A Brief History of FLO22

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JRV Symposium

Four Decades of CFD:
Looking Back and Moving Forward

San Diego, CA
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OUTLINE

- CONTRIBUTORS
- BACKGROUND
- FLO22 DEVELOPMENT
- FLO22 APPLICATIONS
- FLO22 IN A NUTSHELL
- GRID GROWTH TREND
- FLO22 REAL-TIME RUN

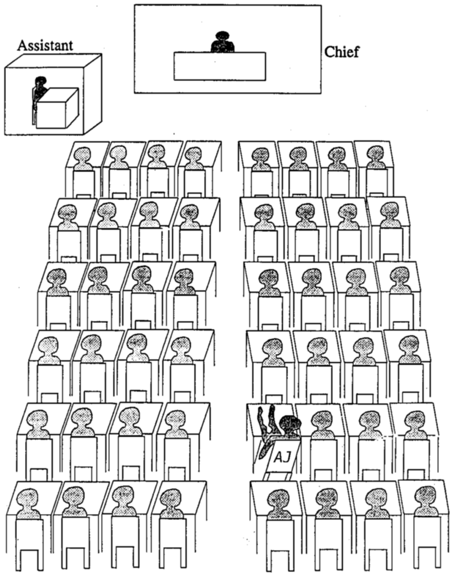
CONTRIBUTORS

- Antony Jameson, Stanford University
- David A. Caughey, Cornell University
- Preston A. Henne, Gulfstream Aerospace Corp.
- Dennis L. McDowell, The Boeing Company
- Pradeep Raj, Lockheed-Martin

BACKGROUND

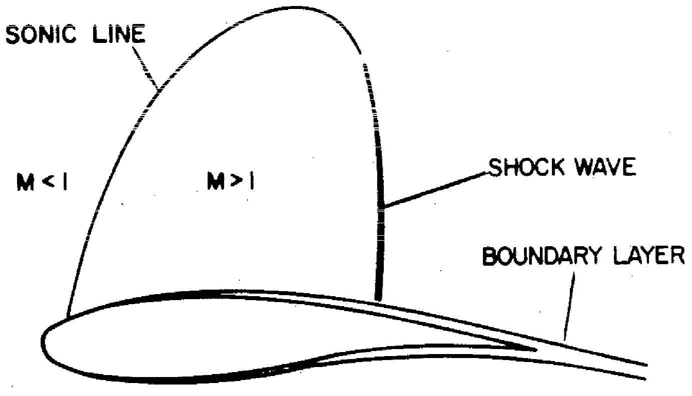
- **SEP 1966: Antony Jameson joins Grumann**
  - Staff to Stu Harvie, Head of Flight Sciences
  - Antony's First Task: Design a Wind Tunnel

Grumann Aerodynamics



BACKGROUND

- **DEC 1969: Wings in Transonic Flow**
  - Harvie-to-Jameson:
    - *We must do something about supercritical wings!*
    - *We cannot rely on Whitcomb's file for design!*
  - Jameson:
    - *What is a supercritical wing?*



TRANSONIC FLOW PAST AN AIRFOIL

BACKGROUND

- **JAN 1970: Aerospace Sciences Meeting, NYC**
  - Jameson very interested in transonic flows
  - Drove to the ASM each day
  - Papers by Yoshihara and Murman
    - AIAA Papers 70-47 and 70-188, respectively
  - Small crowd at Murman's talk
    - Garabedian & Jameson included
  - Grumann Aero dismisses Murman's paper
    - Not interested in a bi-circular airfoil
  - Jameson pushes to study Murman's method
  - Grumann & Boeing team on the B-1

BACKGROUND

- **MAR 1970: B-1 Coordination with Boeing**
  - Harvie & Jameson visit Seattle
    - Meet with Murman & Rubbert
    - Murman studying a symmetric Korn airfoil
  - Then Jameson visits Douglas Aircraft
    - Meets with Malcolm James
    - Discusses Malcolm's inverse design method

BACKGROUND

- **APR 1970: Jameson Visits NYU**
  - Primarily talks with David Korn
    - Graduate student of Garabedian's
  - First introduction to Paul Garabedian
- **APR 1970: Korn Consultant to Grumann**
  - Hired by Grant Hedrick, VP Engineering
    - 20 days at $150 per day
  - Reports to Bill Murphy, Head of Aero
    - Jameson left out-of-the-loop
    - Murphy did not want Jameson second-guessing him

BACKGROUND

- **JUN 1970: Jameson begins to Code**
  - Cedrick Sells, RAE
    - ∗ Subsonic compressible code based on stream function
    - ∗ Transformed stream function by conformal mapping
  - Jameson adopts conformal mappings for meshes
    - ∗ Theodorsen method: Airfoil → perfect circle
    - ∗ Malcolm coded Lighthill's method, ref. Thwaits
  - FLO1: Based on Theodorsen
  - FLO2: Based on Derivative Conformal Mapping
  - SYN1: FLO2 in reverse
    - ∗ Inverse design method
    - ∗ Lighthill with Cp vs S, instead of Cp vs Θ

BACKGROUND

- **Late 1970: Coding continues**
  - FLO4: Based on Sells stream-function method
    - Could not resolve which root to take
  - Switched to using the potential equation
  - FLO5: Subsonic code
  - FLO6: Transonic code
    - Murman's scheme in Θ in the circle plane
    - Jameson not fully satisfied with this approach
    - Later, retrofitted with rotated difference scheme

BACKGROUND

- **1971: Coding continues**
  - FLO7: Axisymmetric version of FLO6
    - Computed solutions about sphere & ellipsoids
    - Print-outs of these still exist
  - Jameson thinks FPE still too costly for 3D
    - Backs off full-potential & investigates small-disturbance
  - FLO8: 2D small-disturbance code
  - FLO9: ???
  - FLO10: 3D small-disturbance code
    - Similar to Bailey-Ballhaus code
    - Jameson never published anything on FLO10

BACKGROUND

- **JAN 1972: Garabedian's Invitation to NYU**
  - Grant for 3 month visit available to Jameson
    - ∗ Ginky Daforno does not want Jameson to go
    - ∗ Claims he will be a full professor within 2 years
  - Takes a leave-of-absence from Grumann
  - Works for Garabedian
    - ∗ Paul tests Antony: Map a square to a circle
  - Garabedian offers Jameson a job at NYU
    - ∗ Senior Research Scientist
    - ∗ Salary $\sim$ Grumman $-$ some benefits
  - Jameson returns to Grumann for a few months

BACKGROUND

- **SEP 1972: Jameson Moves to NYU**
  - Teaches mathematics during fall semester
    - ∗ Asked to do this with 3-days notice
    - ∗ Graduate Numerical Analysis, ref. Isaacson & Keller
  - Officially works for Garabedian on 2 grants
    - ∗ Whitcomb grant: Hodograph-based shock-free airfoils
    - ∗ RT Jones grant: Oblique wings
  - Develops rotated-difference scheme
    - ∗ Retrofits FLO6 & FLO7 with rotated-difference scheme
  - Courant Institute gets a CDC 6600
    - ∗ Seymour Cray's first computer
    - ∗ Speed: ∼1 MFLOP
    - ∗ Core: ∼1 MB: 131K x 64-bit words

BACKGROUND

- **Fall 1972: Garabedian's Push to 3D**
  - Paul: *It's time to write a 3D Yawed-Wing code*
  - Paul suggests the square-root mapping
  - FLO11: 2D code experiment
    - Solves the full-potential equation
    - Tests the square-root mapping
  - FLO12: 2D code experiment
    - Solves the small-disturbance equation
    - Investigates unsteady flows
    - Tests multigrid acceleration
  - FLO13: ???
  - FLO14: ???

BACKGROUND

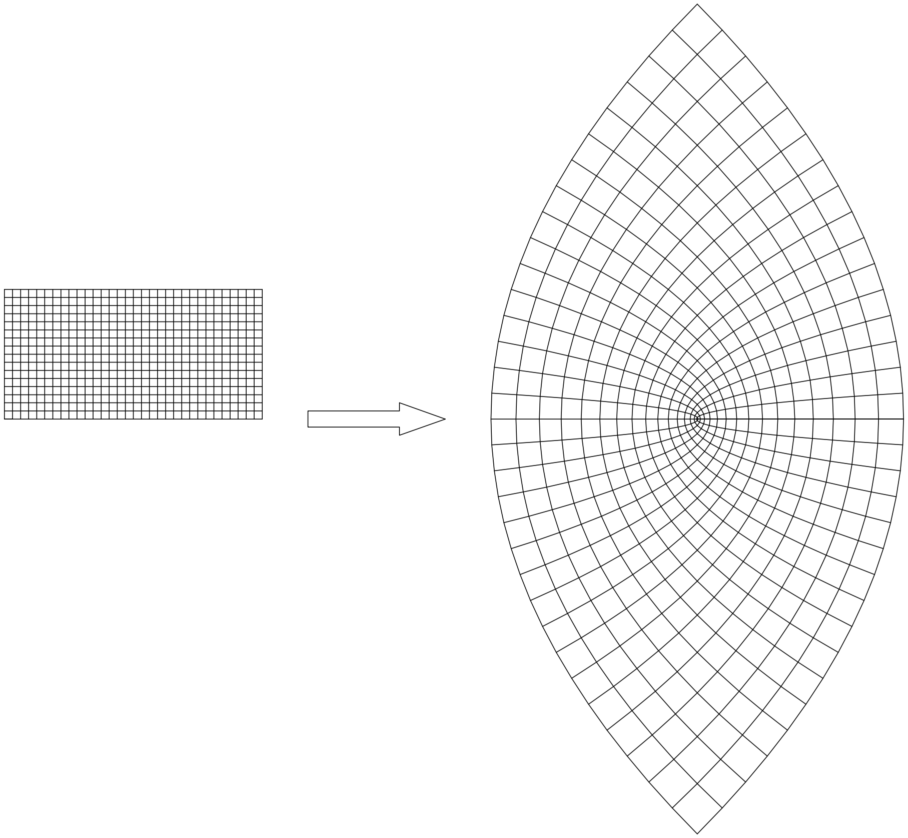


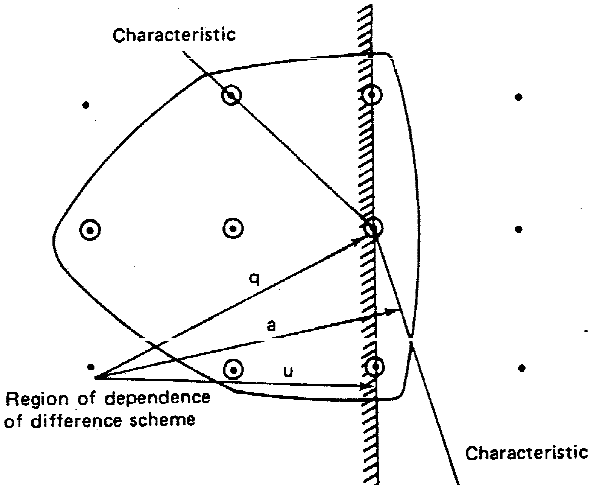
Illustration of the Square-Root Mapping

BACKGROUND

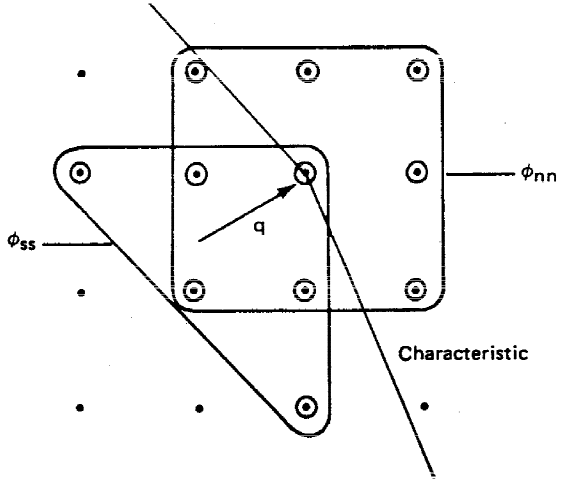
- **Mid 1973: Code Experiments continue**
  - FLO15: Infinite quasi-3D Yawed-Wing code
    - Full-potential equation
    - Rotated-difference scheme
    - Stand-alone check case
    - Wing yawed 45° at $M = 1$
    - Compared with 2D at $M = 0.707$
    - Airfoils had same grid resolution
    - Results over-plotted each other
    - Quasi-3D shock smeared relative to 2D shock
    - Confirmed yawed-wing calculations
  - FLO16: ???

BACKGROUND

- **JUL 1973: 1st CFD Conference, Palm Springs**
  - Paper by Jerry South and Antony Jameson
  - 1st publication on rotated-difference scheme



Simple difference scheme



Rotated difference scheme

BACKGROUND

- **Fall 1973: Going 3D & Enhancing 2D**
  - FLO17: 3D Yawed-Wing code
    - Full-potential equation
    - Rotated-difference scheme
    - Variable in-flow angle
    - Mesh attached to wing leading-edge
    - Listing in **Supercritical Wing Sections II**
  - PGMH: 2D airfoil code with viscous effects
    - David Korn used FLO2's Derivative Conformal Mapping
    - Francis Bauer added a 2D Boundary-Layer method
    - Also in **Supercritical Wing Sections II**

FLO22 DEVELOPMENT

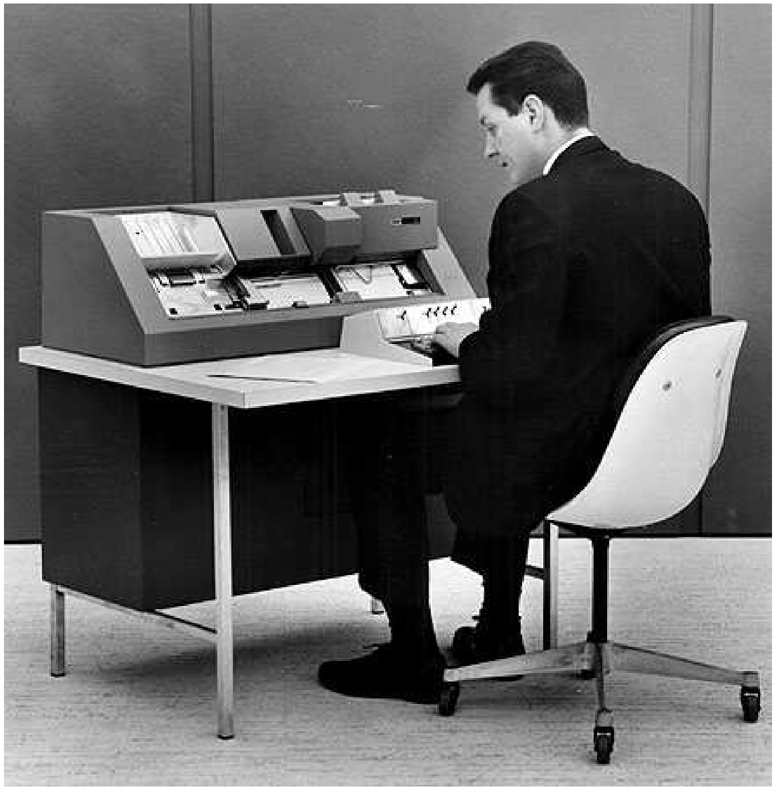
- **Spring 1974: John Dahlin visits NYU**
  - Grant available for 3 months, FEB-APR
  - Dahlin & Jameson eat subs across the street
    - John: *A yawed-wing method is useless. We need methods for swept wings and nacelles.*
    - Antony: *I'll write them if you'll debug them.*
  - Blitz Coding Effort ensues
  - FLO21: Axisymmetric-Nacelle code
  - FLO22: 3D Swept-Wing code
    - Out-of-Core solver due to memory limitations
    - Carried only 3 K-planes in-core
    - Stegosaurus grid at TE of tapered wings

FLO22 DEVELOPMENT

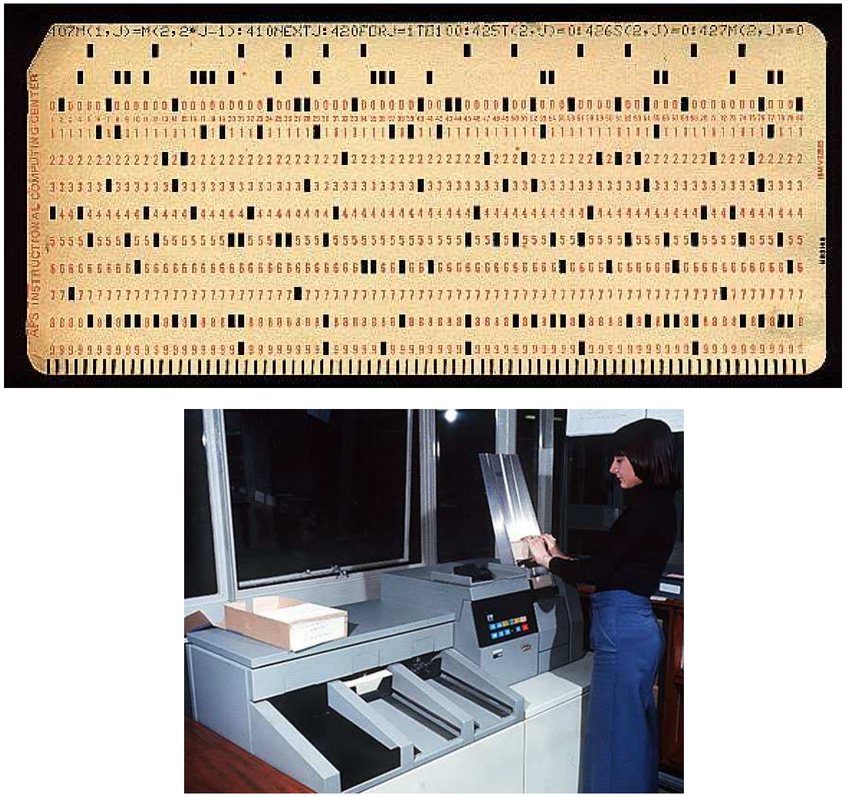
- **MAR 1974: Announcing FLO21 & FLO22**
  - Garabedian upset with Jameson & Dahlin
    - Writing **Supercritical Wing Sections II**
    - Accuses Jameson of trying to be famous
    - Jameson agrees
  - Dahlin & Jameson stop work on these methods
    - Each code filled $\sim$1 box of cards
    - Boxes sit in Jameson's office, 9^{th} floor Courant Inst.
    - Neither code tested at this stage
  - Jameson refocuses
    - Fully-conservative formula
    - Studies in 2D

