OpenVSP Inertia Calculation Capability

Mark McMillin
NASA Langley Research Center

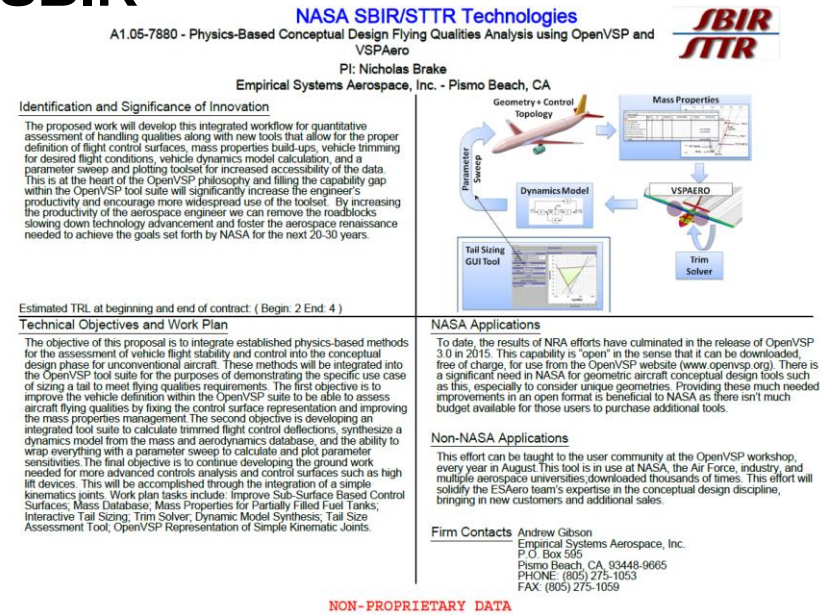
OpenVSP Workshop
NASA Ames Research Center
August 23-25, 2016

Outline

- Motivation
- Tool Set Interfaces
- Inertia Calculation Verifications
- Test Case
- Considerations

Motivation

- **Conceptual analysis process for LEAPS inertia calculations**
  - Input - Geometry - OpenVSP
  - Input - Mass statement - FLOPS
  - Output - Vehicle level inertias
- **Previous workshops**
- **SBIR**



NASA SBIR/STTR Technologies

A1.05-7880 - Physics-Based Conceptual Design Flying Qualities Analysis using OpenVSP and VSPAero

PI: Nicholas Brake

Empirical Systems Aerospace, Inc. - Pismo Beach, CA

Identification and Significance of Innovation

The proposed work will develop this integrated workflow for quantitative assessment of handling qualities along with new tools that allow for the proper definition of flight control surfaces, mass properties build-ups, vehicle trimming for desired flight conditions, vehicle dynamics model calculation, and a parameter sweep and plotting toolset for increased accessibility of the data. This is at the heart of the OpenVSP philosophy and filling the capability gap within the OpenVSP tool suite will significantly increase the engineer's productivity and encourage more widespread use of the toolset. By increasing the productivity of the aerospace engineer we can remove the roadblocks slowing down technology advancement and foster the aerospace renaissance needed to achieve the goals set forth by NASA for the next 20-30 years.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

The objective of this proposal is to integrate established physics-based methods for the assessment of vehicle flight stability and control into the conceptual design phase for unconventional aircraft. These methods will be integrated into the OpenVSP tool suite for the purposes of demonstrating the specific use case of sizing a tail to meet flying qualities requirements. The first objective is to improve the vehicle definition within the OpenVSP suite to be able to assess aircraft flying qualities by fixing the control surface representation and improving the mass properties management. The second objective is developing an integrated tool suite to calculate trimmed flight control deflections, synthesize a dynamics model from the mass and aerodynamics database, and the ability to wrap everything with a parameter sweep to calculate and plot parameter sensitivities. The final objective is to continue developing the ground work needed for more advanced controls analysis and control surfaces such as high lift devices. This will be accomplished through the integration of a simple kinematics joints. Work plan tasks include: Improve Sub-Surface Based Control Surfaces; Mass Database; Mass Properties for Partially Filled Fuel Tanks; Interactive Tail Sizing; Trim Solver; Dynamic Model Synthesis; Tail Size Assessment Tool; OpenVSP Representation of Simple Kinematic Joints.

NASA Applications

To date, the results of NRA efforts have culminated in the release of OpenVSP 3.0 in 2015. This capability is "open" in the sense that it can be downloaded, free of charge, for use from the OpenVSP website (www.openvsp.org). There is a significant need in NASA for geometric aircraft conceptual design tools such as this, especially to consider unique geometries. Providing these much needed improvements in an open format is beneficial to NASA as there isn't much budget available for those users to purchase additional tools.

Non-NASA Applications

This effort can be taught to the user community at the OpenVSP workshop, every year in August. This tool is in use at NASA, the Air Force, industry, and multiple aerospace universities;downloaded thousands of times. This effort will solidify the ESAero team's expertise in the conceptual design discipline, bringing in new customers and additional sales.

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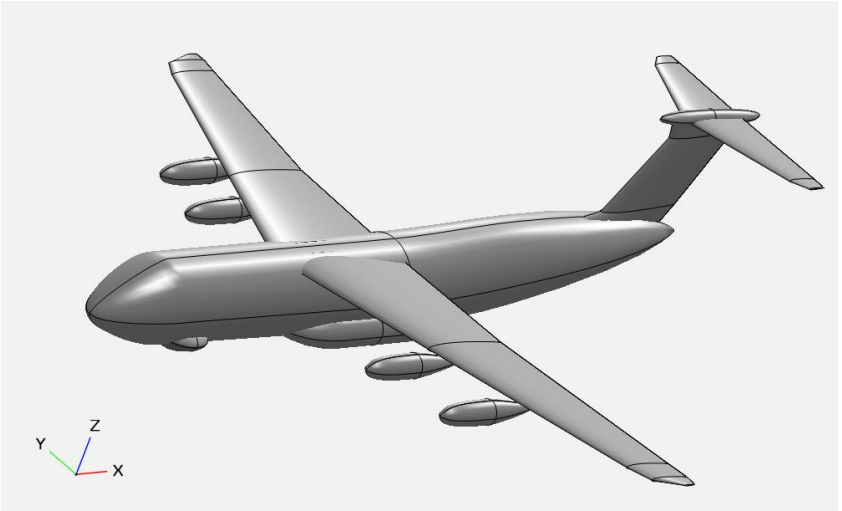
NON-PROPRIETARY DATA

