NAG–1–2217

MULTIDISCIPLINARY DESIGN INVESTIGATION OF TRUSS-BRACED WING AIRCRAFT: PHASE 4

Final Report

April 2000

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MULTIDISCIPLINARY DESIGN INVESTIGATION OF TRUSS-BRACED WING AIRCRAFT: PHASE 4

FINAL REPORT

The subject grant NAG-1-2217 was in effect from 7/1/99 to 10/31/99. The objective of this grant was to complete a strut-braced wing study which began under grant NAG–1–1852, which was in effect from 6/27/96 until 9/15/99. While the initial grant was on-going, we were also under subcontract to Lockheed-Martin, Aerospace Systems Division, Marietta, GA to do additional studies related to the strut-braced wing grant under contract RV28007, "A Structural and Aerodynamic Investigation of a Strut-Braced Wing Transonic Aircraft Concept", 4/1/98–11/15/98. Lockheed-Martin was under contract to NASA Langley under contract NAS1–96014 DA17. Finally the research under this grant has led to a joint proposal from NASA Langley, Locheed-Martin, Virginia Tech and NASA Dryden to develop a transonic strut-braced wing demonstration aircraft in response to NASA NRA 99–LaRC–3, Flight Research for Revolutionary Aeronautical Concepts (REVCON). This final report summarizes the research done under NAG-1-2217, augmented by the additional concommitant research projects mentioned above.

The transonic truss-braced wing is a highly integrated technology concept that has large potential payoffs including aircraft weight reduction and increased cruise performance. The operational benefits are a higher aspect ratio, lower thickness ratio, and lower wing weight compared to the conventional cantilever wing. The reduction in thickness allows the wing sweep to be reduced without incurring a transonic wave drag penalty and results in a further reduction of the wing weight. The reduced wing sweep also allows a larger percentage of the wing area to achieve natural laminar flow resulting in lower drag.

The basic idea of a transonic strut-braced wing can be traced to early studies conducted from 1954 to 1981, which concluded that although the strut-braced wing concept showed promise, it also required careful technology integration between aerodynamics and structures. Design tools needed to perform the integrated analysis required for this concept were not available. However, when contemporary Multidisciplinary Design Optimization (MDO) techniques are employed to integrate the aerodynamic and structural design requirements, results indicate that not only is take-off gross weight reduced by more than 10-percent, but fuel usage is reduced in excess of 20-percent. This is for the case of fuselage-mounted engines. Significantly larger weight reductions (19% TOGW) are obtained for the wing-mounted engine case. An extensive follow-on industry study additionally found a 42-percent reduction in emissions and a 26-percent reduction in direct operating cost when a strut-braced wing was installed on a 2010 entry advanced transport aircraft compared to a 1995 technology baseline aircraft.

Two key technology issues are critical. These are the aerodynamic interference penalties associated with the wing-strut junction at transonic speeds, and the need for an innovative tension-only strut mechanism to avoid the problem of strut buckling at the negative g loading condition. In previous studies, the need for the strut to be strong enough to avoid buckling under the negative g condition resulted in the transonic strut-braced wing concept actually becoming heavier than the corresponding cantilever wing design.

In the course of our research, three students have completed M. S. theses, Joel Grasmeyer, Amir Naghshineh-Pour and Jay Gundlach, and one student has completed a Ph.D. dissertation, Philippe Tétrault. Another M.S. degree, Andy Ko and another Ph. D. degree, Erwin Sulaeman are in progress. In addition, Dr. Frank H. Gern, working as a Post-Doc participated fully in this research.

On January 11, 2000, Joel Grasmeyer won the Dr. Abe M. Zarem Award for Distinguished Achievement. The award was "presented as a means for students pursuing advanced degrees in aeronautics and astronautics to showcase their talent and work." Joel's award was for his master's level work on "Multidisciplinary Design Optimization of a Truss-Braced Wing Aircraft" and was presented at the 38th AIAA Aerospace Sciences Meeting in Reno NV.

The results of our research may be found in the viewgraphs at the end of this report. The research is also reported in Refs. 1–16 below.

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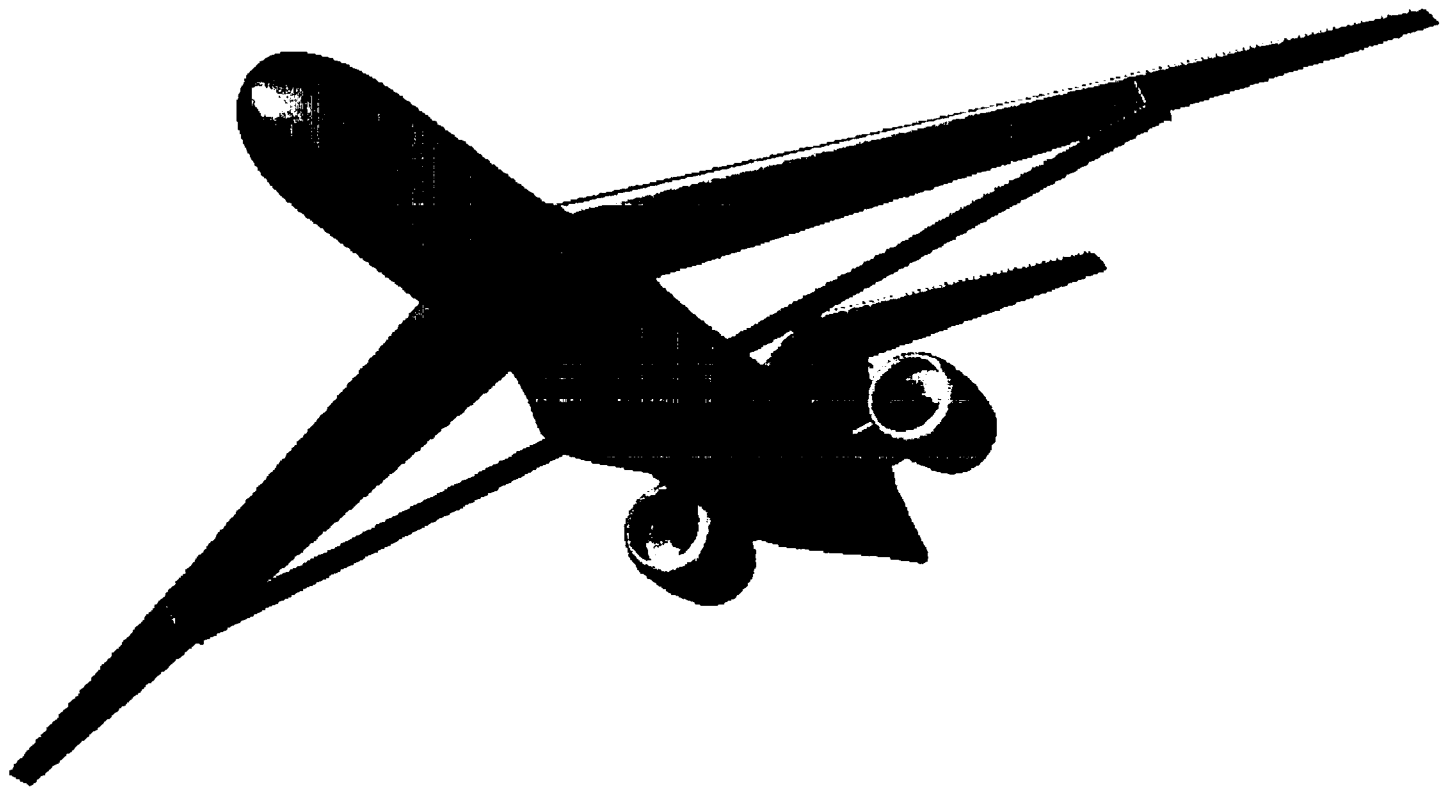
Multidisciplinary Analysis and Design Center for Advanced Vehicles



Multidisciplinary Design Optimization of a Transonic Commercial Transport with a Strut-Braced Wing

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Overview and Team Composition

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- Aerodynamics and MDO
  - Andy Ko
  - Joel Grasmeyer*
  - John Gundlach IV*
- Structures
  - Dr. Frank H. Gern
  - Amir Naghshineh-Pour*
- Aeroelasticity
  - Erwin Sulaeman
- CFD and Interference Drag
  - Philippe-Andre Tetrault*

- Faculty Members
  - Dr. B. Grossman,
  - Dr. R.K. Kapania
  - Dr. W.H.Mason
  - Dr. J.A. Schetz
  - Dr. R.T. Haftka (University of Florida)

*Students that have graduated

Some History

- Werner Pfenninger proposes concept by early 1950s
- 1978: AFWAL studies include strut concepts
- 1996: VPI Starts MDO work under NASA Support
- 1997: Results look promising
- Late 1997/early 1998: Internal LaRC study
- 1998: VPI briefs both Boeing and Lockheed Martin
- 1998: LMAS contracted by NASA LaRC
  - VPI works as subcontractor to LMAS
- 1999: Both VPI and LMAS do additional work
- 1999: NASA/LMAS/VPI Team propose a demonstrator aircraft for the REVCON Program

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Strut-Braced Wing Advantages

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- The strut increases the structural efficiency of the wing
  - Wing t/c reduced without a weight penalty
- Lower weight and increased span reduce induced drag
- Reduced t/c allows less sweep without wave drag penalty
- Parasite drag is reduced via increased laminar flow
  - Un-sweeping the wing reduces cross-flow instability
  - Higher aspect ratio means smaller chords and smaller Re

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Description of the MDO Process

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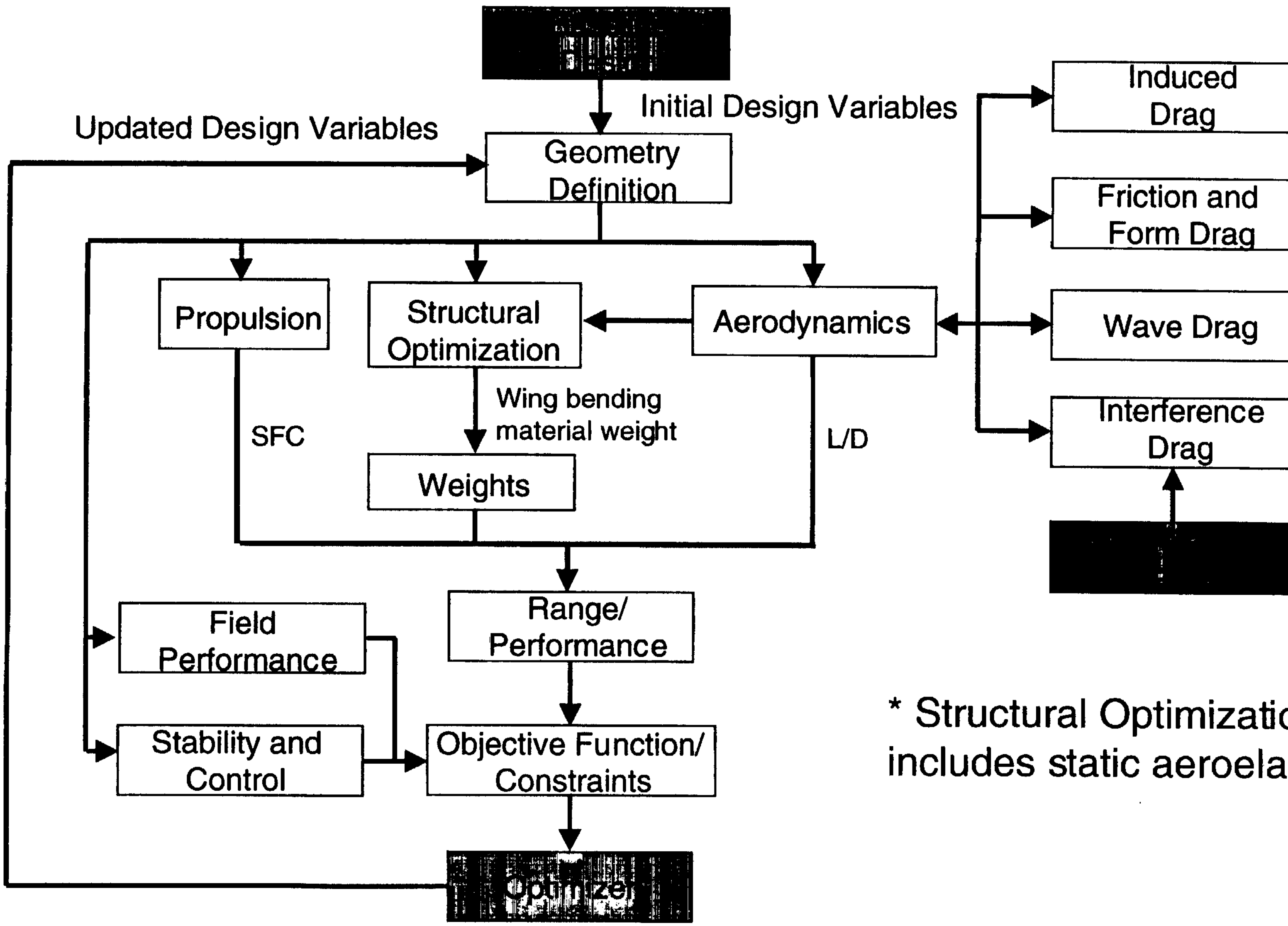