FLO22 DEVELOPMENT

One Card = One Line of Code



IBM 29 Card Punch

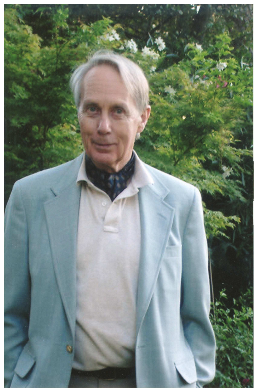


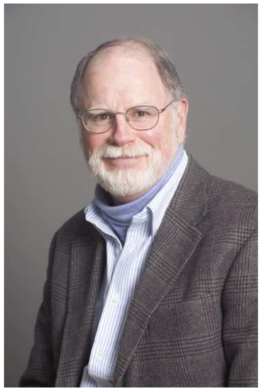
```
407M(1,J)=M(2,2*J-1):410NEXTJ:420FORJ=1TO100:425T(2,J)=0:426S(2,J)=0:427M(2,J)=0
```

Punch Card & Card Reader

FLO22 DEVELOPMENT

- **APR 1974: Dahlin Returns to DAC**
  - Reports back that FLO21 & FLO22 exist
  - David Caughey, MDRL St. Louis
    - ∗ Contacts Jameson regarding FLO21
  - Jameson flys to St. Louis to visit Caughey
    - ∗ Leaves a copy box of FLO21 with Dave



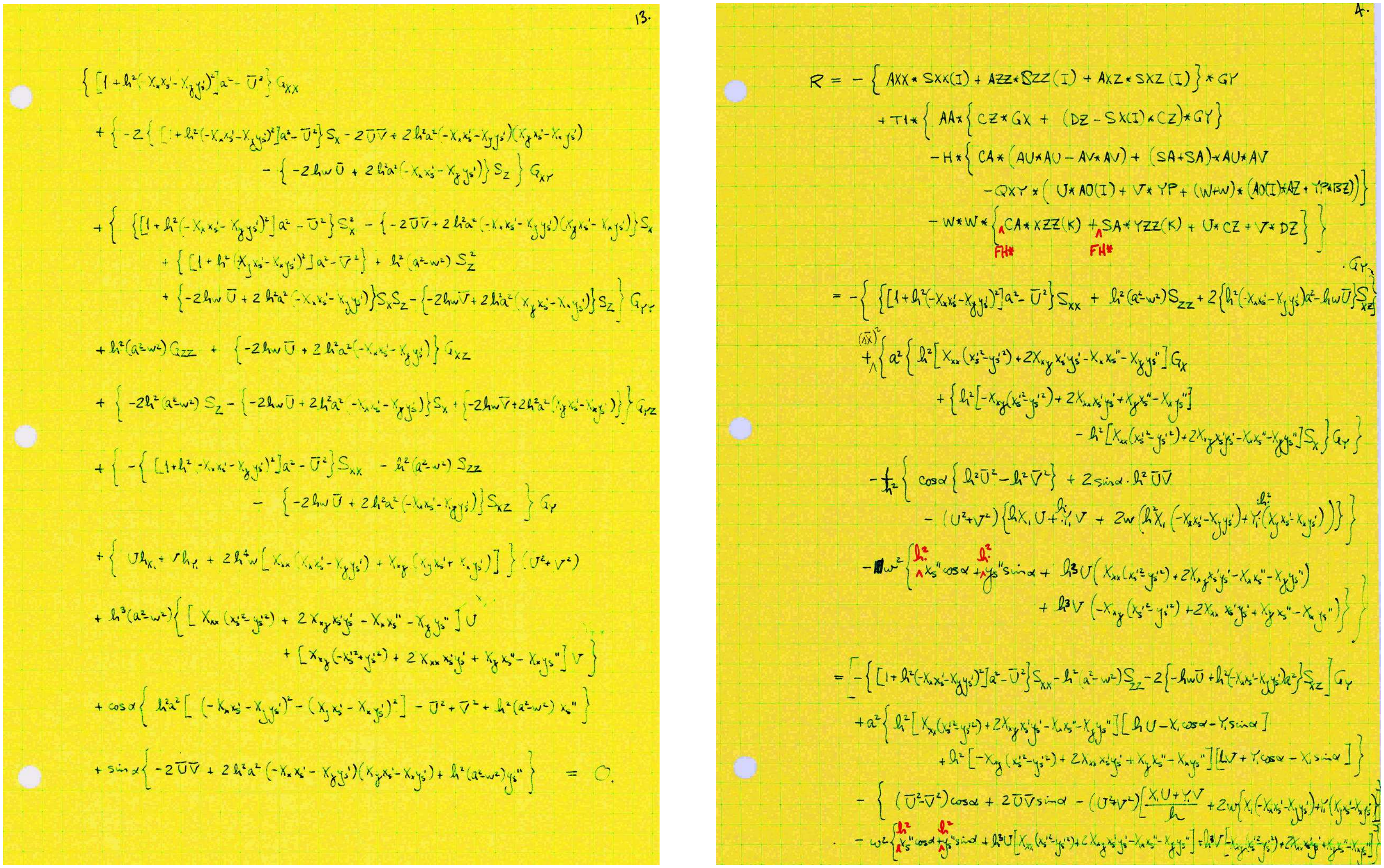


FLO22 DEVELOPMENT

- **Summer 1974: Sears & Seebass leave Cornell**
  - Caughey, Visiting Assistant Professor, 1 year
    - ∗ Starts that Fall semester
    - ∗ Asks Jameson if he can take FLO21 to Cornell
    - ∗ Has FLO21 running within a month
- **SEP 1974: Jameson Full Professor at NYU**
  - *That's great! Now how about FLO22?*
    - ∗ Jameson asks Caughey to work out formulas
    - ∗ Complicated transformations need independent check
    - ∗ Caughey works on this circa OCT 1974

FLO22 DEVELOPMENT

- **NOV 1974: Caughey Visits Jameson at NYU**
  - At First, Formulas Did Not Appear to Agree
    - After hours of effort, they found equivalent forms
    - Only minor errors identified in their derivations
    - Most errors were scaling factors
  - Jameson gave Caughey a copy box of FLO22
  - Caughey had FLO22 running within a week
    - There was a miss-count error in the 3-disk I/O
  - Symmetry-Plane BC was only 1st-order
    - Caughey developed a 2nd-order BC



13.

$$\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}G_{XX}$$

$$+\left\{-2\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}S_X-2\bar{U}\bar{V}+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')\right.$$
$$\left.-\left\{-2hw\bar{U}+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_Z\right\}G_{XY}$$

$$+\left\{\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}S_X^2-\left\{-2\bar{U}\bar{V}+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')\right\}S_X\right.$$
$$+\left\{\left[1+h^2(X_y x_s'-X_x y_s')^2\right]a^2-\bar{V}^2\right\}+h^2(a^2-w^2)S_Z^2$$
$$\left.+\left\{-2hw\bar{U}+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_X S_Z-\left\{-2hw\bar{V}+2h^2a^2(X_y x_s'-X_x y_s')\right\}S_Z\right\}G_{YY}$$

$$+h^2(a^2-w^2)G_{ZZ}+\left\{-2hw\bar{U}+2h^2a^2(-X_x x_s'-X_y y_s')\right\}G_{XZ}$$

$$+\left\{-2h^2(a^2-w^2)S_Z-\left\{-2hw\bar{U}+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_X+\left\{-2hw\bar{V}+2h^2a^2(X_y x_s'-X_x y_s')\right\}\right\}G_{YZ}$$

$$+\left\{-\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}S_{XX}-h^2(a^2-w^2)S_{ZZ}\right.$$
$$\left.-\left\{-2hw\bar{U}+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_{XZ}\right\}G_Y$$

$$+\left\{Uh_{X_1}+Vh_{Y_1}+2h^4w\left[X_{xx}(X_x x_s'-X_y y_s')+X_{xy}(X_y x_s'+X_x y_s')\right]\right\}(U^2+V^2)$$

$$+h^3(a^2-w^2)\left\{\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]U\right.$$
$$\left.+\left[X_{xy}(-x_s'^2+y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]V\right\}$$

$$+\cos\alpha\left\{h^2a^2\left[(-X_x x_s'-X_y y_s')^2-(X_y x_s'-X_x y_s')^2\right]-\bar{U}^2+\bar{V}^2+h^2(a^2-w^2)x_s''\right\}$$

$$+\sin\alpha\left\{-2\bar{U}\bar{V}+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')+h^2(a^2-w^2)y_s''\right\}=0.$$

4.

$$R=-\left\{AXX*SXX(I)+AZZ*SZZ(I)+AXZ*SXZ(I)\right\}*GY$$
$$+T1*\left\{AA*\left\{CZ*GX+(DZ-SX(I)*CZ)*GY\right\}\right.$$
$$-H*\left\{CA*(AU*AU-AV*AV)+(SA+SA)*AU*AV\right.$$
$$\left.-QXY*\left(U*AO(I)+V*YP+(W+W)*(AO(I)*AZ+YP*BZ)\right)\right\}$$
$$\left.-W*W*\left\{\underset{FH*}{\wedge}CA*XZZ(K)+\underset{FH*}{\wedge}SA*YZZ(K)+U*CZ+V*DZ\right\}\right\}$$

$$=-\left\{\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}S_{XX}+h^2(a^2-w^2)S_{ZZ}+2\left\{h^2(-X_x x_s'-X_y y_s')a^2-hw\bar{U}\right\}S_{XZ}\right\}\cdot G_Y$$

$$+\overset{(\Delta X)^2}{\wedge}\left\{a^2\left\{h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]G_X\right.\right.$$
$$+\left\{h^2\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\right.$$
$$\left.\left.\left.-h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]S_X\right\}G_Y\right\}\right.$$

$$-\frac{1}{h^2}\left\{\cos\alpha\left\{h^2\bar{U}^2-h^2\bar{V}^2\right\}+2\sin\alpha\cdot h^2\bar{U}\bar{V}\right.$$
$$\left.-(U^2+V^2)\left\{hX_1U+\overset{h}{\cdot}Y_1V+2w\left(h^2X_1(-X_x x_s'-X_y y_s')+\overset{h^2}{\cdot}Y_1(X_y x_s'-X_x y_s')\right)\right\}\right\}$$

$$-w^2\left\{\overset{h^2}{\wedge}x_s''\cos\alpha+\overset{h^2}{\wedge}y_s''\sin\alpha+h^3U\left(X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right)\right.$$
$$\left.+h^3V\left(-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right)\right\}$$

$$=\left[-\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar{U}^2\right\}S_{XX}-h^2(a^2-w^2)S_{ZZ}-2\left\{-hw\bar{U}+h^2(-X_x x_s'-X_y y_s')a^2\right\}S_{XZ}\right]G_Y$$

$$+a^2\left\{h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]\left[hU-X_1\cos\alpha-Y_1\sin\alpha\right]\right.$$
$$\left.+h^2\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\left[hV+Y_1\cos\alpha-X_1\sin\alpha\right]\right\}$$

$$-\left\{(\bar{U}^2-\bar{V}^2)\cos\alpha+2\bar{U}\bar{V}\sin\alpha-(U^2+V^2)\left[\frac{X_1U+Y_1V}{h}+2w\left\{X_1(-X_x x_s'-X_y y_s')+Y_1(X_y x_s'-X_x y_s')\right\}\right]\right\}$$

$$-w^2\left\{\overset{h^2}{\wedge}x_s''\cos\alpha+\overset{h^2}{\wedge}y_s''\sin\alpha+h^3U\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]+h^3V\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\right\}$$

Caughey's Original Notes with Corrections

13.

$$\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}G_{XX}$$

$$+\left\{-2\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}S_X-2\bar U\bar V+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')\right.$$

$$\left.-\left\{-2hw\bar U+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_Z\right\}G_{XY}$$

$$+\left\{\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}S_X^2-\left\{-2\bar U\bar V+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')\right\}S_X\right.$$

$$+\left\{\left[1+h^2(X_y x_s'-X_x y_s')^2\right]a^2-\bar V^2\right\}+h^2(a^2-w^2)S_Z^2$$

$$\left.+\left\{-2hw\bar U+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_XS_Z-\left\{-2hw\bar V+2h^2a^2(X_y x_s'-X_x y_s')\right\}S_Z\right\}G_{YY}$$

$$+h^2(a^2-w^2)G_{ZZ}+\left\{-2hw\bar U+2h^2a^2(-X_x x_s'-X_y y_s')\right\}G_{XZ}$$

$$+\left\{-2h^2(a^2-w^2)S_Z-\left\{-2hw\bar U+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_X+\left\{-2hw\bar V+2h^2a^2(X_y x_s'-X_x y_s')\right\}\right\}G_{YZ}$$

$$+\left\{-\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}S_{XX}-h^2(a^2-w^2)S_{ZZ}\right.$$

$$\left.-\left\{-2hw\bar U+2h^2a^2(-X_x x_s'-X_y y_s')\right\}S_{XZ}\right\}G_Y$$

$$+\left\{Uh_{X_1}+Vh_{Y_1}+2h^4w\left[X_{xx}(X_x x_s'-X_y y_s')+X_{xy}(X_y x_s'+X_x y_s')\right]\right\}(U^2+V^2)$$

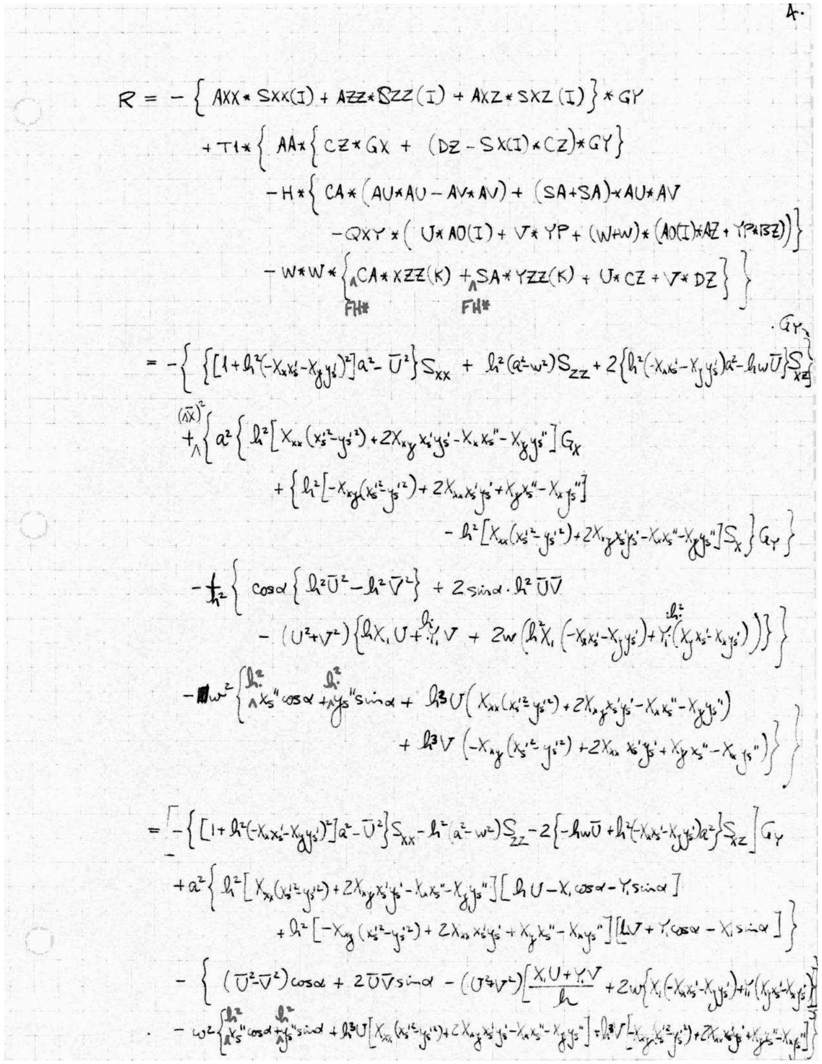
$$+h^3(a^2-w^2)\left\{\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]U\right.$$

$$\left.+\left[X_{xy}(-x_s'^2+y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]V\right\}$$

$$+\cos\alpha\left\{h^2a^2\left[(-X_x x_s'-X_y y_s')^2-(X_y x_s'-X_x y_s')^2\right]-\bar U^2+\bar V^2+h^2(a^2-w^2)x_s''\right\}$$

$$+\sin\alpha\left\{-2\bar U\bar V+2h^2a^2(-X_x x_s'-X_y y_s')(X_y x_s'-X_x y_s')+h^2(a^2-w^2)y_s''\right\}=0.$$

Transformed G Equation



4.

```
R = - { AXX * SXX(I) + AZZ * SZZ(I) + AXZ * SXZ(I) } * GY
      + T1 * { AA * { CZ * GX + (DZ - SX(I) * CZ) * GY }
             - H * { CA * (AU * AU - AV * AV) + (SA + SA) * AU * AV
                     - QXY * ( U * AO(I) + V * YP + (W + W) * (AO(I) * AZ + YP * BZ)) }
             - W * W * { FH* CA * XZZ(K) + FH* SA * YZZ(K) + U * CZ + V * DZ } }
```

$$=-\left\{\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}S_{XX}+h^2(a^2-w^2)S_{ZZ}+2\left\{h^2(-X_x x_s'-X_y y_s')a^2-hw\bar U\right\}S_{XZ}\right\}\cdot G_Y$$

$$+\overset{(\Delta X)^2}{\wedge}\left\{a^2\left\{h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]G_X\right.\right.$$

$$+\left\{h^2\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\right.$$

$$\left.\left.-h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]S_X\right\}G_Y\right\}$$

$$-\cancel{\frac{1}{h^2}}\left\{\cos\alpha\left\{h^2\bar U^2-h^2\bar V^2\right\}+2\sin\alpha\cdot h^2\bar U\bar V\right.$$

$$\left.-(U^2+V^2)\left\{hX_1U+\overset{h}{\cdot}Y_1V+2w\left(h^2X_1(-X_x x_s'-X_y y_s')+\overset{h^2}{\cdot}Y_1(X_y x_s'-X_x y_s')\right)\right\}\right\}$$

$$-w^2\left\{\overset{h^2}{\wedge}x_s''\cos\alpha+\overset{h^2}{\wedge}y_s''\sin\alpha+h^3U\left(X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right)\right.$$

$$\left.+h^3V\left(-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right)\right\}$$

$$=\left[-\left\{\left[1+h^2(-X_x x_s'-X_y y_s')^2\right]a^2-\bar U^2\right\}S_{XX}-h^2(a^2-w^2)S_{ZZ}-2\left\{-hw\bar U+h^2(-X_x x_s'-X_y y_s')a^2\right\}S_{XZ}\right]G_Y$$

