MODIFICATION OF FLIGHT SIMULATOR

FOR DEMONSTRATION FLIGHT OF HYDROGEN-ELECTRIC HYBRID POWERTRAIN

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AeroTEC
TESTING | ENGINEERING | CERTIFICATION

A level D flight simulator was temporarily modified to mimic the asymmetries in both the flight performance and engine response for a highly modified Dash 8 hybrid electric demonstrator. The modified simulator was used for pilot familiarization prior to the first demonstration flight for the electrically powered aircraft. Modified performance and electric motor thrust characteristics were analyzed and modeled as delta inputs on top of existing simulator parameters and combined back into the simulation through the use of Bihrle's high alpha software called "StallBox." The methodology of the implementation is presented along with the goals of the simulator training for the program. The use of the "StallBox" software for mimicking heavily modified aircraft presents a useful solution for risk reduction on electric demonstrator programs and in the emerging field of electrification conversions to existing aircraft.

I. NOMENCLATURE

CG = Coefficient of Gravity
EDP = Engine Driven Pump
FMEA = Failure Modes and Effects Analysis
LHS = Left Hand Side
NTO = Normal Takeoff Power
OEI = One Engine Inoperative
RHS = Right Hand Side
RTO = Rejected Takeoff
RPM = Revolutions per Minute
SBIR = Small-Business Innovation Research
SPU = Standby Power Unit
PTU = Power Transfer Unit
UPRT = Upset Prevention and Recovery Training

II. INTRODUCTION

There are a growing number of electrification demonstrator and certification programs in development across the United States and Europe. While many “clean sheet” designs have emerged in the past decade, there is a growing trend towards powertrain and energy storage system development using purpose driven modifications to existing aircraft. The Universal Hydrogen demonstrator is one such program hoping to prove the viability of on-board storage and distribution of gaseous hydrogen as an alternative, clean energy source, for fuel cells to power electric drive trains.

The program chose to heavily modify a twin engine De Havilland DHC-8-311, removing the right-hand side (RHS) Pratt & Whitney PW123 engine, extensively redesigning the support structure and under wing nacelles to accommodate electric motors, fuel cells, and power inverters; and adding large, ducted radiators on either side for active cooling. These modifications caused a shift of the zero-fuel lateral center of gravity (CG) to approximately 3 inches to the right and increased the drag asymmetry due to the larger engine nacelle. A smaller propeller was installed to match higher rotation speed of the electric motor; the smaller propeller, in combination with the lower power output of the electric motors, reduced the installed thrust on the RHS. Lastly, hydrogen storage tanks were added to the passenger compartment, increasing the takeoff weight, and moving the CG significantly aft, both parameters moved close to the aircraft certified limits. These changes were expected to significantly alter take-off performance and handling qualities from the baseline aircraft. As a risk reduction to the first flight, the program sought to use training time in the simulator to estimate the performance and handling quality impacts and to better prepare the flight test pilots.

The team used the modified simulated performance and handling to help develop return-to-runway flight profiles, way points and crew resource management techniques for possible failure cases such as a loss of either left-hand side (LHS) engine or RHS motor and/or hydraulic controls. The various simulation runs were also used to develop weight & balance and fuel management strategies. Since the overall fuel consumption was reduced owing to installation of the electric powertrain, fuel loading in wings along with weight ballasts were the key parameters used to keep the CG within the accepted aircraft limits. The RHS physical throttle control and condition lever in the simulator cockpit were remapped to accurately represent the installed thrust of the right-hand electric motor and propeller. Additionally, the correct airport and runways were loaded to maximize situational realism for the training environment. A fully certified level D simulator was used, including simulated motion for flight dynamics, and pilot feedback was recorded after each maneuver to assess handling qualities and workload during the flight.