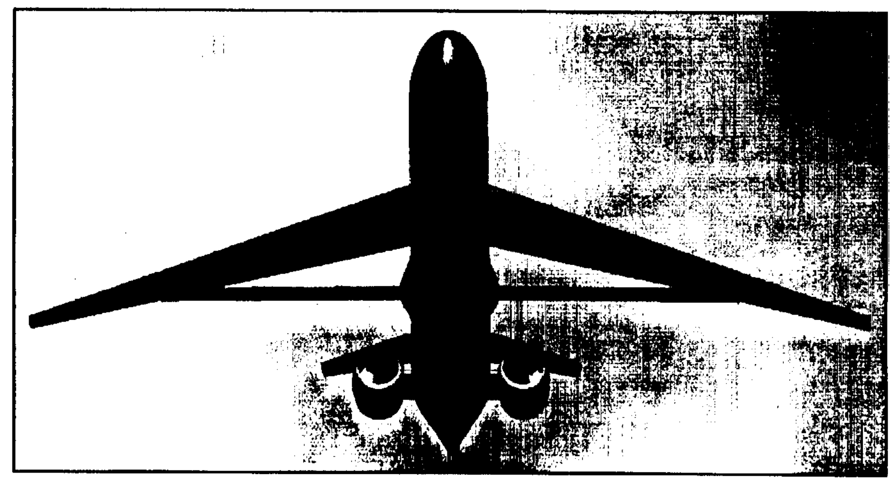
* Structural Optimization includes static aeroelasicity

MDO Problem Statement

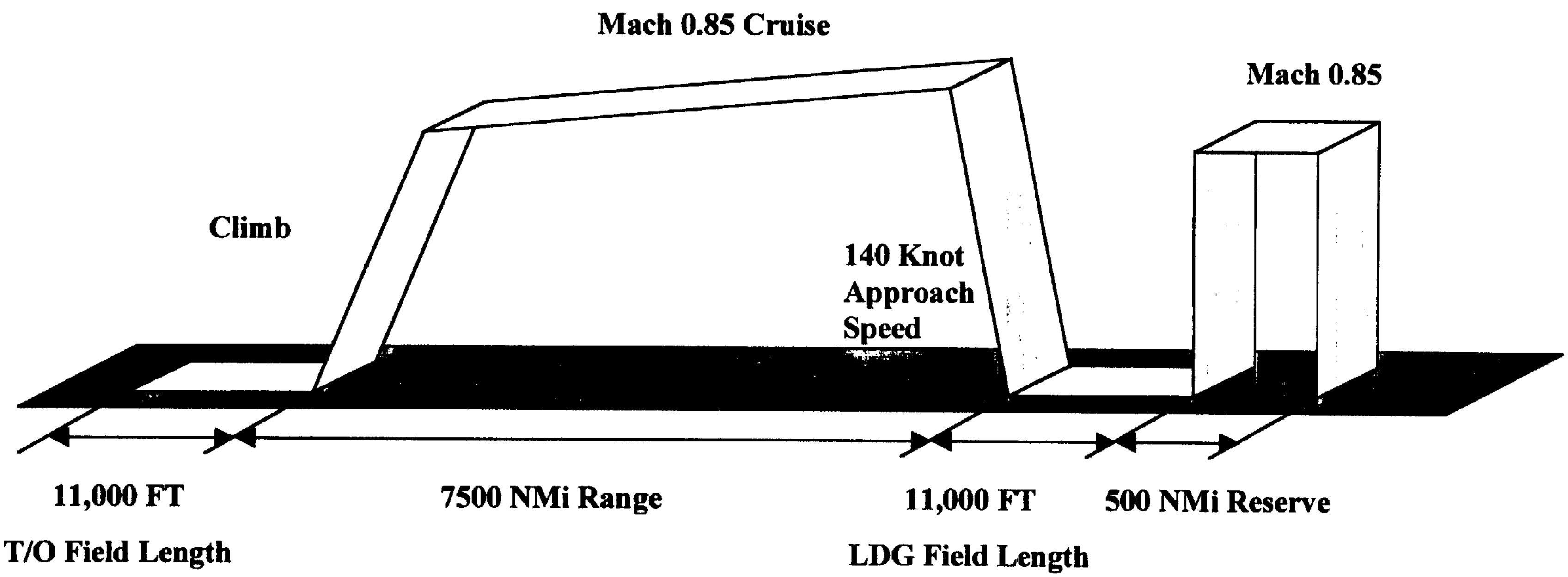
- Objective: Minimize Takeoff Gross Weight
- Aircraft Design Variables:
  - Wing Half Span
  - Wing 1/4 Chord Sweep
  - Wing Chord
    - Cantilever centerline chord = 52 ft.
    - Centerline and tip chord for SBW
  - Wing t/c (3)
  - Wing centerline skin thickness
  - Fuel Weight
  - Engine Thrust
  - Altitude
  - Position of engine
    - Under Wing Engine SBW only
  - Vertical Tail Scaling Factor
    - Tip Mounted Engines SBW only
- Strut Design Variables:
  - Position of Strut
  - Strut Sweep
  - Strut Offset
    - Chordwise
    - Vertical
  - Strut Chord
  - Strut t/c
  - Strut Force

MDO Problem Statement

- Optimization Method: Method of Feasible Directions (DOT)
- Constraints
  - Range
  - Initial Cruise Rate of Climb
  - Maximum Section Cl
  - Fuel Capacity
  - Engine Out
  - Wing Deflection
  - Second Segment Climb Gradient
  - Balanced Field Length
  - Approach Velocity
  - Missed Approach Climb Gradient
  - Landing Distance
  - Slack Load Factor



Design Mission

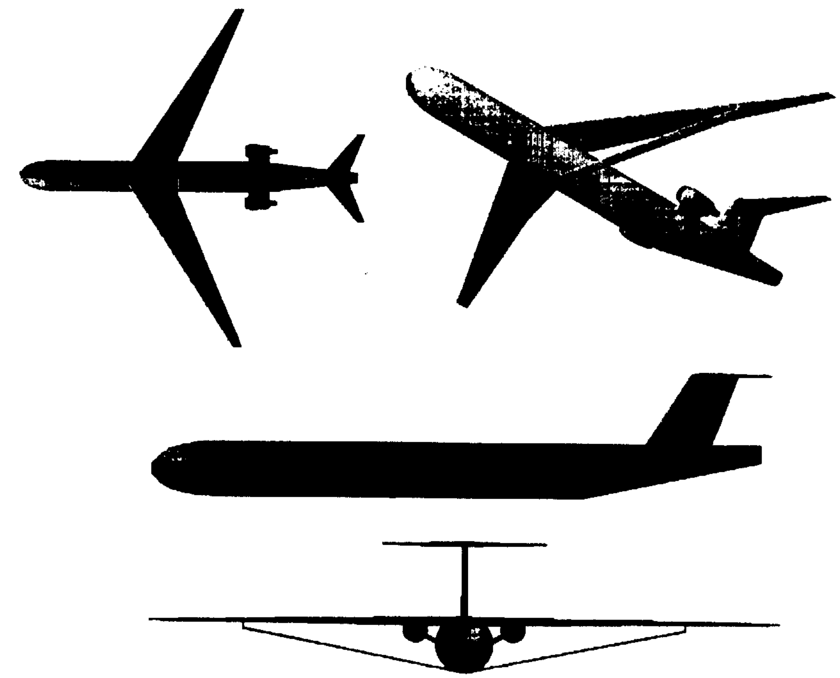


- Two GE-90 Class Engines
- 325 Passengers

Current Designs

Cantilever Optimum

TOGW = 607656 lbs.
Fuel Weight = 221692 lbs.



Fuselage Mounted Engines SBW

TOGW = 546709 lbs. (10.0%)
Fuel Weight = 190366 lbs. (14.1%)

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Current Designs

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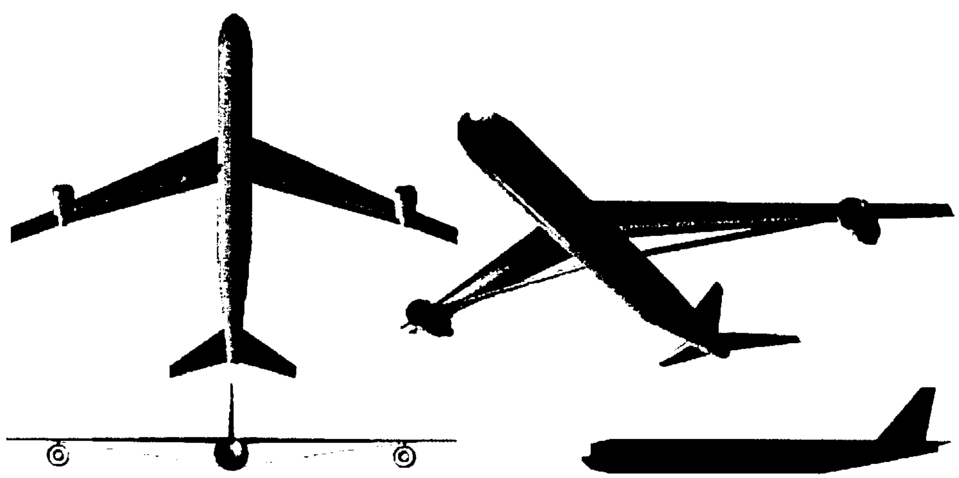

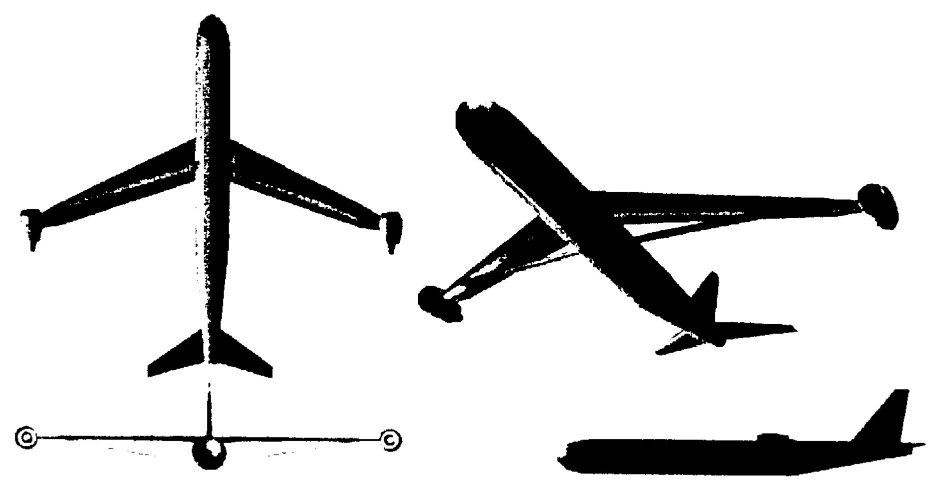

Wing Mounted Engines SBW		Tip Mounted Engines SBW	
TOGW	= 521023 lbs. (14.3%)	TOGW	= 523563 lbs. (13.8%)
Fuel Weight	= 185892 lbs. (16.1%)	Fuel Weight	= 185159 lbs. (16.5%)

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Design Comparisons

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Mission Profile:
- 325 Passengers
- 7500 nmi. range + 500 nmi. reserve

	Cantilever Optimum	Fuselage Mounted Engines SBW	Wing Mounted Engines SBW	Tip Mounted Engines SBW
Weights				
Calculated Takeoff Weight (lb)	607656	546709	521023	523563
Wing Weight (lb)	79196	71571	56629	55554
Fuel Weight (lb)	221692	190366	185892	185159
Zero fuel weight (lb)	385964	356343	335131	338404
Geometry				
Wing Half-Span (ft)	104.4	106.6	101.8	95.6
Reference Area (ft^2)	4620.2	4369.6	4077.5	4102.3
Aspect Ratio	9.43	10.40	10.17	8.92
Wing 1/4-Chord Sweep (deg)	37.6	32.1	31.5	32.1
Average Wing t/c	0.1231	0.0950	0.0965	0.0963
Performance				
Thrust to Weight Ratio	0.28	0.26	0.27	0.29
Wing Loading (lb/ft^2)	131.5	125.1	127.8	127.6

SBW Savings

- Based on Cantilever Baseline optimum results

	Fuselage Mounted Engines SBW	Wing Mounted Engines SBW	Tip Mounted Engines SBW
Weights (%)			
Calculated Takeoff Weight	-10.0	-14.3	-13.8
Wing Weight	-9.6	-28.5	-29.9
Fuel Weight	-14.1	-16.1	-16.5
Zero fuel weight	-7.7	-13.2	-12.3
Geometry (%)			
Wing Half-Span	2.1	-2.4	-8.4
Reference Area	-5.4	-11.7	-11.2
Aspect Ratio	10.2	7.9	-5.5
Average Wing t/c	-22.8	-21.6	-21.7
Performance (%)			
Thrust to Weight Ratio	-5.6	-3.3	4.2
Wing Loading	-4.9	-2.8	-3.0

Latest Developments

- Constraint studies
  - Need to know the sensitivity of the designs with respect to constraints
- Double deck fuselage design
- Flexible wing sizing
  - Incorporation of passive load alleviation into optimization process
- Wing buckling
  - Strut imposes compressive forces on the inboard wing.