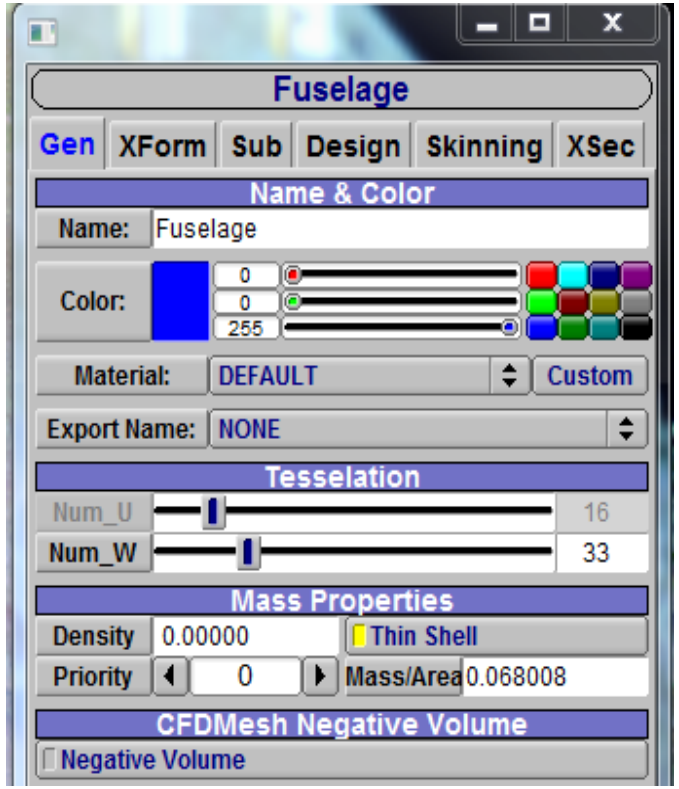


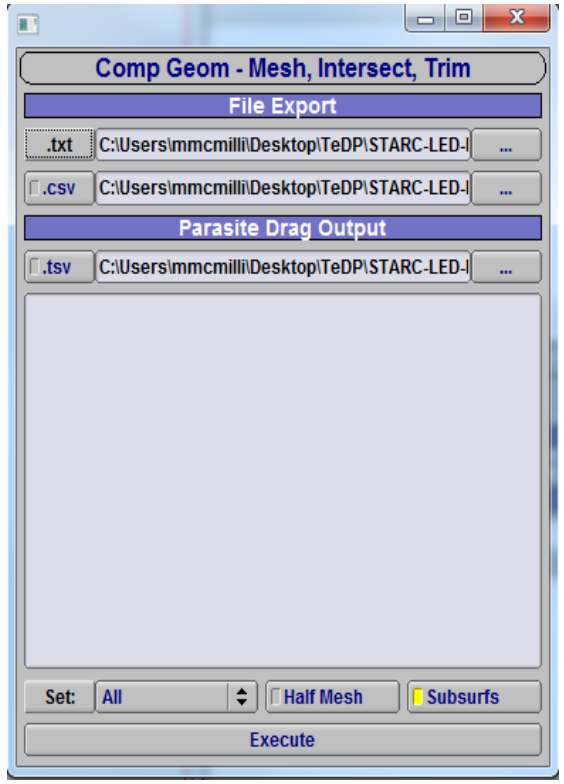
MASS AND BALANCE SUMMARY	PERCENT WREF	POUNDS
WING	10.40	23258.
HORIZONTAL TAIL	0.73	1640.
VERTICAL TAIL	0.63	1414.
VERTICAL FIN	0.00	0.
CANARD	0.00	0.
FUSELAGE	13.89	31048.
LANDING GEAR	5.22	11672.
NACELLE (AIR INDUCTION)	1.23	2756.
STRUCTURE TOTAL	(32.12)	(71788.)
ENGINES	6.97	15583.
THRUST REVERSERS	0.00	0.
MISCELLANEOUS SYSTEMS	0.32	706.
FUEL SYSTEM-TANKS AND PLUMBING	0.38	850.
PROPULSION TOTAL	(7.67)	(17139.)
SURFACE CONTROLS	1.13	2518.
AUXILIARY POWER	0.54	1200.
INSTRUMENTS	0.32	722.
HYDRAULICS	0.76	1704.
ELECTRICAL	1.05	2343.
AVIONICS	0.96	2151.
FURNISHINGS AND EQUIPMENT	9.09	20322.
AIR CONDITIONING	1.03	2292.
ANTI-ICING	0.11	238.
SYSTEMS AND EQUIPMENT TOTAL	(14.98)	(33489.)
WEIGHT EMPTY	54.77	122416.
CREW AND BAGGAGE-FLIGHT, 3	0.30	675.
-CABIN, 7	0.51	1130.
UNUSABLE FUEL	0.26	589.
ENGINE OIL	0.07	167.
PASSENGER SERVICE	1.53	3415.
CARGO CONTAINERS	0.70	1575.
OPERATING WEIGHT	58.14	129967.
PASSENGERS, 200	14.76	33000.
PASSENGER BAGGAGE	3.58	8000.
CARGO	0.00	0.
ZERO FUEL WEIGHT	76.49	170967.
MISSION FUEL	23.51	52562.
RAMP (GROSS) WEIGHT	100.00	223529.

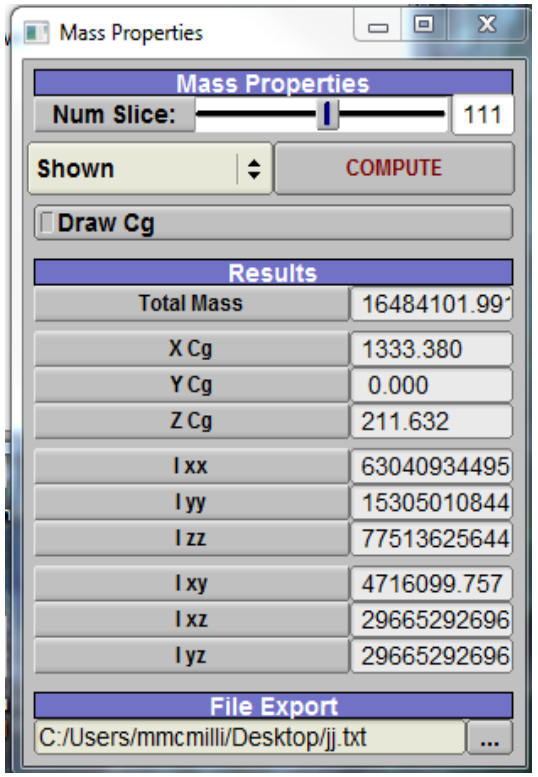
Tool Set Interfaces

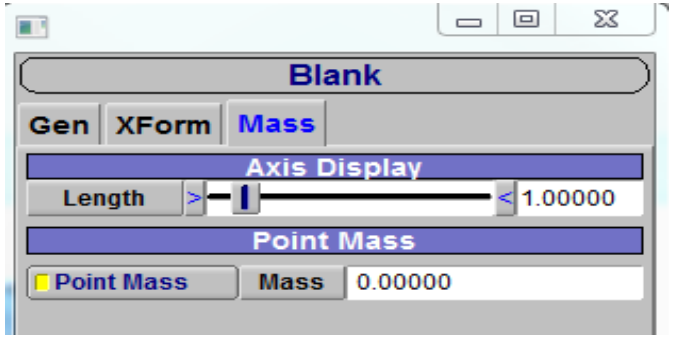
Mass Properties Tool Set

- **Tools**
  - Component General Tab
  - Blank Component Mass Tab
  - Analysis Menu
    - Comp Geom
    - Mass Properties





