Team 4 Simulation Report 1

Avneet Singh, Nick Gunady, Logan Clark, Robert Parrish

Purdue University AAE 451 Senior Design Spring 2021, West Lafayette, IN, 47906, USA

Jared Braden, John Hartmann, Charlie Barnes, Abram Gettelfinger

Purdue University AAE 451 Senior Design Spring 2021, West Lafayette, IN, 47906, USA

This report outlines the work Team 4 in AAE 451 Spring 2021 performed to model the controls, aerodynamics, and propulsion systems of the BR1 aircraft. Various mission stages were tested including ground, hover, and cruise. The visual model used was the provided F35-B2 package for the sake of simplicity, running BR1-specific xml files for flight dynamics and geometries and the variant GE CF34-9BR, designed specifically for the BR1. This paper introduces the simulation, aircraft, engines and xml files used in the first section, followed by a discussion of the aerodynamics and propulsion analysis in section two, leading into flight controls and trimming.

A.   Introduction

Over the last 30 years, aircraft safety has greatly improved due to the use of flight simulation[1]. From testing flight dynamics models to advanced training, simulation has aided in the improvement of aircraft safety by allowing engineers and designers to find flaws earlier in the design process, before production begins. Similarly, in the context of AAE 451 senior design, simulation is used to test various aspects of the aircraft designed such as geometry, aerodynamic effects, propulsion, and flight controls.

Methods

In order to test different aspects of the aircraft, data were pulled from various calculations to model the aircraft in jsbsim. Locations of key components such as the wings, engines, landing gear, and fuel were pulled from the 3-dimensional model of the aircraft as well as the moments of inertia of the aircraft. The aerodynamics were then set up by providing the lift coefficients at different angles of attack as well as the sizes of the control surfaces, the sizes of the high lift devices, and the drag coefficients. After the aerodynamics were completed the propulsion model was implemented into the aircraft model. The CF34 engine variant, the CF34-9BR, designed for the aircraft was modeled by providing thrusts at different Mach numbers and altitudes, as well as the bleed air, thrust specific fuel consumption, and bypass ratio. The lift fan in the nose of the aircraft was modeled in the same manner. The aircraft model was completed by assigning the controls associated with each engine and control surface and normalizing each engine and control surface. After modeling the aircraft, three conditions were tested, the aircraft sitting on the ground, the aircraft hovering at a fixed height, and the aircraft during steady level flight. A python script was used to trim the aircraft in jsbsim during each test.

B.   Aerodynamics

We had previously calculated the aerodynamic performance of our aircraft using XFLR and FLOW5. Then we created the aircraft xml using the jsbsim website applet. After seeing the initial xml file, we realized we need to

change some values like Cl vs Alpha in the xml code. So we took our aero performance data and imported it into the xml file. Example of that can be seen below.

```xml
<function name="aero/force/Lift_alpha">
  <description>Lift due to alpha</description>
  <product>
      <property>aero/qbar-psf</property>
      <property>metrics/Sw-sqft</property>
      <table>
        <independentVar lookup="row">aero/alpha-rad</independentVar>
        <tableData>
          -0.34906585 -1.134456
          -0.340339204  -1.094702
          -0.331612558  -1.054775
          -0.322885912  -1.014679
          -0.314159265  -0.9744217
          -0.305432619  -0.9340071
          -0.296705973  -0.8934413
          -0.287979327  -0.8527298
          -0.27925268 -0.8118784
          -0.270526034  -0.7708928
          -0.261799388  -0.7297788
          -0.253072742  -0.6885424
```

The way JSBsim is setup, we did not have to change the values exported from XFLR5. XFLR5 calculates the aerodynamic coefficients with the main wing area as the reference area. The aerodynamic model equations used in JSBsim can be seen below:

Lift (aircraft)	$L = QSC_{L\alpha}$
Lift (Elevator Deflection)	$L_{Elevator} = 0.2QS\theta_{Elevator}$
Lift (Wing Flap)	$L_{Flap} = 0.01167QS\theta_{Flaps}$
Drag (aircraft)	$D = QSC_{D\alpha}$
Drag (Flaps)	$D_{Flap} = 0.00250QS\theta_{Flaps}$
Drag (Induced)	$D_i = 0.12QSC_{L\alpha}^{\ 2}$
Drag (gear)	$D_{gear} = 0.02QSG$
Drag (elevator)	$D_{Elevator} = 0.04QS|\theta_{Elevator}|$

S = main wing area for each calculation.