Constraint Studies

- Need to determine the sensitivity of designs towards design constraints
- Constraints considered
  - Range
  - Section Cl max
  - Engine out
  - Wing deflection
  - Second segment climb gradient
  - Balanced field length
  - Approach velocity
  - Strut slack load factor
- Lagrange multipliers used to calculate sensitivities

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Logarithmic Sensitivity

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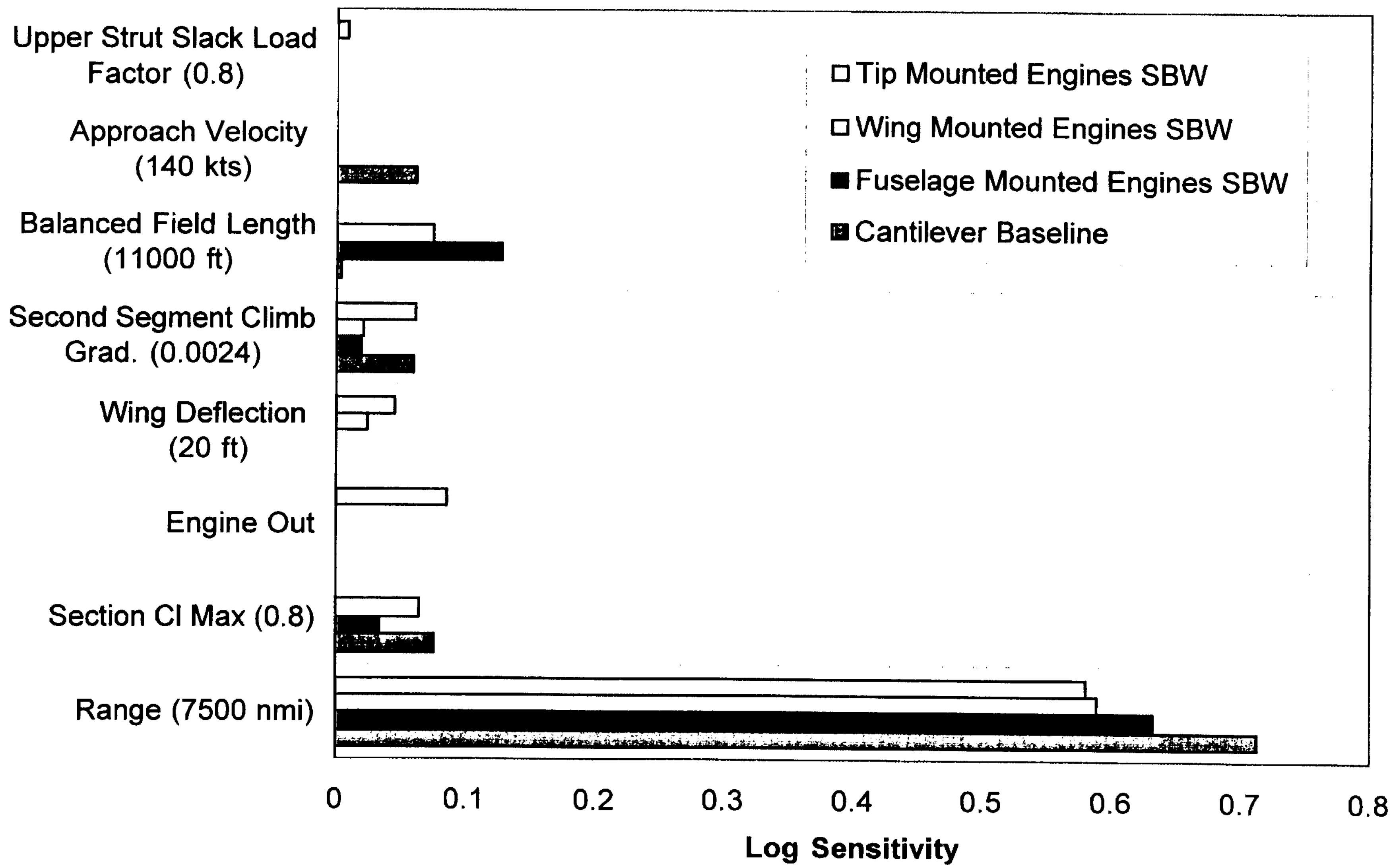

Rankings

	Rankings			
1	**Cantilever Optimum**	**Fuselage Mounted Engines SBW**	**Wing Mounted Engines SBW**	**Tip Mounted Engines SBW**
2	Range	Range	Range	Range
3	Section Cl Max	Balanced Field Length	Balanced Field Length	Engine Out
4	Approach Velocity	Section Cl Max	Section Cl Max	Second Segment Climb Gradient
5	Second Segment Climb	Second Segment Climb Gradient	Wing Deflection	Wing Deflection
6	Balanced Field Length	Upper Strut Slack Load Factor	Second Segment Climb Gradient	Upper Strut Slack Load Factor
7			Upper Strut Slack Load Factor	Section Cl Max

Unscaled Sensitivities

Constraint	Unscaled Sensitivities (lbs/*)			
	Cantilever Optimum	Fuselage Mounted Engines SBW	Wing Mounted Engines SBW	Tip Mounted Engines SBW
Range (7500 nmi)	57.74	46.12	40.53	41.22
Section Cl Max (0.8)	-57238.13	-23312.63	-41368.00	85.92
Engine Out	0.00	0.00	0.00	469357.89
Wing Deflection (20 ft)	0.00	0.00	-630.55	-1197.90
Second Segment Climb Grad. (0.0024)	1518637.50	452233.33	457766.67	1335883.33
Second Segment Climb Grad. (lbs/deg)	26520.49	7897.51	7994.14	23328.99
Balanced Field Length (11000 ft)	-0.16	-6.34	-3.51	0.00
Approach Velocity (140 kts)	-264.71	0.00	0.00	0.00
Upper Strut Slack Load Factor (0.8)	0.00	-556.56	-738.05	-5411.56

- Sensitivities are valid within 5% of the optimum design
- The SBW is generally less sensitive than the cantilever optimum

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Double Deck Fuselage Design

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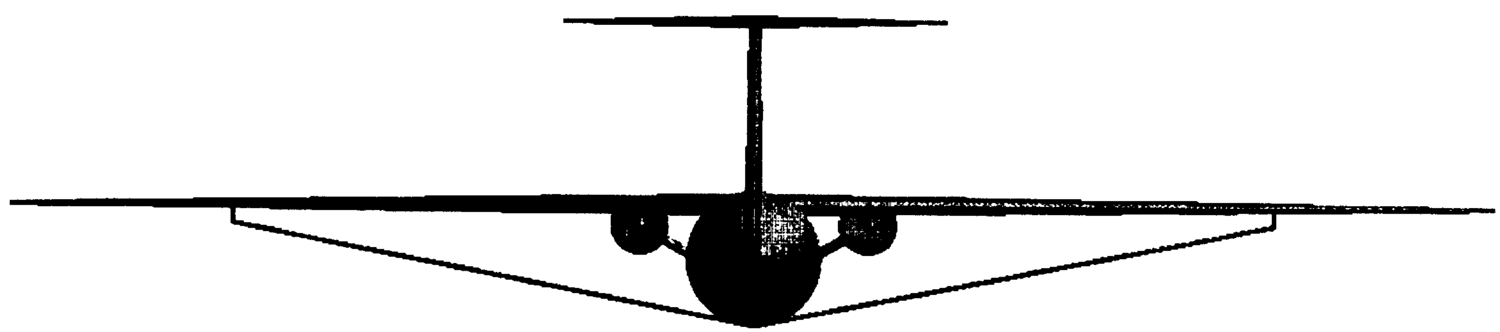
- Probable improvement in TOGW savings due to larger wing-strut separation
- Seat and cargo layout was investigated to determine dimensions of the fuselage
- A double bubble design was adopted giving an extra 5 ft of wing-strut separation



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Double Deck Layout

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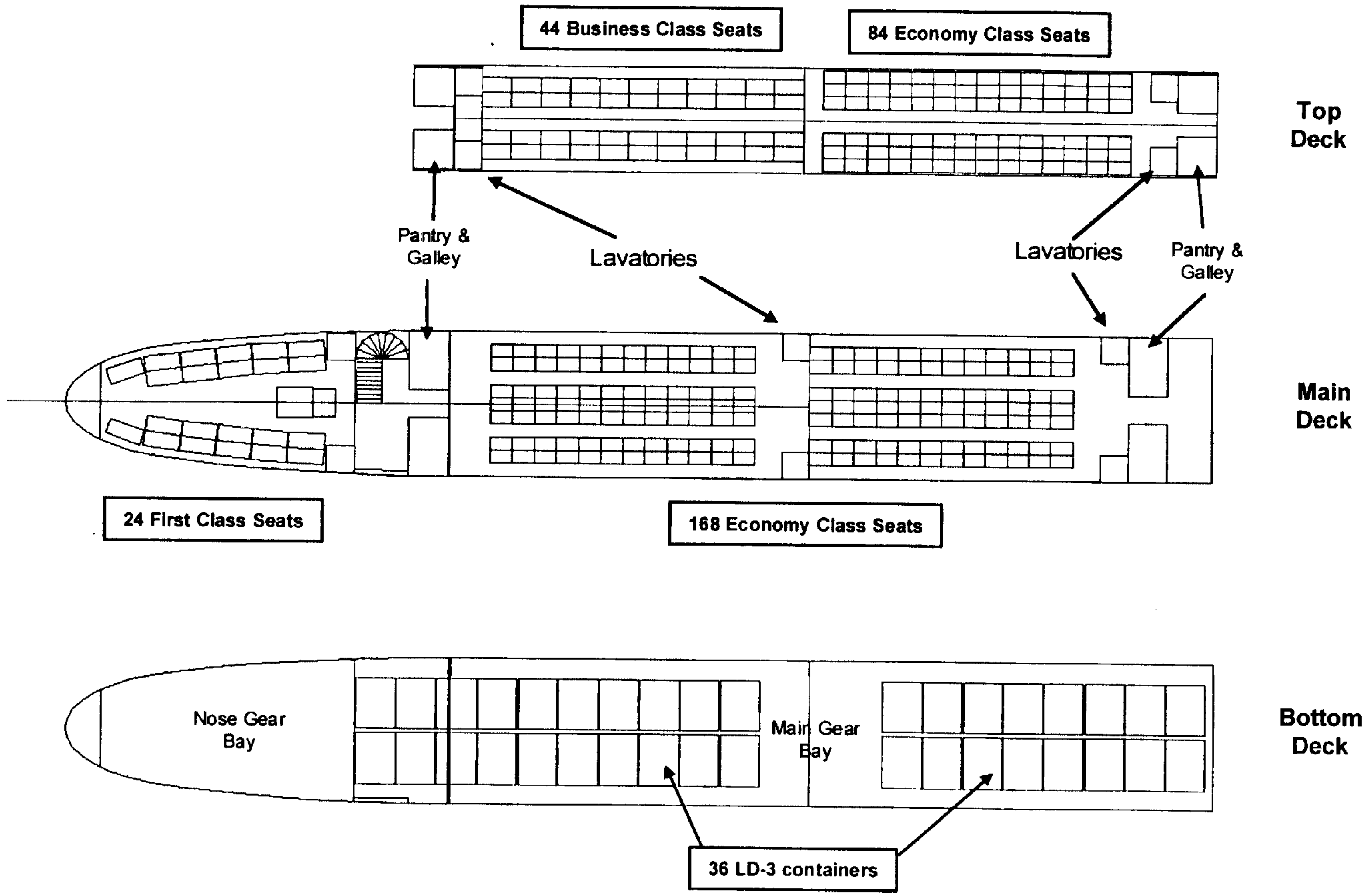
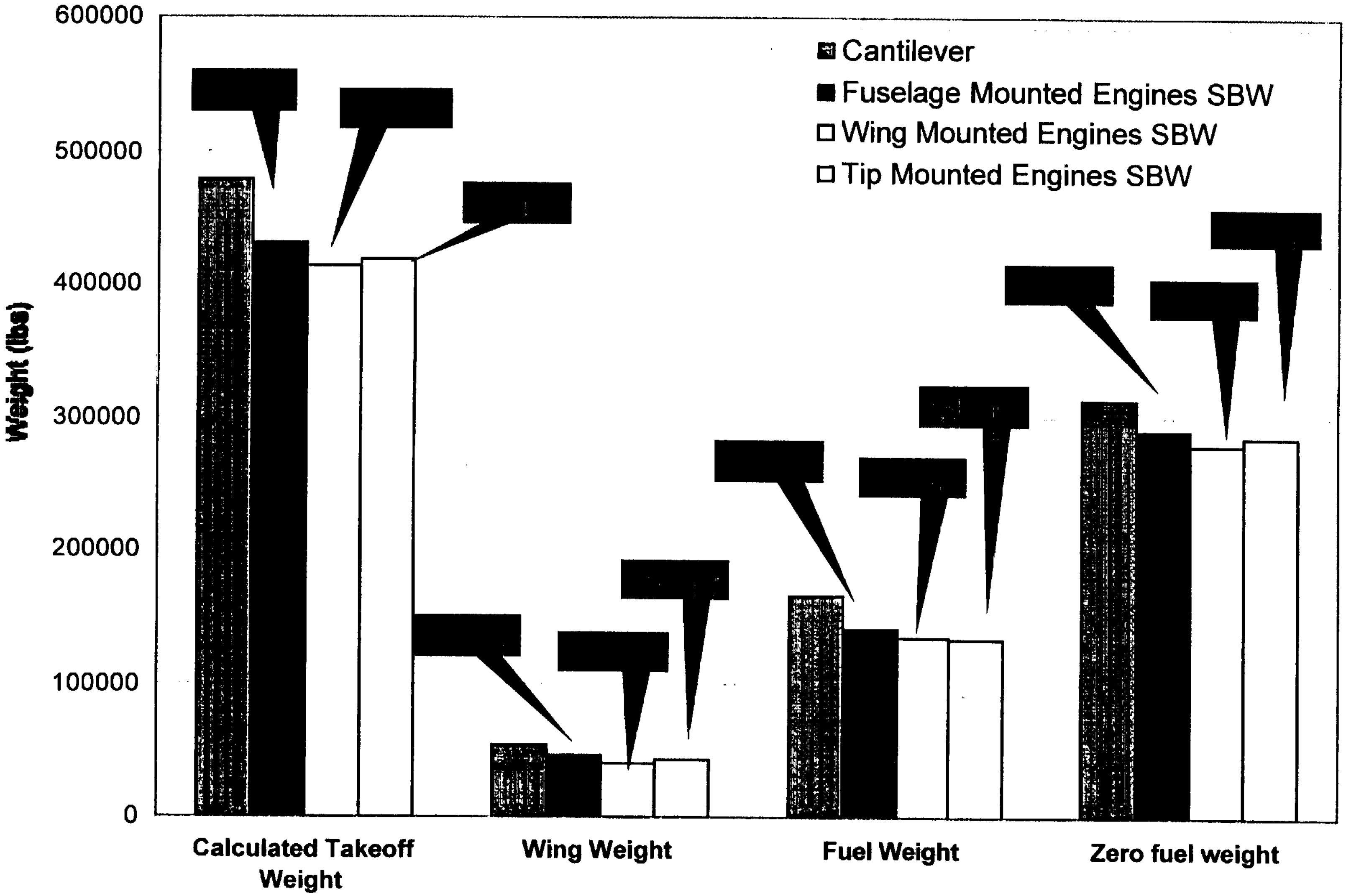