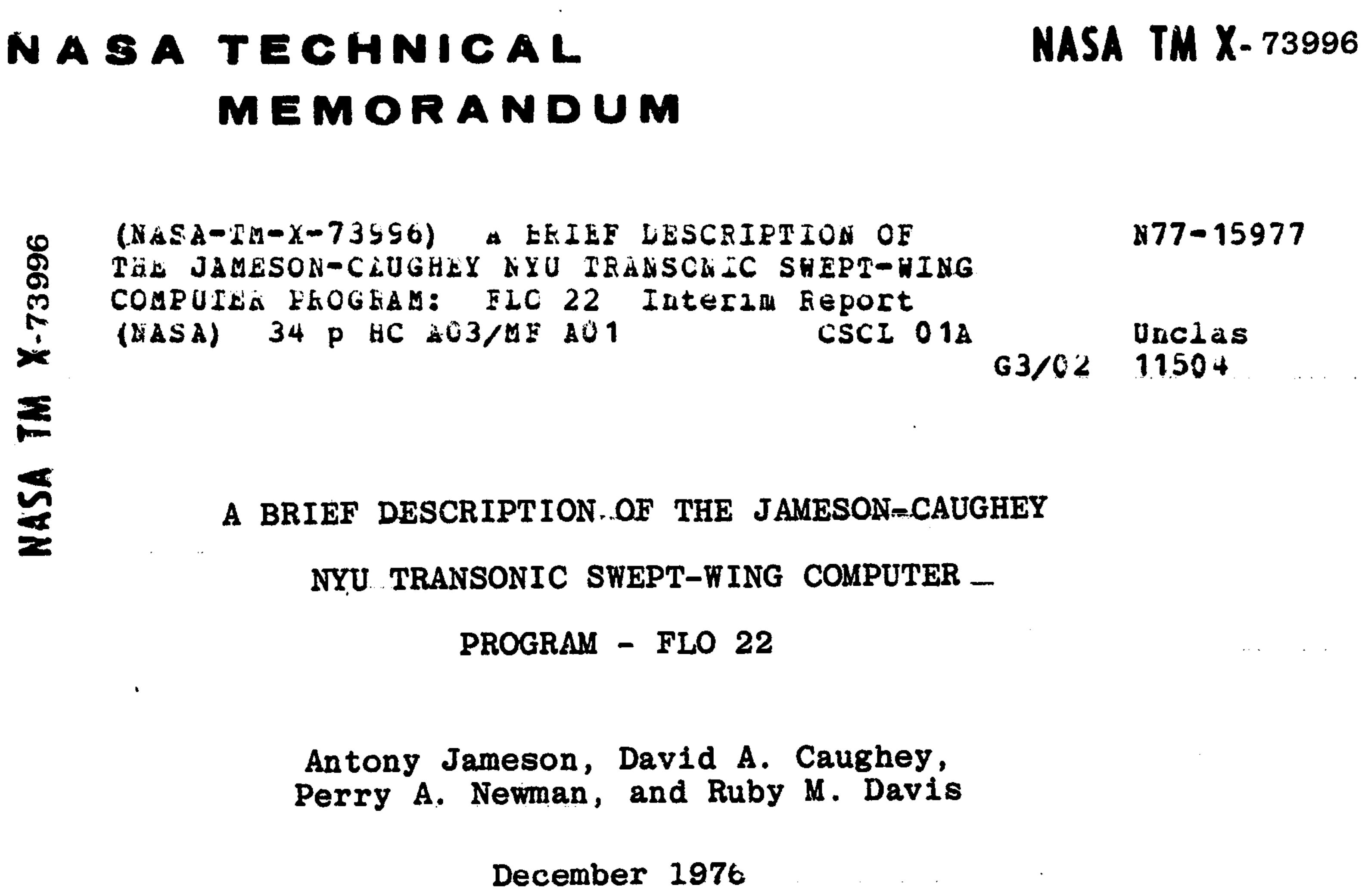
$$+a^2\left\{h^2\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]\left[hU-X_1\cos\alpha-Y_1\sin\alpha\right]\right.$$

$$\left.+h^2\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\left[hV+Y_1\cos\alpha-X_1\sin\alpha\right]\right\}$$

$$-\left\{(\bar U^2-\bar V^2)\cos\alpha+2\bar U\bar V\sin\alpha-(U^2+V^2)\left[\frac{X_1U+Y_1V}{h}+2w\left\{X_1(-X_x x_s'-X_y y_s')+Y_1(X_y x_s'-X_x y_s')\right\}\right]\right\}$$

$$-w^2\left\{\overset{h^2}{\wedge}x_s''\cos\alpha+\overset{h^2}{\wedge}y_s''\sin\alpha+h^3U\left[X_{xx}(x_s'^2-y_s'^2)+2X_{xy}x_s'y_s'-X_x x_s''-X_y y_s''\right]+h^3V\left[-X_{xy}(x_s'^2-y_s'^2)+2X_{xx}x_s'y_s'+X_y x_s''-X_x y_s''\right]\right\}$$

Residual Notation



NASA TECHNICAL MEMORANDUM

NASA TM X-73996

NASA TM X-73996

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(NASA-TM-X-73996)  A BRIEF DESCRIPTION OF            N77-15977
THE JAMESON-CAUGHEY NYU TRANSONIC SWEPT-WING
COMPUTER PROGRAM:  FLO 22  Interim Report
(NASA)  34 p HC A03/MF A01          CSCL 01A         Unclas
                                             G3/02   11504
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A BRIEF DESCRIPTION OF THE JAMESON-CAUGHEY
NYU TRANSONIC SWEPT-WING COMPUTER
PROGRAM - FLO 22

Antony Jameson, David A. Caughey,
Perry A. Newman, and Ruby M. Davis

December 1976

CALCULATION OF THE FLOW PAST A SWEPT WING

It is desired to solve the three-dimensional potential flow equation which can be written in quasilinear form as

$$(a^2-u^2)\phi_{xx} + (a^2-v^2)\phi_{yy} + (a^2-w^2)\phi_{zz} - 2uv\phi_{xy} - 2vw\phi_{yz} - 2uw\phi_{xz} = 0 \qquad (1)$$

where u, v and w are the velocity components and a is the local speed of sound. The singularity at infinity in the velocity potential is removed by introducing a reduced potential

$$G = \phi - x \cos \alpha - y \sin \alpha \qquad (2)$$

where α is the angle of attack.

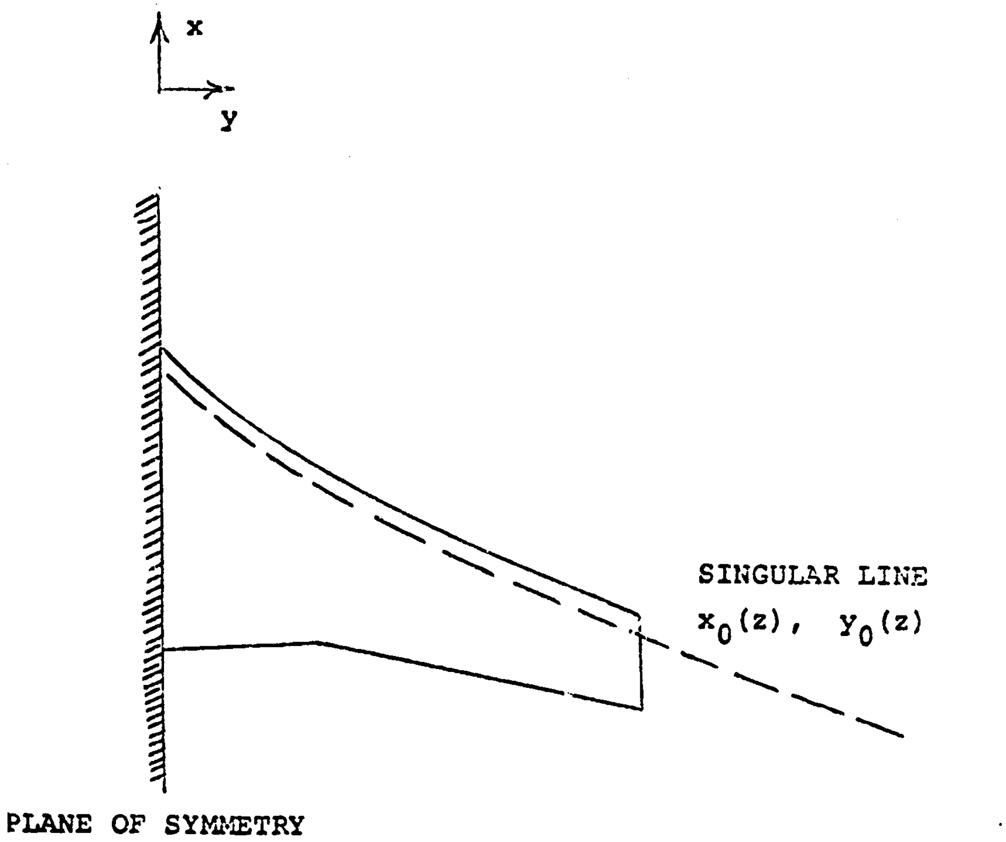


FIGURE 1. CONFIGURATION OF SWEPT WING

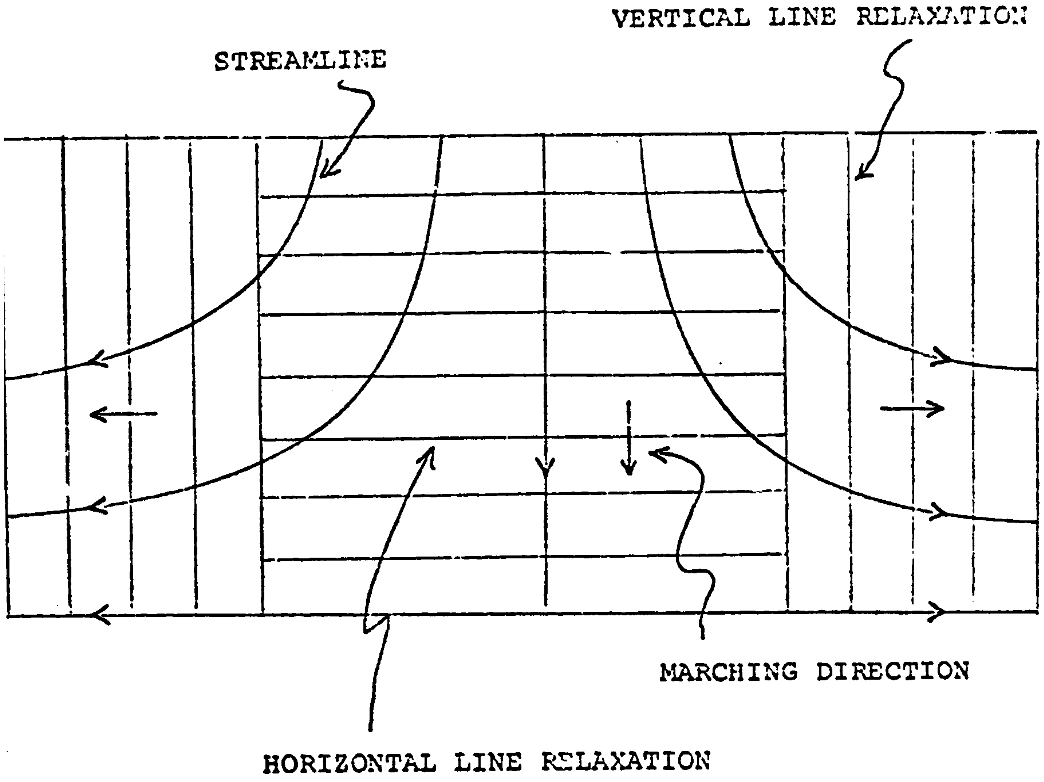
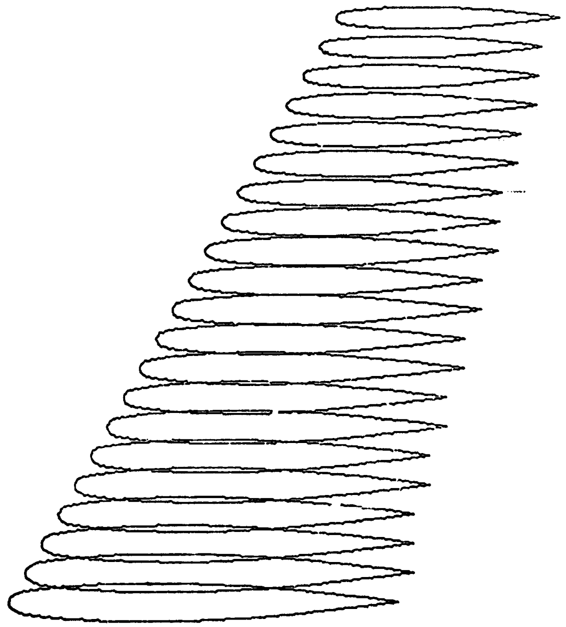


FIGURE 3. MARCHING DIRECTIONS OF RELAXATION SCHEME
FOR SWEPT WING CALCULATION

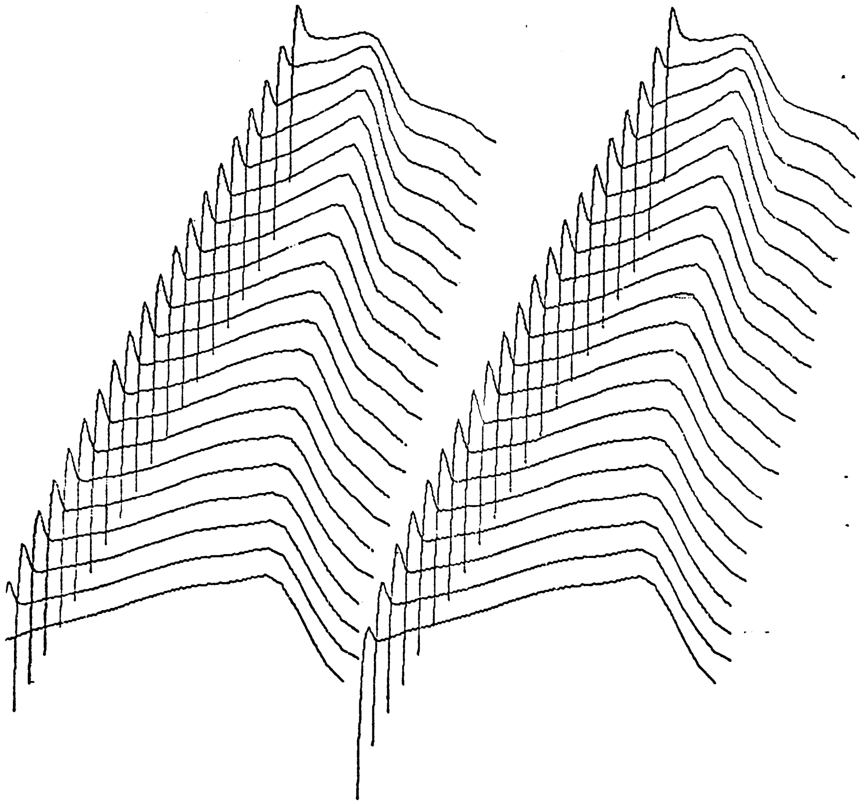


VIEW OF WING

```
ONERA WING M6    L.E. SWEEP 30 DEG    ASPECT RATIO 3.8
MACH     .923    YAW     0.000     ALPHA  0.000
L/D     -.00     CL     -.0000     CD      .0246
```

FIGURE 4(A)

13



PER SURFACE PRESSURE   LOWER SURFACE PRESSURE

```
ONERA WING M6    L.E. SWEEP 30 DEG    ASPECT RATIO 3.8
MACH     .923    YAW     0.000     ALPHA  0.000
L/D     -.00     CL     -.0000     CD      .0246
```

14

FIGURE 4(B)

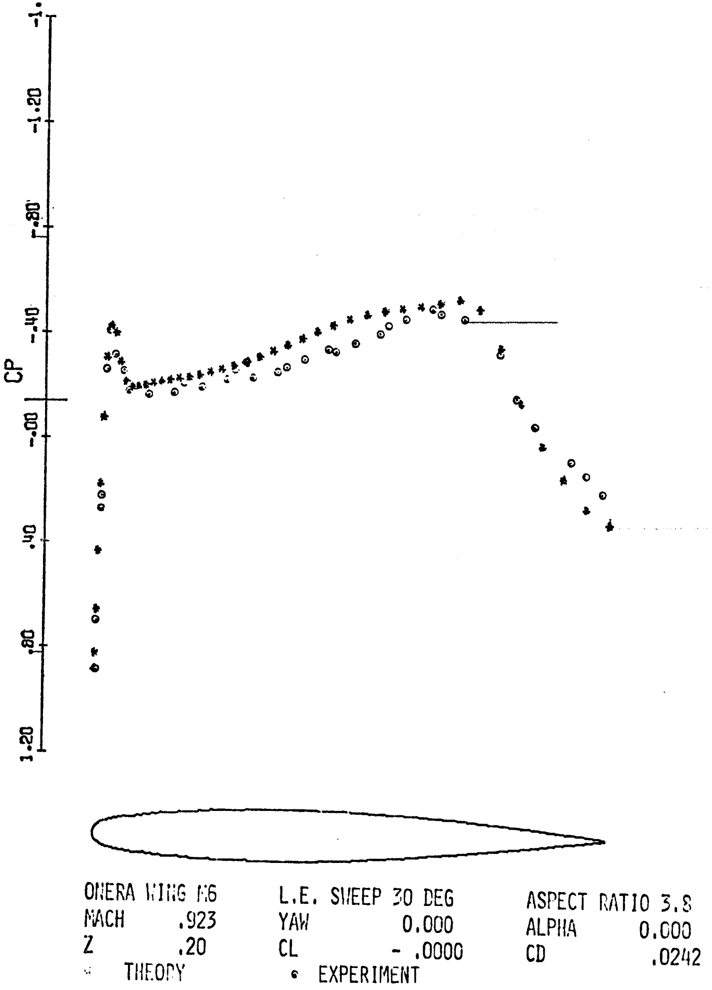


FIGURE 4(C)