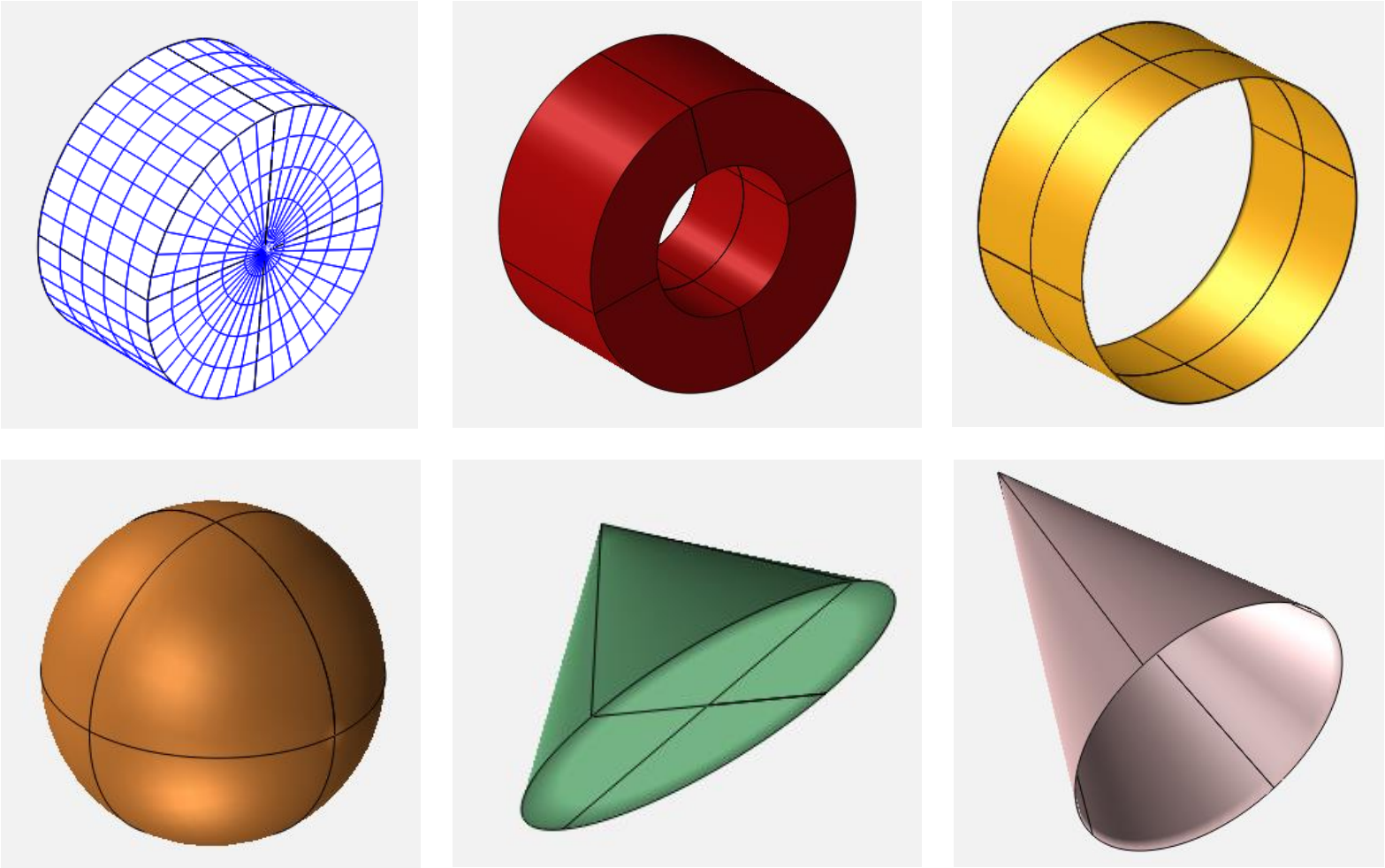




Inertia Calculation Verifications

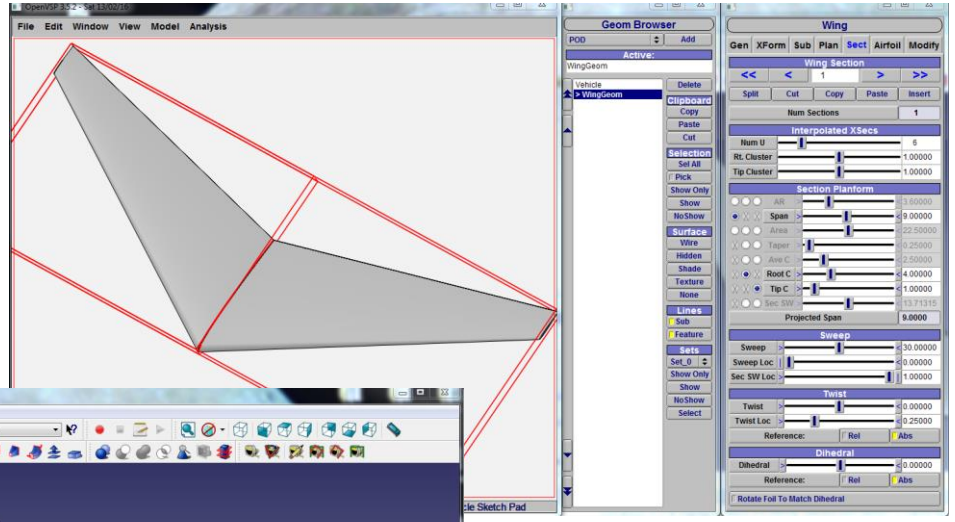
Comparison to Analytic Solids and Shells

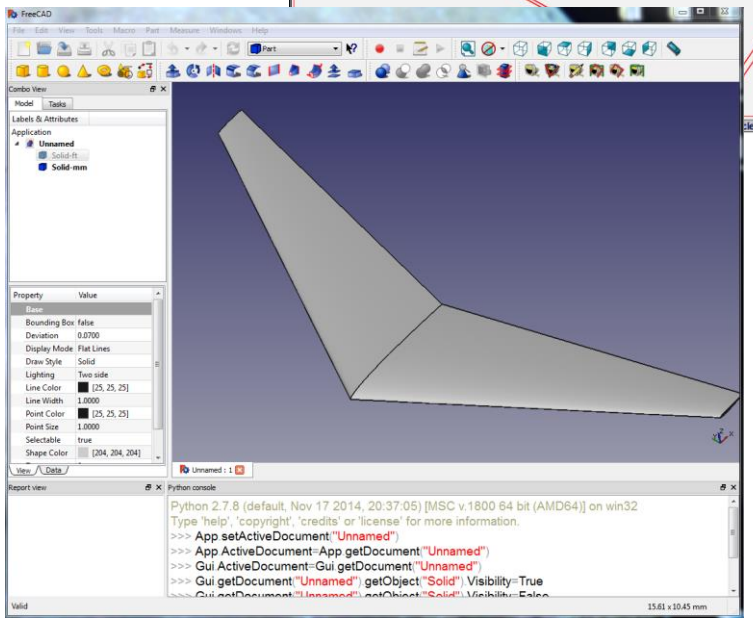
- All shells and solids checked were accurate to at least three decimal places



Comparison of Wing to CAD Computation

- **Solid Wing From OpenVSP Transferred to FreeCAD (OCC) via IGES (mm)**
- **VSP**
  - Volume 8.4471
  - Center of Mass (2.9477, 0.0, 0.0)
  - Inertia Matrix
    - (111.377, 0, 0)
    - (0, 12.184, 0)
    - (0, 0, 123.466)
- **FreeCAD**
  - Volume 8.5253
  - Center of Mass (2.9378, 0.0, 0.0)
  - Inertia Matrix
    - (111.980, 0, 0)
    - (0, 12.318, 0)
    - (0, 0, 124.201)