Double Deck Results



Lift Distribution of the Flexible Wing

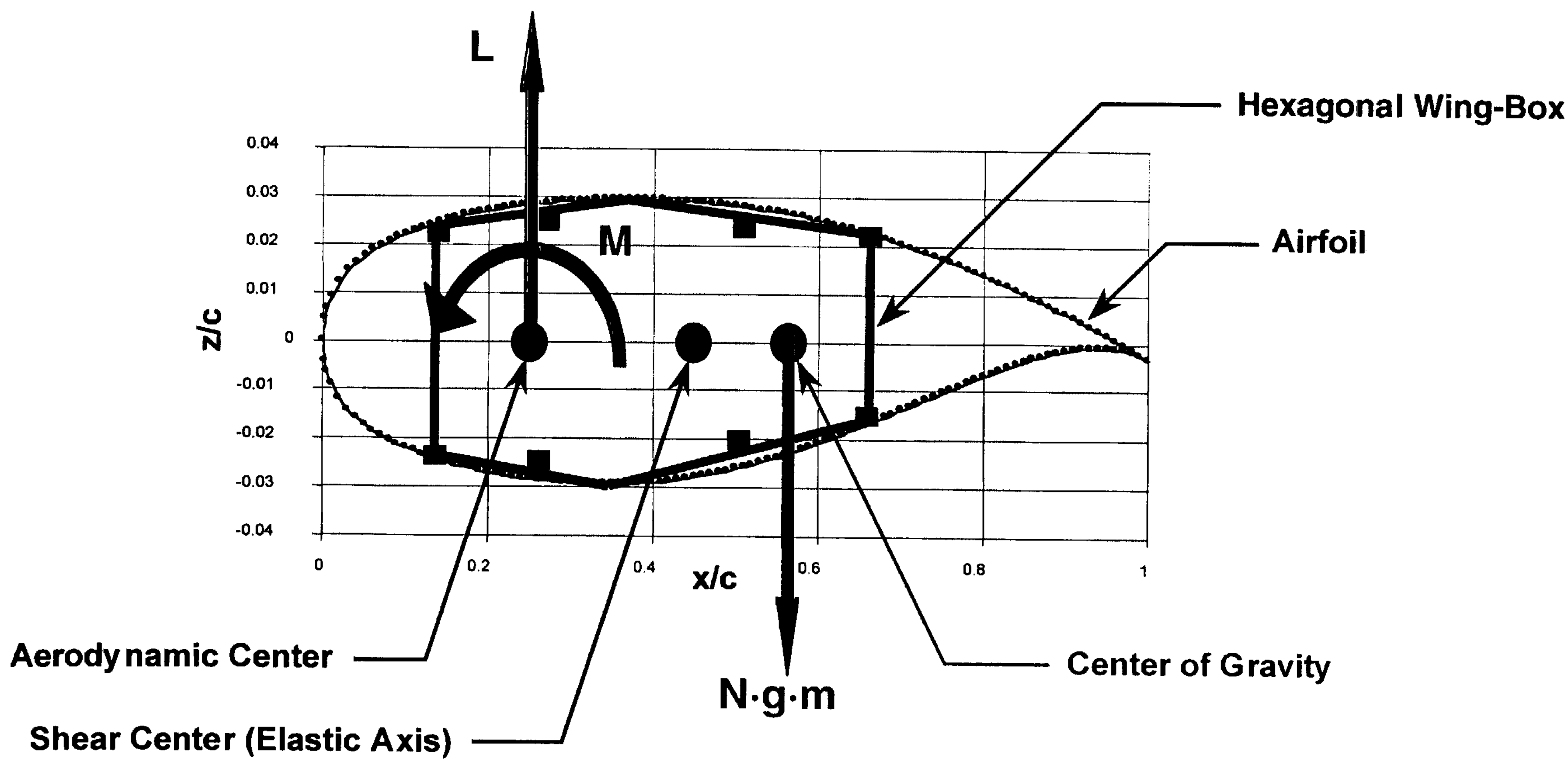
- Wing sizing from rigid lift distribution gives inaccurate results for maneuver spanload (2.5g and -1g)
- Lift redistribution due to wing deformation
- Torsional and bending stiffness from hexagonal wing box
- Calculation of wing deformation → Vortex Lattice Method
- → Recalculation of wing weight from flexible wing spanloads

Flexible Wing Sizing

- Structural wing model
  - Hexagonal wing box with
  - Optimized area/thickness ratios for spar webs, spar caps, stringers, and skins
  - High accuracy (based on Lockheed wing sizing experience)
  - Piecewise linear load representation
  - Validated with Lockheed C-5B and Boeing 747-100 data
- Aerodynamic model
  - Vortex lattice method
  - 40 spanwise and 1-10 chordwise vortex panels (single analysis or optimization mode)
  - Consideration of panel twist and dihedral
  - Validated with several standard test cases

Hexagonal Wing Box

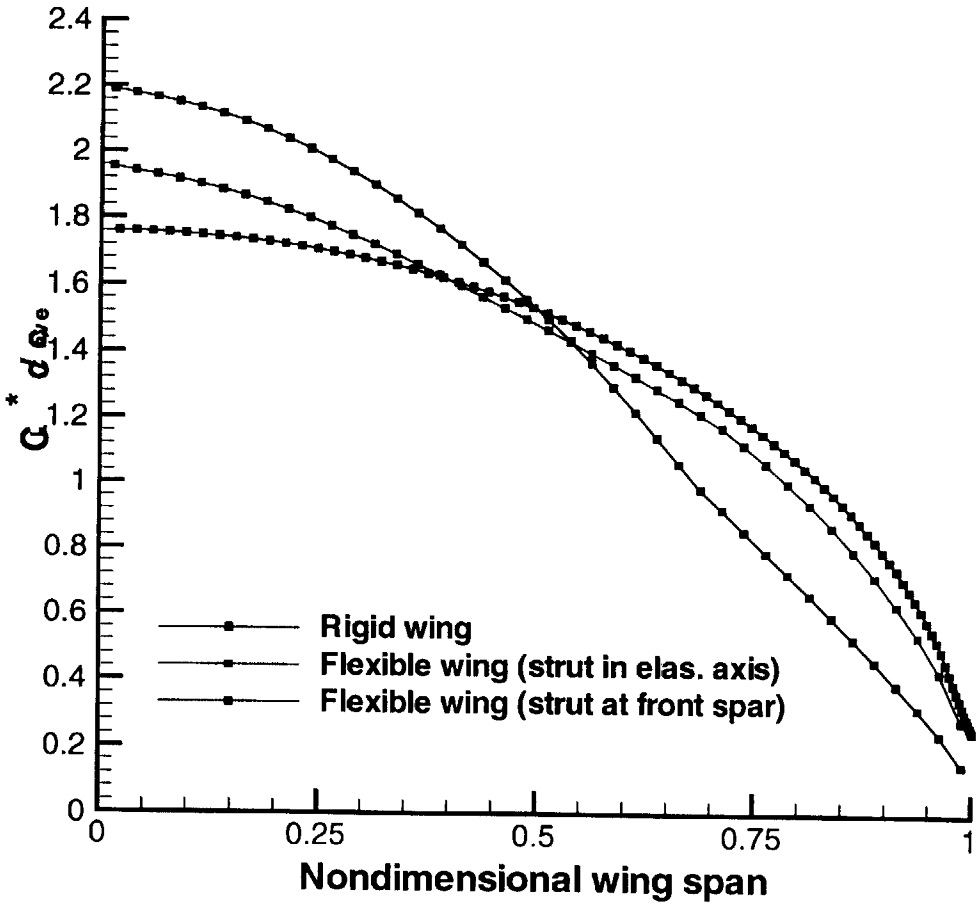
- Sectional forces and moments on the wing box



Maneuver Load Alleviation

- Fuselage mounted engine design
- Reduction of outboard wing angles of attack due to upward bending (wash-out)
- Aerodynamic loads are shifted inboard
- SBW load alleviation weaker due to reduced wing box torsional stiffness
- Further load alleviation possible by employment of strut moment (chordwise strut offset)

Normalized lift coefficients
$C_L \cdot c/c_{ave}$ at 2.5g



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Flexible Wing Weight Calculation

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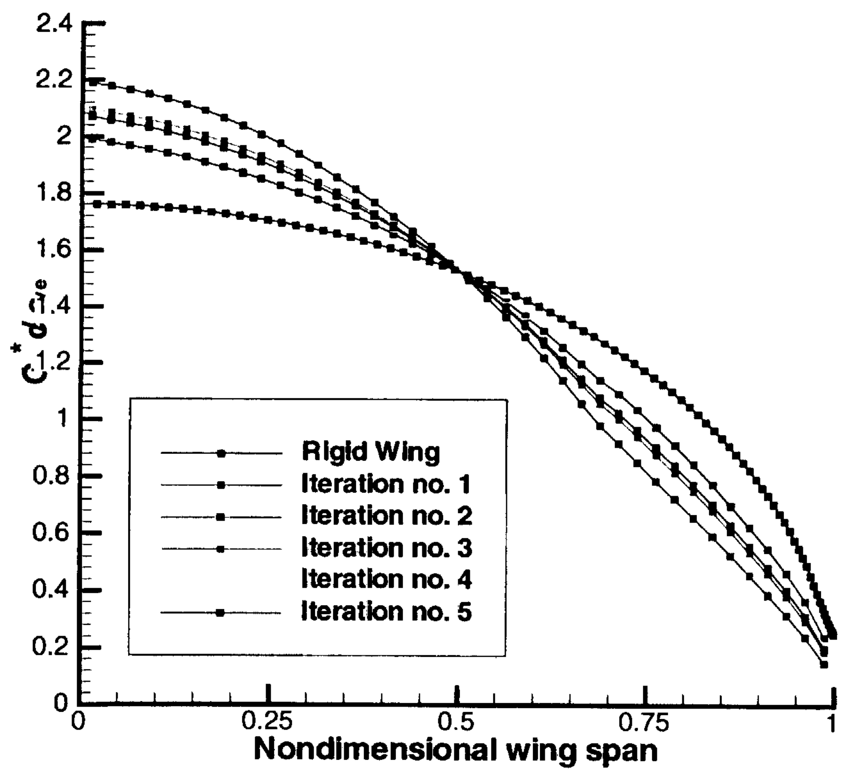
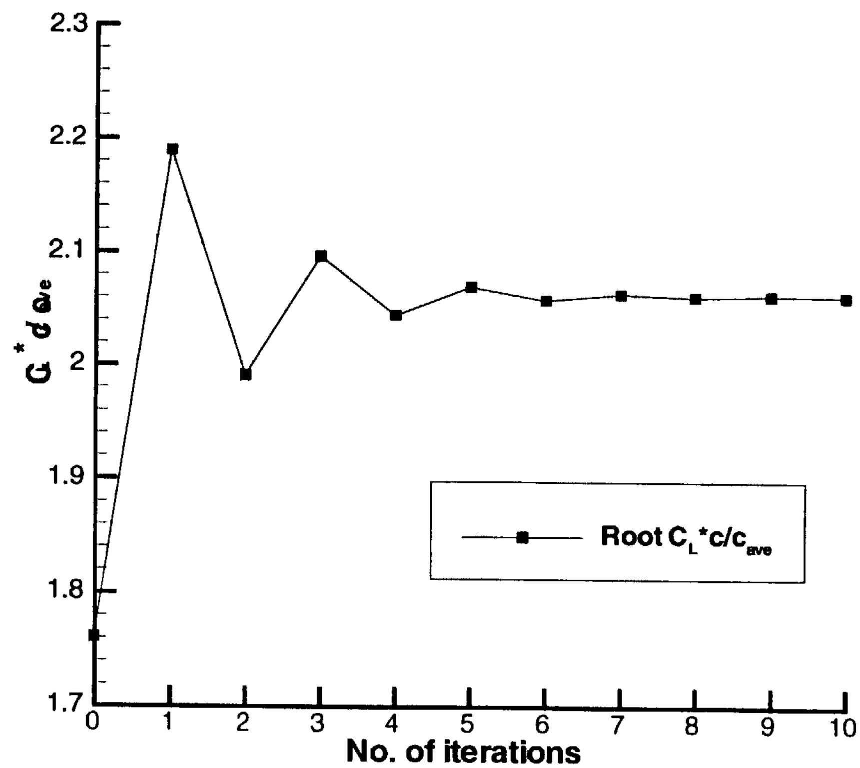
- LMAS Configuration (Strut at Wing-Box Front Spar)