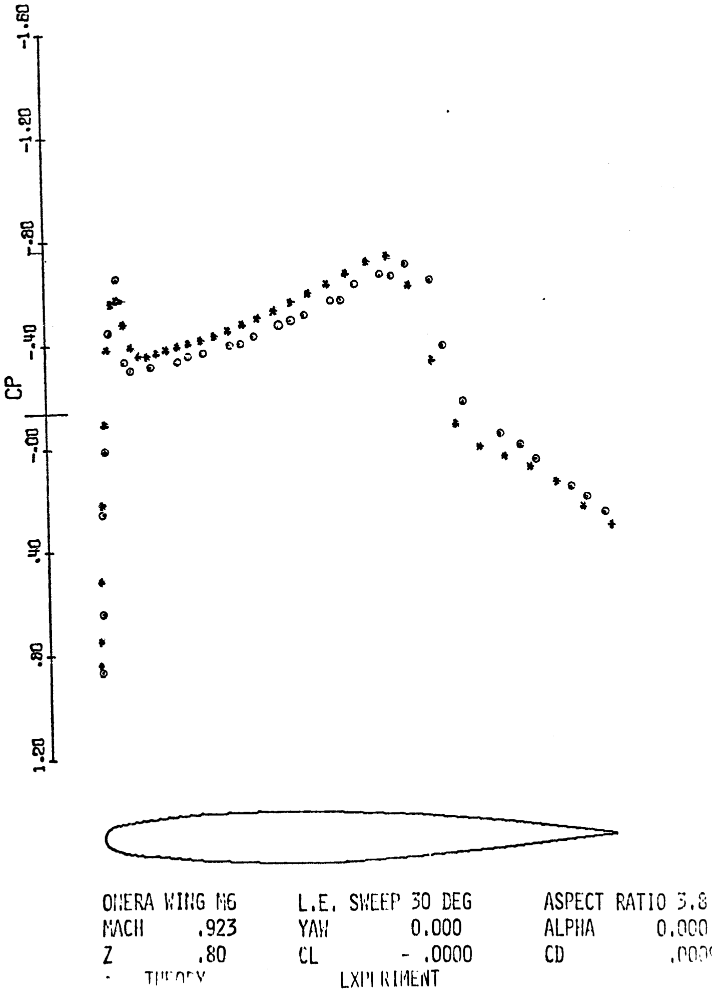


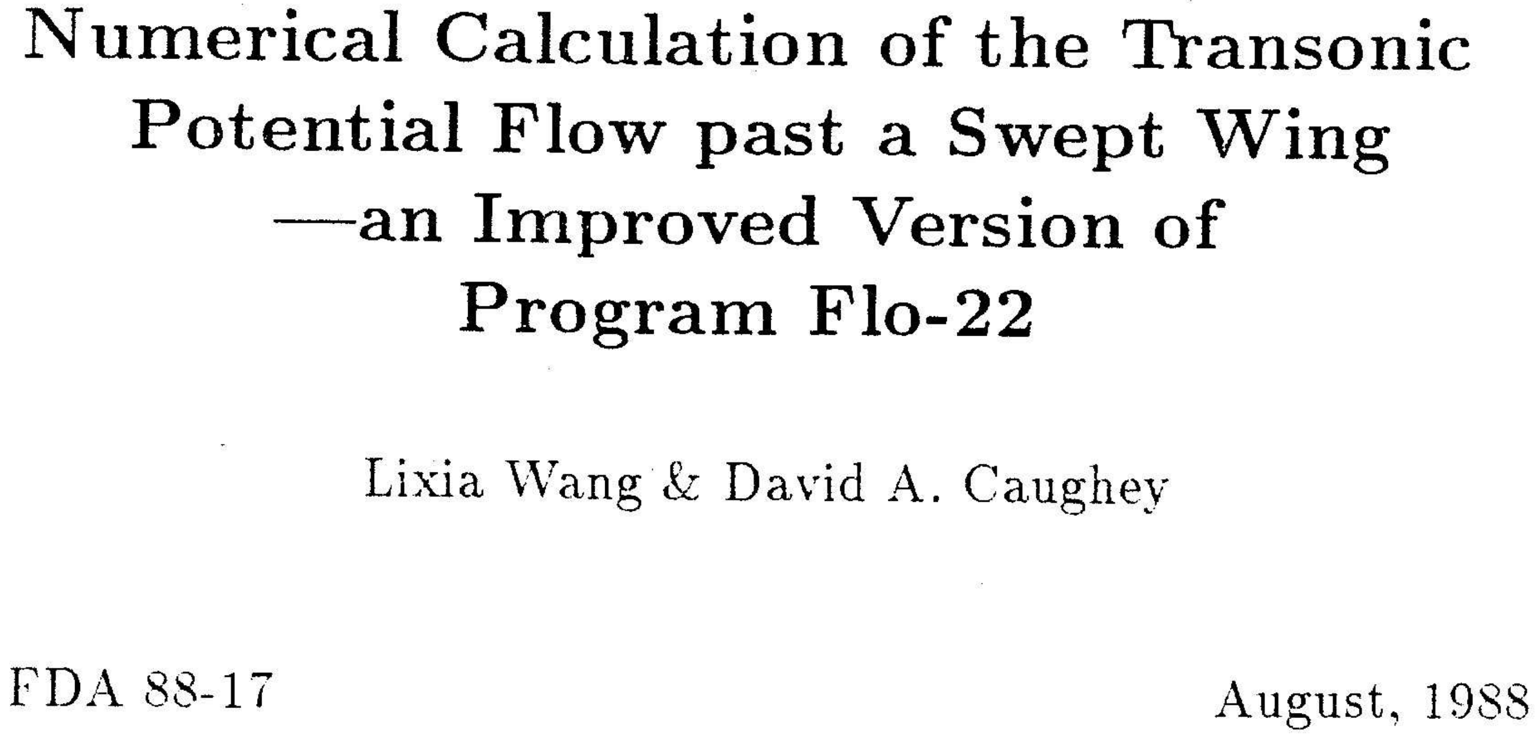
FIGURE 4(D)

FLO22 DEVELOPMENT

- **Circa 1982: Singular-Line Bug Found**
  - Scale factor dropped in 2nd-derivative term
  - This was a typo in the code only
  - Jameson's notes had it correct
  - Only bug found in FLO22 since first released
- **MAR 1983: Multigrid Conf, Copper Mtn, CO**
  - Vassberg meets with Caughey re SNGLmod
    - SNGLmod affected minimal lines of code
    - Updated DAC's version of FLO22

FLO22 DEVELOPMENT

- **1975-1990: Miscellaneous Enhancements**
  - Pres Henne, DAC
    - Symmetry Plane at Side-of-Body
    - Pseudo-Body Mach & Aero-Twist Effects
    - 2D-Strip Boundary Layer: Displaced Surface
    - Farfield Control-Volume Integrations
    - 3D Inverse-Design code
  - Pradeep Raj, Lockheed
    - Multigrid Acceleration
  - Lixia Wang, Cornell
    - Trailing-Edge Conforming Transformation
    - Improved Symmetry-Plane Boundary Condition
  - John Vassberg, DAC
    - In-Core Solver
    - Spanload Matching via Re-Twist
    - Rapid Drag-Rise Calculations

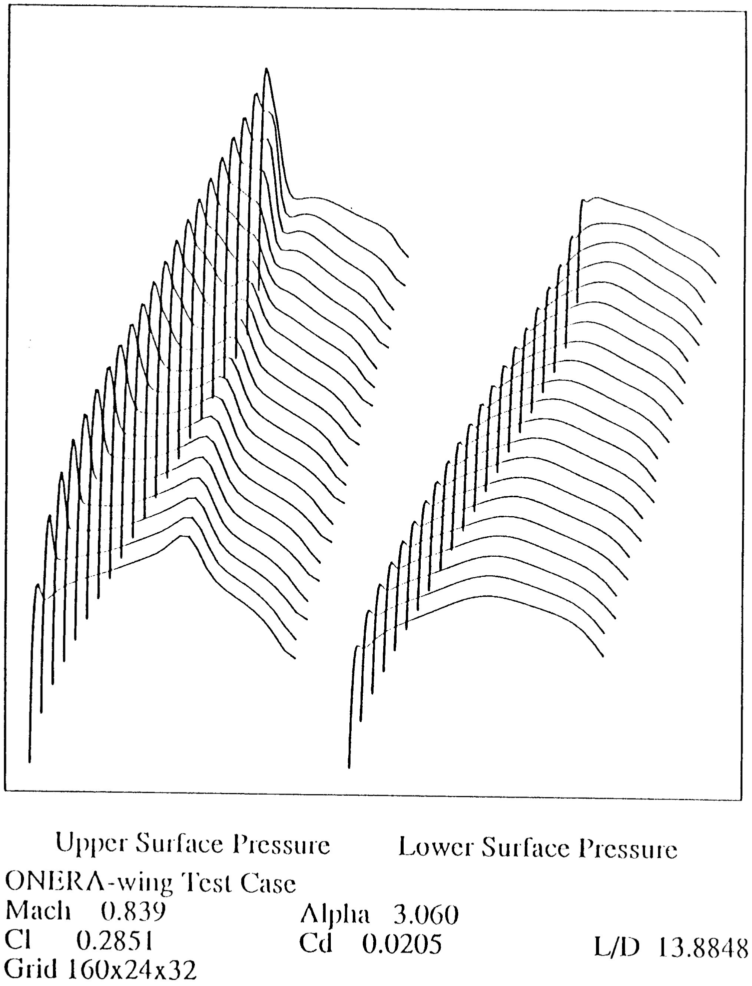


Numerical Calculation of the Transonic Potential Flow past a Swept Wing —an Improved Version of Program Flo-22

Lixia Wang & David A. Caughey

FDA 88-17

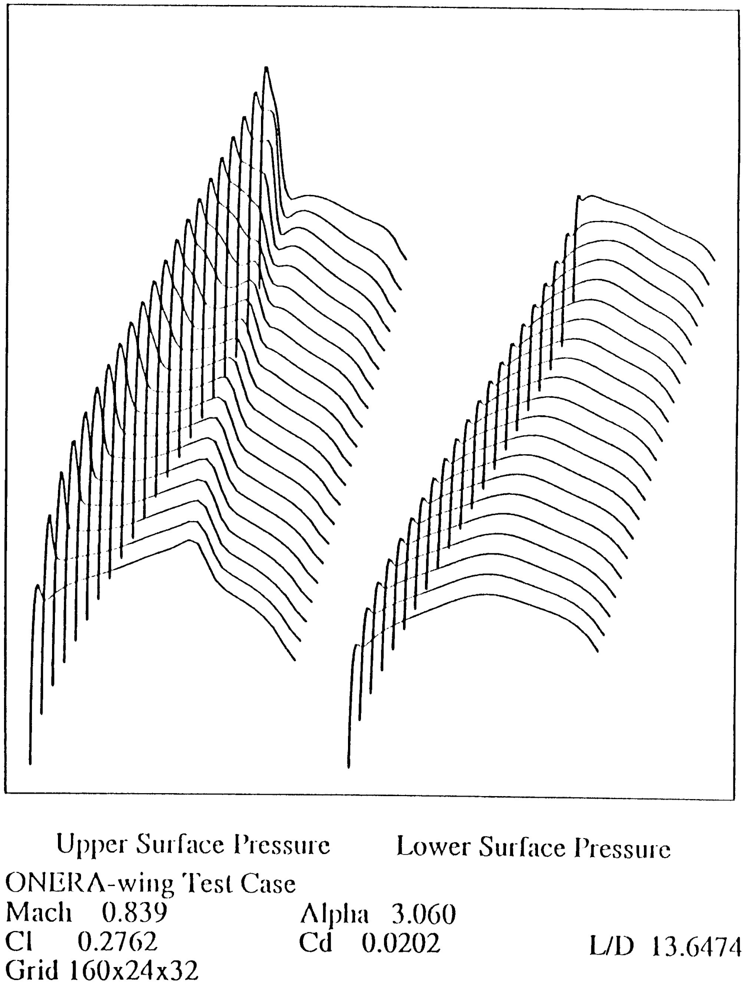
August, 1988



ONERA-wing Test Case
Mach 0.839 Alpha 3.060
Cl 0.2851 Cd 0.0205 L/D 13.8848
Grid 160x24x32

Original FLO22

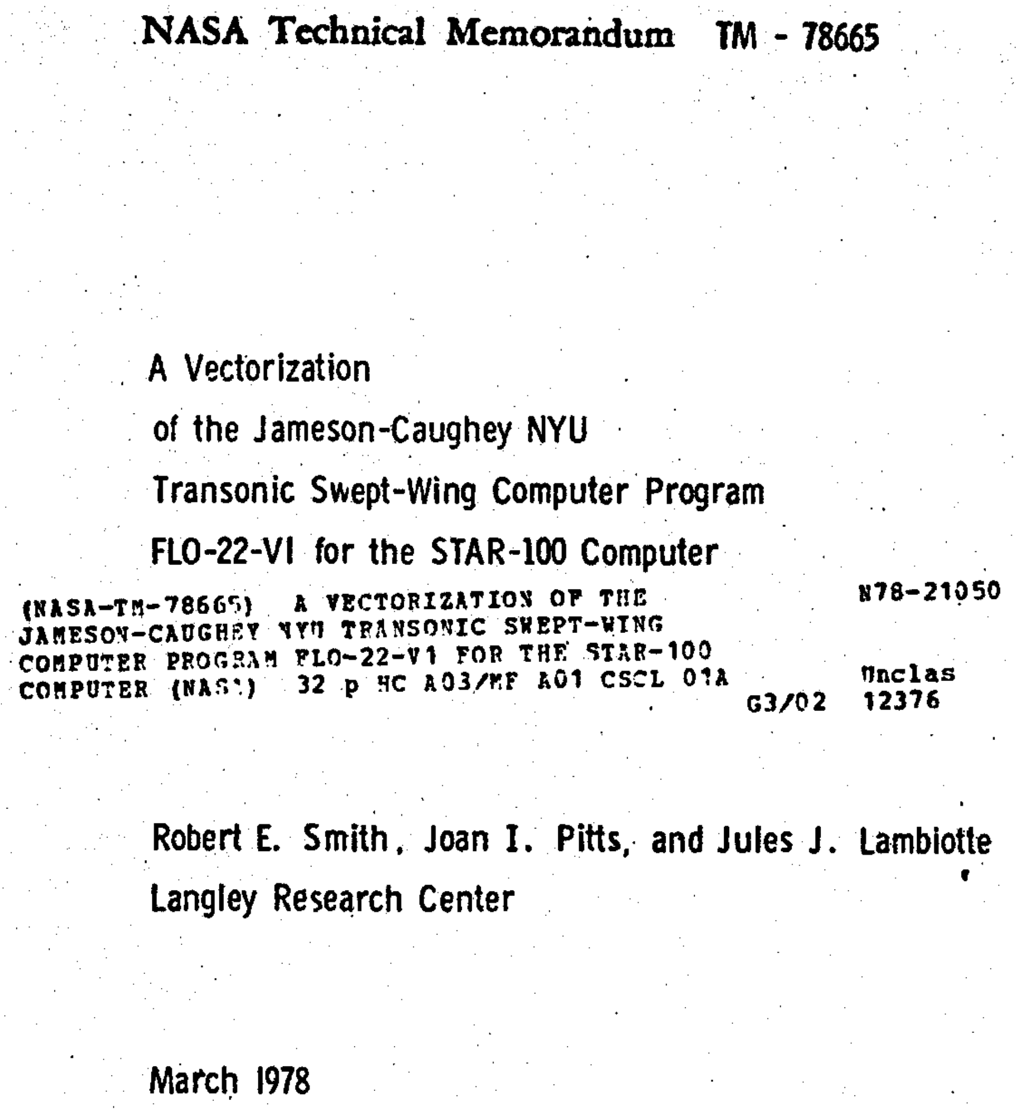
$C_L = 0.2851$, $C_D = 0.0205$, $\frac{L}{D} = 13.8848$



ONERA-wing Test Case
Mach 0.839 Alpha 3.060
Cl 0.2762 Cd 0.0202 L/D 13.6474
Grid 160x24x32

Modified FLO22

$C_L = 0.2762$, $C_D = 0.0202$, $\frac{L}{D} = 13.6474$



NASA Technical Memorandum TM - 78665

A Vectorization
of the Jameson-Caughey NYU
Transonic Swept-Wing Computer Program
FLO-22-VI for the STAR-100 Computer

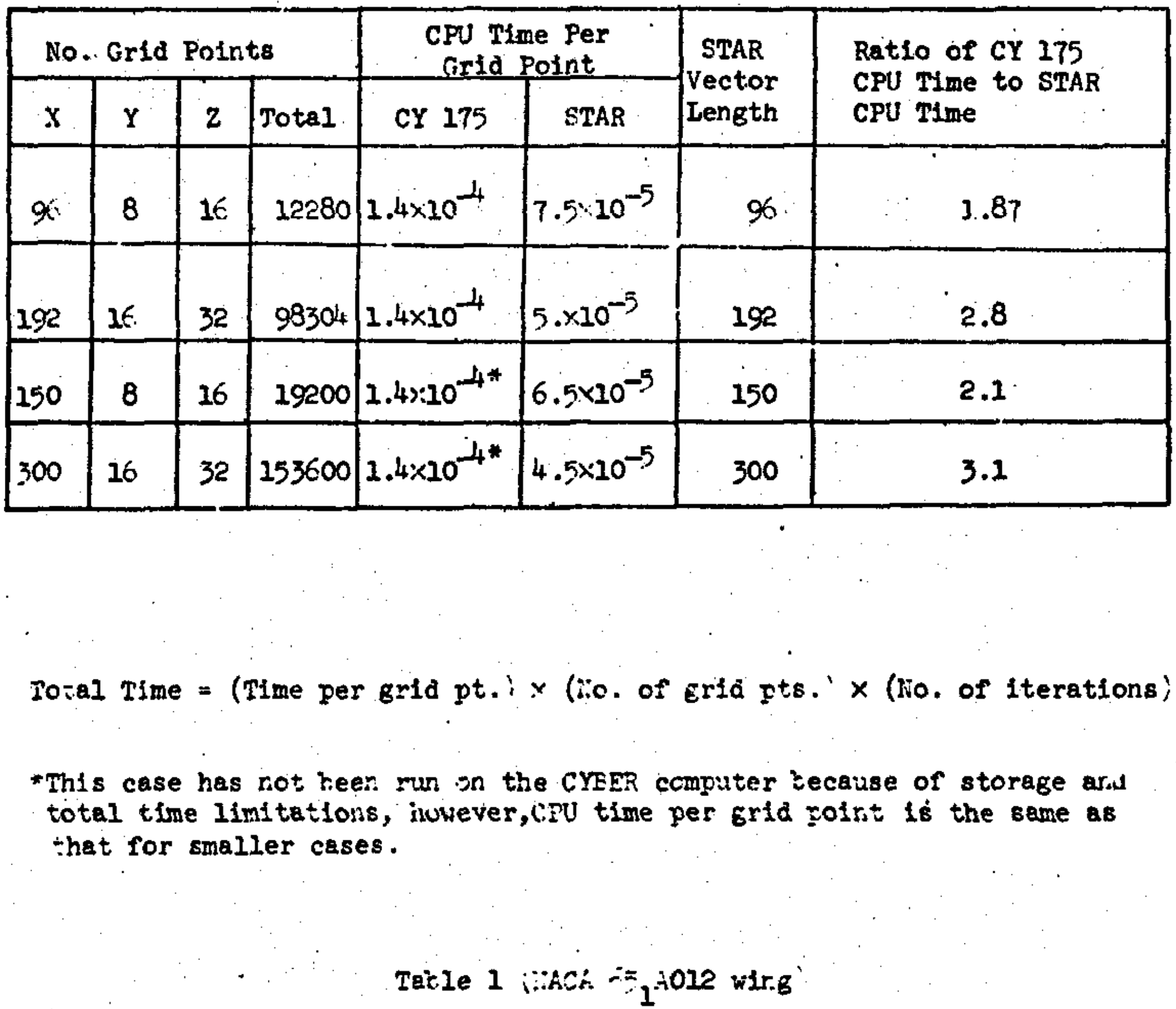
(NASA-TM-78665) A VECTORIZATION OF THE
JAMESON-CAUGHEY NYU TRANSONIC SWEPT-WING
COMPUTER PROGRAM FLO-22-V1 FOR THE STAR-100
COMPUTER (NASA) 32 p HC A03/MF A01 CSCL 01A