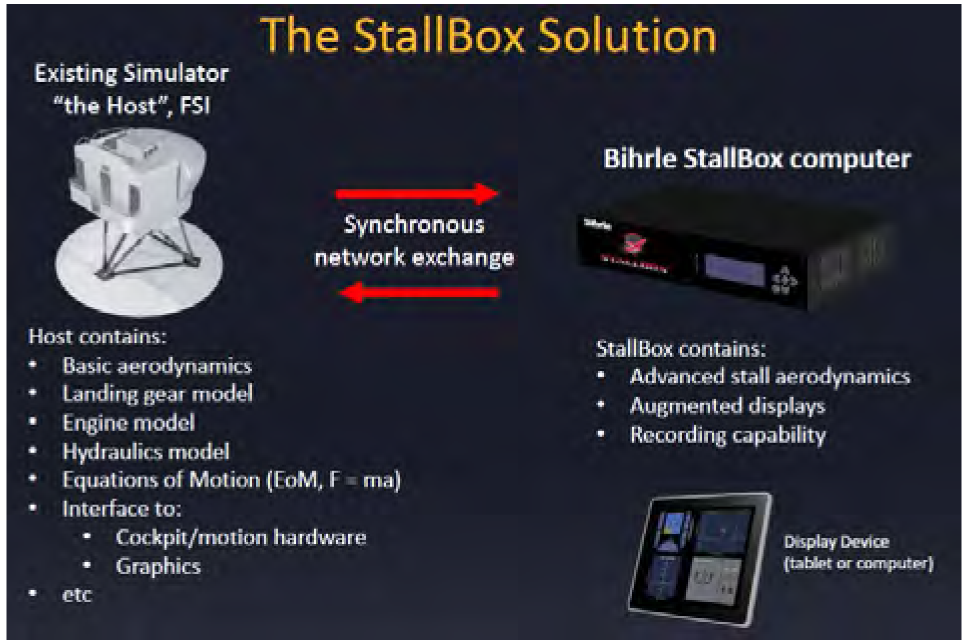
Bihrle Applied Research came to the project with developed and proven software tools to model and augment flight behavior under abnormal conditions or at extreme flight attitudes. The “StallBox” software was initially developed under a U.S. Navy Small-Business Innovation Research (SBIR) program to provide modeling for stall and post-stall aerodynamics and Upset Prevention and Recovery Training (UPRT) for P-8A pilots. While this application used the same methodology and tools to augment aircraft handling, it was applied globally across the flight modeling for the modified electric hybrid demonstrator to simulate performance and handling during nominal flight maneuvers.

III. METHODOLOGY FOR SIMULATED DASH 8 MODIFICATIONS

The StallBox provides a solution to update an existing simulator’s aerodynamics modeling and augment instructor displays. The StallBox computer is housed separately from the simulators “Host” computer and the two share data over a synchronous network exchange.

For the modification of the Dash 8 flight simulator, the changes from the baseline aircraft were shared between manipulating existing parameters available through the simulator and adding delta components calculated through the StallBox computer, back onto the “Host” equations of motion. Specifically, the StallBox was used to simulate the additional drag from the modified nacelle of the right-hand engine pod and the thrust of the electric motor/propeller. The simulator’s “Host” computer was accessed to zero out the thrust of the conventional RHS engine, simulate the additional installed weight on the RHS, and activate host malfunctions of secondary systems like the hydraulic Standby Power Unit (SPU) and Power Transfer Unit (PTU) to mimic the impacts of the aircraft modifications. A graphic of the exchange of information is shown in Figure 2.

The drag increment on the RHS due to the larger nacelle was initially handled as a single increment and was later updated as a function of angle of attack. This capability is possible in the StallBox software through the use of look-up tables and the fidelity of the calculation could be improved for future implementation. The thrust of the RHS electric motor was a more complex input and was calculated as a function of condition lever angle (for RPM), power lever angle and current airspeed. This calculation was a series of lookup tables for prescribed RPMs and airspeeds to generate a nominal thrust. Values were calculated through linear interpolation between defined performance points identified by AeroTEC’s flight sciences analytical modeling. The baseline thrust of the original RHS engine in the simulator was removed from the aerodynamic model so only the modified electric motor added additional thrust on the RHS. This change was confirmed at the beginning of each session by reviewing thrust output during static engine runs to ensure correct end to end implementation.