Spanload



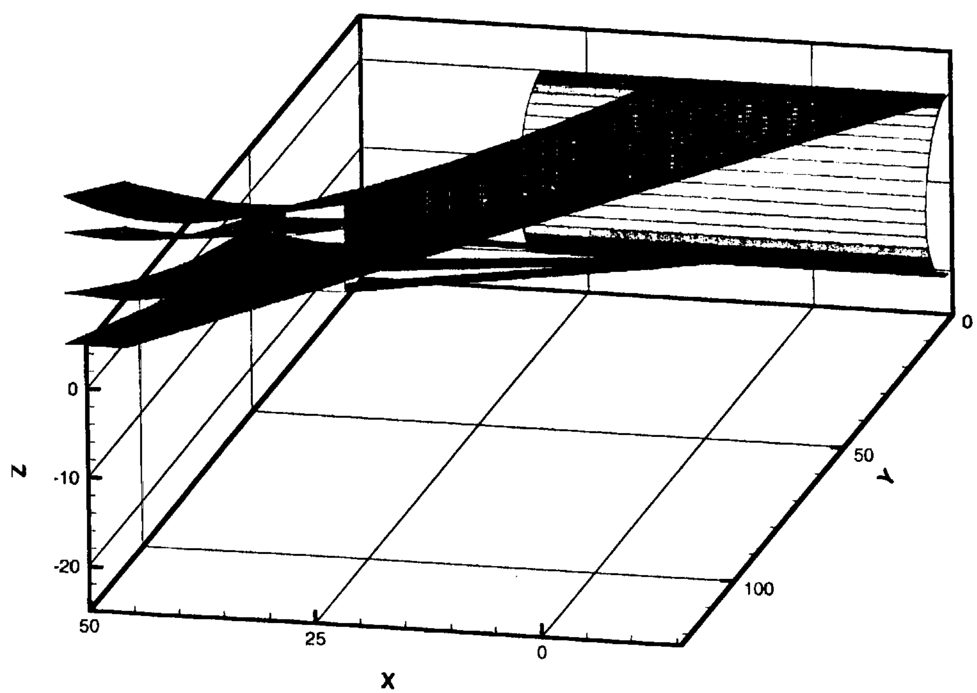
C_L at Wing Root - Convergence History



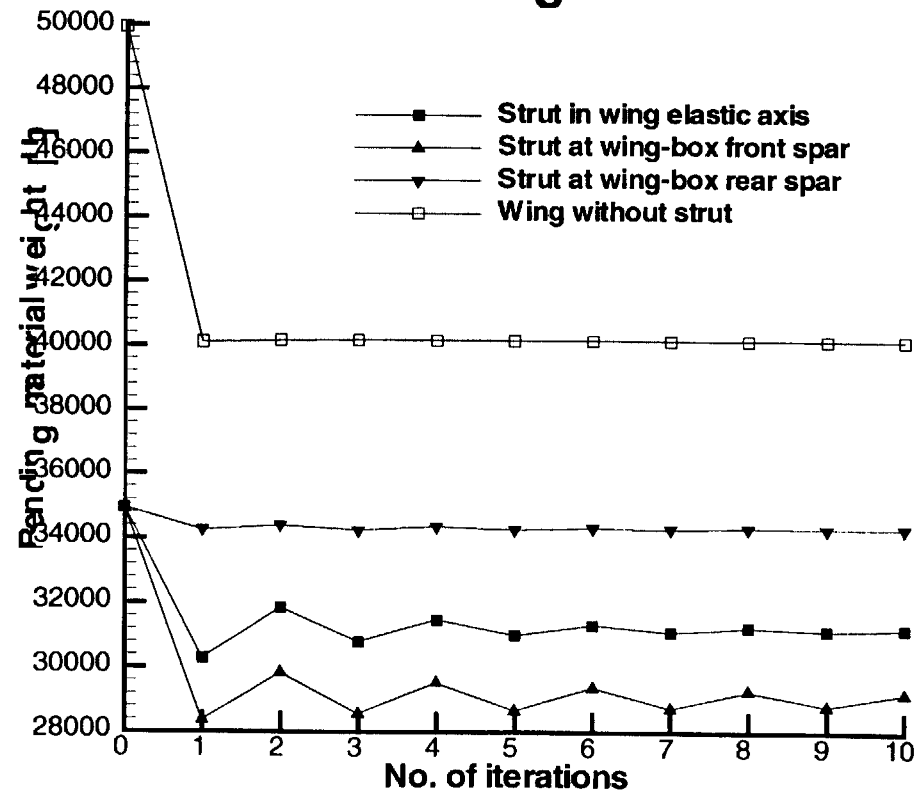
Maneuver Load Alleviation

- Fuselage mounted engine design (Influence of chordwise strut offset)

Wing deformation at 2.5g



Wing bending weight convergence



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Significance of Flexible Wing Sizing

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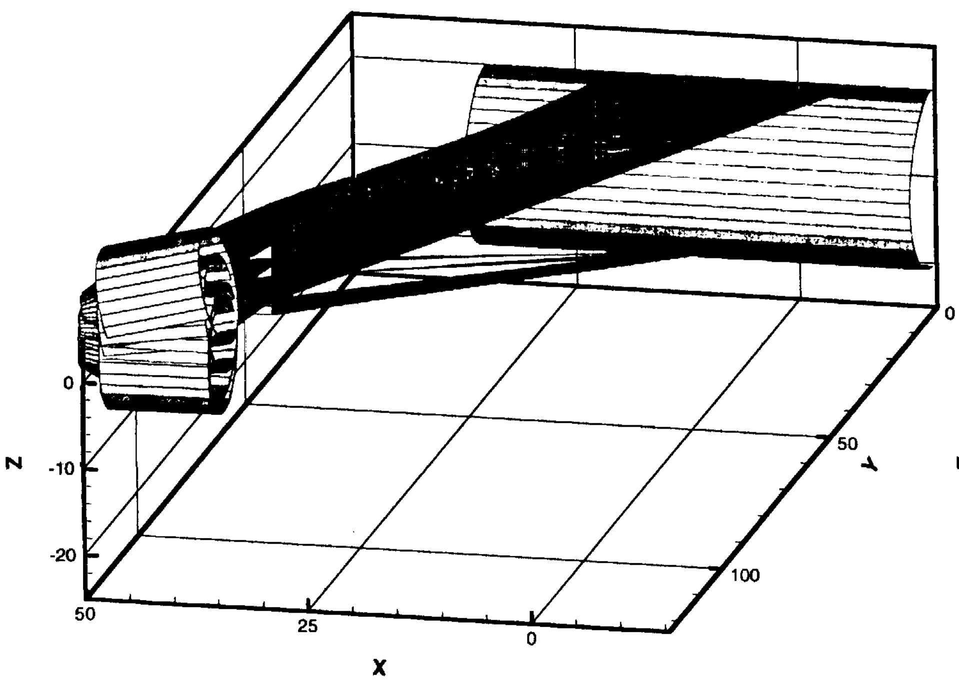
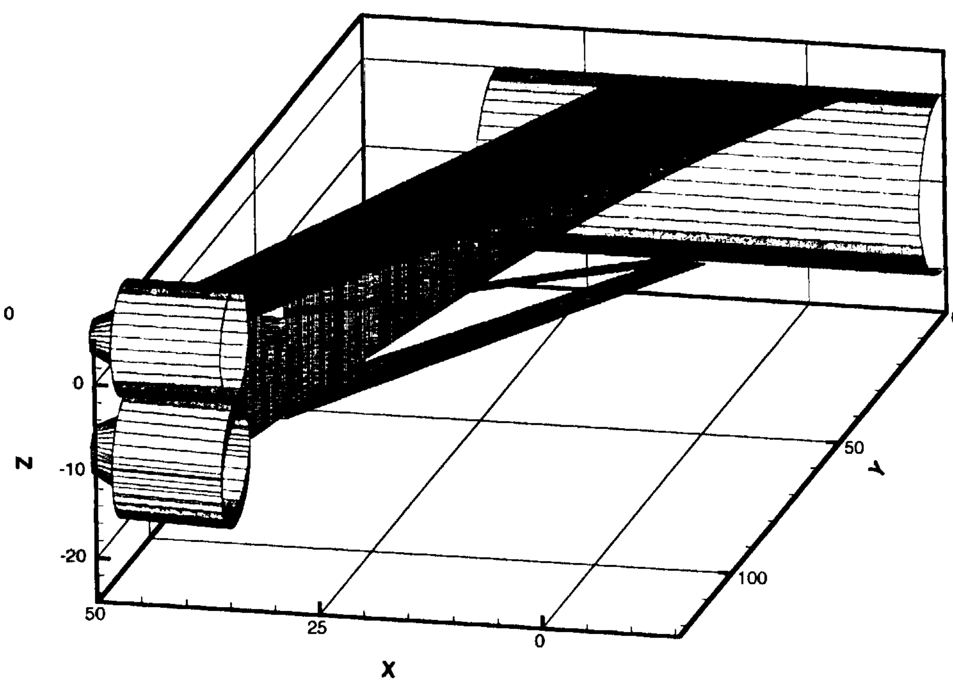
- Wing sizing using flexible wing loads is more accurate
- Impact on MDO results is comparably small
- Rigid wing sizing gives conservative results for cantilever wing, fuselage mounted and underwing mounted engines SBW
- But: flexible wing sizing indicates higher wing weights for tip mounted engines SBW

Maneuver Wing Deformation
Tip Mounted Engine Case

2.5g (engine C.G. in el. axis)



-1g (engine C.G. in el. axis)

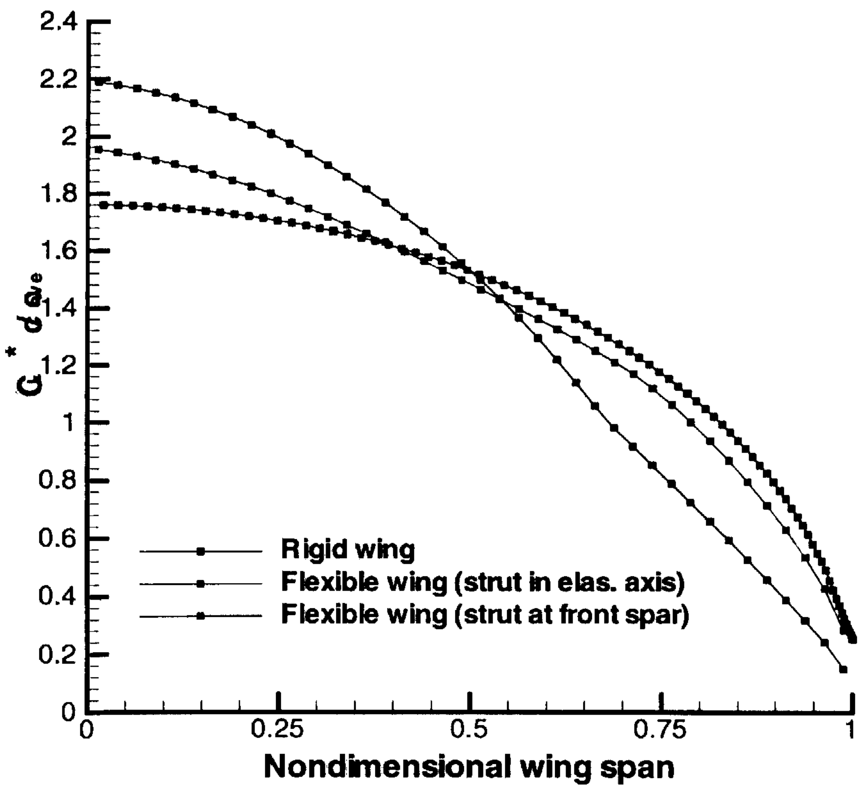


- 2.5g maneuver
  - downward deflection of the outboard wing sections
  - increased outboard wing loading (wash-in!)