C. Propulsion

Engine Variant: CF34-9BR

To power the BR1, an engine core was initially selected from a selection matrix presented during the propulsion PDR. After selecting the CF34-8 as the core, it was determined that modifications could significantly improve the performance and weight of the engine. Through implementing various technical improvements to the base CF34 such as carbon composite fan blades and fan case, ceramic matrix composite turbine blades, etc, performance values were estimated through a case study of the CFM LEAP engine, shown in the figure below:

	CF34 - 8C	CF34-9BR
Static Thrust @ SL (lbf)	14,500	~ 14,500
Dry Weight (lb)	2,450	~ 2,072 *
Fan Diameter (in)	52	52
Bypass Ratio	5:1	~ 5.5:1 *
OPR (Top of Climb)	28.5:1	~ 29:1 *
SFC (lb / lbf * hr) (SL | Cruise)	0.39 | 0.67	0.35 | 0.60

From these values, the team used NASA's EngineSim application to verify and update the performance values of the -9BR variant by inputting materials and other criteria such as number of stages, bypass ratio, etc. The values from EngineSim, coupled with the heuristics learned through the CFM LEAP case study, allowed for a more robust estimation of performance values of the -9BR. The characteristics used for JSBsim are shown in the figure below:
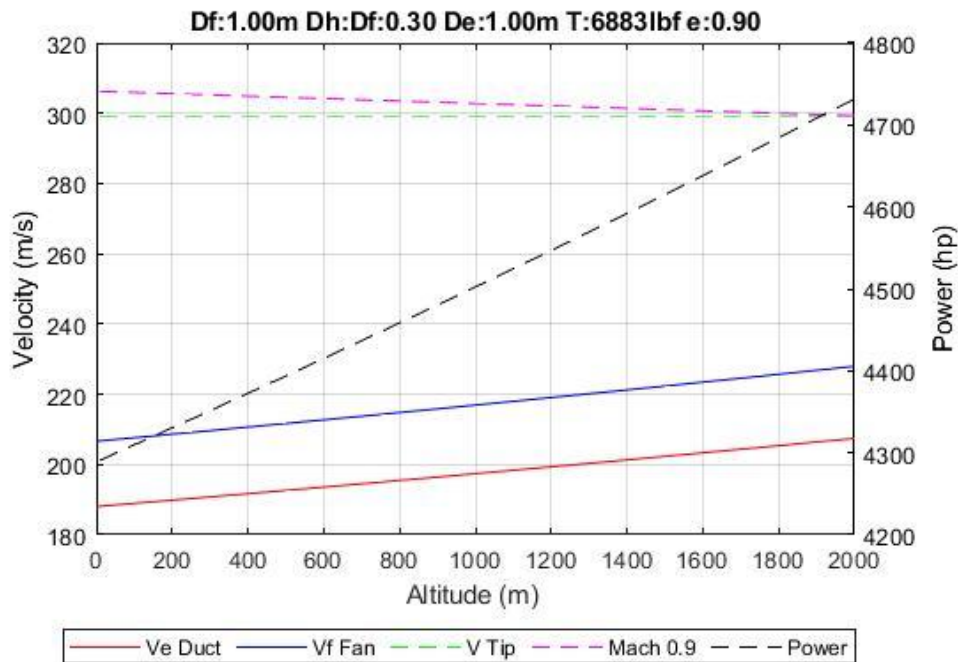
Physical Characteristics

Fan / Compressor Stages	1 / 10
LPT / HPT	4 / 2
Max Diameter (in)	52
Length (in)	90
Dry Weight (lbs)	2072

Performance Characteristics

Max Thrust at Sea Level (lbsf)	15,500
OPR at Max Power	29 : 1
Bypass Ratio	6.1 : 1
SFC (lbs / lbf / hr)	0.35

Lift Fan

The lift fan was modeled to meet the required thrust of 6883lbf to provide enough lift to meet a 1.2 thrust to weight ratio and balance the aircraft when the engines are a maximum thrust, a 2000-meter hover ceiling was used to find the power required and air outlet velocity of the lift fan. Various fan diameters were tested to find a diameter which would fit in the nose of the aircraft with room for structures and electronics while also limiting the power required to run the lift fan and ensuring a blade tip speed below Mach 0.9. After testing different diameters, a 1 meter diameter was chosen based on the criteria listed earlier.