The StallBox Solution

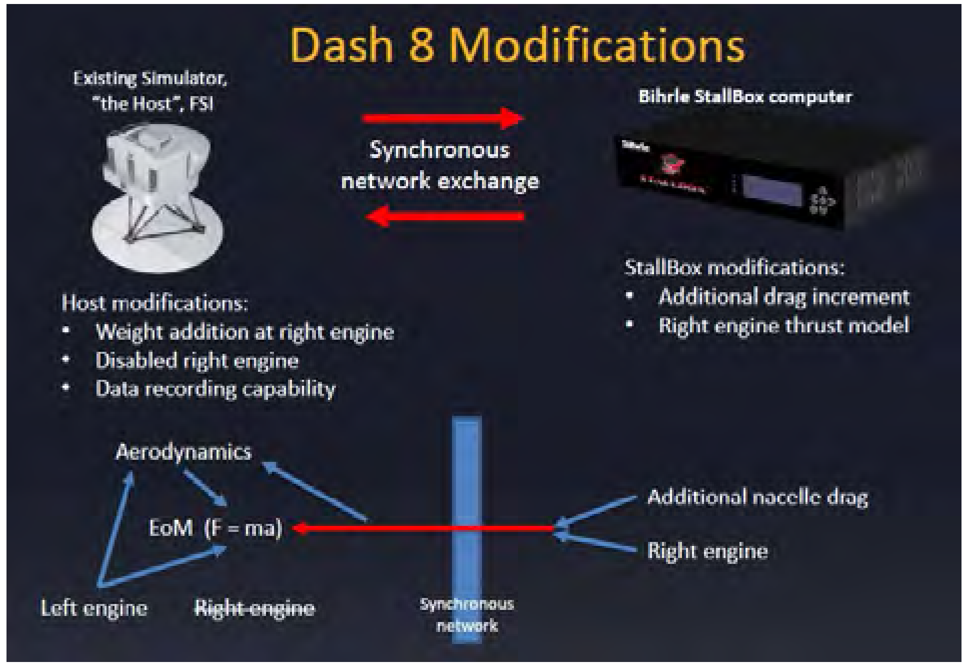
Existing Simulator
“the Host”, FSI

Host contains:
- Basic aerodynamics
- Landing gear model
- Engine model
- Hydraulics model
- Equations of Motion (EoM, F = ma)
- Interface to:
  - Cockpit/motion hardware
  - Graphics
- etc

Bihrle StallBox computer

StallBox contains:
- Advanced stall aerodynamics
- Augmented displays
- Recording capability

Figure 1 shows the key characteristics of the network set-up.



Dash 8 Modifications

Existing Simulator,
“the Host”, FSI

Host modifications:
- Weight addition at right engine
- Disabled right engine
- Data recording capability

Bihrle StallBox computer

StallBox modifications:
- Additional drag increment
- Right engine thrust model

Figure 2 Dash 8 Modifications and Information Exchange

Time history files were recorded from both host and StallBox computers. Key parameters were chosen to be recorded by both systems to align data files post process, however, the StallBox output files were considered the primary data source for analysis. Furthermore, the training sessions focused on pilot familiarization with the handling qualities of the modified aircraft and were not conducted to be a rigorous check on the aerodynamic modeling. Subsets of the data or future sessions could be used to fly more controlled and discrete validation points but were not to be covered as a subject in this paper.

IV. FLIGHT PROFILES AND TRAINING GOALS FOR SIMULATOR SESSIONS

The first flight profile was broken up into discrete segments of interest for simulator testing. These segments were prioritized and further detailed based on pilot input across multiple planning meetings. Normal and abnormal conditions were considered including several highly likely "failure" cases that were identified through Failure Modes and Effects Analysis (FMEA). All profiles were flown at the airport and runways planned for the demonstration flight (Moses Lake, WA, Airport code: KMWH, Altitude 1167 feet, Runway 32R with length 13,503 feet). This was chosen to allow the pilots to train in as realistic an environment as possible. In addition to the correct starting altitude for the runway, ambient conditions were chosen based on historical averages for the location and time of year for the first flight. The following sections comprise the main flight profiles that were flown over the three separate, four hour long simulator sessions.

A. NO FAILURE TAKE-OFF AND CLIMB PROFILE BUILD

This profile was used to develop a procedure for ramping up the power on the ground during the takeoff run for the left- and right-hand sides while maintaining good control of the aircraft as the speed increased. The difference in throttle response from the air-breathing LHS engine compared to the RHS electric motor meant that the normal procedure of moving the throttles together was not advisable. The suggested procedure for the RHS engine was to set a low power at brake release and quickly increase the power to the takeoff setting as airspeed increased. The pilots experimented with various initial power for the LHS engine and with various rates of throttle movement, avoiding settings which produced so much asymmetry as to overcome the pilot's ability to maintain runway centerline using tiller and rudder inputs.

The profile was also used to develop acceptable and desired takeoff power settings. The difference in total thrust available from the unmodified LHS engine compared to the electric motor and smaller propeller on the RHS created a large asymmetry at normal takeoff (NTO) power. These simulated takeoffs allowed the pilots to experiment with various thrust settings to determine the maximum asymmetry which could be mitigated through pilot rudder deflections and still allow for a safe and controllable rotation and initial climb. RHS power was set to the expected power output of the experimental engine while LHS power was decreased from NTO. Various settings were investigated for sufficient total power output with controllable asymmetry.