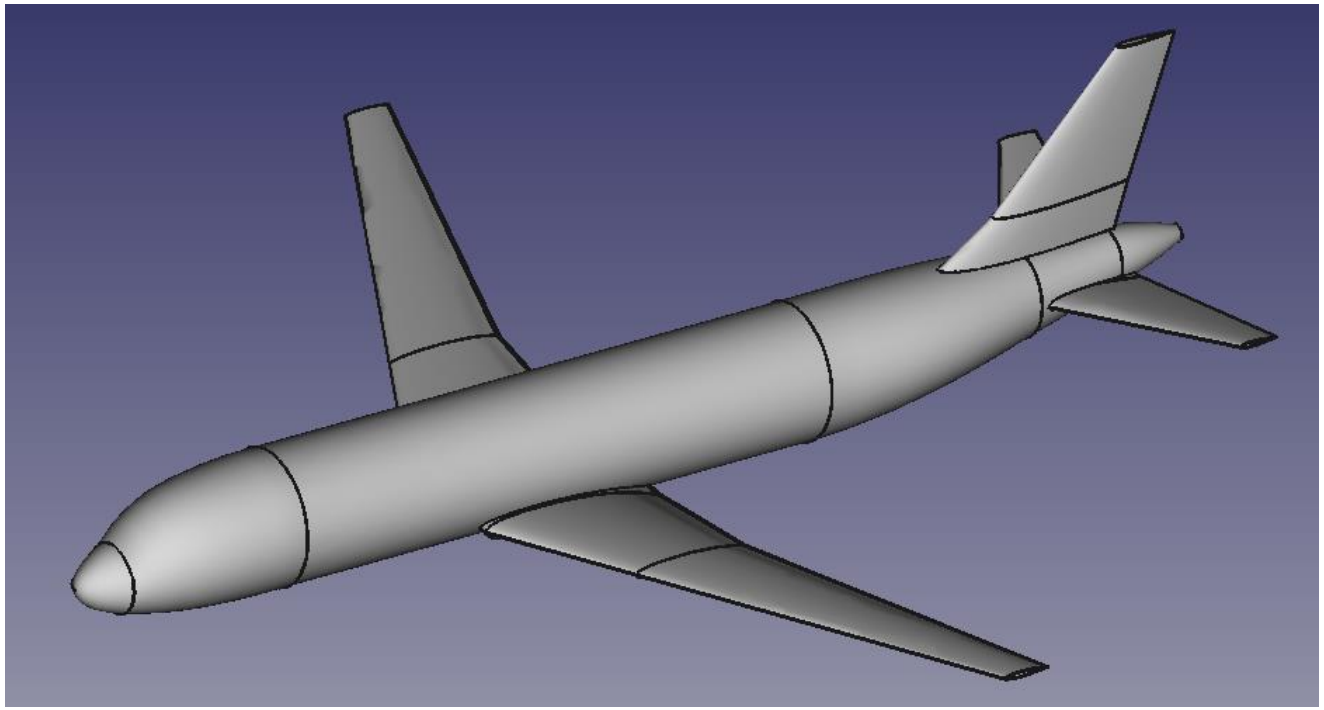


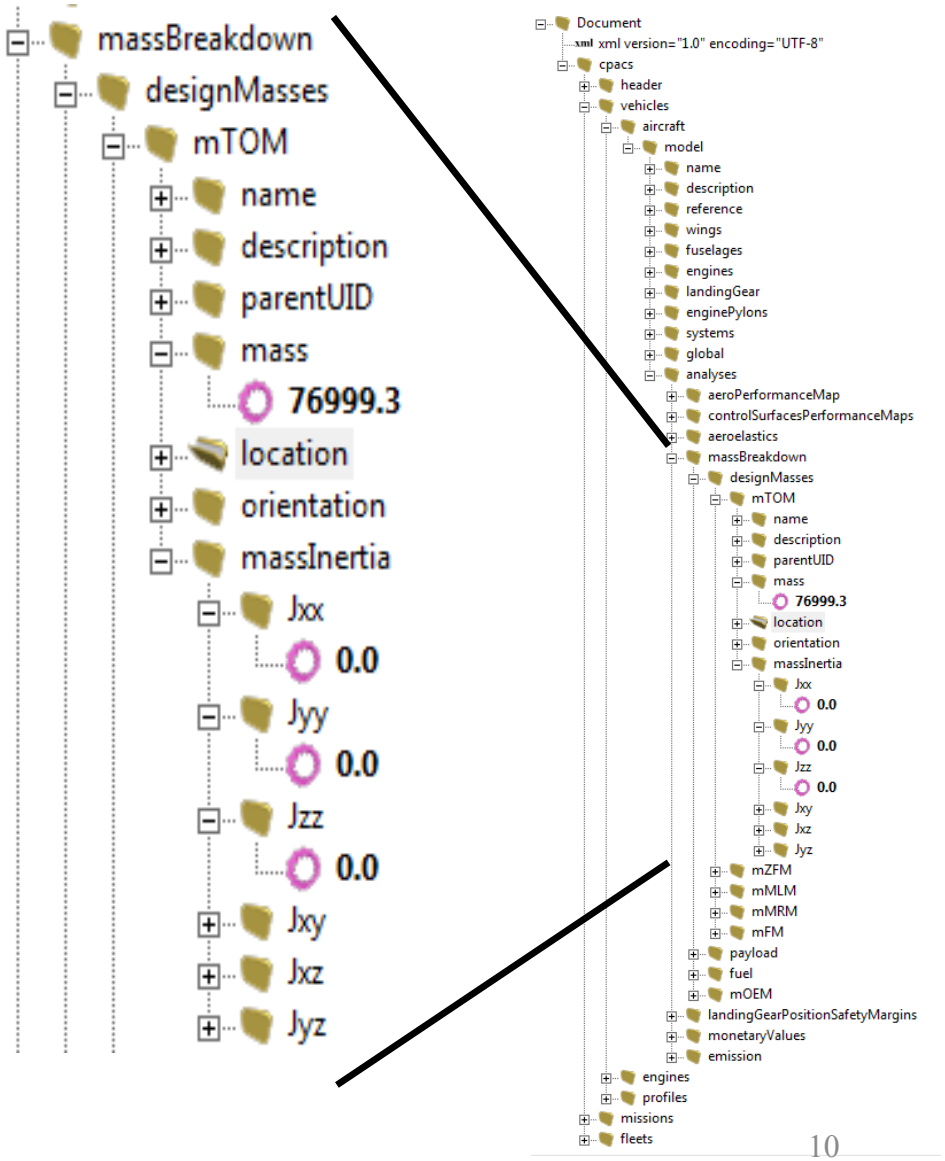


Test Case

Test Case: CeRAS

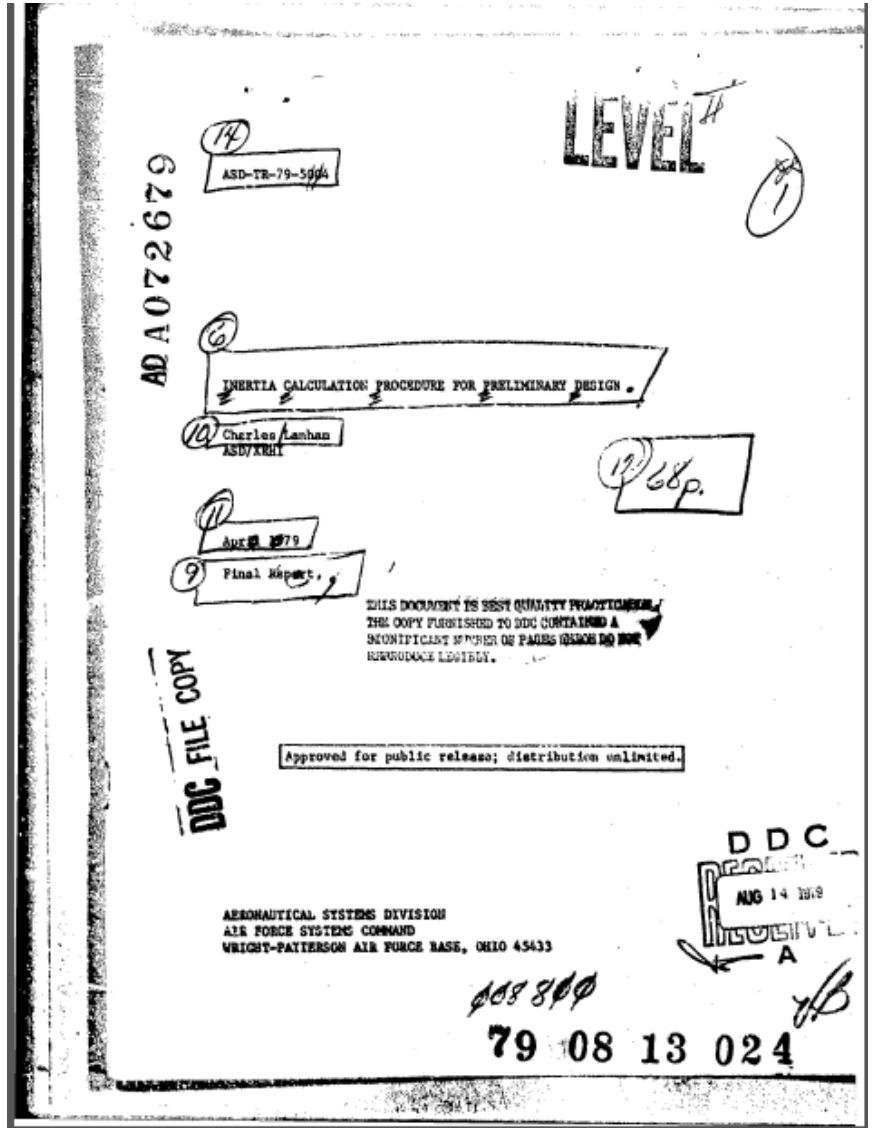
- Investigate OpenVSP enabled mass properties capability for LEAPS Inertias
- CeRAS/CPACS (XML) file has no inertia data
- Need VSP model, IGES is provided





Test Case: 1979 AFRL Document

- **"Inertia Calculation for Preliminary Design" - 1979 AFRL Document**
- **Procedure**
  - Define Geometry using basic shapes
  - Allocate mass, assign densities
    - Components, distributed, point, volumes
  - Calculate component inertias about reference axis
    - Eight shape based inertia calculations
  - Sum and translate inertias to vehicle cg
    - Parallel Axis Theorem in a spreadsheet
- **Several comparisons with existing aircraft, one detailed example for a C5-A!**



AD A072679

LEVEL II

ASD-TR-79-5004

INERTIA CALCULATION PROCEDURE FOR PRELIMINARY DESIGN.

Charles Lanhan
ASD/XRHT

68p.

April 1979

Final Report.

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AIR FORCE SYSTEMS COMMAND
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Test Case: C5-A Example

- **Inputs**
  - Mass statement
  - Geometry
  - Vehicle and component level inertias for comparison