Propulsion JSBSim Model Equations

To input propulsion considerations into the model, JSBSim model equations were determined to accommodate the specifications of the CF34-9BR variant performance characteristics. Using the provided F-35 engine model and the JSBSim FGTurbine Class Reference as guides allowed for the propulsion model equations to be determined:

Thrust	$T = T_{idle} + T_{max} \cdot (N2_{norm})^2$
N2 normalized	$N2_{norm} = \dfrac{N2 - N2_{idle}}{N2_{max} - N2_{idle}}$
EGT - Exhaust Gas Temperature	$EGT = Temp_{engine} + 363.1 + 357.1 Pos_{Throttle}$
Idle Thrust	$T_{idle} = T_{max} \cdot T_{idle\,(table\,percentage)}$
Oil Pressure	$P_{oil} = 0.62 N2$

These equations represent the model equations used by the "Turbine Equations.ipynb" code provided for the F35 model, which are applicable to the BR1. Since the CF34-9BR engines are similar to the PW-600 engine on the F35 in that they are both turbofan engines, much of the propulsion calculations were virtually identical for the basic computation. However, several key characteristic differences exist, including the lack of water injection and thrust augmentation. These were accommodated for through the XML file developed for the CF34-9BR, the performance characteristics of which are shown in the figure below:

```xml
<turbine_engine name="CF34-9BR">
 <milthrust> 15500.0 </milthrust>
 <bypassratio>     6.0 </bypassratio>
 <tsfc>            0.6 </tsfc>
 <bleed>           0.03</bleed>
 <idlen1>         30.0 </idlen1>
 <idlen2>         60.0 </idlen2>
 <maxn1>         100.0 </maxn1>
 <maxn2>         100.0 </maxn2>
 <augmented>        0 </augmented>
 <injected>         0 </injected>
```

D.   Flight Control

From our Propulsion PDR, we had found that the total available thrust is 140kN and for stable hover we only need 113kN. That left us with 25kN in excess thrust that we could put towards the yawing,rolling or other movements. Accordingly we set the mixing matrix that allows us sufficient control authority.

Hover Condition

Component	Thrust available	Thrust needed (kN)	%age	gain
Lift Fan	30	25	83%	0.83

Main Engine	110	88	80%	0.80

In the mix, we use a little higher value just to have enough control and anyway this will be optimized in the trim python code.

```xml
<function name="fcs/lift-fan-thrust-mix">
    <table>
        <independentVar>velocities/vt-fps</independentVar>
        <tableData>
            0   0.9
            100 0.9
            200 0.9
            300 0.0
        </tableData>
    </table>
</function>
```

```xml
<function name="fcs/engine-thrust-mix">
    <table>
        <independentVar>velocities/vt-fps</independentVar>
        <tableData>
            0   0.9
            100 0.9
            200 0.9
            300 1.0
        </tableData>
    </table>
</function>
```

```
<!-- Left Engine -->
    <channel name="Engine0">
        <pure_gain name="fcs/elevator_to_engine0">
            <input>fcs/elevator-cmd-norm</input>
            <gain>fcs/engine-pitch-mix</gain>
        </pure_gain>
        <pure_gain name="fcs/throttle_to_engine0">
            <input>fcs/throttle-cmd-norm</input>
            <gain>fcs/engine-thrust-mix</gain>
        </pure_gain>
        <summer>
            <input>fcs/elevator_to_engine0</input>
            <input>fcs/throttle_to_engine0</input>
            <output>fcs/throttle-pos-norm</output>
        </summer>
    </channel>
```

We do the same algorithm for the right engine and the lift fan.