The procedure was expected to require a higher workload from pilot and co-pilot, with aerodynamic and steering controls handled by the pilot, leaving the co-pilot to operate throttle and power controls for both engines and monitor for abnormal conditions.

B. NO FAILURE LANDING

This profile simulated the expected thrust and lateral CG asymmetries during landing with no failures. Restrictions on the experimental test flight were prescriptive to exclude any challenging weather such as high cross or tail winds or ground conditions such as rain, ice or snow, so these profiles were flown in nominal weather conditions. Pilots were able to experiment with throttle movement during the descent, flare, and landing to avoid unnecessary thrust asymmetry and determine desired timing for moving each throttle to idle. Controllability of the aircraft, preferred landing speed & flap configurations, descent glideslope, and required stopping distance were assessed. These landing conditions served as a baseline to start building upon to assess possible failure cases in aircraft control, thresholds in altitude and distance for emergency landings and alternate runway and taxiways to be considered.

C. GENERAL MANEUVERING ONE ENGINE INOPERATIVE (OEI)

In the event the RHS electric engine failed in flight, this profile was flown for the pilots to get a feel for the general control responsiveness in steady level flight, wings level heading changes, and gradual to aggressively banked turns in both directions. In later sessions this also included profiles with only the RHS electric engine operating in the event the LHS engine failed. Both versions of the single engine operating flights were used to develop contingency maneuvers. Sink rate was assessed during banked turns to determine a maximum acceptable bank angle and minimum altitude from which a return to runway turn could be executed. These results were directly applied to the testing in sections F and H, as positions of secondary runways and possible taxiways were studied to simulate alternate return to base options in the event of emergency. Strategic waypoints were identified for the first flight using this information.

D. LANDING OEI

As in the General Maneuvering OEI cases, this profile started with assessing the failed RHS electric engine but also expanded to evaluating landing descent gradients and approach distances in the case of a failed LHS engine. Optimum flap angles for landing were assessed along with the workload to track along the center of the runway at touchdown. As in the takeoff profiles, the controllability and steering transition procedures had to be developed for this highly asymmetric configuration. Workload was split between the pilot and copilot with aerodynamic and steering controls handled by the pilot, throttle and power controls for the remaining engine operated by the co-pilot.

E. DUAL ENGINE FAILURE LANDING

As in the Landing OEI profile, dual engine failure landings were flown to assess aircraft controllability and sink rate in a dual engine failure scenario. The results of these profiles were used to evaluate return to runway capability in the event of a dual engine failure at various points along the flight path.

In the event of a dual engine failure on the unmodified Dash 8, all hydraulic power is lost. The Dash 8 has mechanically actuated ailerons and elevator, but hydraulically actuated rudder and flaps, so a dual engine failure results in degraded flight controls. In the modified aircraft, this loss of all hydraulics would happen in the event of a LHS engine failure, regardless of the state of the RHS engine. To mitigate this single failure scenario, a special purpose, backup hydraulic pump was plumbed into the RHS hydraulic system on the experimental aircraft. This backup pump was powered by a limited capacity, dedicated battery, and provided hydraulic power to the rudder in the event of a LHS engine failure. However, the available flowrate of the backup hydraulic pump was significantly lower than the standard flowrate of either the Engine Driven Pump (EDP) or the Standby Power Unit (SPU). It was assumed that this limited flowrate would allow full deflection of the rudder, but at a reduced rate of surface movement.

To mimic this unique dual engine configuration the host computer was set to maintain operation of one SPU in the event of a dual engine shutdown. The pilots used only minor pedal inputs to approximate the assumed decrease in rudder rate. Additionally, the backup hydraulic pump did not provide power to the flaps, which meant the flaps would be frozen in the setting they were in at the time of the engine failure. Therefore, dual engine failure landings were attempted with several flap settings, from 0 to 15, to assess controllability and sink rates for a dual engine failure at any point during the first flight profile.

F. TAKE-OFF AND ENGINE FAILURE AT VERY LOW ALTITUDE, LAND IMMEDIATELY AT LOW ALTITUDE, TURN AND LAND

This was assumed to be the worst-case scenario for the first flight and was of critical interest from the system safety and safety of flight teams. Initial thoughts were to have the pilots assess a dual engine failure at low altitude just after takeoff. Updates to the modification allowed this to be relaxed to just look at loss of the LHS engine. Engine failure was initiated at various altitudes during the initial climb. At very low altitudes the pilot would land straight ahead on the same runway. An assessment was made as to the threshold altitude after which straight ahead landing was no longer feasible. Engine failures at higher altitudes were attempted to assess a maneuver to return to the same runway or to maneuver to an alternate runway or taxiway. In all cases sink rate and controllability were also assessed, with consideration of the effects of banked turns during maneuvering.