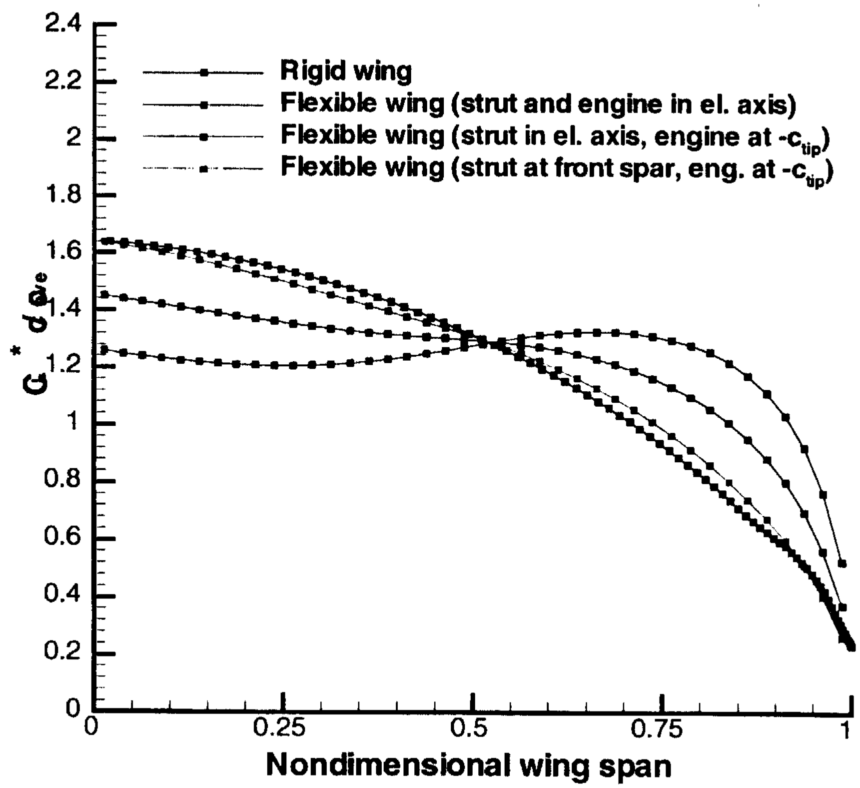
Flexible Wing Lift Distribution

- Normalized lift coefficients $C_L \cdot c/c_{ave}$ at 2.5g

Fuselage mounted engine

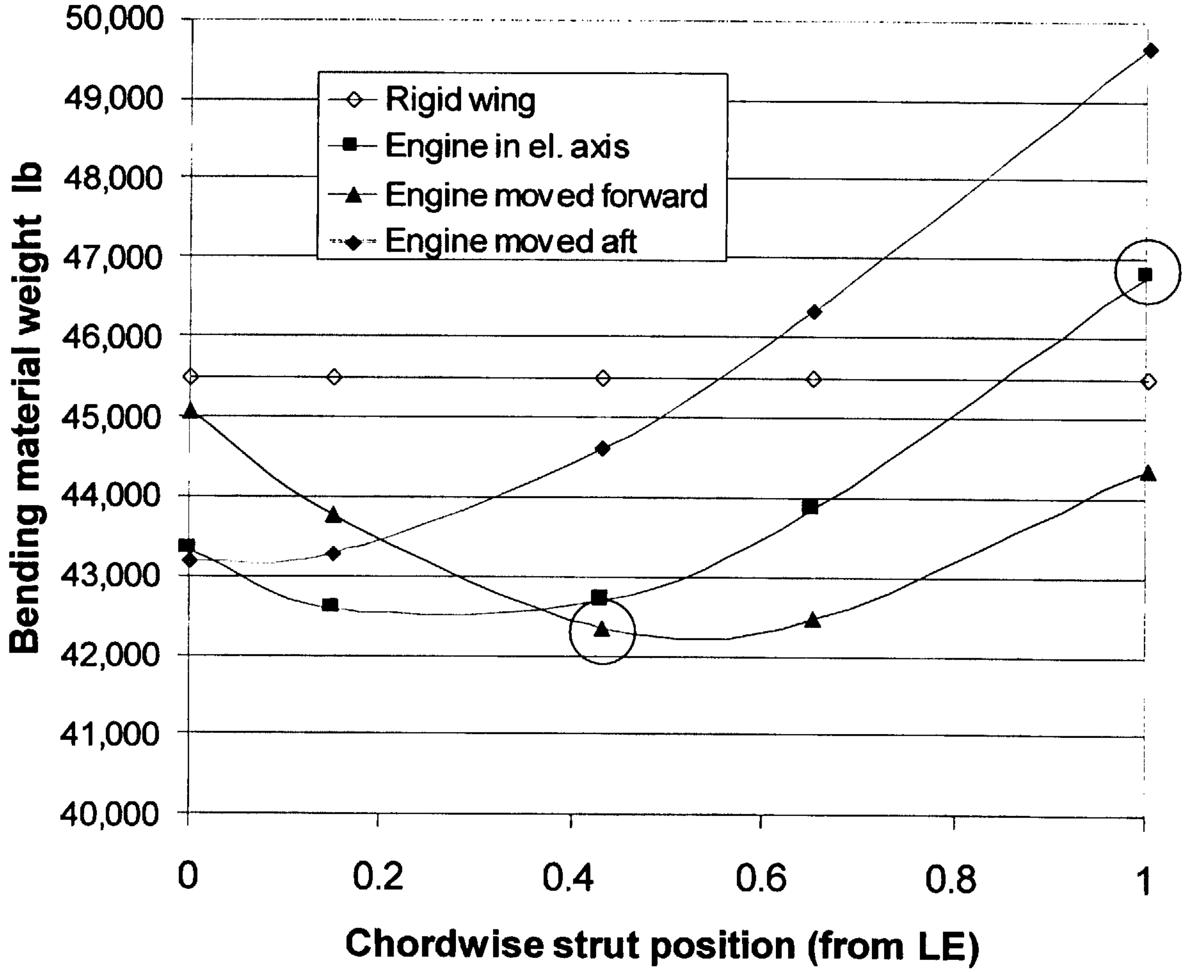


Tip mounted engine



Wing Bending Material Weight

- Reduction of wing loading using chordwise engine and strut position

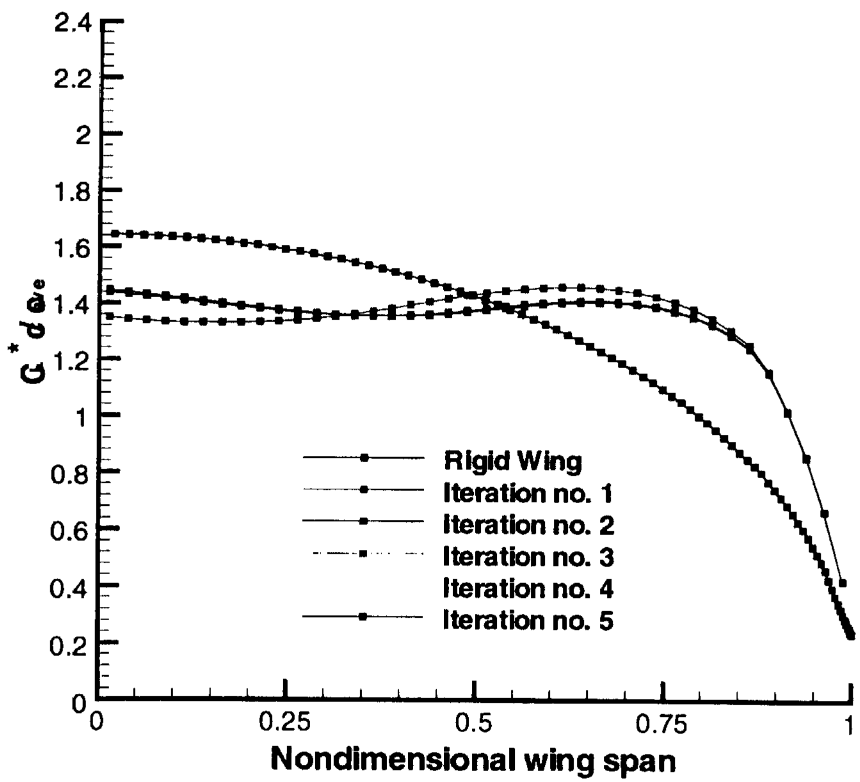


Engine offset = $\pm c_{tip}$

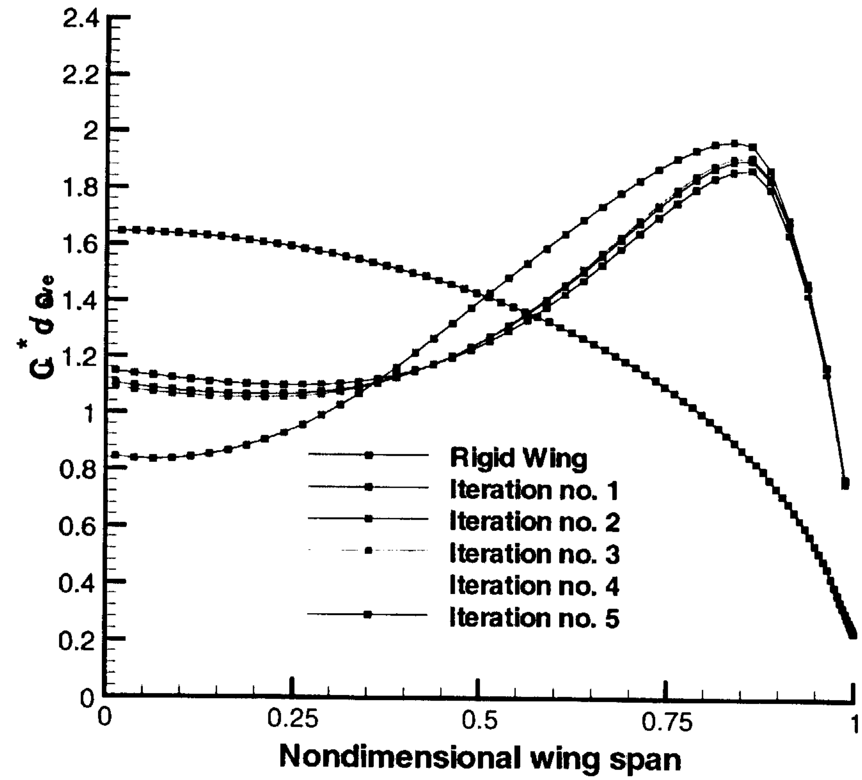
Tip Mounted Engine

- 2.5g maneuver spanload convergence

Lowest weight configuration



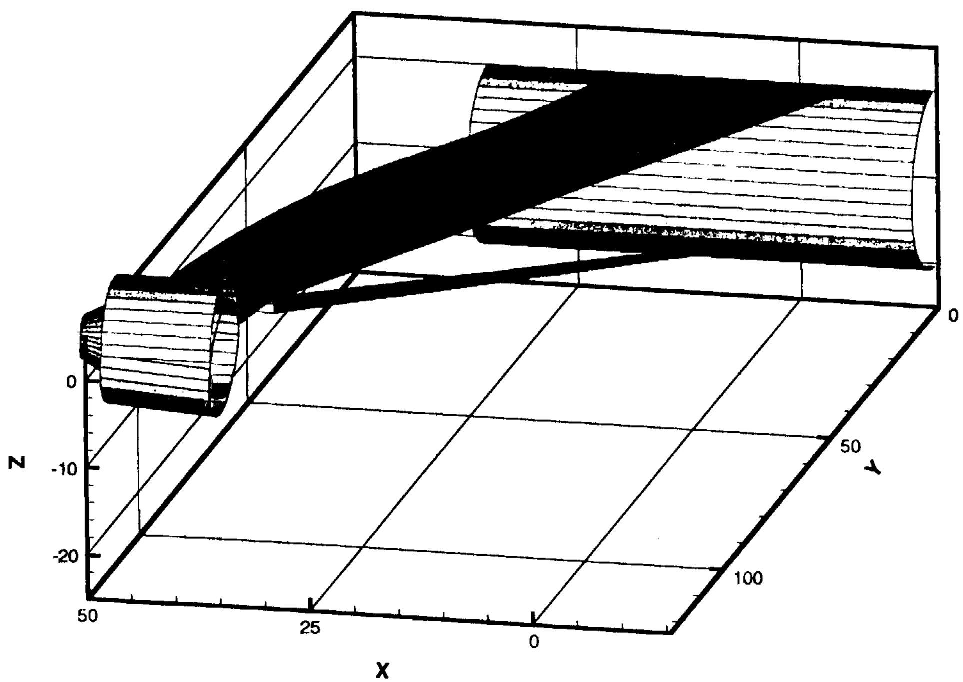
Higher weight configuration



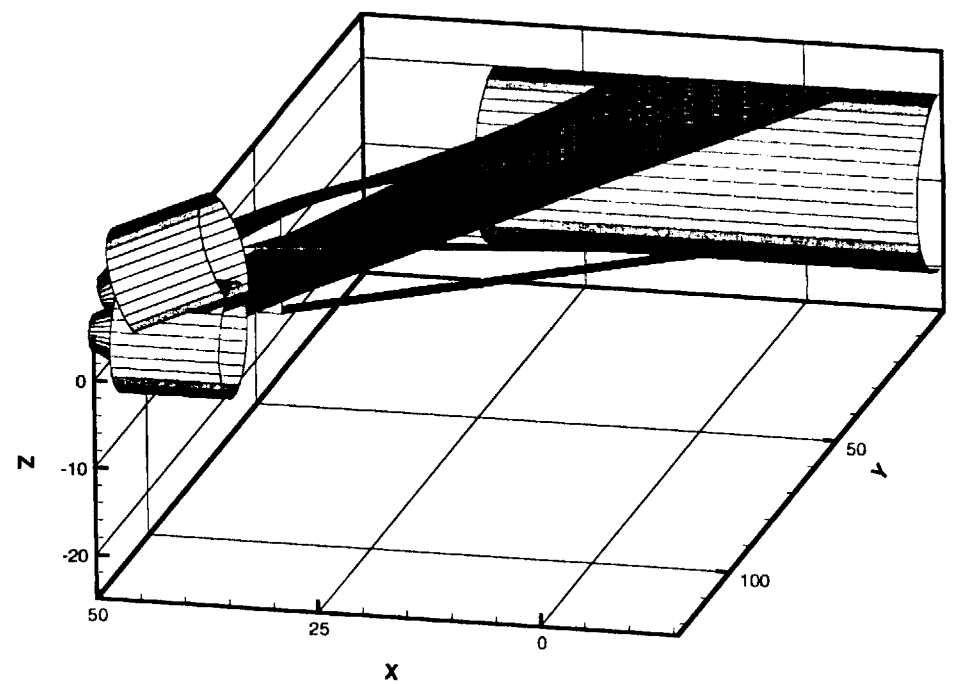
Tip Mounted Engine

- 2.5g maneuver wing deformation

Lowest weight configuration



Higher weight configuration



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Inboard Wing Buckling

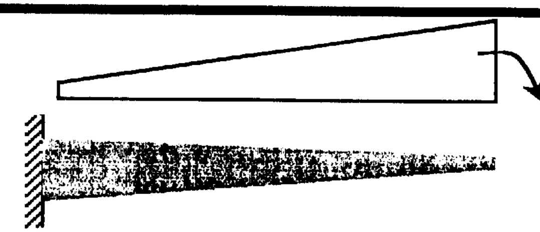
MAD Center
Multidisciplinary Analysis and Design Center for Advanced Vehicles