N78-21050

Unclas
G3/02 12376

Robert E. Smith, Joan I. Pitts, and Jules J. Lambiotte
Langley Research Center

March 1978



No. Grid Points				CPU Time Per Grid Point		STAR Vector Length	Ratio of CY 175 CPU Time to STAR CPU Time
X	Y	Z	Total	CY 175	STAR		
96	8	16	12280	1.4×10^{-4}	7.5×10^{-5}	96	1.87
192	16	32	98304	1.4×10^{-4}	$5.\times10^{-5}$	192	2.8
150	8	16	19200	1.4×10^{-4}*	6.5×10^{-5}	150	2.1
300	16	32	153600	1.4×10^{-4}*	4.5×10^{-5}	300	3.1

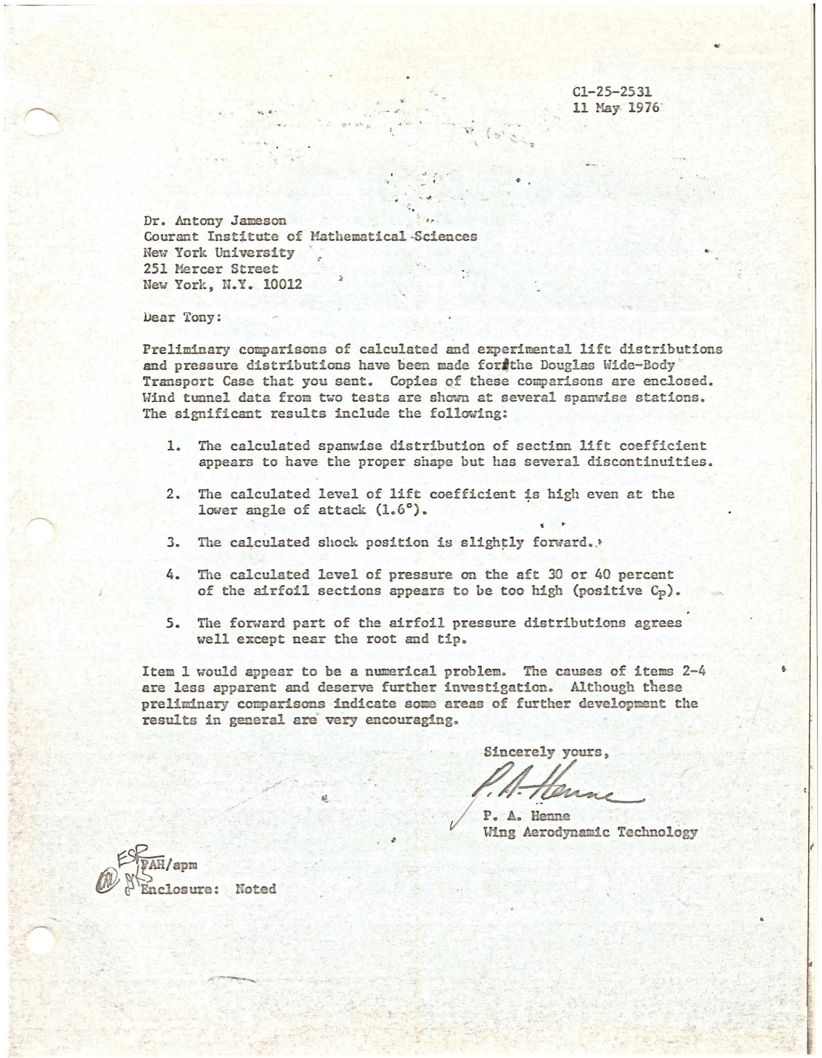
Total Time = (Time per grid pt.) × (No. of grid pts.) × (No. of iterations)

*This case has not been run on the CYBER computer because of storage and total time limitations, however,CPU time per grid point is the same as that for smaller cases.

Table 1 (NACA 65_1A012 wing)

FLO22 APPLICATIONS

- **APR 1976: First FLO22 Solution at DAC**
  - Transport Wing, Pres Henne, DAC
    - $M = 0.85$, $\alpha = 1.6°$, Inviscid
    - Grid: (192 x 24 x 32), ~ 150K nodes
    - IBM Mainframe CPU Cost: ~$8,000
    - Soon After, CDC 7600: ~$3,000
    - Implications: *Priceless*



C1-25-2531
11 May 1976

Dr. Antony Jameson
Courant Institute of Mathematical Sciences
New York University
251 Mercer Street
New York, N.Y. 10012

Dear Tony:

Preliminary comparisons of calculated and experimental lift distributions and pressure distributions have been made for the Douglas Wide-Body Transport Case that you sent. Copies of these comparisons are enclosed. Wind tunnel data from two tests are shown at several spanwise stations. The significant results include the following:

1. The calculated spanwise distribution of section lift coefficient appears to have the proper shape but has several discontinuities.
2. The calculated level of lift coefficient is high even at the lower angle of attack (1.6°).
3. The calculated shock position is slightly forward.
4. The calculated level of pressure on the aft 30 or 40 percent of the airfoil sections appears to be too high (positive C_p).
5. The forward part of the airfoil pressure distributions agrees well except near the root and tip.

Item 1 would appear to be a numerical problem. The causes of items 2-4 are less apparent and deserve further investigation. Although these preliminary comparisons indicate some areas of further development the results in general are very encouraging.

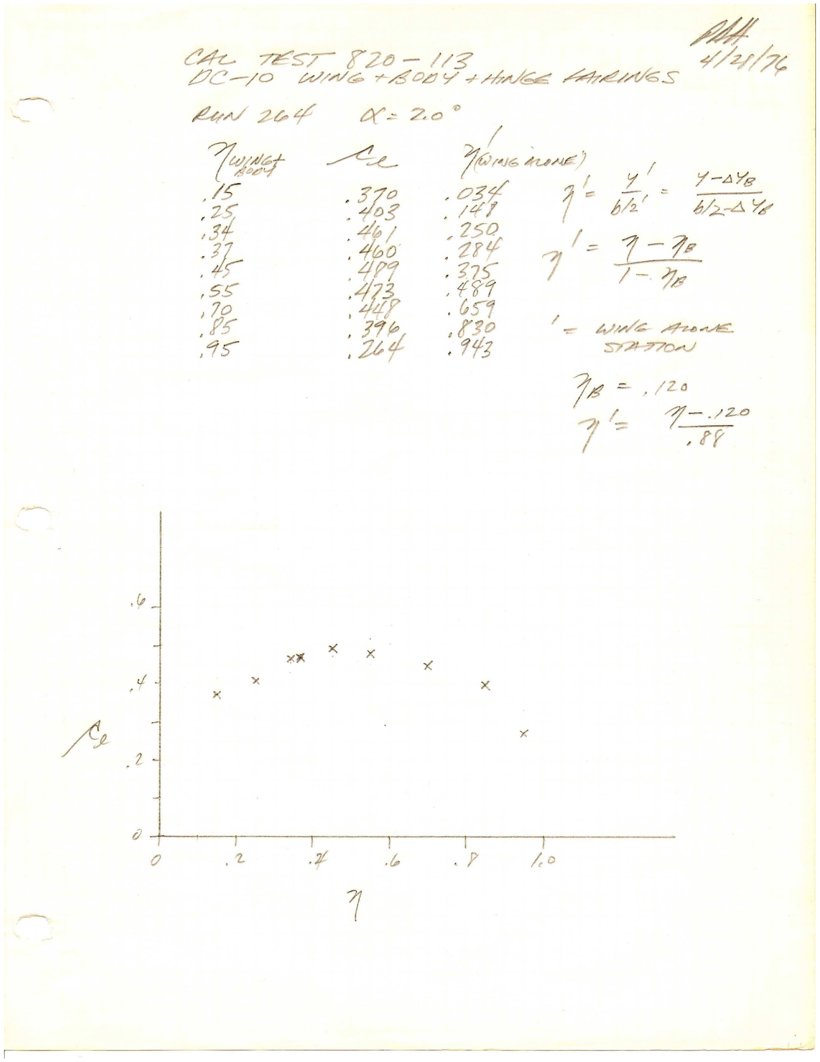
Sincerely yours,

P. A. Henne

P. A. Henne
Wing Aerodynamic Technology

ESR
PAH/apm
Enclosure: Noted

May 1976 Letter from Pres Henne



CAL TEST 820-113
DC-10 WING + BODY + HINGE FAIRINGS

PAH
4/28/76

RUN 264 $\alpha = 2.0°$

$\eta_{\text{WING+BODY}}$	c_ℓ	η' (WING ALONE)
.15	.370	.034
.25	.403	.148
.34	.461	.250
.37	.460	.284
.45	.489	.375
.55	.473	.489
.70	.448	.659
.85	.396	.830
.95	.264	.943

$$\eta' = \frac{y'}{b/2'} = \frac{y - \Delta y_B}{b/2 - \Delta y_B}$$

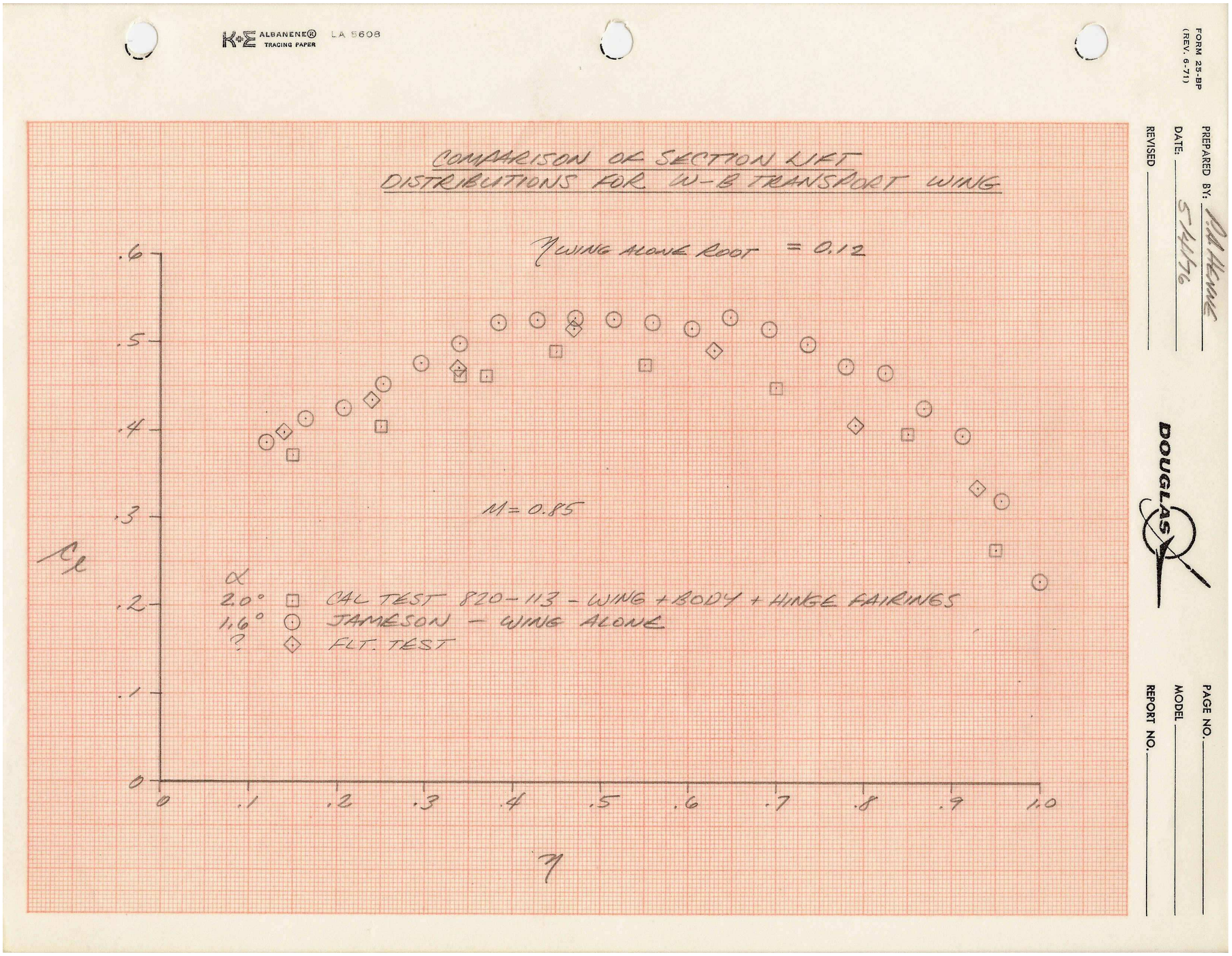
$$\eta' = \frac{\eta - \eta_B}{1 - \eta_B}$$

' = WING ALONE STATION

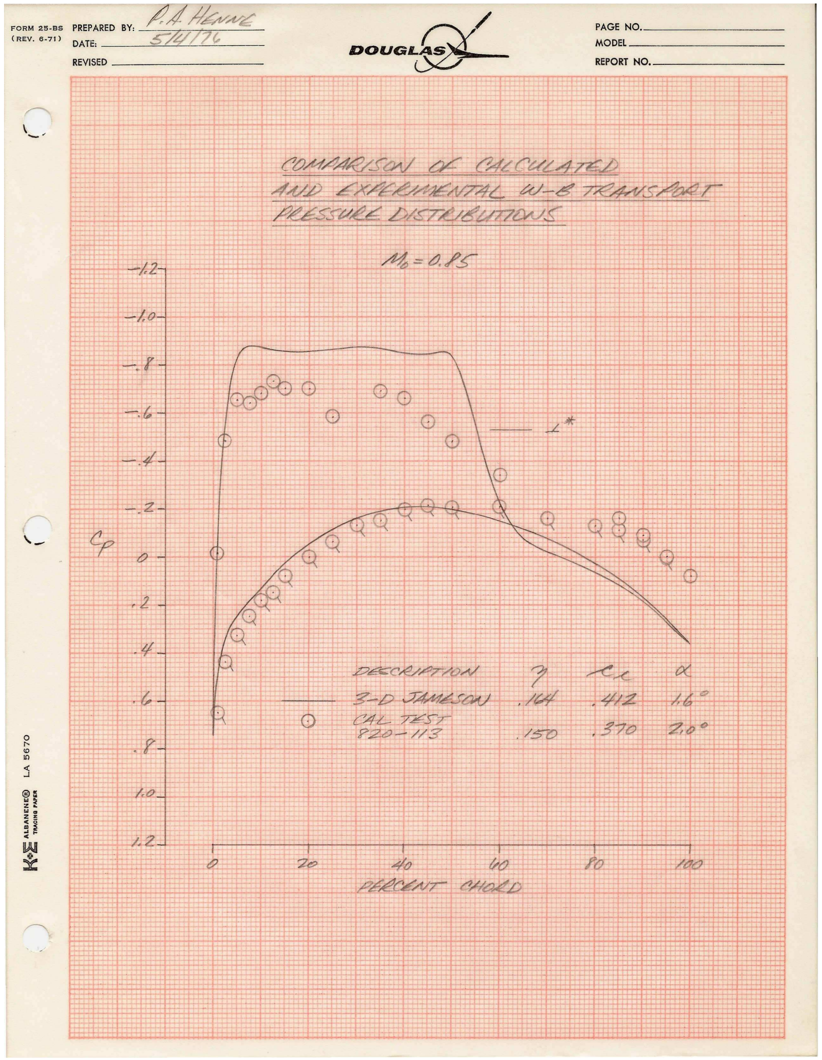
$$\eta_B = .120$$

$$\eta' = \frac{\eta - .120}{.88}$$

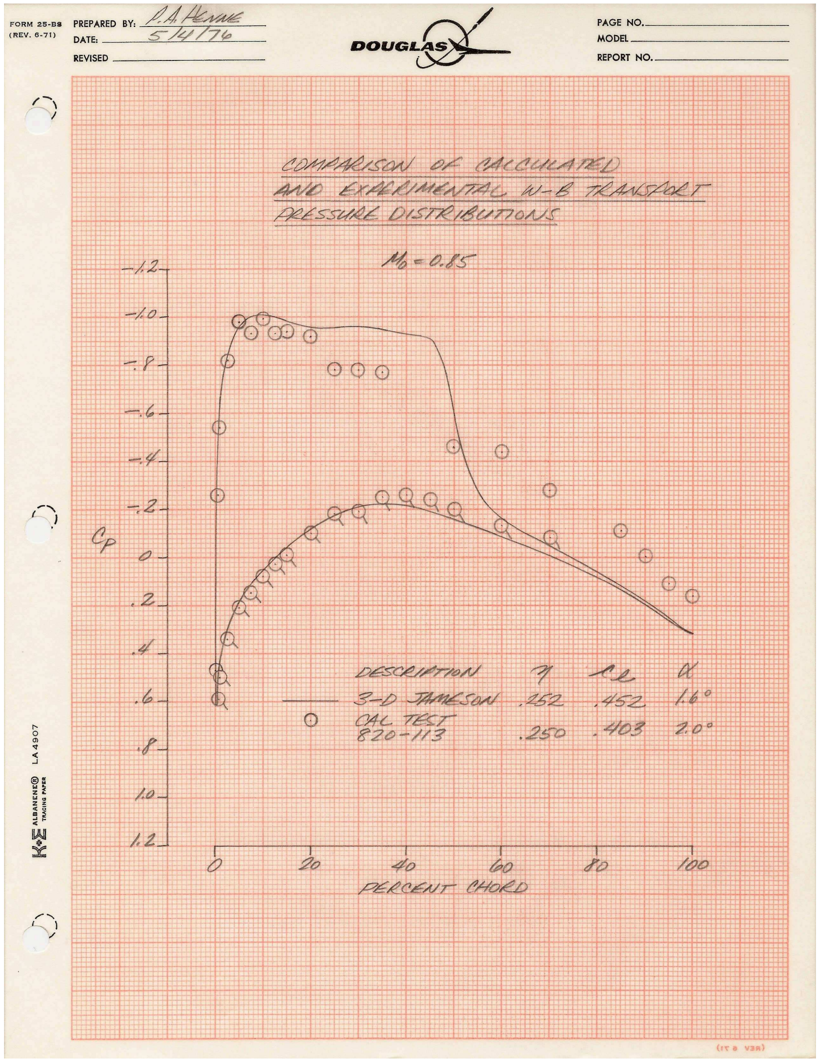
Rough Sketch of Transport Wing Spanload



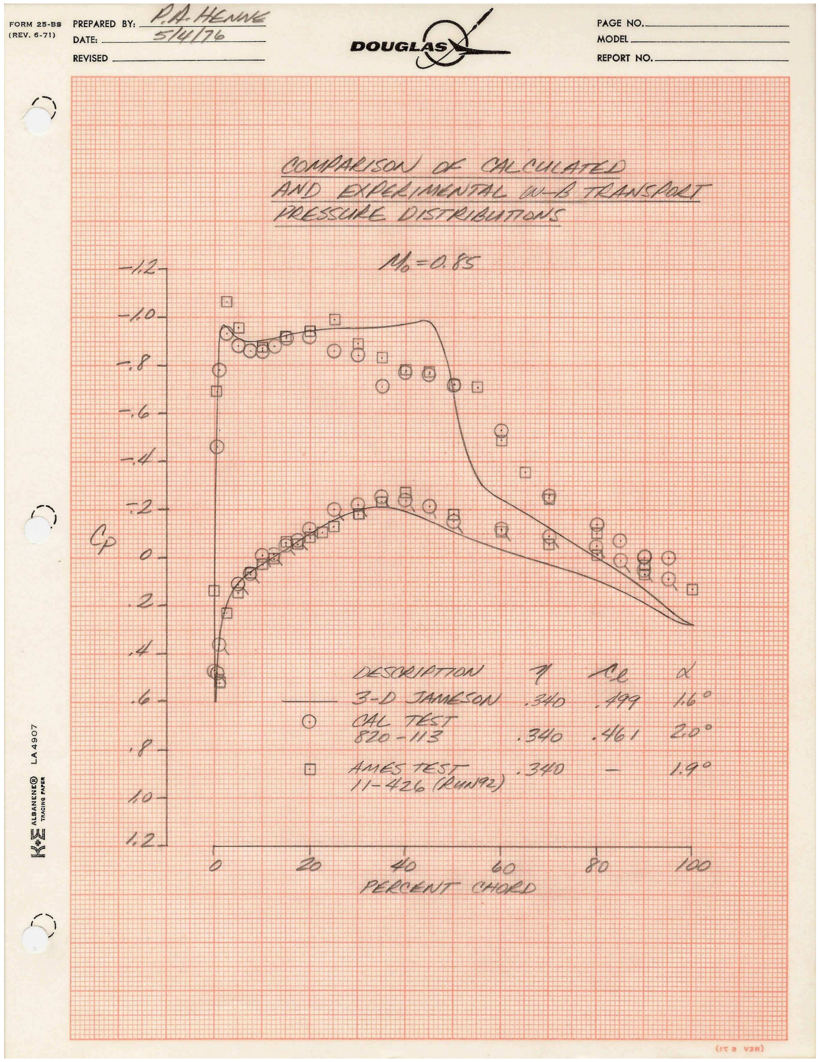
Comparison of Transport Wing Sectional Lift Distributions



