landing with two engines out

Solution approach

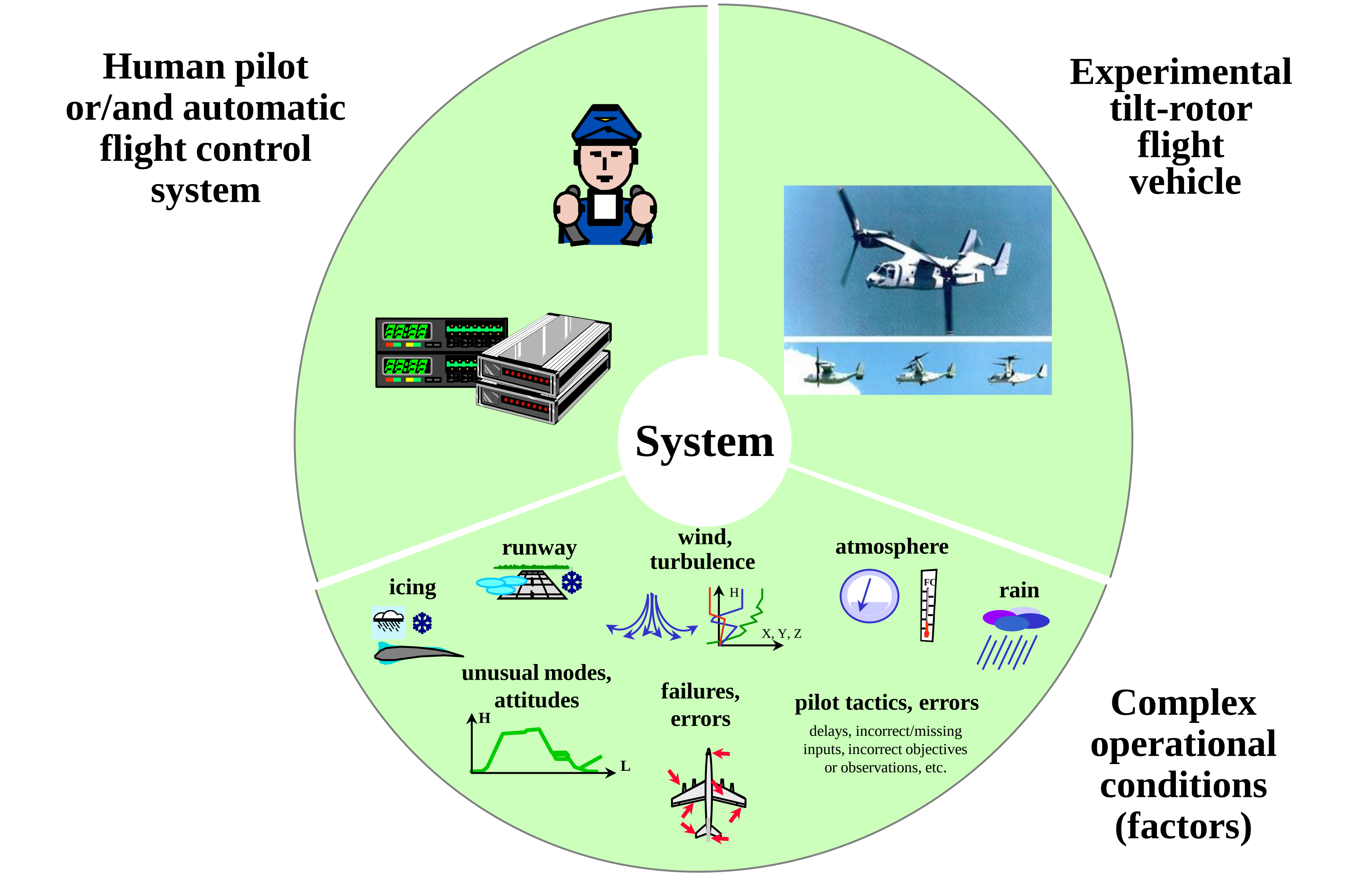
Virtual flight test experiments using autonomous modeling and simulation

Objective

- Examine vehicle flight performance and control tactics under complex conditions
- Assess sensitivity of the system dynamics to contributing operational factors
- Propose recovery control scenario

⇒ Complement flight test and manned simulations

System Under Examination



Virtual Flight Test Technique

Autonomous situational model of flight (VATES* tool)

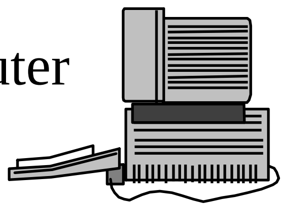
6DOF non-linear flight dynamics model
pilot decision making model ("silicon pilot")
models of anticipated operational conditions
flight situation scenario planning tool

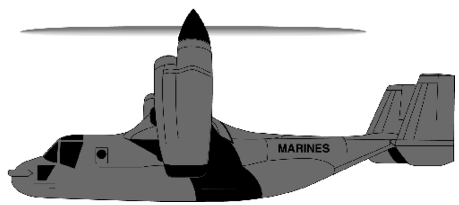
→

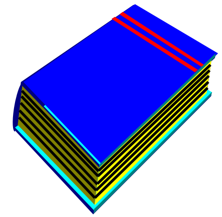
Pilot
Vehicle
Environment
Scenario

$$\frac{d\mathbf{x}}{dt} = f\,(\mathbf{x},\mathbf{u},\mathbf{w},t)$$

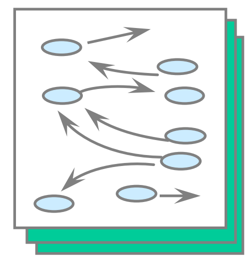
Computer





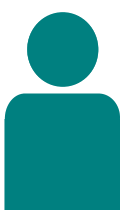


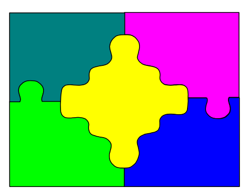
FAR, or test program, or Pilot's manual, or accident report, or FDR, ..