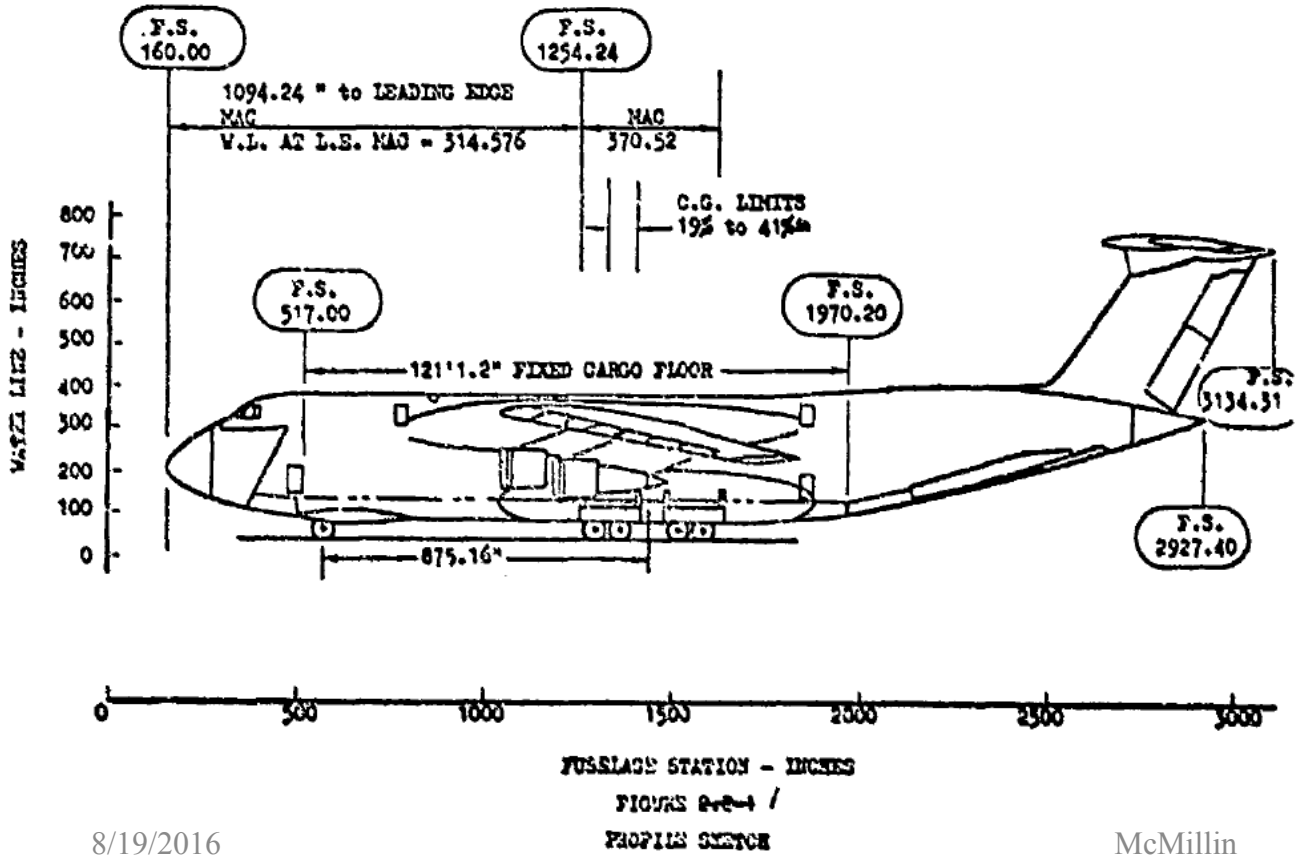


Table 6. C-5A Weight Statement

WING GROUP		82044.8
BASIC STRUCTURE - CENTER SECTION	8281.2	
- INTERMEDIATE PANEL	31036.4	
- OUTER PANEL	13160.0	
SECONDARY STRUCTURE	3729.6	
AILERONS (INCLUDING 816. LB BALANCE WEIGHT)	2327.0	
FLAPS - TRAILING EDGE	10736.8	
SLATS - LEADING EDGE	4955.0	
SPOILERS	2474.8	
TAIL GROUP		12135.3
STABILIZER - BASIC STRUCTURE	4711.3	
- SECONDARY STRUCTURE	829.3	
- ELEVATOR (INCL. 2410. LB BALANCE WEIGHT)	1251.2	
FIN - BASIC STRUCTURE	4577.5	
- SECONDARY STRUCTURE	346.7	
- RUDDER	678.7	
BODY GROUP (INCLUDING MANUFACTURING VARIATION OF -27.2)		116047.5
FUSELAGE - BASIC STRUCTURE	61394.8	
GEAR PODS (INCLUDING MLG AND NLG DOORS)	9661.2	
CARGO FLOOR (INCLUDING TIEDOWN RINGS + RECEPTACLES)	17074.1	
RAILS AND ROLLERS (REEL SYSTEM)	2590.2	
FUSELAGE - SECONDARY STRUCTURE	6308.2	
FORWARD LOADING DOORS (VISOR DOOR)	5322.5	
FORWARD RAMP (INCLUDING RAMP EXTENSION + TOE)	4975.6	
AFT LOADING DOORS (SIDE + CENTER)	2236.1	
AFT RAMP (INCLUDING PRESSURE DOOR + TOE)	6483.1	

C5-A Model – Geometry

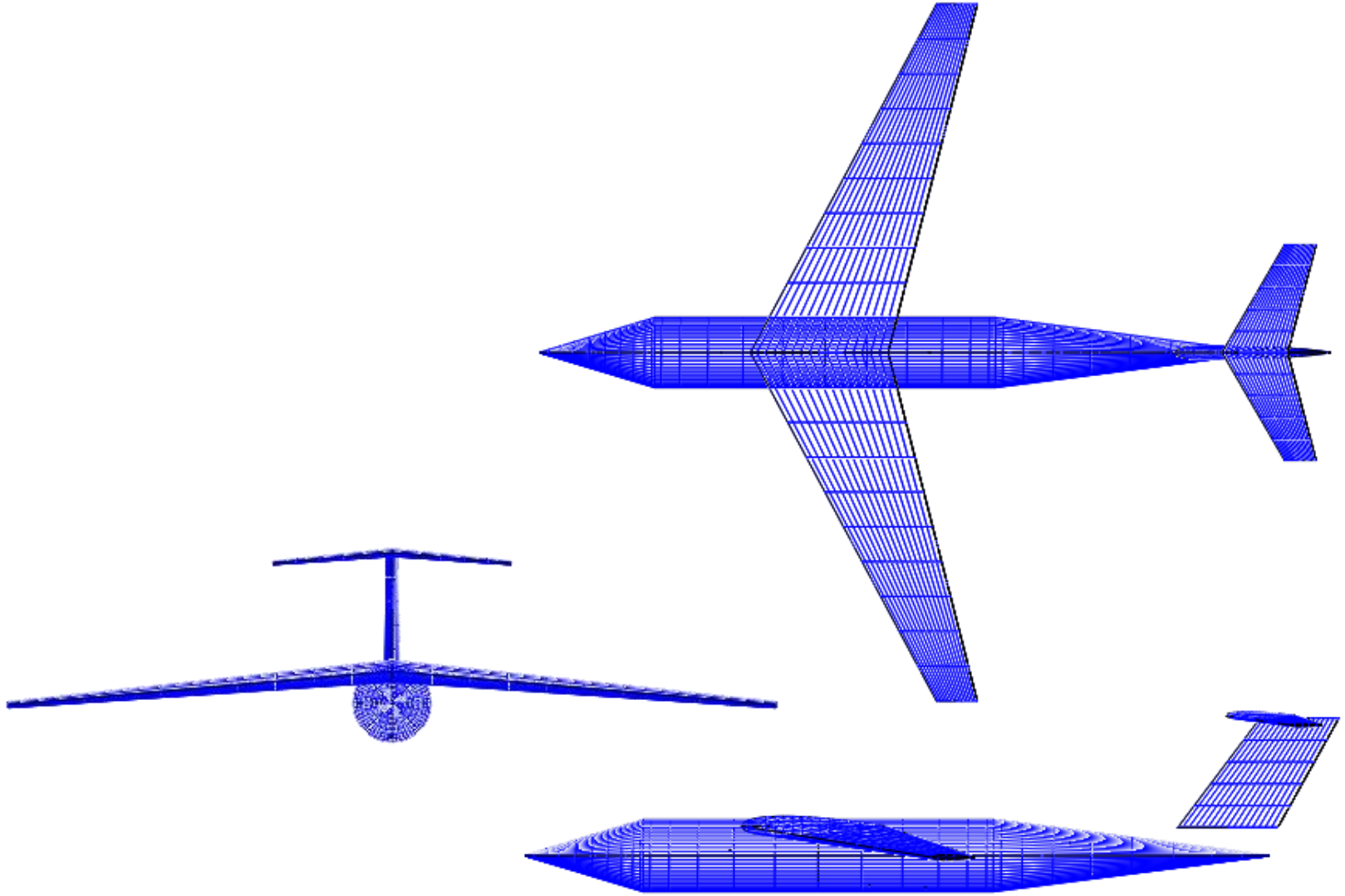
♦ Geometry Parameters

Table 10. C-5A Geometry Definitions for Inertia

GEOMETRY DATA

WING		HORIZ	VERT
Λ_{L1} -	28°	30°	37°
Λ_T -	14°	9°	30°
b -	1336	412	405
c -	525	250	371
t_r -	72	26	48
t_t -	20	10	39
XS4 -	806	2605	2425
ZS1 -	370	780	365
YS4 -	0	0	0
Θ -	-5°	-5°	90°

FUSELAGE		PROPULSION			
l_h -	440	R_e -	80		
l_c -	1300	l_e -	312		
l_t -	1027	XP_1 -	1020	XP_2 -	1165
R -	138	YP_1 -	476	YP_2 -	743
Z_b -	260	ZP_1 -	222	ZP_2 -	198



C5-A Model – Mass Breakdown

- **35 Weight components - allocated to six groups**
  - Wing
  - Horizontal tail
  - Vertical tail
  - Fuselage
  - Propulsion
  - Subsystems
    - Point masses
    - Distributed items
    - Volumes
- **20 cg location estimation/specifications**

Aircraft Weight Allocation Components:

- Horizontal tail structure
- Vertical tail structure
- Fuselage structure
- Main gear
- Nose gear
- Engine Nacelle & Pylons
- Other structure
- Engine
- Aux gearboxes
- Exhaust system
- Cooling & drain
- Lubricating system
- Engine controls
- Oil
- Liquid Nitrogen
- Miscellaneous
- Payload
- Guns
- Starting system
- Auxiliary power unit
- Instruments
- Hydraulics
- Electrical
- Electronics
- Armament
- Air conditioning
- Photographic
- Auxiliary gear
- Other equipment
- Crew
- Wing Pylons
- Ext Wing tanks
- fuselage pylons
- Ext Fuselage tanks
- Fuel

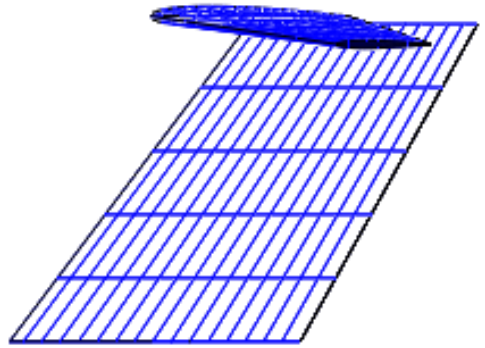
CG Location Groups:

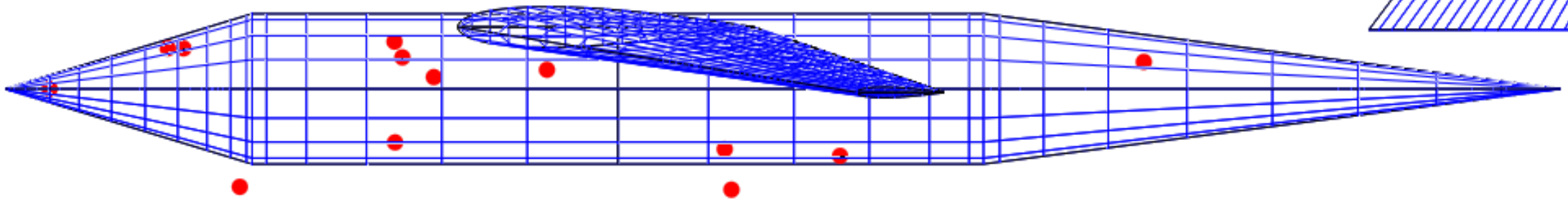
- Main and nose landing gear
- Auxiliary power unit
- Air conditioning
- Auxiliary gear
- Gun
- Crew
- Weapons
- Fuel system (Centroid of fuselage fuel tank)
- Avionics bays
- Radar
- Furnishings & Equipment
- Photographic equipment
- Other equipment
- Liquid nitrogen
- Miscellaneous items
- Fuselage store and tank pylons
- Fuselage external stores and tanks
- Wing store and tank pylons
- Wing external stores and tanks
- Internal Payload

C5-A Model – Point Masses

- Blank components
- Visual cg verification
- Volumes included here

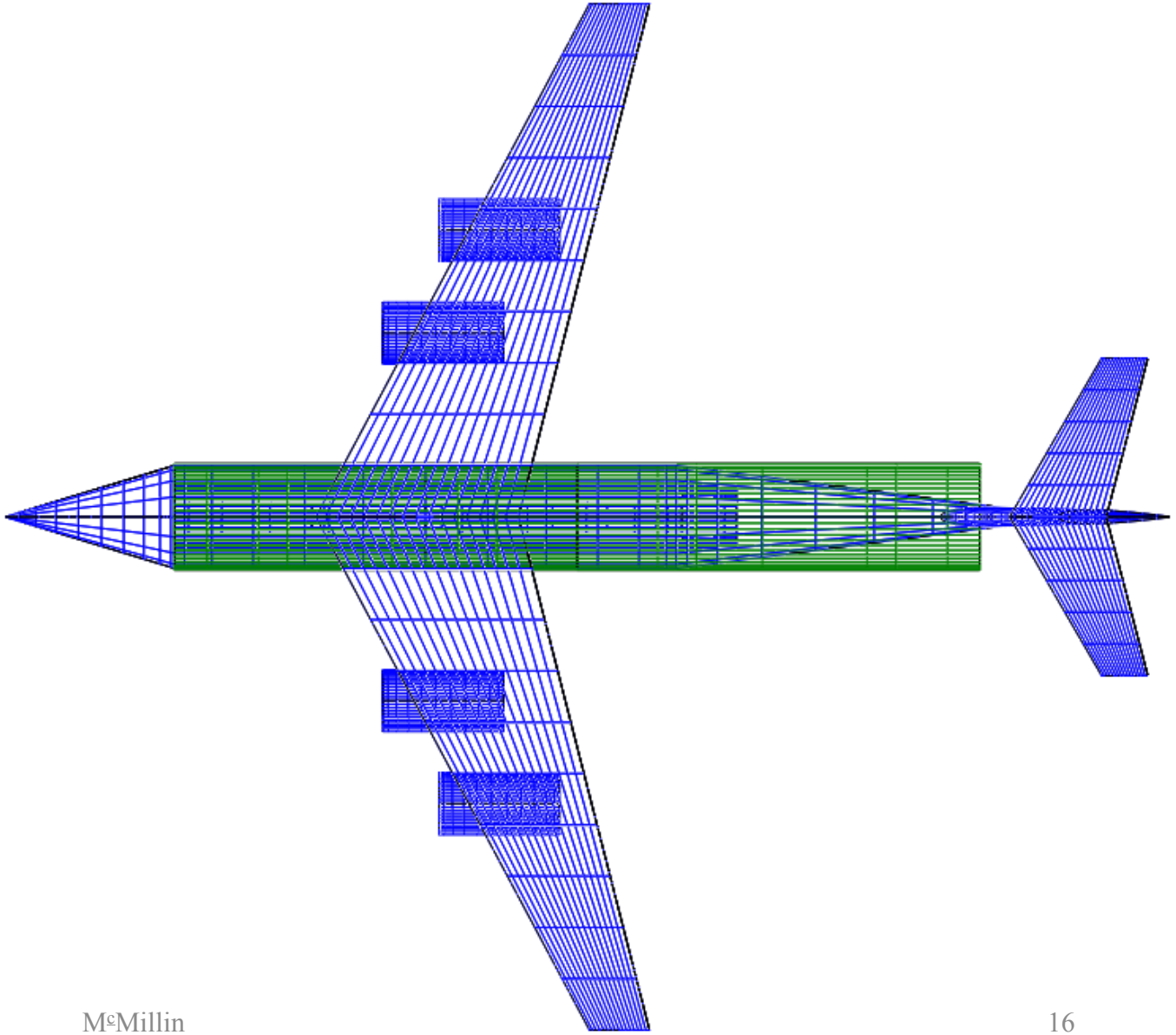
Name	Mass	CGx	CGz
POINT-MASSES			
Main-Landing-Gear	33681.00	1292.00	81.00
Nose-Landing-Gear	4407.00	418.00	86.00
Auxiliary-Power-Unit	933.00	1485.00	141.00
Air-Conditioning	3411.00	964.00	294.00
Auxiliary-Gear	39.00	2025.00	308.00
Crew	1290.00	318.00	332.00
Radar	376.00	80.00	260.00
Surface-Controls	271.00	290.00	332.00
Instruments-&-Navigation	657.00	290.00	332.00
Tiedown-Devices	1750.00	694.00	165.00
Life-Rafts	200.00	698.00	334.00
Food	17.00	690.00	335.00
Water	43.00	691.00	365.00
Liquid-Oxygen	63.00	1280.00	153.00
Total-Pt-Mass	47138.00		
	47138.00		
VOLUMES			
Avionics	3514.00	707.00	316.00
Furnishings	6836.00	763.00	281.00





C5-A Model – Distributed Masses

- Distributed mass allocated to green cylindrical shell
- Propulsion modeled as solid cylinders



VSP Inertia Comparison to C5-A from 1979 Paper

- OWE – fuel level not addressed here
- Wing and Vertical differences due to modeling actual wing versus a trapezoidal slab
- Point mass difference due to treating avionics and furnishings as point masses
- Cg comparison also very favorable

	Cgx	Cgz
VSP	1251	270
1979	1254	270

	Ixx-origin	Iyy-origin	Izz-origin	Ixz-origin
Fuselage	9.651E+09	2.369E+11	2.290E+11	3.723E+10
VSP	9.532E+09	2.370E+11	2.292E+11	3.776E+10
% diff	1.2	-0.1	-0.1	-1.4
Distributed	6.046E+08	1.791E+10	1.744E+10	2.614E+09
VSP	6.039E+08	1.843E+10	1.796E+10	2.692E+09
% diff	0.1	-2.9	-3.0	-3.0
Wing	3.685E+10	1.596E+11	1.791E+11	3.450E+10
VSP	3.673E+10	1.425E+11	1.594E+11	3.536E+10
% diff	0.3	10.7	11.0	-2.5
Horizontal	4.779E+09	6.389E+10	5.963E+10	1.635E+10
VSP	4.804E+09	6.406E+10	5.981E+10	1.641E+10
% diff	-0.5	-0.3	-0.3	-0.4
Vertical	2.302E+09	5.040E+10	4.810E+10	9.953E+09
VSP	2.044E+09	4.958E+10	4.754E+10	9.694E+09
% diff	11.2	1.6	1.2	2.6
Engines	1.994E+10	5.720E+10	7.295E+10	1.044E+10
VSP	1.996E+10	5.719E+10	7.296E+10	1.044E+10
% diff	-0.1	0.0	0.0	0.0
Point mass	3.412E+09	6.458E+10	6.366E+10	5.376E+09
VSP	3.874E+09	6.458E+10	6.366E+10	5.376E+09
% diff	-13.5	0.0	0.0	0.0

Observations

- **My experience**
  - All component based inertias
  - Use of spreadsheet required
  - Used ~100 slices (default 10), but is still very fast