The results were considered to determine best landing options and critical waypoints along the flight path where turns should be initiated to achieve a successful landing.

G. REJECTED TAKEOFF (RTO)

Rejected Takeoff was mainly simulated to assess the main runway usage during takeoff and assess the required length to stop the aircraft at various speeds. Thrust asymmetry was assessed but was not a major impact during RTO as it would never be greater than the certified asymmetry for RTO due to engine failure at decision speed. Later sessions included “hops” where the aircraft took off and briefly achieved positive rate of climb before setting back down and assessing landing impact, controllability and length of runway required to stop.

H. ABNORMAL FULL FLIGHT PROFILE

Left, Right, and Dual Engine Failures were simulated randomly at various points as the expected full flight profile was flown. In each of these instances the upset recovery technique was recorded and discussed. These simulations were used as a training opportunity to fine tune the flight path flown and study the crew reactions and resource management.

I. NOMINAL FULL FLIGHT PROFILE

Each simulator session was planned to allot enough time at the end for the pilots to fly one complete first flight profile. This was used to reorient the pilots from failure scenarios back to the expected first flight and allowed multiple repetitions and refinements to the crew management procedures. Since each simulator session increased the team’s knowledge of expected aircraft airspeed, maneuvering capability, climb rate, and sink rate, the first flight waypoints were updated, and the most current expected flight path was practiced during this Nominal Full Flight Profile.

J. POST PROFILE PILOT ASSESSMENTS

Following each flight segment pilot feedback was noted by the Flight Test Engineer in the cab. Time in the sessions was limited so a larger debrief was held following each four-hour block. The questions below detail the specific interests of the team and helped guide changes to the plan for future sessions. In addition, a pilot’s report of findings was created to document pertinent information on handling qualities and feel of the aircraft as well as detail procedural improvements from the flight crew back to the larger development team.

Pilot Assessment Questions:
1. Comment on the controllability and difficulty of the takeoff, climb, turn, etc. How high was the workload? Approximately how much force was needed on column/wheel/pedal?
2. Comment on the nosewheel steering, rudder control during the asymmetric takeoff run. Note down the speed for rudder activation.
3. What bank angles were the turns done at? What bank angles should they be done at?
4. Was it possible to maintain the runway centerline?
5. Was it possible to come to a stop on the runway? If not, what was the speed of the runway overrun?
6. When should the turn back toward the runway(s) be started? At what height?
7. When should the gear be retracted? How long does it take and how difficult is it to manually deploy the landing gear?
8. When should the flaps be retracted?
9. If possible: What was the takeoff run distance?
10. Does the simulator ground model/ground handling seem realistic?

V. FUTURE IMPROVEMENTS

Data was recorded nearly continuously from both the host and StallBox computers during the sessions. Breakpoints were included when possible, however manipulating and naming the data files on the fly proved to be a heavy workload for the single simulator operator. Post processing and aligning of the data was also harder than expected and could be improved for future ease of use. Differing data rates and time stamps made data alignment between the two systems both difficult and somewhat inaccurate. While data accuracy was not important for the pilot familiarization purposes of these sessions, future uses could require better accuracy especially if simulator data would be used to confirm or tune flight analysis modeling.

The use of shared parameters between the two systems proved an effective means to assess alignment accuracy, however a dedicated alignment channel could be employed in future sessions. Acquisition rates of the two systems also revealed some data biasing over the duration of each time trace.

Crew resource management during the simulator sessions also revealed the need for multiple note takers to capture on-the-fly changes as well as the need for better set-up checklists and checkout procedures. Several profiles had to be repeated after settings in the simulator were missed or wrongly communicated. Simulator sessions were all carried out in four (4) hour blocks of time, longer durations would not be recommended, and the team could have benefited from a more structured (and adhered to) execution plan.

VI. CONCLUSION

This project proved the value of the StallBox software to modify the flight characteristics and simulate the heavily modified aircraft, while leveraging the advanced full motion, level D simulators, already available. These tools provided highly accurate representations of real flight performance and invaluable familiarization for the test pilots. The simulator sessions influenced and solidified the different restrictions and limitations that were ultimately put on the actual first flight flown. Additionally, the simulator sessions helped mature future test plans, proving to be a valuable flight planning resource. The StallBox software, while developed for an entirely different training purpose, was shown to be a valuable tool for electrification programs in the future.