Flight scenario library

Designer, certification /safety analyst





New knowledge of the "pilot - vehicle - operational environment" system dynamics in complex flight situations

Note: * VATES - Virtual Autonomous Test and Evaluation Simulator (proprietary software)

Flight Test and Manned Simulation Vs. Autonomous Modeling and Simulation

Comparison criterion	flight tests	manned simulation	autonomous M&S
• study of complex (extreme) operational conditions	NO	YES*	YES*
• systematic exploration of flight domains	NO	NO	YES
• inexpensiveness to establish and run	NO	NO	YES
• careful evaluation of combined and ”thin” effects	NO	NO	YES*
• broad use in aerospace research & education	NO	NO	YES
• accuracy and fidelity of results	YES	YES*	YES*
• “what-if” experimentation capability	NO	YES**	YES
• autonomy and independence (of test pilot/equipment)	NO	NO	YES
• preservation and automation of flight scenarios	NO	YES**	YES
• faster-than-real-time performance of flight	NO	NO	YES
• safety of experimentation	YES**	YES	YES
• suitability for pilot training	YES**	YES	YES**

Note: (*****) depends on the comprehensiveness and fidelity of flight dynamics model
(******) limited capability

Assumptions and Limitations. Disclaimer

Assumptions and limitations

1. GTRSIM-based (1988) flight dynamics and control model of XV-15 tilt-rotorcraft, including vehicle-ground aerodynamic interaction
2. Vehicle undercarriage kinematics and dynamics not modeled though possible ⇒ Load factor at vehicle-ground contact point not modeled
3. Discrete-continuous model of human pilot situational/tactical decision making
4. Only longitudinal motion studied (though full flight dynamics implemented)
5. Non-systematic series of experiments (limited by one flight case) ⇒ Statistical experiments should and can be conducted in the future
7. Flight analysis based on knowledge mapping formats not performed

Disclaimer

1. Results obtained at this stage are for demonstration purposes only. They are applicable to a model, not to the actual vehicle
2. Material does not contain piloting recommendations for immediate use in operation
3. Proprietary flight modeling and simulation tool VATES used

Virtual Flight Test and Evaluation Process*

1. Obtain verbal description and other input data of complex situation for testing
2. Select key operational factors for examination
3. Formalize flight test scenario
4. Define subset of output flight variables for analysis
5. Define ranges of variation of examined operational factors
6. Tune system model (VATES package) to given flight situation
7. Develop “virtual flight test” plan
8. Conduct flight simulation experiments (for sensitivity analysis, piloting tactics development, etc.). Record “flights” in output database
9. Prepare graphics and other output formats. Analyze results
10. Write report. Identify conditions of possible “chain reaction”. Propose recovery tactics and/or design improvements if applicable/possible

Note: * - without connection to present T&E practices

Test Case Details

Vehicle type and flight situation under study

XV-15 experimental tilt-rotorcraft
Landing in auto-rotation with two engines out at altitude of 200 ft

Key operational factors

1. Engines power out
2. Collective control
3. Vehicle pitch control
4. Flaps position
5. Decision events timing (based on vehicle altitude, speed, and attitude)

Situation duration

25-35 s

Examined Complex Flight Condition

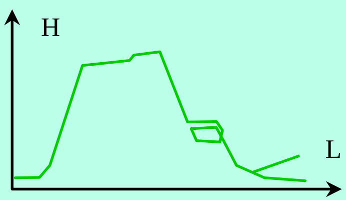
1 **Pilot error** **2** **Non-standard motion mode and control tactics** **3** **Two engines failure** ← **Complex (multi-factor) flight condition under study**

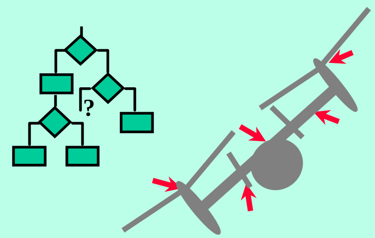
pilot errors or inattention

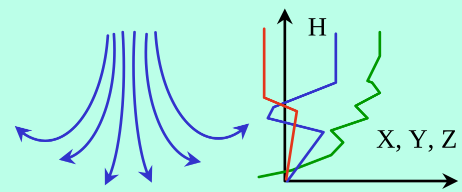
non-standard flight profile/ attitude or/and control tactics

mechanical failures, software logic errors

wind and turbulence (crosswind, windshear, microburst, …)







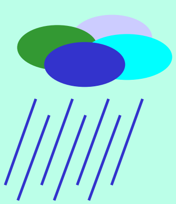
heavy rain, shower

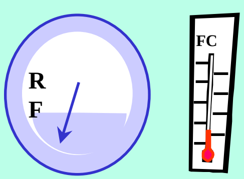
extreme atmospheric conditions (P, T)

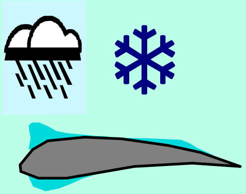
aircraft surface icing

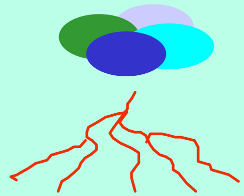
electromagnetic discharges

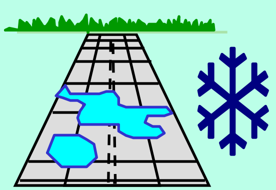
water-, ice-, snow-covered runway











Initial Conditions of Flight

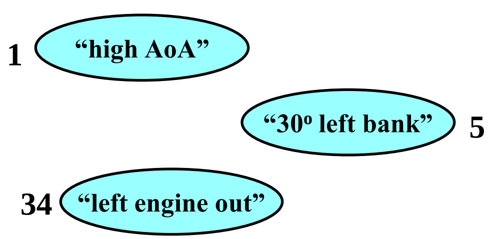
Gross Weight	14000.0	lb
C.G. (S.L.)	299.8	inch
Altitude	575.0	ft
Pressure Altitude	575.0	ft
Calibrated Airspeed	110.0	knots
Pitch Angle	-5.0	deg
Collective Position	10.0	inch
R.P.M. Selection	517.6	rpm
Center Rotor R.P.M.	517.6	rpm
Mast Tilt Angle	10.0	deg
Horizontal Stabilizer Incidence	2.0	deg
Flaps Position	0.0	deg
Landing Gear	On	-
SCAS	On	-
Flight Duration	32.0	sec