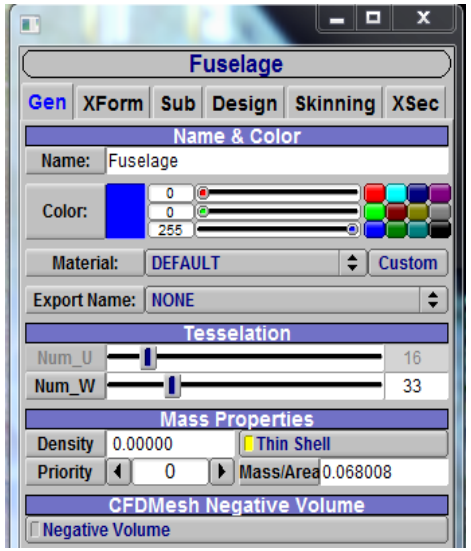
- **1979 Paper process**
  - Ixx trick for “point mass”
  - Avionics/furnishings volumes incorrect?
  - Main gear “point masses” (gear down)
  - Vertical tail location is moved aft
  - Inconsistent selection of origin
  - Sign error in equation on page 9

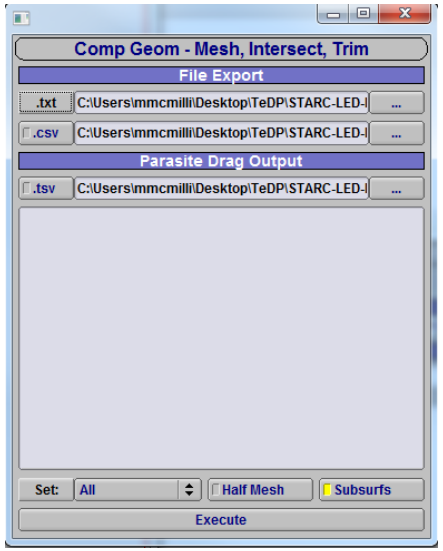
- **Use this process to reverse engineer Roskam’s radius of gyration data**

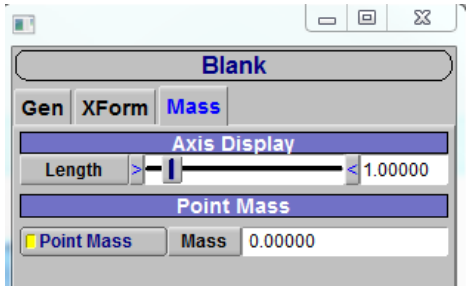
Considerations

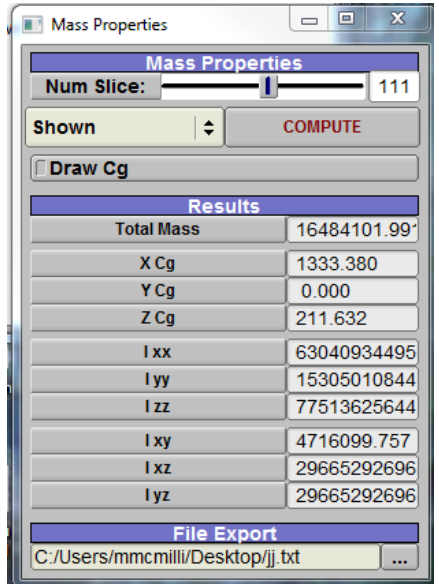
VSP Mass PropertiesTools

- Draw cg not working
- Point mass print out not adequate
- Shell/Solid interface confusing
- Don’t know what priority means – intersected meshes?
- Requires scripting to loop through components to create a csv file, API?
- Assign mass instead of density, save a step
- Stability from version to version could be an issue



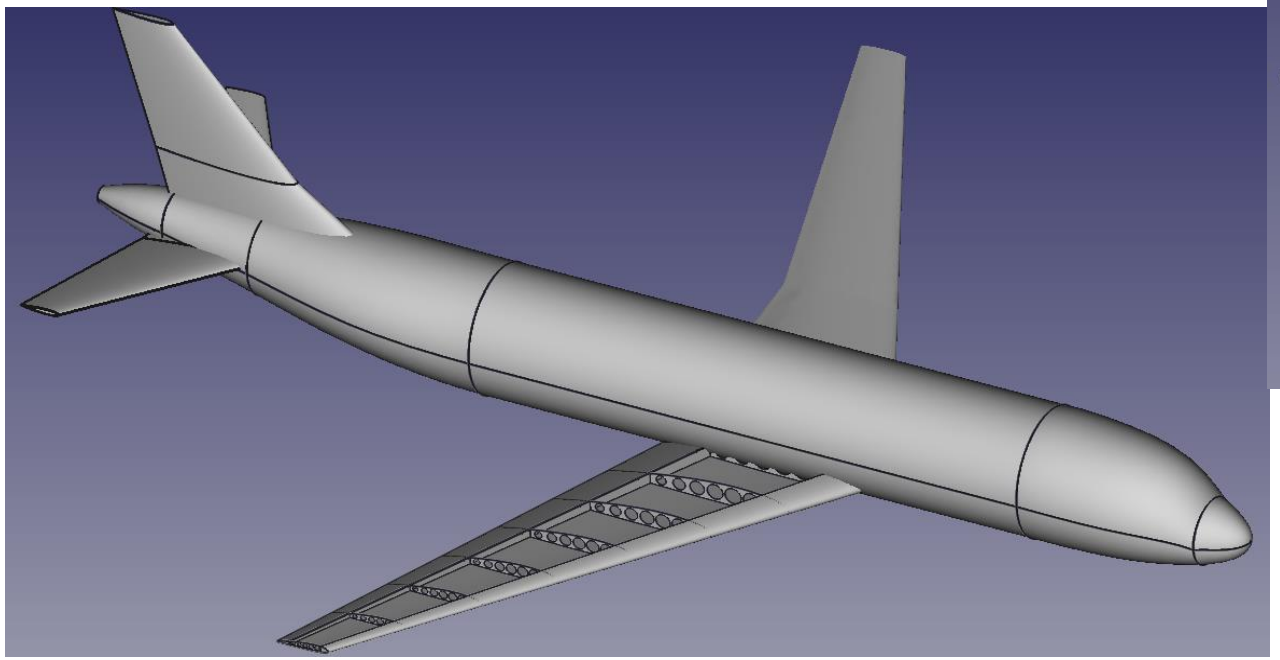


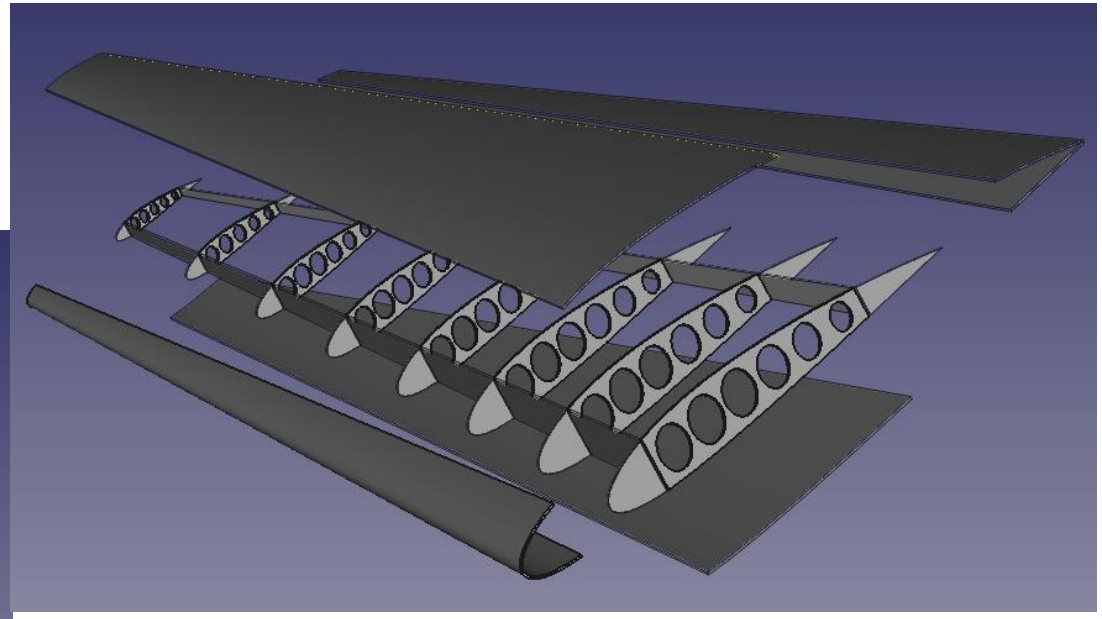




Way Forward

- **FreeCAD**
  - Requires parts to be solids for inertias
  - Investigate OCC area moments of inertia (surfaces)
  - 3-D printer ready!
- **An OpenVSP workbench inside of FreeCAD could provide a very powerful "Best of both worlds" scenario!**





Backup

Mass Properties Tool for Leaps

- **Flexibility is paramount**
  - Variety of mass breakdown structures
    - FLOPS
    - CPACS
  - Mission phase capability
- **Recommendation**
  - Spreadsheet
  - Collect mass data from a variety of sources and initialize VSP
  - Parallel Axis Transfer and summation of VSP component data for inertia