APPENDIX

Figure 3 Takeoff and Return to Runway Patterns Flown

Figure 4 A typical Simulator Cockpit Arrangement for Dash 8 Aircraft set for KMWH Runway 32R

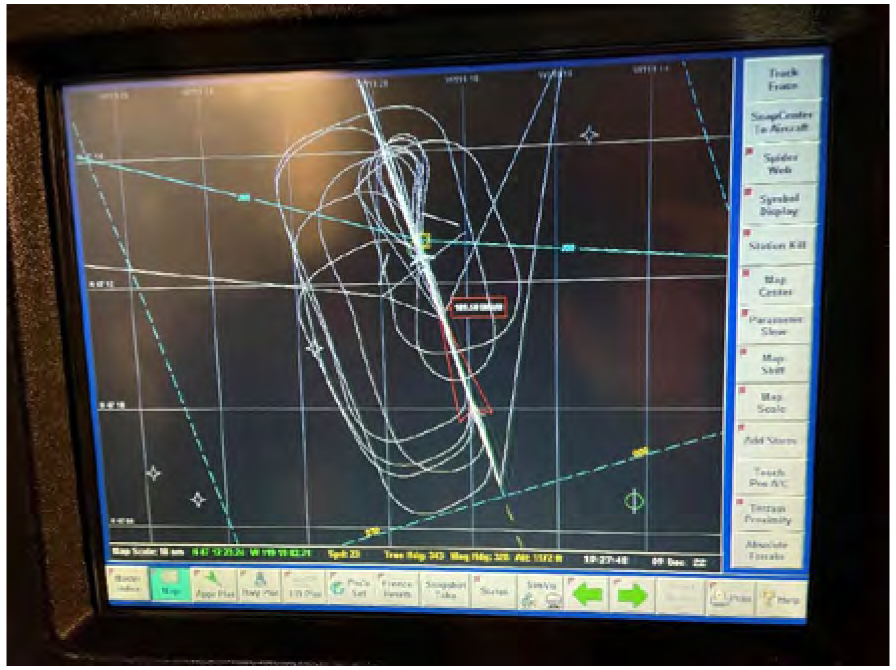


Figure 5 Flight Pattern for Nominal First Flight following Waypoints

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank their parent companies for the continued support, encouragement, and the provisioning of necessary resources to make the simulator sessions happen. Special thank you to FlightSafety International for hosting the sessions and providing excellent technical support and maintenance of the Dash 8 Level D simulator pod. Lastly, the goals of these sessions would not have been met without the technical expertise and software provided by Bihrle Applied Research Inc.

REFERENCES

Aircraft Data
[1] "DHC-8 Series 300, Dash 8 Approved Flight Manual," PSM-1-83-1A, 26 August, 1991, Ontario, Canada.
[2] "DHC-8 Series 300, Dash 8 Aircraft Maintenance Manual," PSM-1-83-2, 02 December, 1988, Ontario, Canada.
[3] "DHC-8 Series 300, Dash 8 Wiring Manual," PSM-1-83-2W, 25 November, 1988, Ontario, Canada.

Books
[4] D. A. Caughey, "Introduction to Aircraft and Stability and Control Course Notes for M&AE 5070," Sibley School of Mechanical & Aerospace Engineering, Cornell University, New York, 2011
[5] Perkins and Hage, "Airplane Performance, Stability and Control," Wiley & Sons, 9th printing, USA, 1963, ISBN-10: 047168046X

Proceedings/Reports
[6] Code of Federal Regulations (CFR): 14 Part 25 Airworthiness Standards: Transport Category Airplanes
[7] Code of Federal Regulations (CFR): 14 Part 33 Airworthiness Standards: Aircraft Engines
[8] Code of Federal Regulations (CFR): 14 Part 35 Airworthiness Standards: Propellers
[9] Code of Federal Regulations (CFR): 14 Part 91 General Operating and Flight Rules
[10] Code of Federal Regulations (CFR): Operating Requirements: Domestic, Flag, and Supplemental Operations
[11] AIR 5005 Aerospace Information Report, "Aerospace – Commercial aircraft Hydraulic Systems," SAE International, March 2000, USA

Computer Software
[11] StallBox software by Birhle Applied Research Inc.
[12] Dash 8 Level D Simulator by FlightSafety International