- Sharp angle between wing and strut
- Very high horizontal strut force component
- Inboard wing compressive loading
- Investigation of inboard wing buckling due to strut force

SBW Wing Buckling Analysis

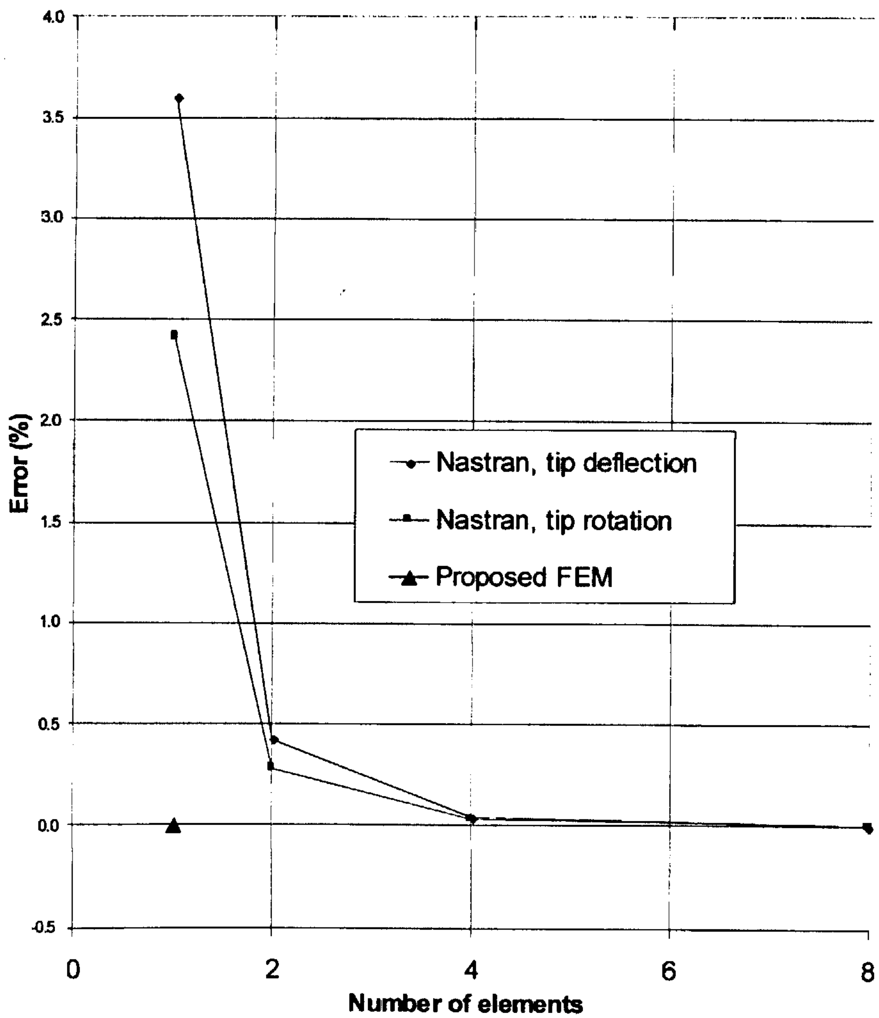
- Developed a finite element code
  - The code should be fast enough as part of the MDO code
  - Analytical formulation for non-prismatic beam elements to increase the accuracy and CPU time
  - The geometric stiffness matrix for buckling analysis is based on the variational principle approach
  - Sensitivity and optimization for the buckling case
- Validation of the finite element code
  - Comparison with Nastran

Validation 1: Cantilever Beam



$$EI(y) = EI_0\left\{+r\,(y/L)^m\right.$$

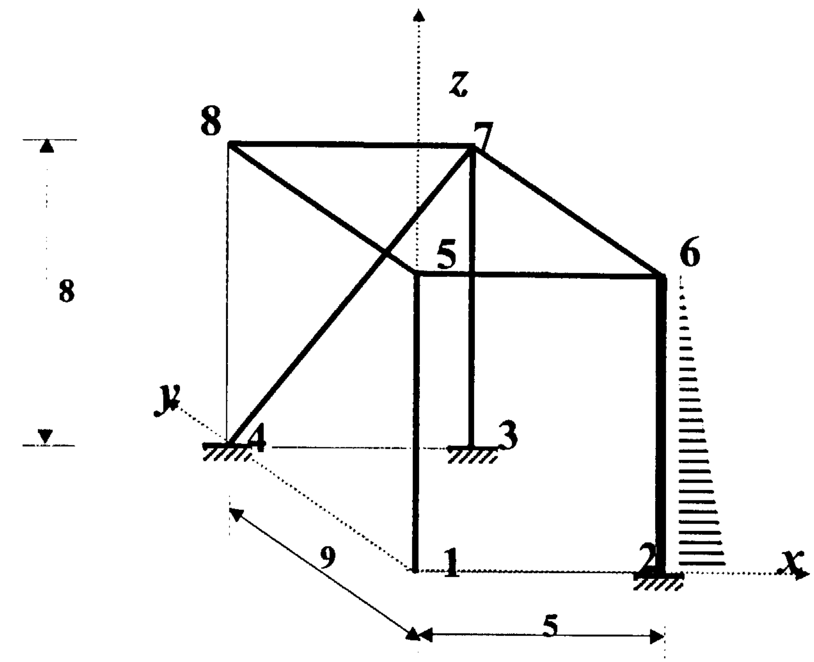
$r = 8,\ m = 1$



Method	n	δ	θ
Exact		43.03081	7.15157
Proposed FEM	1	43.03081	7.15157
Nastran	1	41.47918	6.97917
	2	42.84853	7.13132
	4	43.01138	7.14941
	8	43.02988	7.15147

Validation 4: Frame

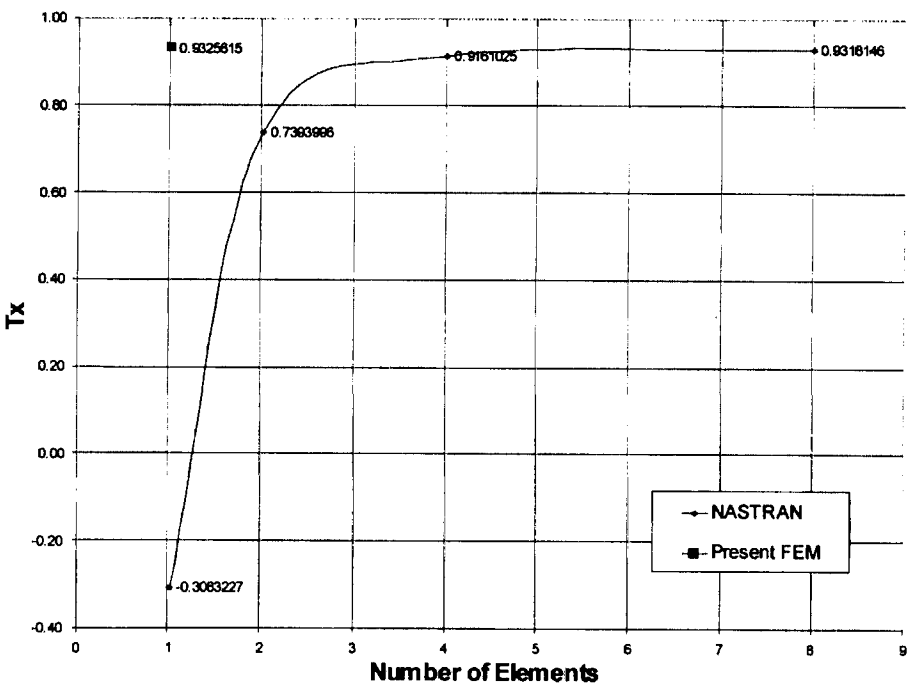
Deformations at Point 1

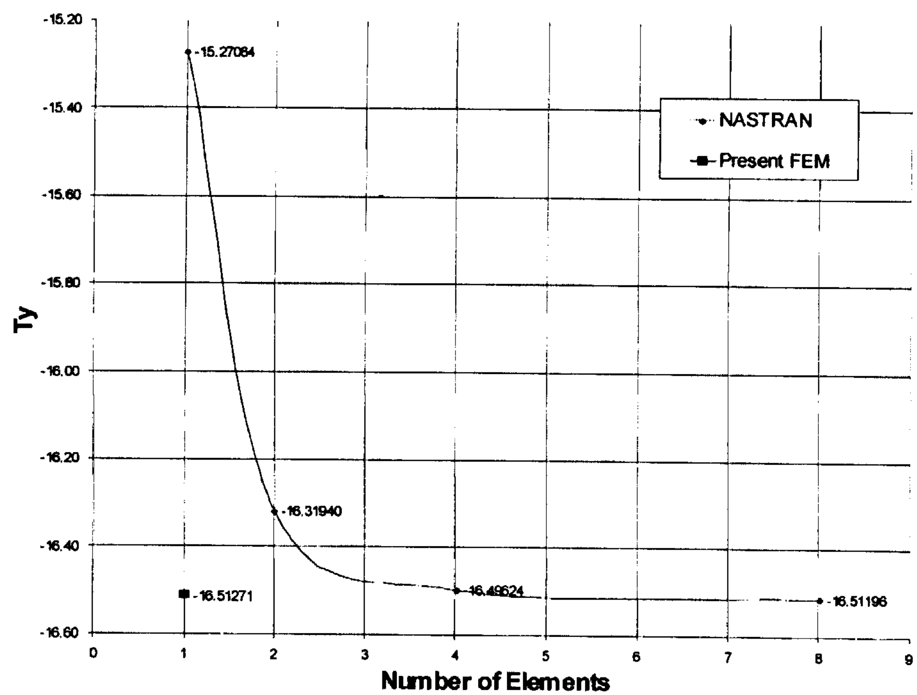


Number of elements used to model the —— CBEAM Element 26

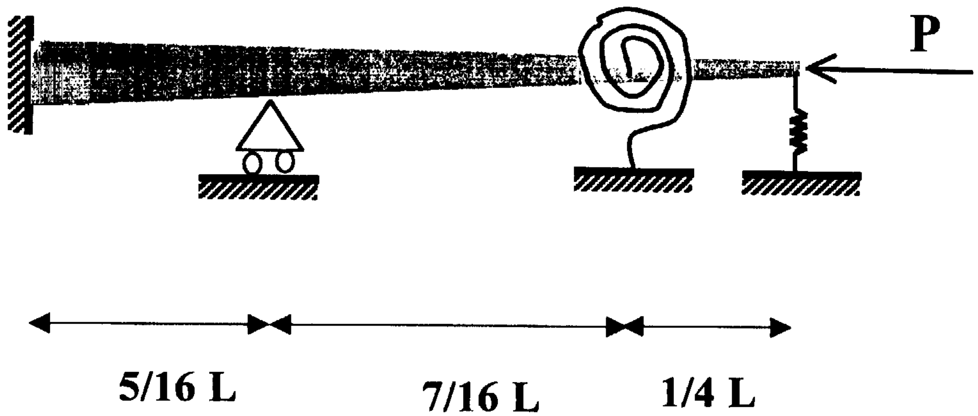
	elements	Tx	Ty	Tz	Rx	Ry	Rz
Nastran	1	-0.3083227	-15.27064	5.8373610	0.1785532	7.0129900	4.4849540
	2	0.7393996	-16.31940	6.1429430	0.1910991	7.3575510	4.8061710
	4	0.9161025	-16.49624	6.1943150	0.1932184	7.4156750	4.8605010
	8	0.9318146	-16.51196	6.1988810	0.1934068	7.4208430	4.8653340
Present FEM	1	0.9325615	-16.51271	6.1990970	0.1934158	7.4210890	4.8655640

Validation 4: Frame





Validation 7: Buckling Analysis



Tapered beam

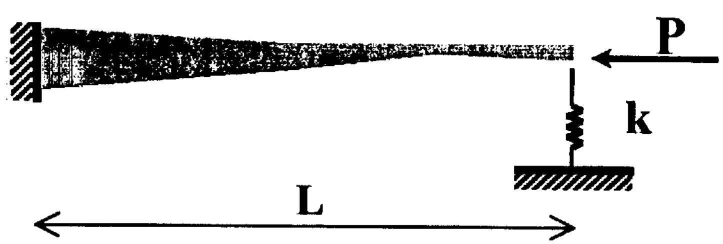
$EI = EI_o\,(1+rx/L)$

$r=8$

Nastran P = 21.405 (16 elements)