Main Concepts

Flight event

The **flight event** is a special state of the system which is important to the pilot/designer and stands for a substantial change in the flight situation, e.g.:

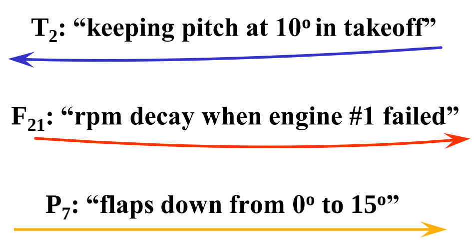
- *"left engine out"*
- *"speed VR achieved"*
- *"altitude 360 ft and speed 180 kt"*
- *"on the runway"*
- *"high angle of attack"*
- *"30° left bank"*
- *"go-around decision"*



Flight process

The **flight process** is a time-history of one or several flight parameters which characterize a certain aspect of the system behavior (dynamics, control, weather, etc.), e.g.:

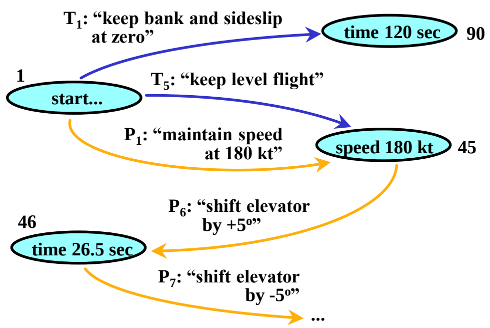
- *"steer runway's centerline"*
- *"keep pitch at 10° in takeoff"*
- *"apply windshear (10 ft/s /H=30 ft)"*
- *"rpm decay during engine #1 failure"*
- *"extend flaps from 0° to 15°"*
- *"turn at 10° bank and 0° sideslip"*
- *"apply wet runway condition (μ=0.3)"*



Flight scenario

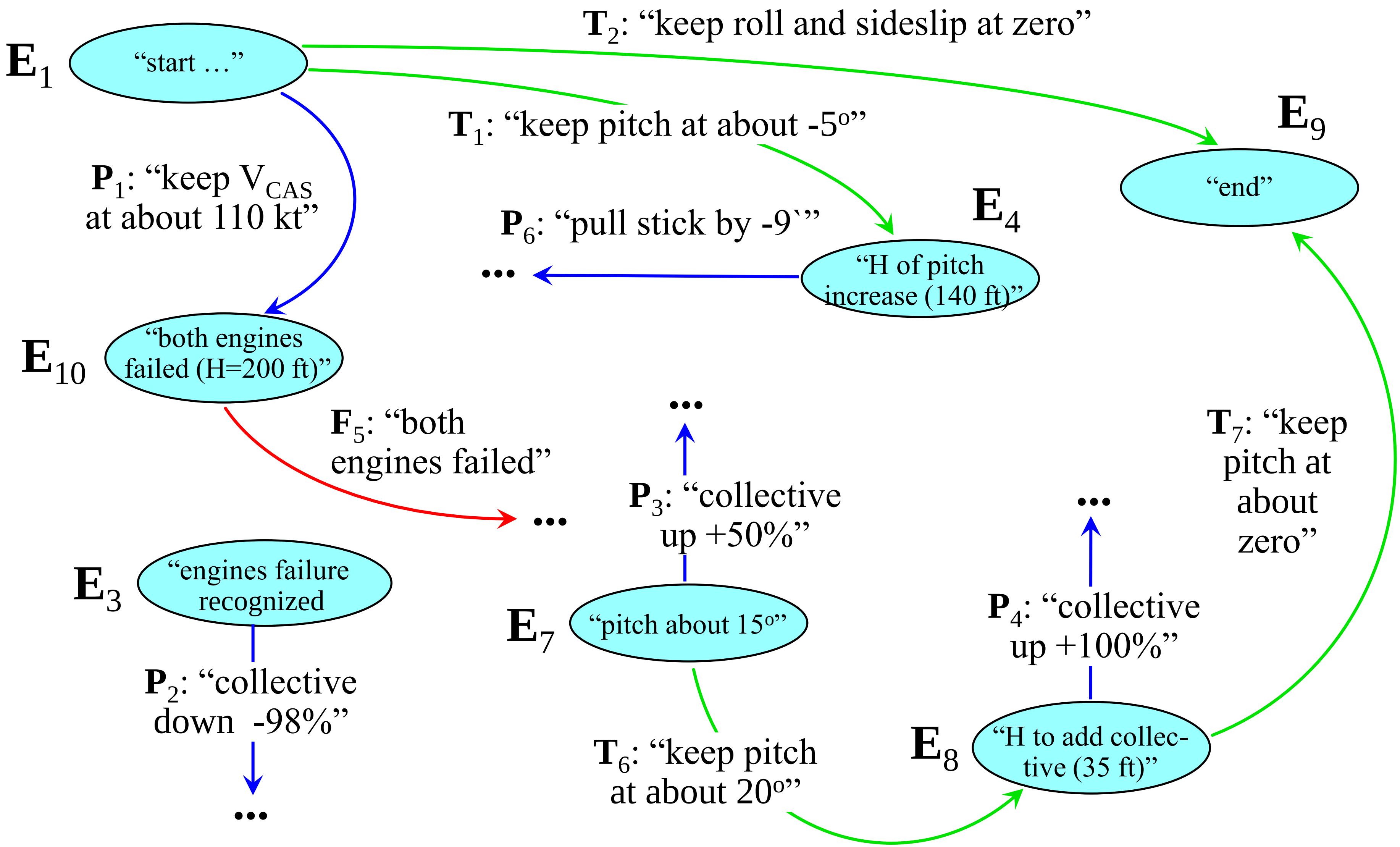
The **flight situation scenario** is a plan of a flight situation. It specifies the content of flight and control in this situation. Flight scenarios are depicted as directed graphs. Examples:

- *"normal takeoff"*
- *"aborted takeoff with engine #1 out"*
- *"landing in crosswind conditions"*
- *"groundroll on wet runway"*
- *"coordinated turn at 15° bank"*
- *"stall in takeoff configuration"*
- *"cruise mode at 600 kt & 30000 ft"*



These concepts provide simple, yet powerful language for generic formalization of the majority of complex flight situations for model-based testing

Scenario S: "XV-15 Auto-Rotation Landing (Two Engines Out)"



Notes: 1. Only 7 events and 10 processes constitute this very complex flight situation scenario.
2. Shown are nominal parameters of switching events and processes.

Flight Situation Scenario Input Data Example

Initial conditions of flight

```
  101 (#3) initial conditions   2 10  1  1
(I5,1X,9A4,F11.3,2X,A8)

   88 GW     - GROSS WEIGHT                       14000.000      LB
  102 SLCG0  - A/C C.G.  S.L.   @BETAD=0            299.800      IN
  104 WLCG0  - A/C C.G.  W.L.   @BETAD=0             81.650      IN
   35 HEIGHT - A/C POSITION GROUND AXIS Z           575.000      FT
  115 PRSALT - PRESSURE ALTITUDE                    575.000      FT
  114 VKCAS  - CALIBRATED AIRSPEED                  120.000     KNOTS
   51 PITCH  -        PITCH ANLGE                    -5.000      DEGR
   14 XCOL   - COLLECTIVE STICK POSITION             10.000      IN
   23 RPMSEL - RPM SELECTION                        517.600      RPM
   22 OMEGR0 - CENTER ROTOR RPM                     517.600      RPM
   66 MAST TILT ANGLE                                10.000     degr
   18 XIH    - HORIZONTAL STAB INCIDENCE              2.000      DEGR
   20 XFLAPS (POSITION INDICATOR)                     1.000      -
   24 landing gear ON                                 1.000      -
  119 SCAS ON (1) OR OFF (0)                          1.000      -
   31 IPSCAS ON (1) OR OFF (0) PITCH                  1.000      -
   32 IRSCAS ON (1) OR OFF (0) ROLL                   1.000      -
   33 IYSCAS ON (1) OR OFF (0) YAW                    1.000      -
  107 flight duration                                32.000      s
  ...
```

Flight events

```
  102 flight events          2  0 17  3  0
(i2,i3,6a4,4i3,i4,a2,a4,i3,i2,f8.2,f4.1,f4.1)

 1  0    start ...            35 38114 51 105GE     0 0     .00  .0
 2  0    time 20 sec          35 38114 51 105GT     0 0   20.00  .0
 4  0    1st pitch increase   35 38114 51  35LE     0 0  120.00  .0
 5  0    2nd pitch increase   35 38114 51  35LE     0 0  100.00  .0
 6  0    3rd pitch increase   35 38114 51  35LE     0 0   80.00  .0
 7  6    pitch 15 deg         35 38114 51  51GE     0 0   15.00  .0
 8  7    collective to pull   35 38114 51  35LE     0 0   55.00  .0
10  3    engines failure      35 38114 51  35AE     0 0  200.00  .0
 3  0    H=200ft + X s        35 38114 51  35AE     0 0  200.00  .0
 9  0    end ...              35 38114 51 105GT     0 0  150.00  .0
```

Piloting tasks

```
  104 piloting tasks            0 16  4  0
(i2,2i3,i2,8a4,4i3,2(1x,f4.3),2(1x,f3.2))

 1  1  4 0 keep pitch at -5 deg          11  0  0  0 .050 .050 .05 .05
 2  1  9 0 sideslip & roll at 0          12 13  0  0 .050 .050 .05 .05
 6  7  8 0 keep pitch at 20 deg          11  0  0  0 .050 .050 .05 .05
 7  8  9 0 keep pitch at  0 deg          11  0  0  0 .050 .050 .05 .05
```

Control procedures

```
  103 (#3) procedures           0 17  3  0
(I2,2I3,I2,5A4,1X,A3,4I3,A4,2I3,F6.1, 2F4.1)

 1  1 10 0 keep CAS=110 kt     THR 73 74  0  0      0  0 110.0-5.0  .3
 5 10  0 0 shut down engines   ABS 73 74  0  0      0  0     .0  .0 9.0
 2  3  0 0 collect. down 98 %  ABS 14  0  0  0      0  0     .2  .0 9.0
 3  7  0 0 collect. up   50 %  ABS 14  0  0  0      0  0    5.0  .0 9.0
 4  8  0 0 collect. up  100 %  ABS 14  0  0  0      0  0   10.0  .0 9.0
 6  4  0 0 pull stick by -9 in REL 11  0  0  0      0  0   -9.0  .0 5.0
```

State observers

```
  105 (#3)  observers           0 10  5  0
(i2,2i4,4a4,a4,i4,i3,f8.2,f8.4,2f6.2,f6.3)

 0  12  52 roll*                 0  0     .00  -.0150   .30   .15  .050
 0  12  55 roll accel.           0  0     .00  -.0100   .30   .15  .050
 0  11  54 pitch rate            0  0     .00   .0300   .30   .15  .050
 0  11  57 pitch accel.          0  0     .00   .0100   .30   .15  .050
 0  13   6 sideslip*             0  0     .00   .0050   .30   .15  .050
 1  11  51 pitch                 0  0   -5.00   .0300   .60   .30  .050
 2  12  49 bank                  0  0     .00  -.0070   .60   .30  .050
 2  13   2 slip angle            0  0     .00   .0030   .60   .30  .050
 6  11  51 pitch                 0  0   20.00   .0300   .60   .30  .050
 7  11  51 pitch                 0  0     .00   .0300   .60   .30  .050
```