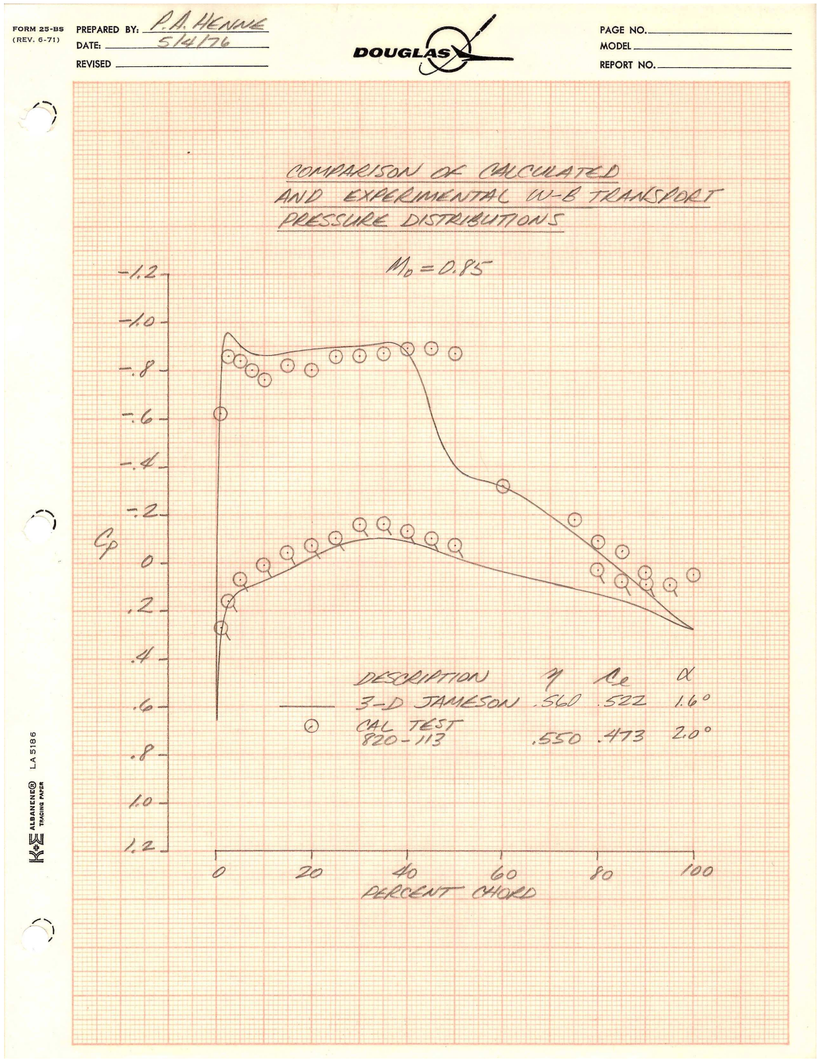
C_P Distributions at 15% Semispan



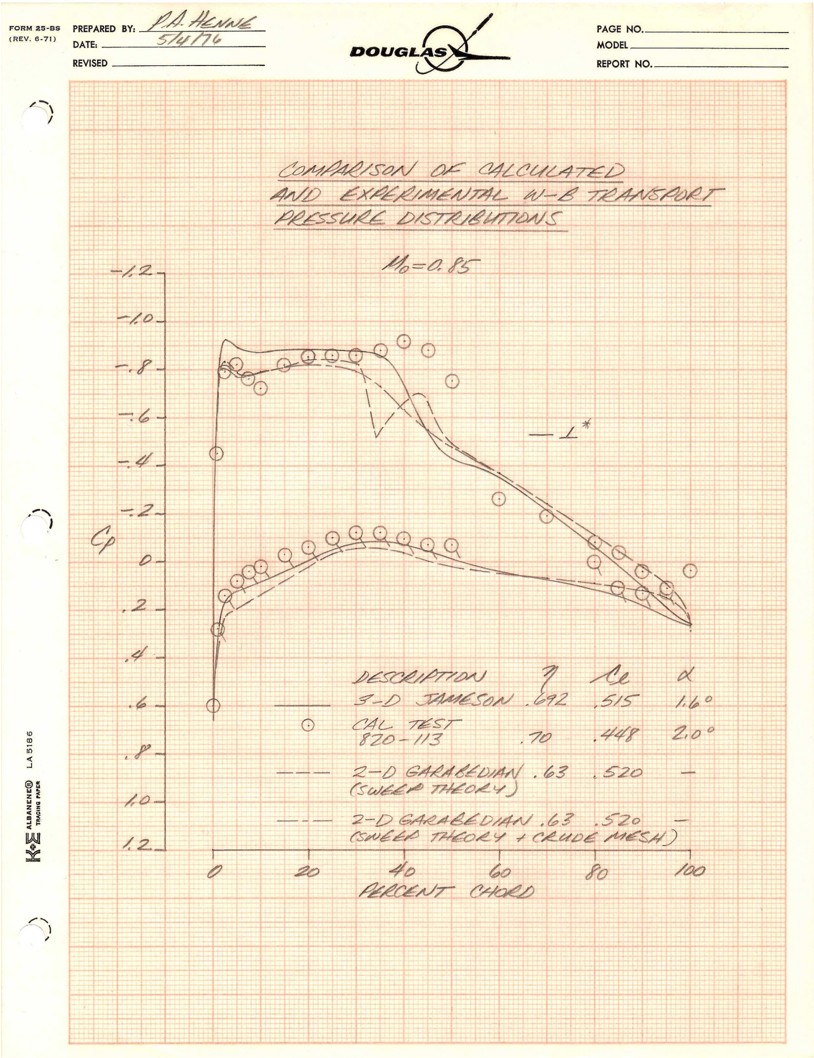
C_P Distributions at 25% Semispan



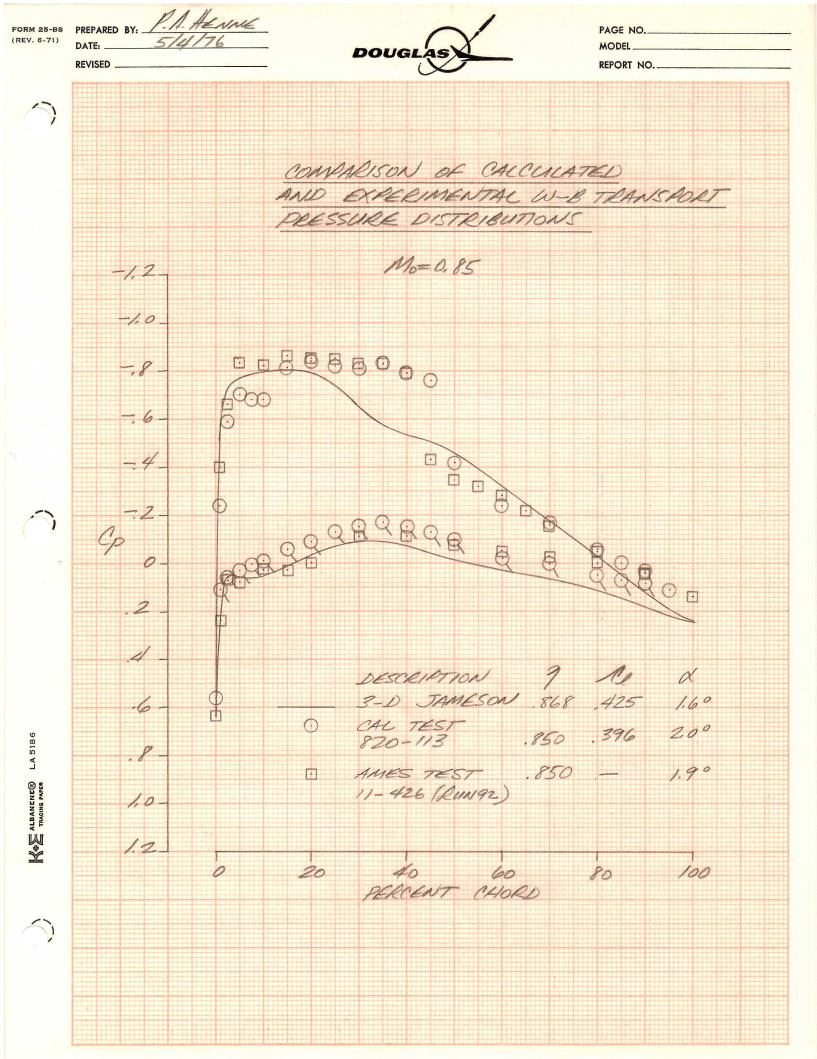
C_P Distributions at 34% Semispan



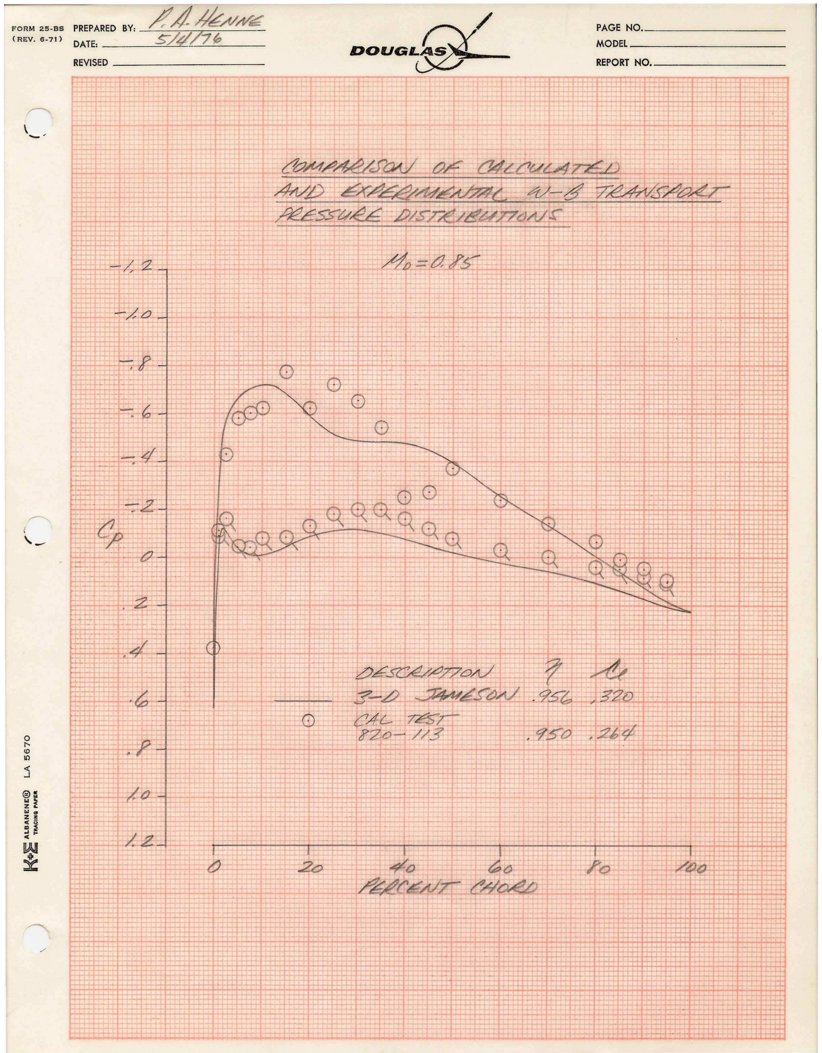
C_P Distributions at 55% Semispan



C_P Distributions at 70% Semispan



C_P Distributions at 85% Semispan



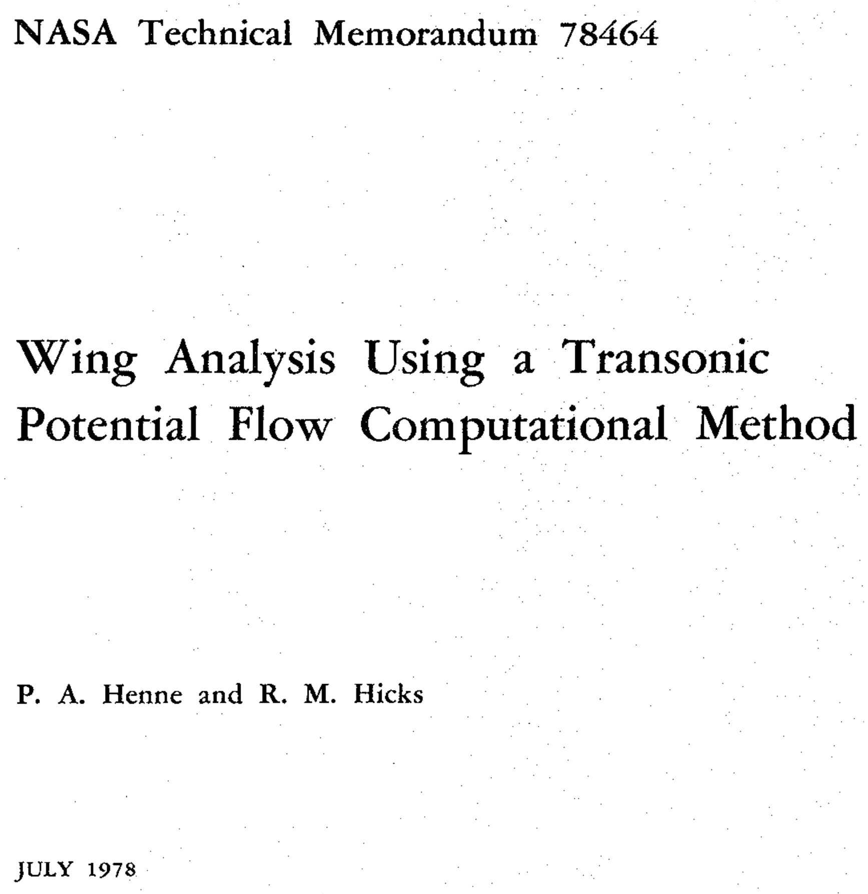
FORM 25-BS (REV. 6-71)
PREPARED BY: P. A. HENNE
DATE: 5/4/76
REVISED
DOUGLAS
PAGE NO.
MODEL
REPORT NO.