Trimming

The trimming process involved manipulation of the provided trim function in python "trim.ipynb". After initializing the second main engine, the brute force method was used to estimate values for trim, used in FlightGear. Identifying the most stable case involved manipulating the cost function in the python script to penalize angular rate and speed. Using the scipy.optimize tool which minimizes a specified objective function, emphasis on reducing angular instability was accomplished, yielding a highly stable hover mode. Additionally, the Nelder Mead method was used for ground stability. A custom weighted function was developed for cruise to optimize stability. The provided optimization code was modified to account for ground conditions, and a second engine was added. Additionally, the design bounds for each design factor were modified to accommodate the BR1 performance specifications. Additional work will be performed to improve stability and responsiveness of the control system in future simulation work. For the ground condition the optimization problem is to minimize the change in roll, pitch, and yaw as well as the velocities in the forward/backward, up/down, and left/right using the brakes and landing gear position. The aircraft is set on the ground. For the ground condition the optimization problem is to minimize the change in roll, pitch, and yaw as well as the velocities in the forward/backward, up/down, and left/right using the lift fan and engines' thrust and vector. The aircraft is set at 10 ft altitude.For the ground condition the optimization problem is to minimize the change in roll, pitch, and yaw as well as the velocities in the forward/backward, up/down, and left/right using engines' thrust, ailerons, rudder, and elevator. The aircraft is set on the ground. 1100 ft/s and 60 ft altitude. An example of our outputs from our hover trimming is shown below.

```
       fun: 1.4544343453656095e-11
  hess_inv: <4x4 LbfgsInvHessProduct with dtype=float64>
       jac: array([-1.43559006e-06, -7.35405320e-08,  6.53890862e-09,  6.57734451e-09])
   message: 'CONVERGENCE: REL_REDUCTION_OF_F_<=_FACTR*EPSMCH'
      nfev: 110
       nit: 16
      njev: 22
    status: 0
   success: True
         x: array([ 0.8588424 , -0.80022156,  1.57079634,  1.57079634])
{'ic/h-agl-ft': 10,
 'ic/vd-fps': 0,
 'ic/vn-fps': 0.0,
 'ic/ve-fps': -0.0,
 'ic/theta-rad': 0,
 'gear/gear-cmd-norm': 1,
 'fcs/left-brake-cmd-norm': 0,
 'fcs/right-brake-cmd-norm': 0,
 'fcs/center-brake-cmd-norm': 0,
 'fcs/throttle-cmd-norm': 0.8588424038097119,
 'fcs/elevator-cmd-norm': -0.8002215587379486,
 'propulsion/engine/pitch-angle-rad': 1.5707963441107573,
 'propulsion/engine[1]/pitch-angle-rad': 1.570796344350225}
```

E.   Conclusion

After modeling the BR-1 in JSBSim, the trimmed aircraft followed the expected behavior well. Both the ground and hover tests show the aircraft with no noticeable velocity or rotation. During the cruise test, the aircraft appears to fly at steady level flight as expected. With the successful testing of the BR-1 in JSBSim, the aircraft control systems can be developed and tested in JSBSim, which will allow for more complex testing and simulations to be conducted. Through conducting the simulation and associated computations, many previously-estimated values were confirmed and tested in the combined system. By using various tools such as NASA's EngineSim and case studies, the variant performance values were estimated and simulated through JSBSim. The successful modeling and testing of the aircraft in these trimmed conditions is an important step towards completing the conceptual design of the BR-1. As the team continues to work towards CDR, additional work will be performed in refining the simulation for the following simulation report in addition to further analysis for more accurate results such as CFD for the thrust buckets and further investigation of cost and onboard systems.

Appendix

The below files can be used to look at our code

BR1-mk3.xml - main aircraft file

CF34-9BR.xml - main engine file

liftfan.xml - lift fan file

Trim.ipynb - Trim code with custom values

Github link - https://github.com/ngunady/Team4SimReport1.git

References

[1] Allerton, D. (2010). The impact of flight simulation in aerospace. The Aeronautical Journal (1968), 114(1162), 747-756. doi:10.1017/S0001924000004231