Flight Simulation Examples

Variation of event $\mathbf{E_8}$: “Altitude to add collective”:
{ 30, **<u>35</u>**, 40, 45, 50} ft

Variation of event $\mathbf{E_4}$: “Altitude to increase pitch”:
{ 120, 125, 130, **135**, **<u>140</u>**, 145, 150} ft

Second collective pull-up input:
{ **<u>yes</u>**, no }

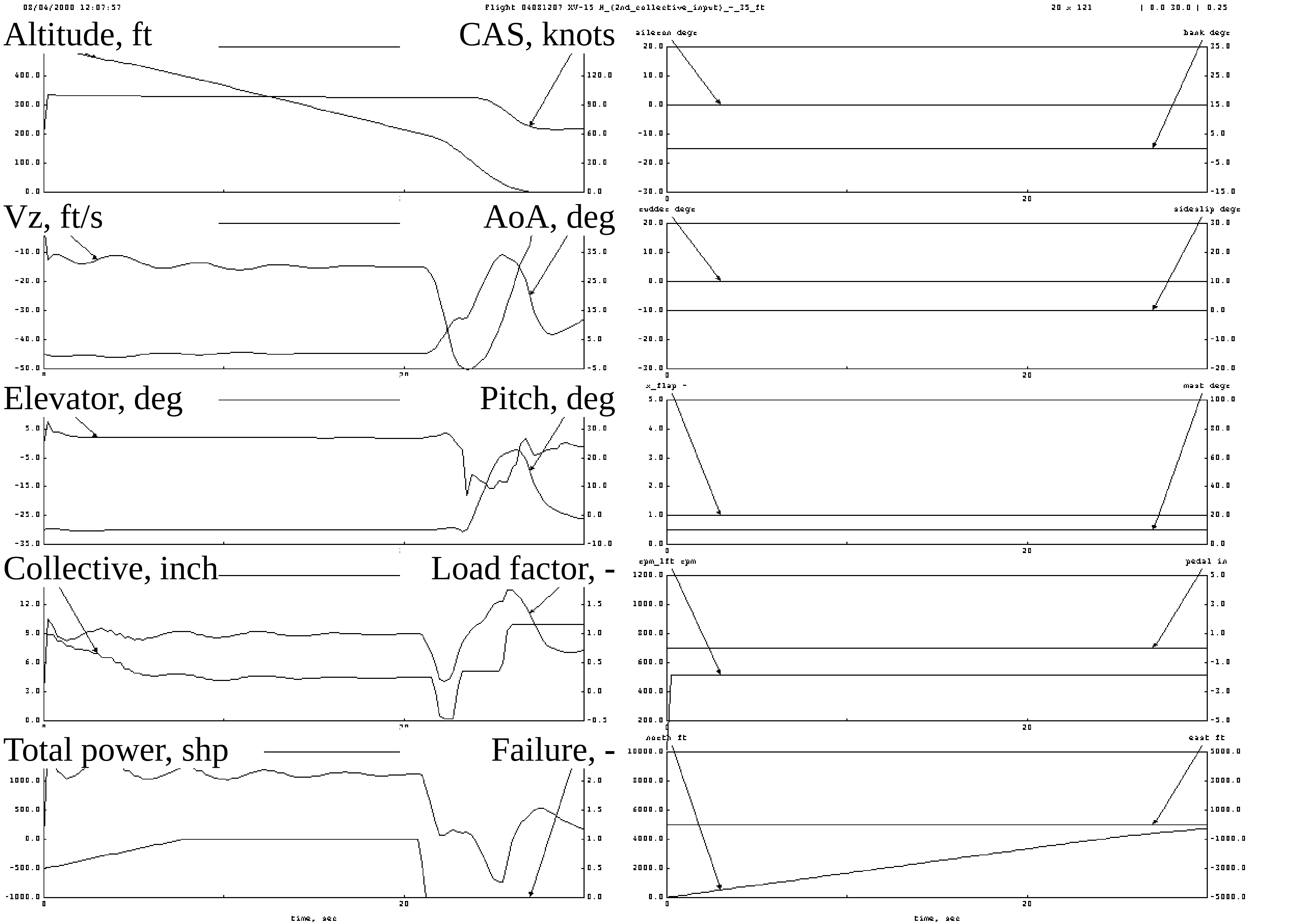
Pitch increase at event $\mathbf{E_4}$: “Altitude to increase pitch”:
{ **<u>yes</u>**, no }

Variation of goal pitch in piloting task $\mathbf{T}_6$: “keep pitch at goal level”: { 15^o, **<u>20</u>**^{o}, 25^o, 30^o, 35^o}”