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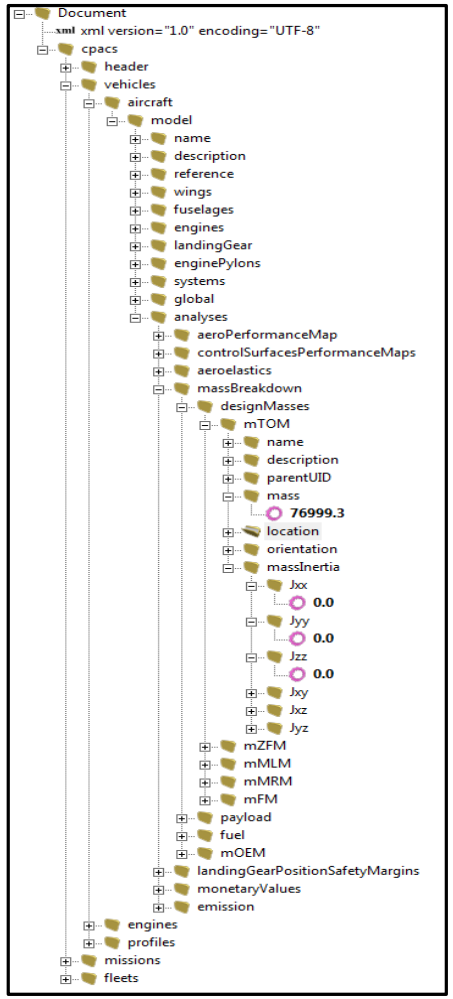
NACELLE (AIR INDUCTION)	1.23	2756.
STRUCTURE TOTAL	(32.12)	(71788.)
ENGINES	6.97	15583.
THRUST REVERSERS	0.00	0.
MISCELLANEOUS SYSTEMS	0.32	706.
FUEL SYSTEM-TANKS AND PLUMBING	0.38	850.
PROPULSION TOTAL	(7.67)	(17139.)
SURFACE CONTROLS	1.13	2518.
AUXILIARY POWER	0.54	1200.
INSTRUMENTS	0.32	722.
HYDRAULICS	0.76	1704.
ELECTRICAL	1.05	2343.
AVIONICS	0.96	2151.
FURNISHINGS AND EQUIPMENT	9.09	20322.
AIR CONDITIONING	1.03	2292.
ANTI-ICING	0.11	238.
SYSTEMS AND EQUIPMENT TOTAL	(14.98)	(33489.)
WEIGHT EMPTY	54.77	122416.
CREW AND BAGGAGE-FLIGHT, 3	0.30	675.
-CABIN, 7	0.51	1130.
UNUSABLE FUEL	0.26	589.
ENGINE OIL	0.07	167.
PASSENGER SERVICE	1.53	3415.
CARGO CONTAINERS	0.70	1575.
OPERATING WEIGHT	58.14	129967.
PASSENGERS, 200	14.76	33000.
PASSENGER BAGGAGE	3.58	8000.
CARGO	0.00	0.
ZERO FUEL WEIGHT	76.49	170967.
MISSION FUEL	23.51	52562.
RAMP (GROSS) WEIGHT	100.00	223529.



C5-A Model – Mass Breakdown

Aircraft Weight Allocation Components:

- Horizontal tail structure
- Vertical tail structure
- Fuselage structure
- Main gear
- Nose gear
- Engine Nacelle & Pylons
- Other structure
- Engine
- Aux gearboxes
- Exhaust system
- Cooling & drain
- Lubricating system
- Engine controls
- Oil
- Liquid Nitrogen
- Miscellaneous
- Payload
- Guns
- Starting system
- Auxiliary power unit
- Instruments
- Hydraulics
- Electrical
- Electronics
- Armament
- Air conditioning
- Photographic
- Auxiliary gear
- Other equipment
- Crew
- Wing Pylons
- Ext Wing tanks
- fuselage pylons
- Ext Fuselage tanks
- Fuel

CG Location Groups:

- Main and nose landing gear
- Auxiliary power unit
- Air conditioning
- Auxiliary gear
- Gun
- Crew
- Weapons
- Fuel system (Centroid of fuselage fuel tank)
- Avionics bays
- Radar
- Furnishings & Equipment
- Photographic equipment
- Other equipment
- Liquid nitrogen
- Miscellaneous items
- Fuselage store and tank pylons
- Fuselage external stores and tanks
- Wing store and tank pylons
- Wing external stores and tanks
- Internal Payload

1979 AFRL Document – Slab wing

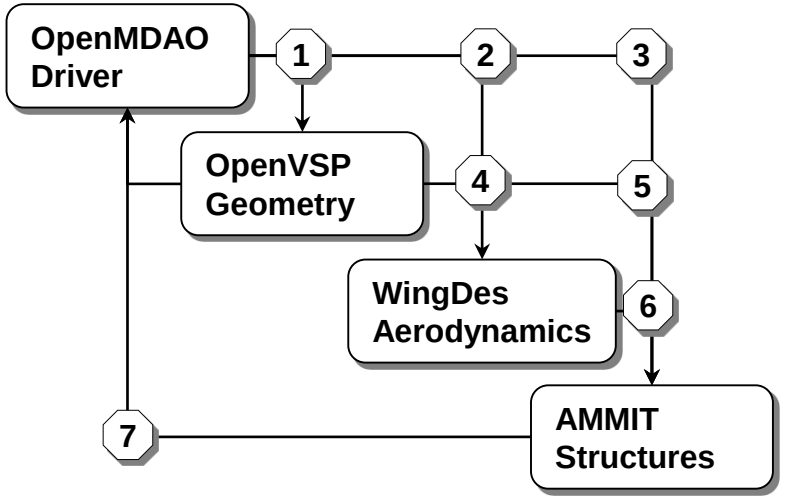
- Wing, horizontal tail, and vertical tail groups are all common
- surfaces. To define the shape of the surface the normal planview (one
- side of wing and horizontal since they're symmetrical) is used. The
- equations are derived for a trapezoidal panel with the thickness varying
- linearly from root to tip. If a surface has edge or thickness breaks,
- it should be separated into inner and outer trapezoidal panels with the
- inertia of each calculated separately. The thickness is assumed
- "constant as you go from leading to trailing edge and equal to the
- maximum for that section.

Early Considerations for Code Development

- **Coding style guide**
- **Configuration control**
  - Suite testing
- **Database**
  - Data dictionary
- **Units**
- **Coordinate Systems**

- **Inertia presentation at VSP workshop?**

TTT Uncertainty Demo
Minimum Wing Weight



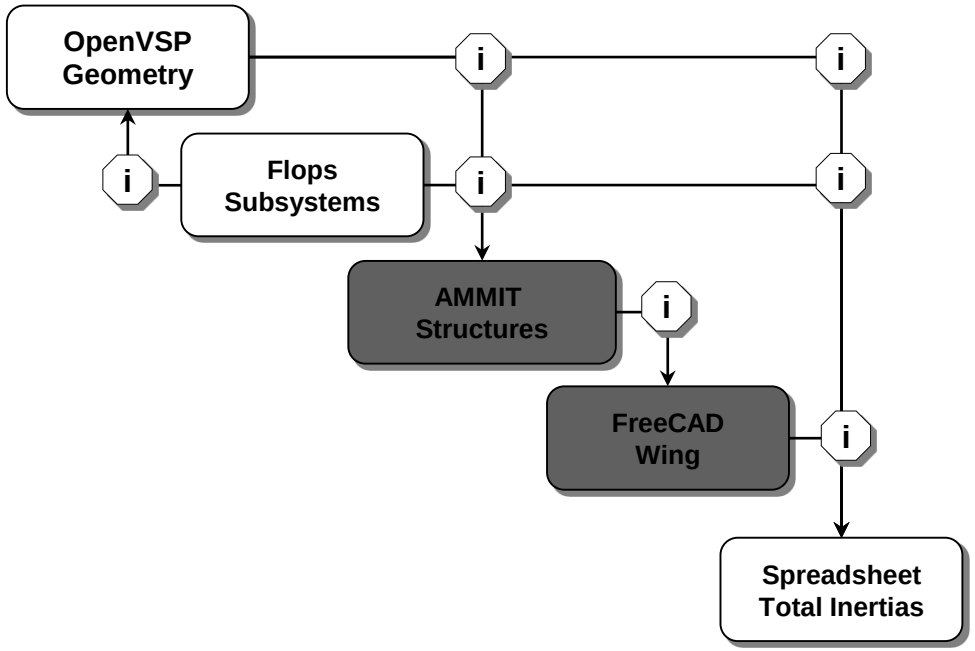
Data Products

1. Wing Parameters
2. Mission Conditions
3. Material Properties
4. Vehicle Geometry
5. Vehicle Geometry
6. Aerodynamic Loads
7. Structural Weight

N2 Diagram

Leverage Uncertainty Demo

- VSP component macro
- VSP to AMMIT Interface
- AMMIT Structural Thickness
- FLOPS Subsystems
- Spreadsheet Mass Prop Calculator Tool



N2 Diagram