Present FEM P = 21.40493227708195

Optimum Beam Stiffness Distribution



$EI = \alpha E A^n$; $n = 1$

$\alpha = (h_{root} + m\,x)^2$; $q = k\,L / P$

$r = h_{root} / h_{tip}$

$\beta^2 = 4P / E$

The optimum buckling load $P_{optimum} = \gamma \dfrac{E\,I_0}{L^2}$

$$\gamma = \frac{(r-1)^4}{r\ln r\left\{\,2(q-1)(r-1) - r\ln r(q-1) - \ln r\,\right\} - (q-2)(r-1)^2}$$

$$A(x) = \frac{\beta^2}{m^2 h(x)} \times$$

$$\left\{ m(q-1)(L-x) + \left(q\frac{h_{root}}{L} + mq - m \right)(L-x)\ln h_{mid} - (q-1-qx/L)h_{tip}\ln h_{tip} - h(x)\ln h(x) \right\}$$

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Variation of the Strut Junction Position

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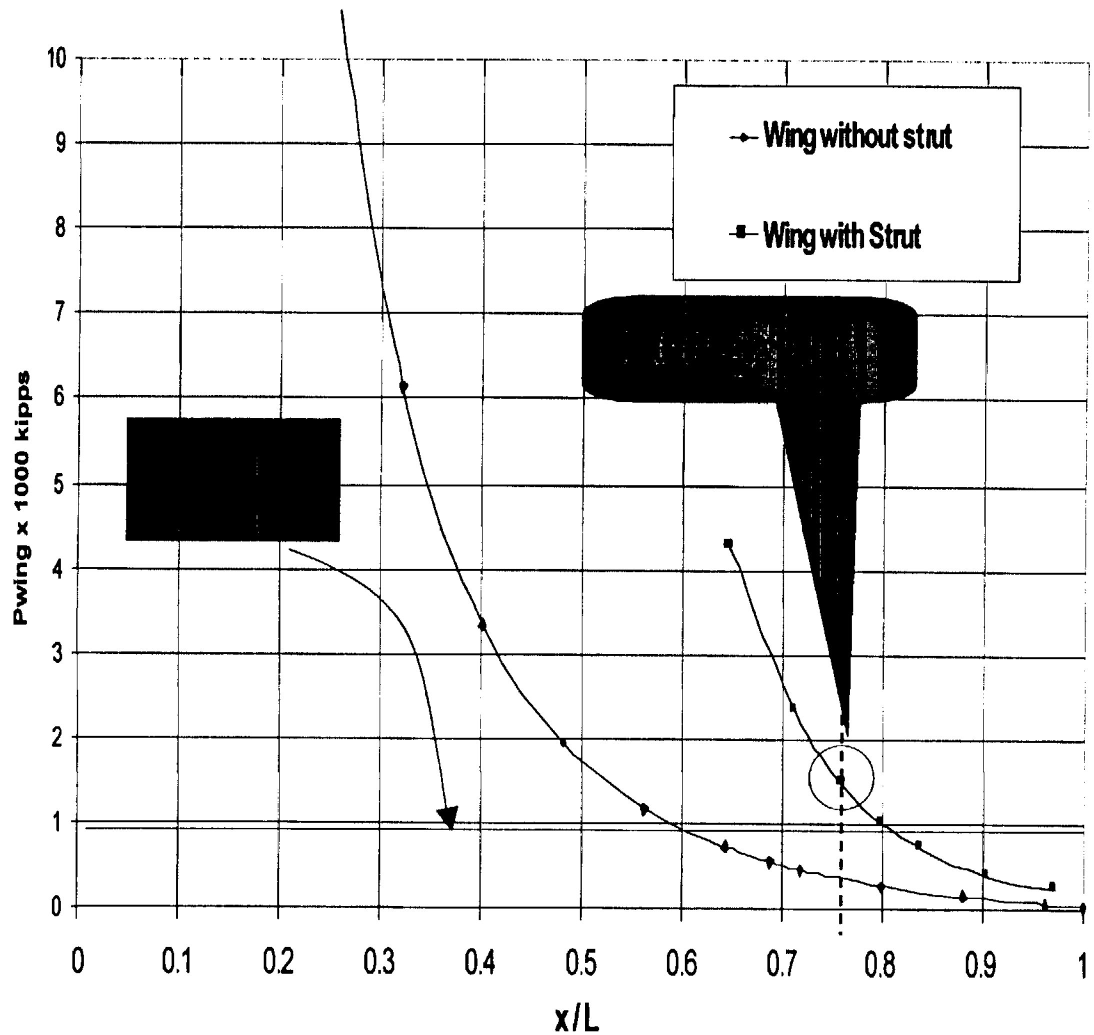
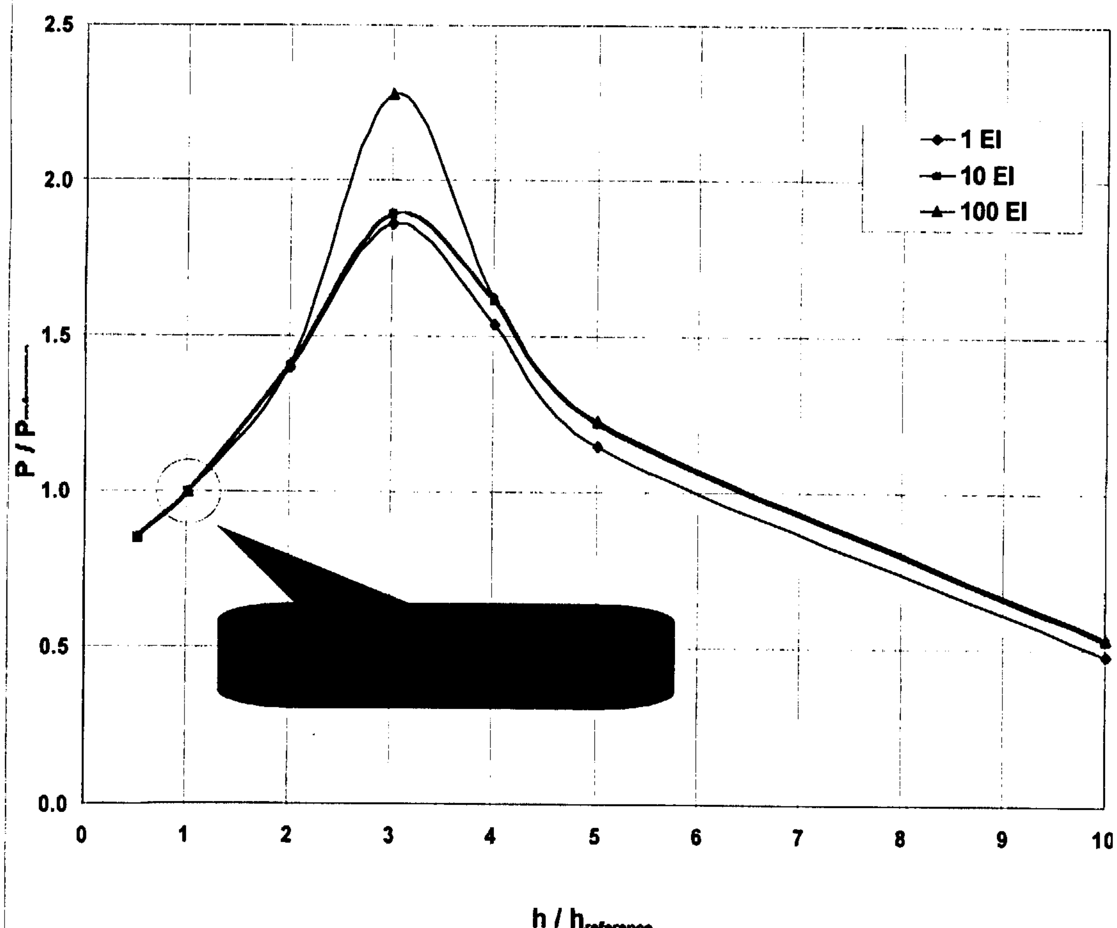
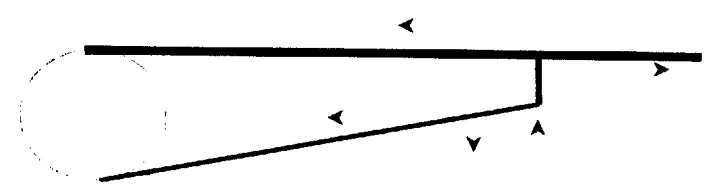


- Assume that the changes of the wing/strut junction position stiffness does not change the wing stiffness
- $P_{buckling}$ increases as the junction moves inboard
- Additional geometric stiffness matrix of the strut increases the buckling load

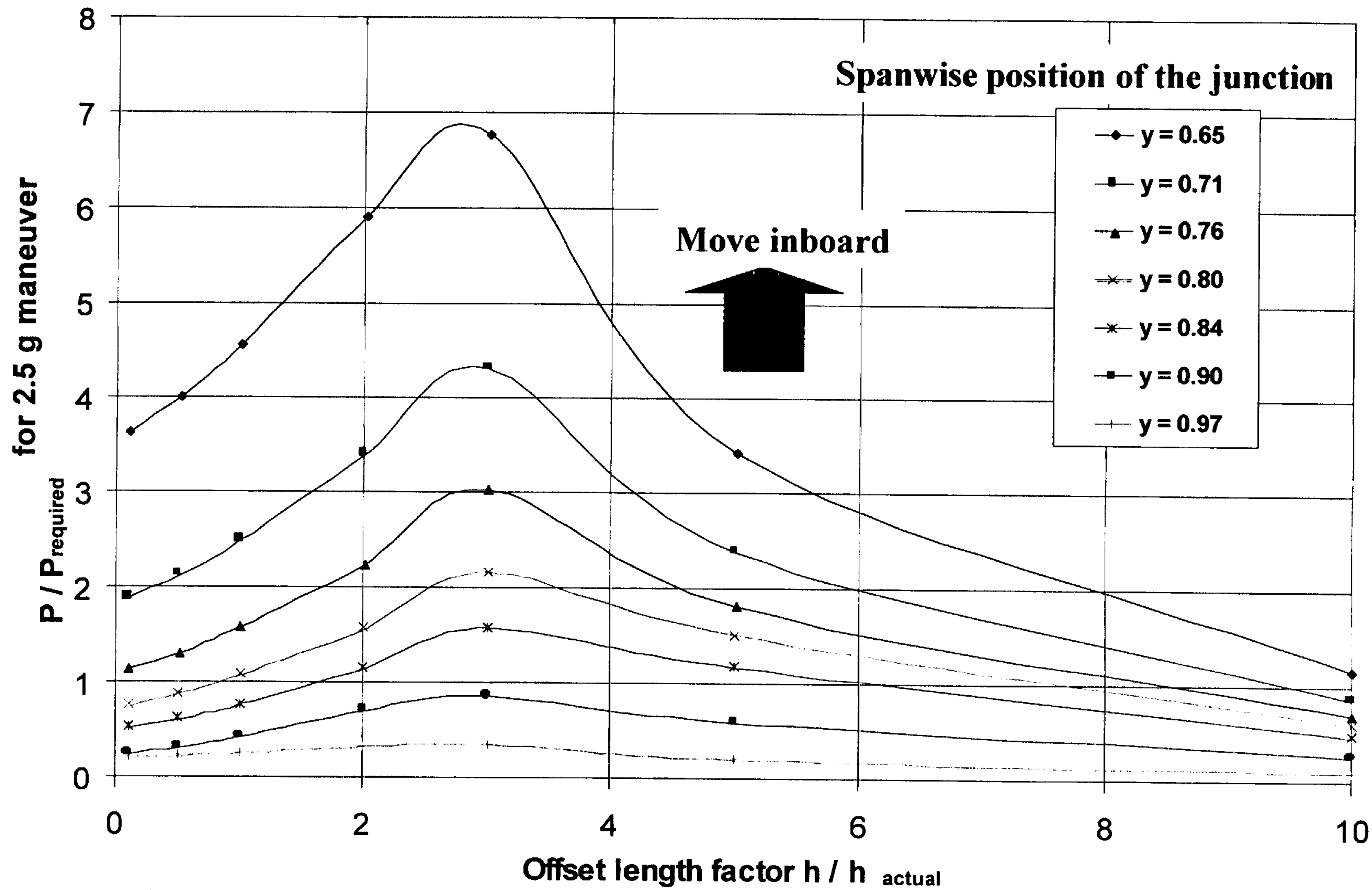
Offset Length Variation



- Config. SF Opt 811, + 2.5 g maneuver
  h = the offset beam length
  $h_{reference} = h_{actual} = 2.21$ ft
- The change of the $P_{buckling}$ is related also to the slope between the strut and wing and the diameter of the fuselage



Offset Length and Position Effects



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Future Work

MAD Multidisciplinary Analysis and Design Center for Advanced Vehicles

- We have submitted a proposal together with NASA Langley and Lockheed Martin for the REVCON (Revolutionary Concepts) project
- REVCON involves building and testing a concept demonstrator within the next three years
- Program phases
  - Phase 1: 9 months
    - $300,000
  - Phase 2: 3 years
    - $20 million