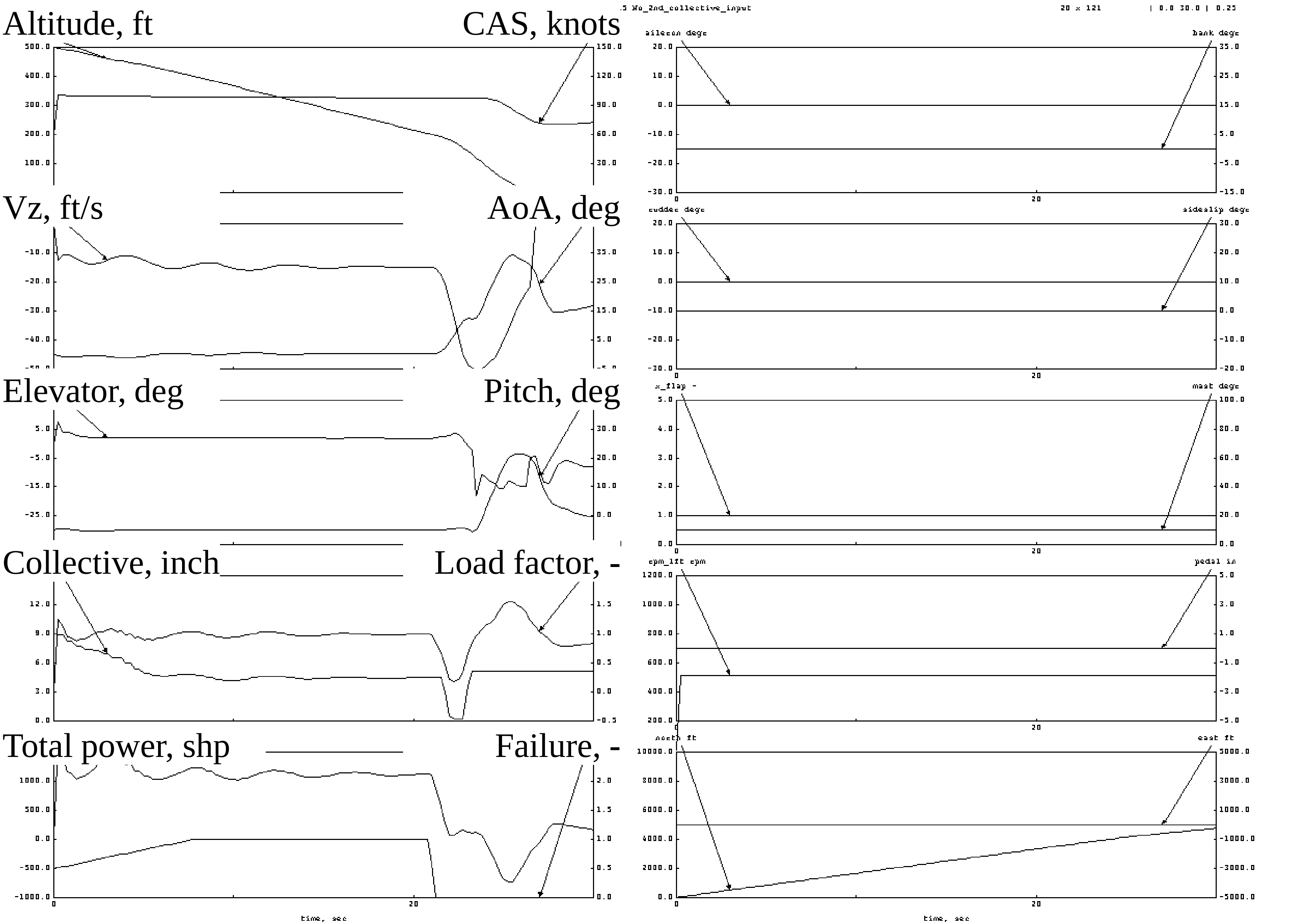
Variation in flap position: all settings, including **<u>0</u>^{o}/<u>0</u>^{o}**

Note: **<u>underlined</u>** are nominal parameters

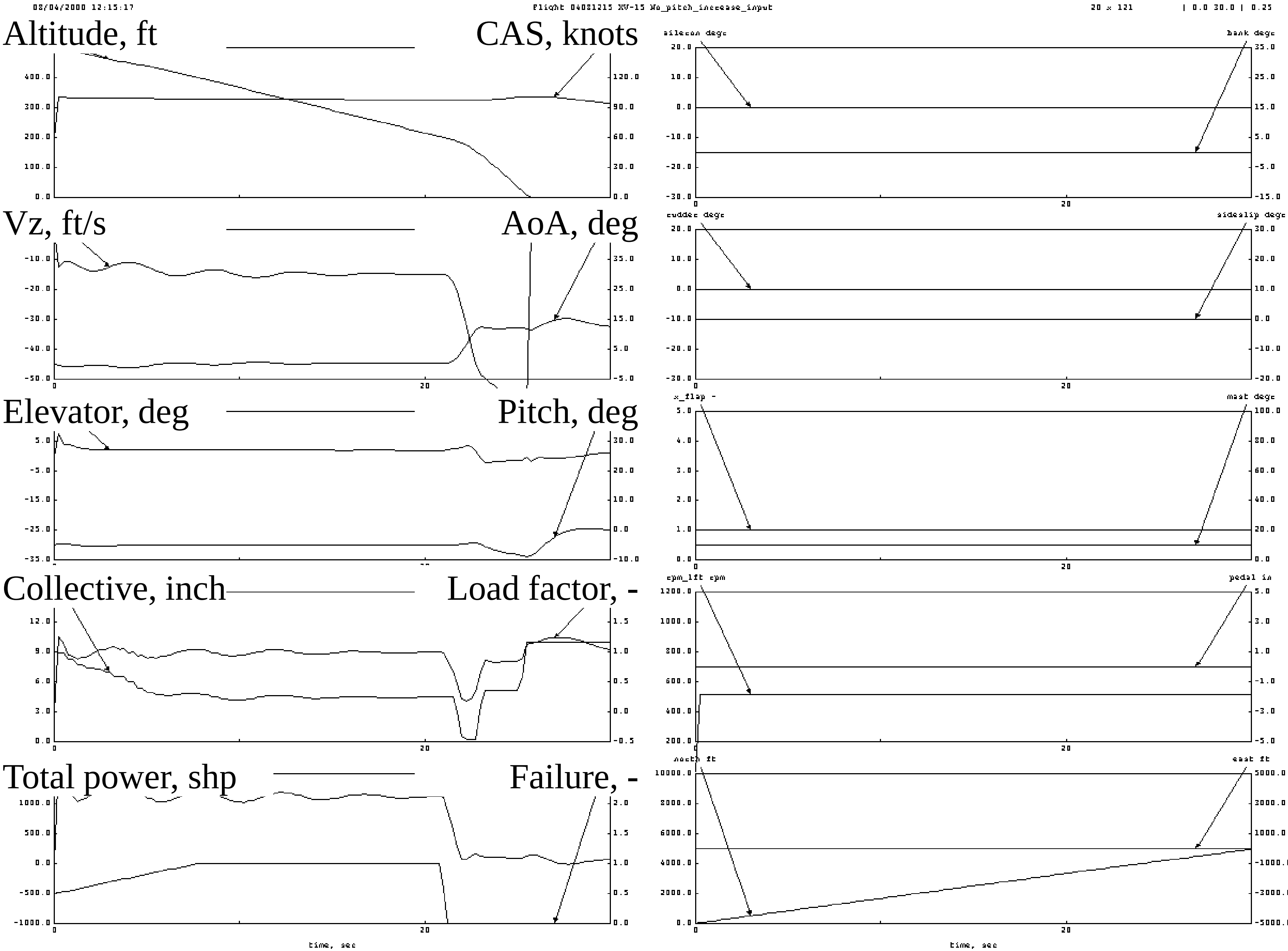
Flight 1209: Nominal Case (Safe)