COMPARISON OF CALCULATED AND EXPERIMENTAL W-B TRANSPORT PRESSURE DISTRIBUTIONS

$M_0 = 0.85$

	DESCRIPTION	η	C_L
—	3-D JAMESON	.956	.320
⊙	CAL TEST 820-113	.950	.264

C_P Distributions at 95% Semispan

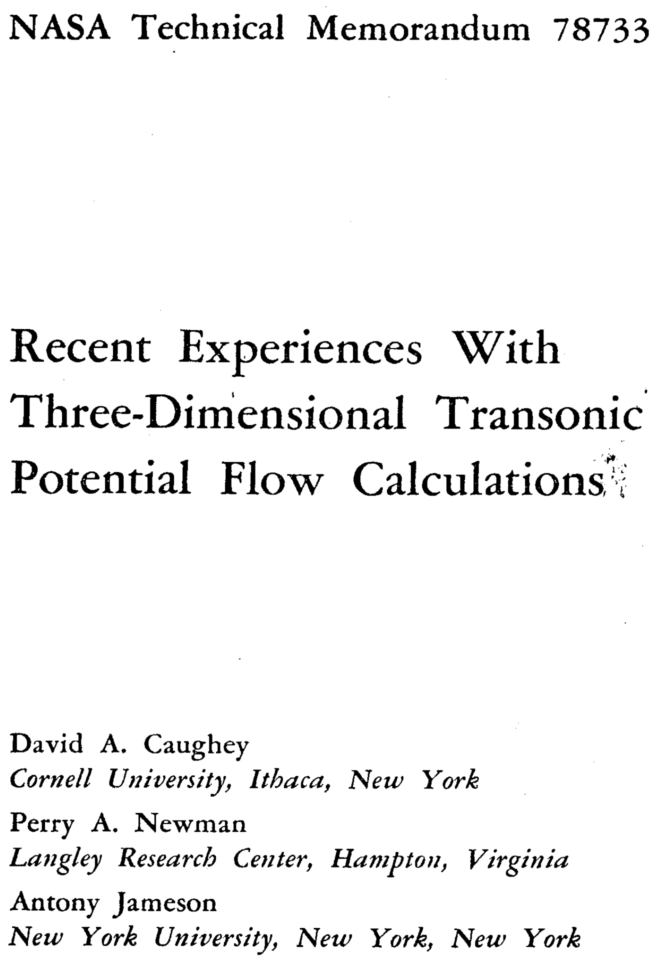


NASA Technical Memorandum 78464

Wing Analysis Using a Transonic Potential Flow Computational Method

P. A. Henne and R. M. Hicks

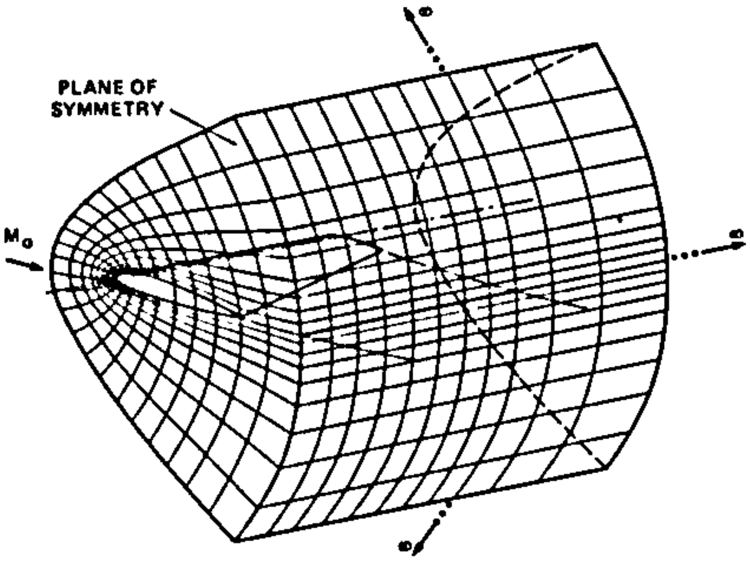
JULY 1978

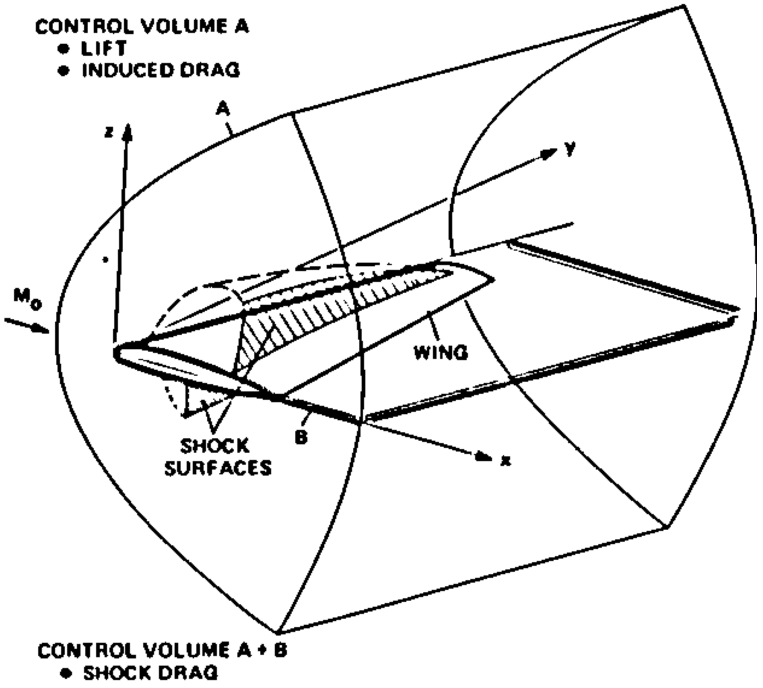


NASA Technical Memorandum 78733

Recent Experiences With Three-Dimensional Transonic Potential Flow Calculations

David A. Caughey
Cornell University, Ithaca, New York
Perry A. Newman
Langley Research Center, Hampton, Virginia
Antony Jameson
New York University, New York, New York


PLANE OF SYMMETRY
M₀
∞
∞
∞


CONTROL VOLUME A
• LIFT
• INDUCED DRAG
A
z
y
M₀
WING
SHOCK SURFACES
B
x
CONTROL VOLUME A + B
• SHOCK DRAG

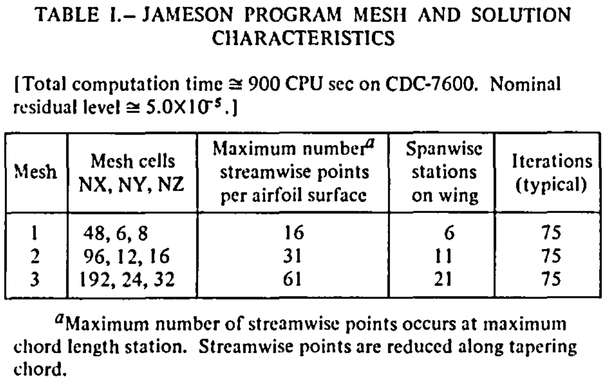


TABLE I.– JAMESON PROGRAM MESH AND SOLUTION CHARACTERISTICS

[Total computation time $\cong$ 900 CPU sec on CDC-7600. Nominal residual level $\cong 5.0\text{X}10^{-5}$.]

Mesh	Mesh cells NX, NY, NZ	Maximum number[a] streamwise points per airfoil surface	Spanwise stations on wing	Iterations (typical)
1	48, 6, 8	16	6	75
2	96, 12, 16	31	11	75
3	192, 24, 32	61	21	75

[a] Maximum number of streamwise points occurs at maximum chord length station. Streamwise points are reduced along tapering chord.

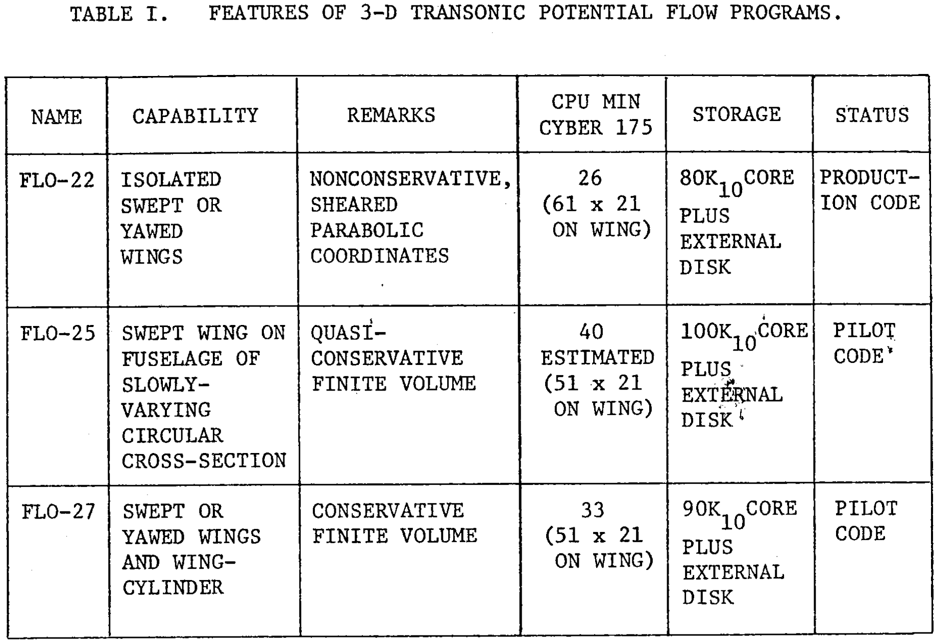


TABLE I. FEATURES OF 3-D TRANSONIC POTENTIAL FLOW PROGRAMS.

NAME	CAPABILITY	REMARKS	CPU MIN CYBER 175	STORAGE	STATUS
FLO-22	ISOLATED SWEPT OR YAWED WINGS	NONCONSERVATIVE, SHEARED PARABOLIC COORDINATES	26 (61 x 21 ON WING)	$80K_{10}$CORE PLUS EXTERNAL DISK	PRODUCTION CODE
FLO-25	SWEPT WING ON FUSELAGE OF SLOWLY-VARYING CIRCULAR CROSS-SECTION	QUASI-CONSERVATIVE FINITE VOLUME	40 ESTIMATED (51 x 21 ON WING)	$100K_{10}$CORE PLUS EXTERNAL DISK	PILOT CODE
FLO-27	SWEPT OR YAWED WINGS AND WING-CYLINDER	CONSERVATIVE FINITE VOLUME	33 (51 x 21 ON WING)	$90K_{10}$CORE PLUS EXTERNAL DISK	PILOT CODE

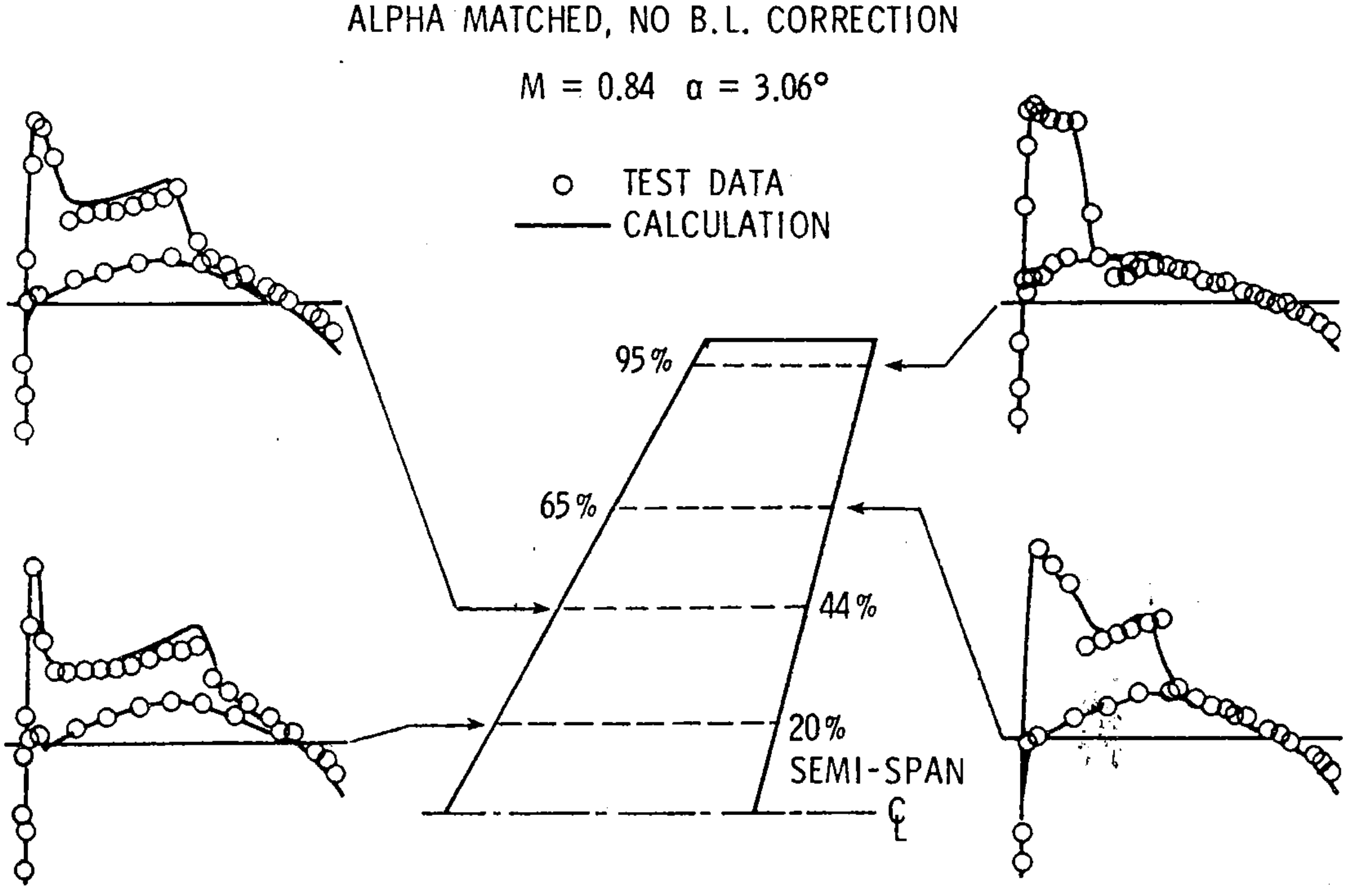


Figure 1.- Comparison of FLO-22 results with experiment for ONERA wing M-6; test conducted at $R_{\bar{c}} = 18 \times 10^6$.

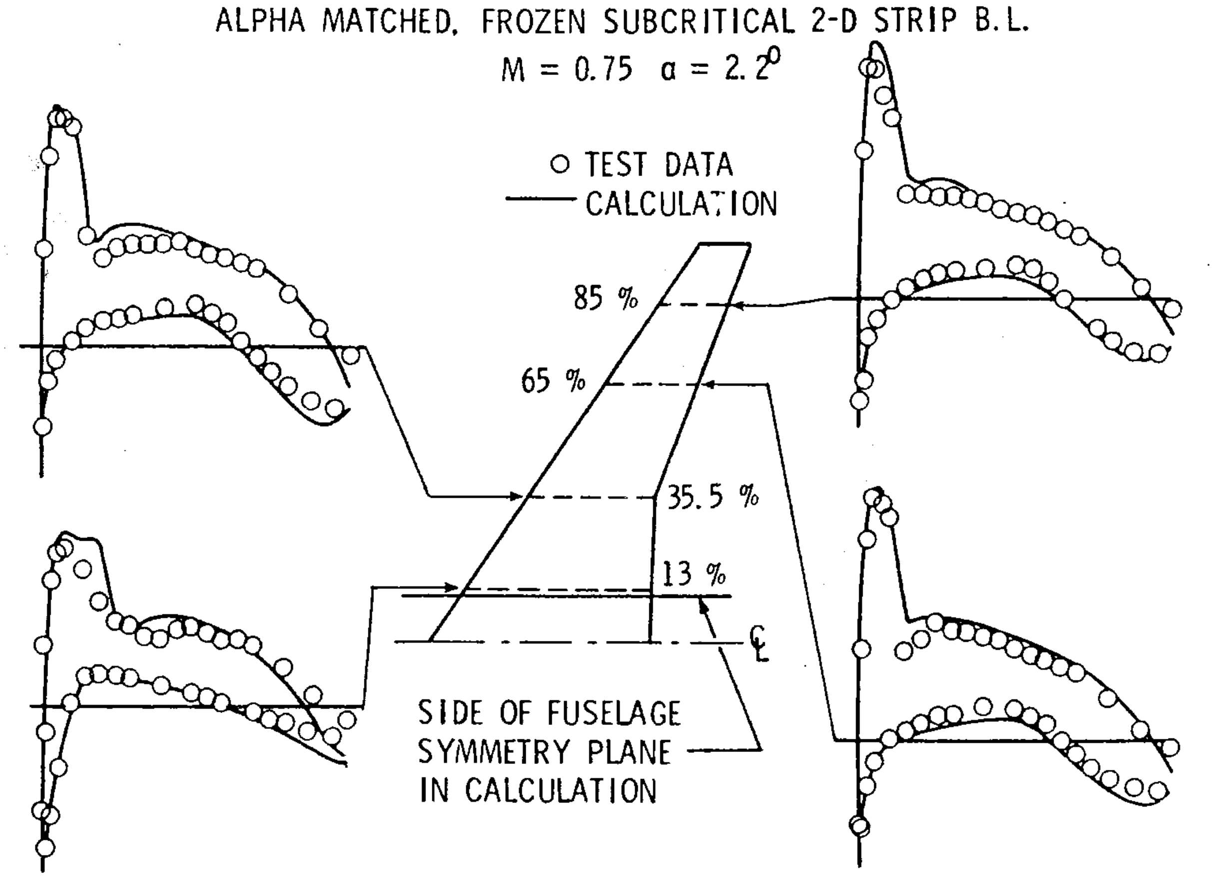


Figure 2.- Comparison of FLO-22 results with experiment for Douglas supercritical wing; test conducted at $R_{\bar{c}} = 5 \times 10^6$.

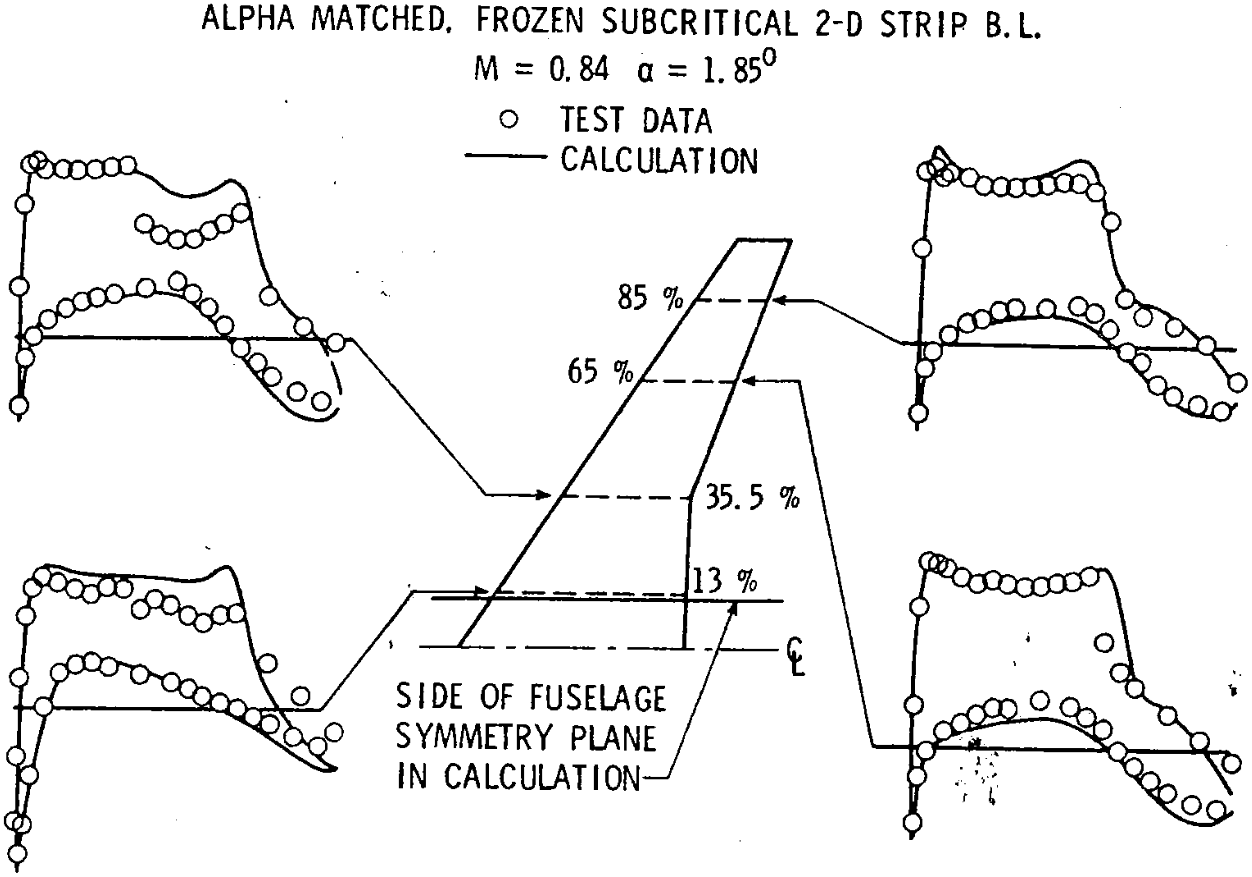


Figure 3.- Comparison of FLO-22 results with experiment for Douglas supercritical wing; test conducted at $R_{\bar{c}} = 5 \times 10^6$.