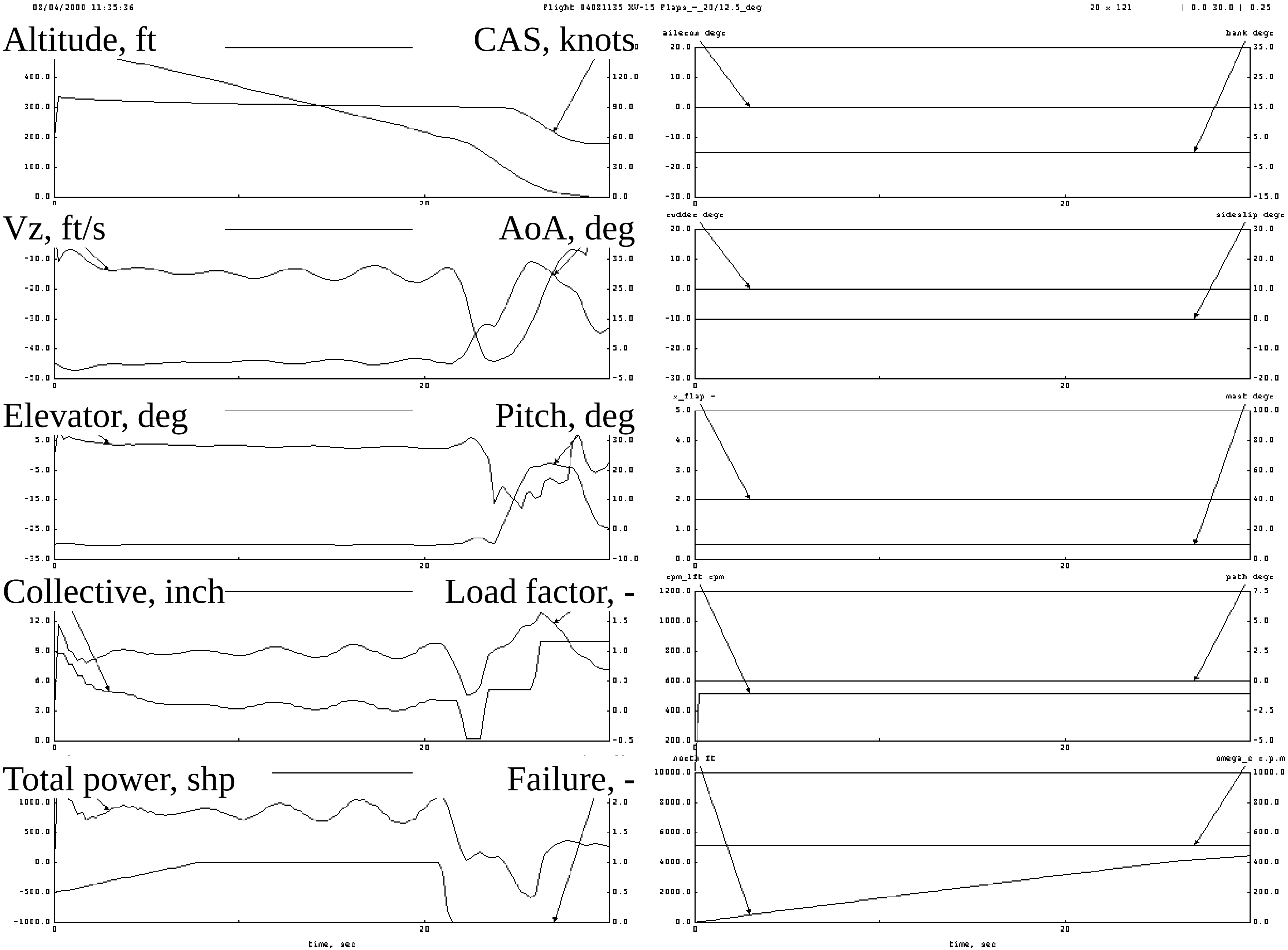
Flight 1213: No 2nd Collective Input (Unsafe)



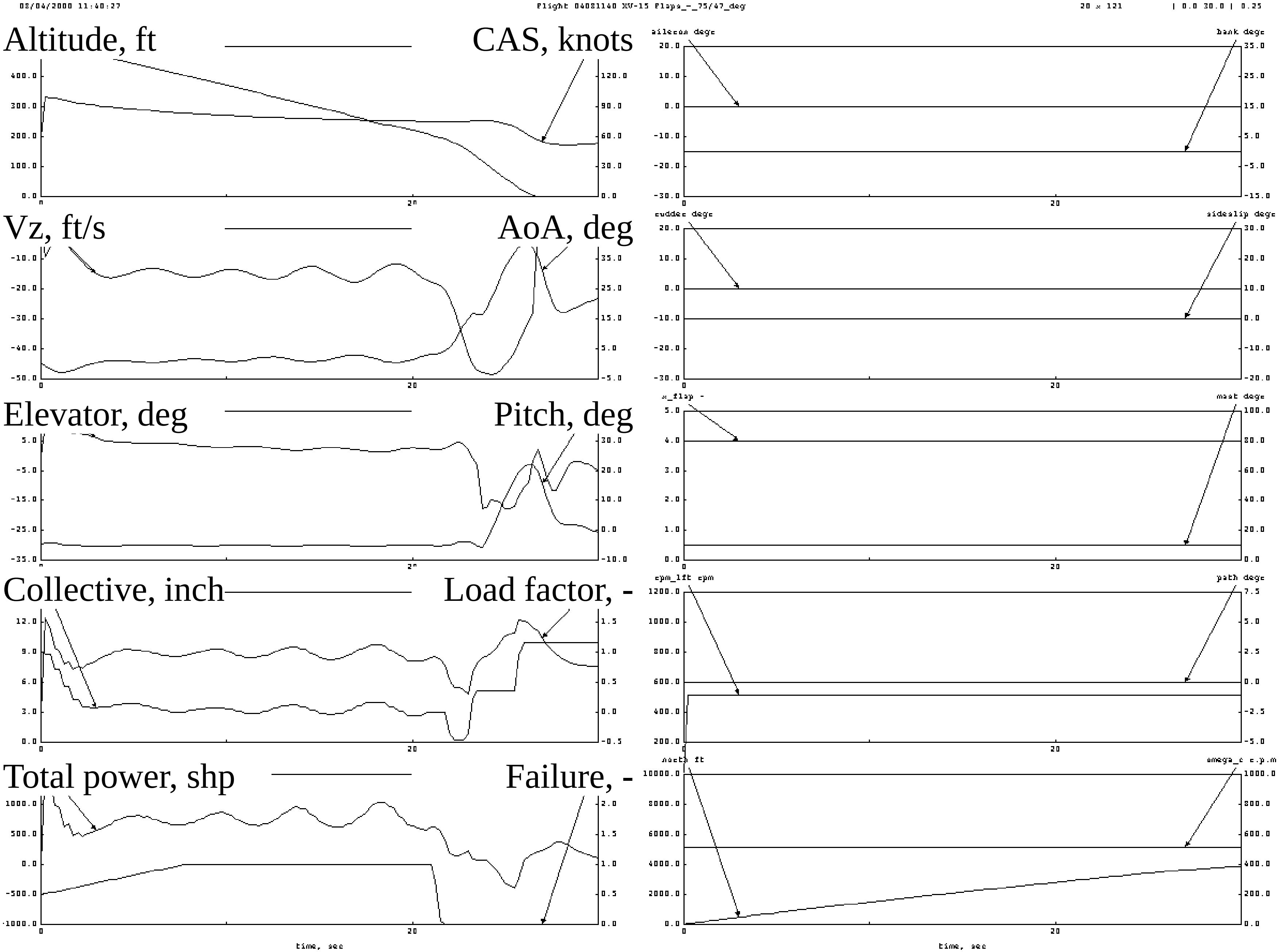
Flight 1215: No Pitch Increase (Unsafe)



Flight 1135: Nominal Case, Flaps = 20º/12.5º (Safe)



Flight 1140: Nominal Case, Flaps = 75º/47º (Unsafe)



XV-15 Model Recovery Scenario

1. Immediately after engines failure has been recognized, push collective down to increase rotor r.p.m. and rotor's kinetic energy.

2. Within altitude range of 135-145 ft pull longitudinal stick by -9 inch to increase pitch (lift and drag). Avoid wing stall.

3. When pitch is within 15^o-20^o, pull collective up by about 5 inch (~50%). Maintain pitch at this level (~20^o) until altitude of 35-45 ft is reached.

4. At altitude of about 35-45 ft apply maximum collective (100%) to convert kinetic energy of rotors into additional lift. Keep landing pitch at about 0^o-5^o to secure a touchdown rate of descent within 5-10 ft/s. Use small pitch adjustments for this purpose.

NB: Only combined pitch and collective control work.

Conclusion - 1

1. The autonomous flight situation modeling and simulation technique can be used for quantitative fast-time analysis of the “pilot (automaton) - tilt-rotorcraft - environment” system dynamics under complex (multi-factor) operational conditions.

2. Legacy flight simulation codes, such as GTRSIM, combined with the autonomous flight situation modeling and simulation technique (VATES) can be used as virtual test articles.

3. The developed virtual flight analysis process is systematic, fast, affordable, detailed and flexible. Expert piloting and programming skills and expensive test/simulation equipment are not required.

4. Given a complex flight condition with two engines out, a marginally safe auto-rotation landing of the XV-15 flight model is possible. The identified hypothetical recovery scenario is essentially a combination of proper pitch and collective control (sequence, parameters) and correct synchronization of these control processes (switching events).

Conclusion - 2

5. The autonomous flight situation modeling and simulation technique may complement manned simulation and flight test methods As a result, the number of required test and simulation hours can be reduced with a simultaneous increase in the volume and quality of output knowledge of the system behavior in critical situations.

6. The developed techniques and obtained results can be used for: new vehicle design, piloting tactics and flight manual development/update, pilot training, and flight test program planning and rehearsal.

7. Further studies would be expedient to conduct in order to:
- verify the identified hypothetical recovery scenario in simulations and flight tests
- add algorithms of undercarriage kinematics and dynamics to the system model
- study effects and identify allowed variation limits of other demanding conditions (e.g.: windshear, pilot errors, mechanical failures, motion asymmetry)
- conduct a more systematic exploration of the auto-rotation sub-domain using VATES knowledge generation/mapping and statistical experiment techniques