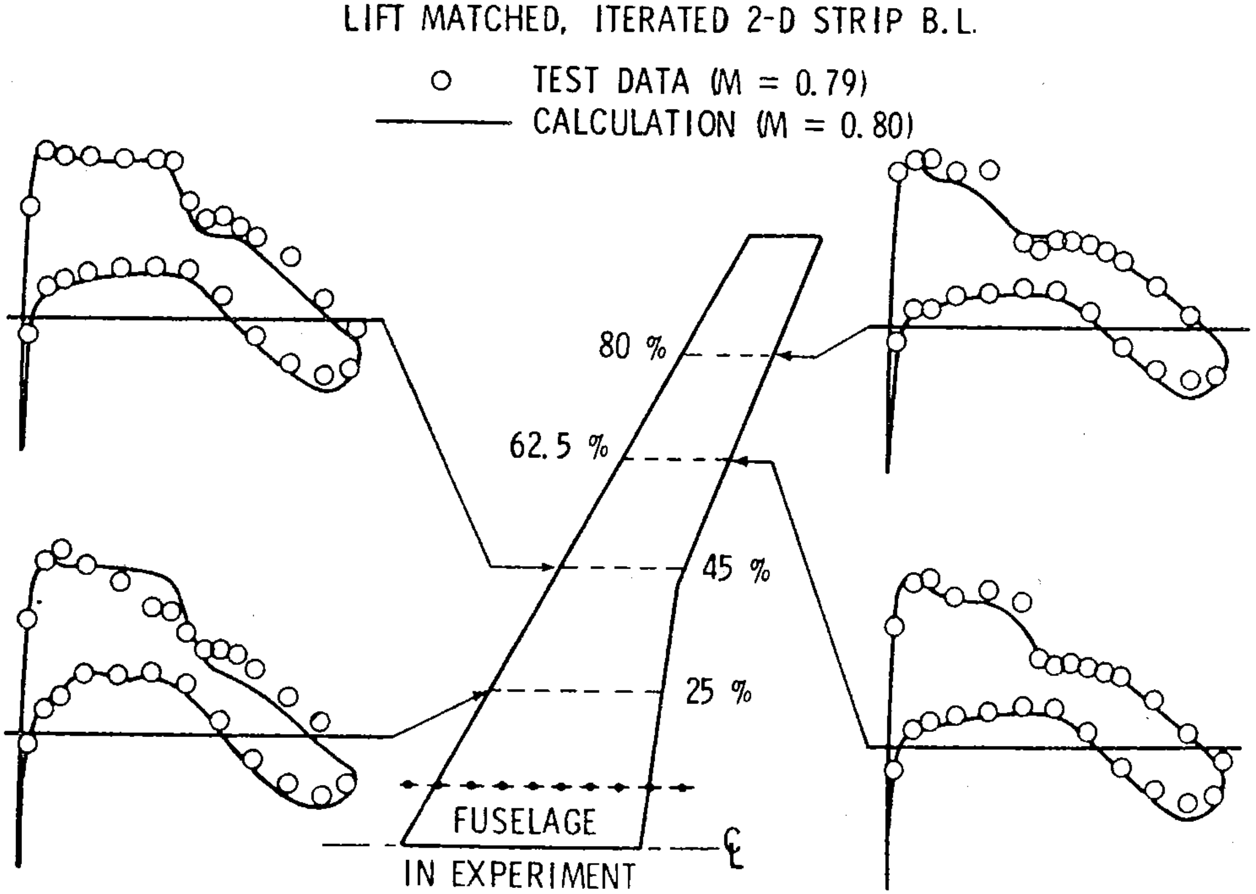


Figure 4.- Comparison of FLO-22 results with experiment for NASA supercritical wing; test conducted at $R_{\bar{c}} = 2.4 \times 10^6$.

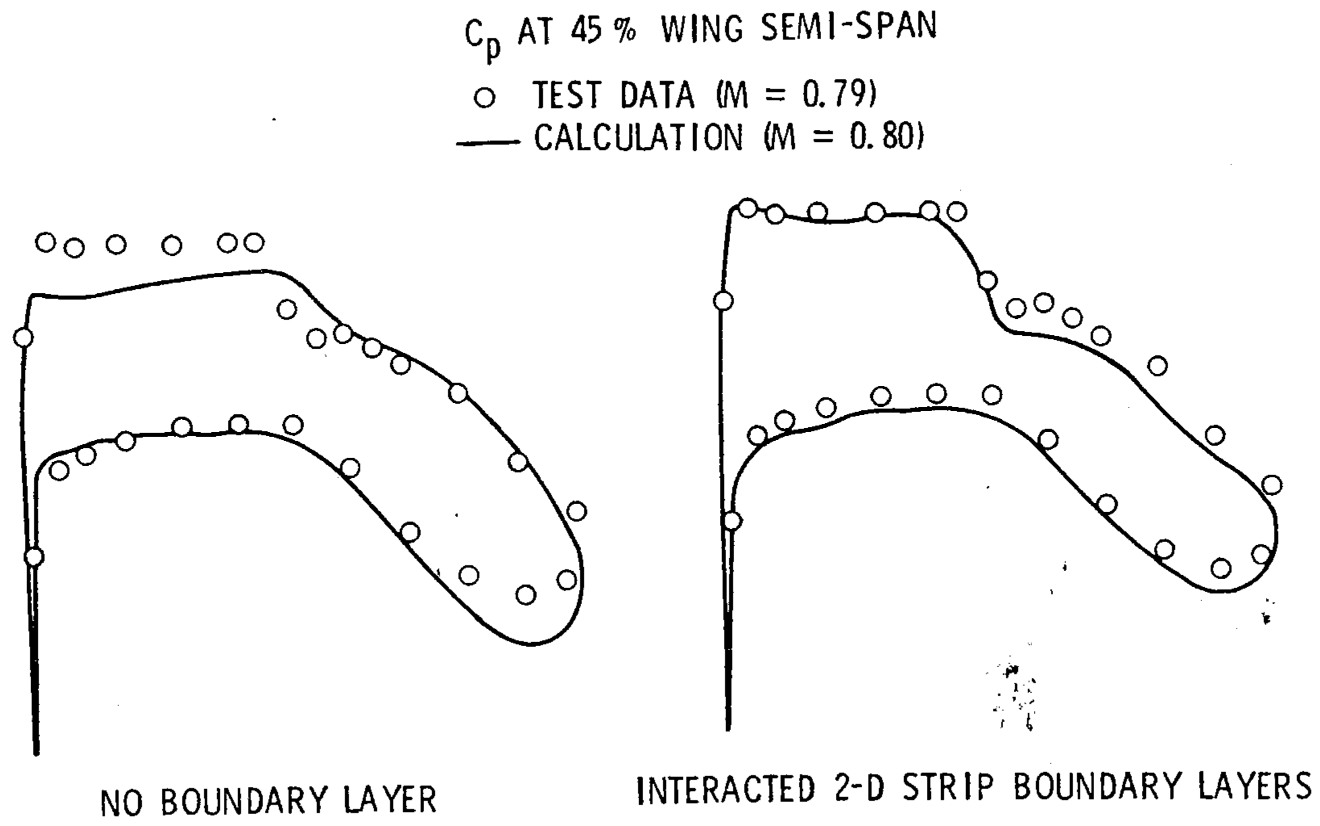


Figure 5.- Effect of boundary-layer displacement thickness on inviscid pressure distribution for NASA supercritical wing with lift matched; FLO-22 calculations and test at $R_{\bar{c}} = 2.4 \times 10^6$.

NASA Awards Jameson $25

It all helps. Another award winner in NASA's Technology Utilization program went to Antony Jameson (R). Presenting the $25 check is 'Cappy' Caprioglio, director of Vehicle Technology. (Photos by Fred Annette)

FLO22 APPLICATIONS

- **1977: Dennis McDowell, Aeronautics R&D**
  - Lear Star 600
  - Canadair Challenger
  - LearJet's *"Dee Howard LR Mod"*
    - Thickened Root to add 250 Gallons Fuel
    - Reduced Stall 1 knot
    - Eliminated Strong Inboard Shock
    - Removed Lower-Surface LE Tip Shock
    - No WT Testing; Straight to Flight
    - Achieved 2 Design/Flight-Test Cycles in 1 Month

FLO22 APPLICATIONS

- **1978-1981: FLO22 Wing Designs at DAC**
  - Adv-Tech Med-Range, McDowell, 1978-1979
    - 180 PAX Aircraft
  - USAF C17, Henne, 1980
  - MDF-100, 1980-1981
    - McDowell, Henne & Dahlin Wing Designers
    - Utilized Henne's Inverse-Design Method
    - C/4 Sweep of 21°
    - All DAC Wings Achieved $M = 0.775$
    - DAC-Fokker Collaboration
    - Greatly Influence Fokker's F-100 Aircraft

FLO22 APPLICATIONS

- **1983-1987: FLO22 Wing Designs at DAC**
  - D-3300, McDowell, 1983
    - 150-PAX, 6-Abreast, Twin-Isle Aircraft
    - Divergent-Trailing-Edge (Henne, Gregg, Vassberg)
    - DTE Technology Worth 4.5% in ML/D
  - MD-87 Horizontal, Joe Morelli, 1985
    - LE Droop (Up-Side-Down) to Increase $C_L max$
  - Series, Robb Gregg & McDowell, 1985-1987
    - $M = 0.80$, 180-200 PAX
    - High-Aspect-Ratio Wings
    - C/4 Sweep from 21° to 35°
    - Optimum Wing: 27.8°, $AR = 12.1$

FLO22 APPLICATIONS

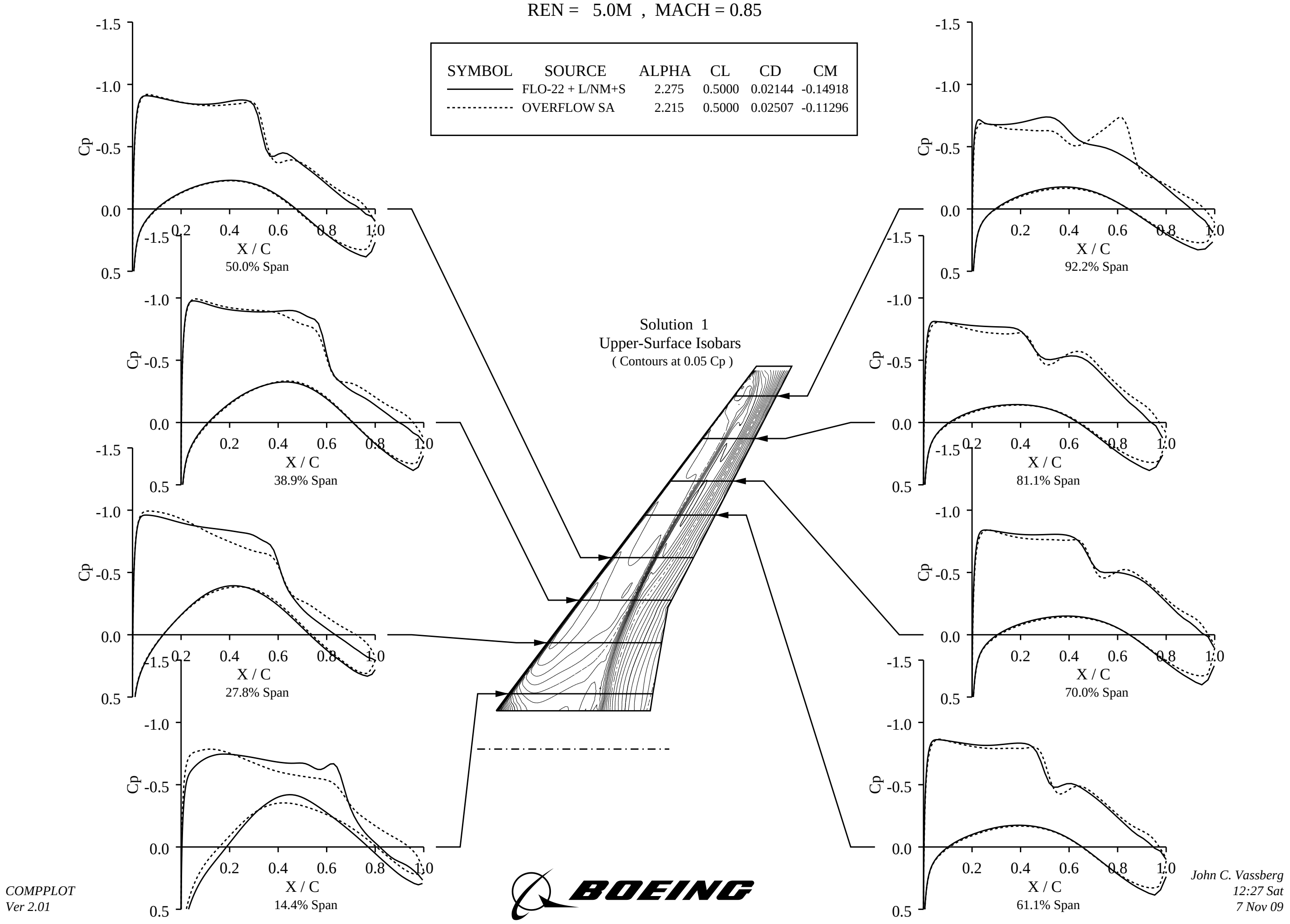
- **1988-1997: FLO22 Wing Designs at DAC**
  - MD-11, John Allen, 1988
    - Incorporated TE Wedge on DC10 Wing
    - Winglet Design
  - MD-12X, Gregg & McDowell, 1988-1991
    - 375-PAX Tri-Jet
    - Aggressive DTE Wing Design
  - B747 Study, McDowell & Vassberg, 1997
    - Post Merger w/ Boeing
    - Developed TE-Wedge Retrofit
    - BTWT Tested, JAN 1998
    - Flight Tested, SEP 1998

FLO22 APPLICATIONS

- **NOV 2009: FLO22 at Boeing**
  - NASA CRM Wing/Body, Vassberg
    - $M = 0.85$, $Re_c = 5\ M$, $C_L = 0.5$, $\alpha = 2.275°$
    - Grid: (385 x 50 x 66), $\sim$ 1.27M nodes
    - Deskside CPU Time: $\sim$ 2 sec

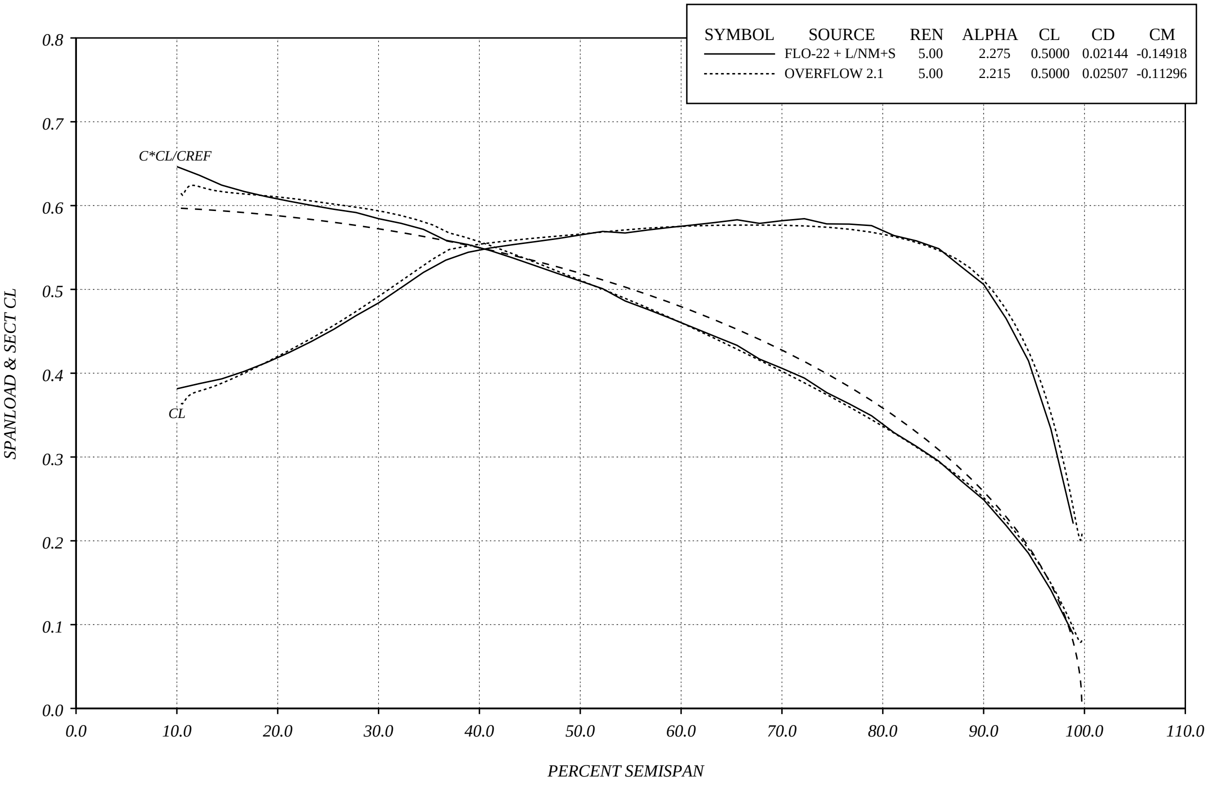
  - OVERFLOW Comparison, DPW-IV
    - $M = 0.85$, $Re_c = 5\ M$, $C_L = 0.5$, $\alpha = 2.215°$
    - Reynolds-Averaged Navier-Stokes; Thin-Layer
    - Over-Set Grid; 11 zones; $\sim$ 12.3M nodes
    - Spalart-Allmaras Turbulence Model
    - Fully-Turbulent
    - Linux-Cluster CPU Time: $\sim$ 300,000 cpu-sec

COMPARISON OF CHORDWISE PRESSURE DISTRIBUTIONS
NASA COMMON RESEARCH MODEL WING/BODY CONFIGURATION
REN = 5.0M , MACH = 0.85



SYMBOL	SOURCE	ALPHA	CL	CD	CM
————	FLO-22 + L/NM+S	2.275	0.5000	0.02144	-0.14918
············	OVERFLOW SA	2.215	0.5000	0.02507	-0.11296

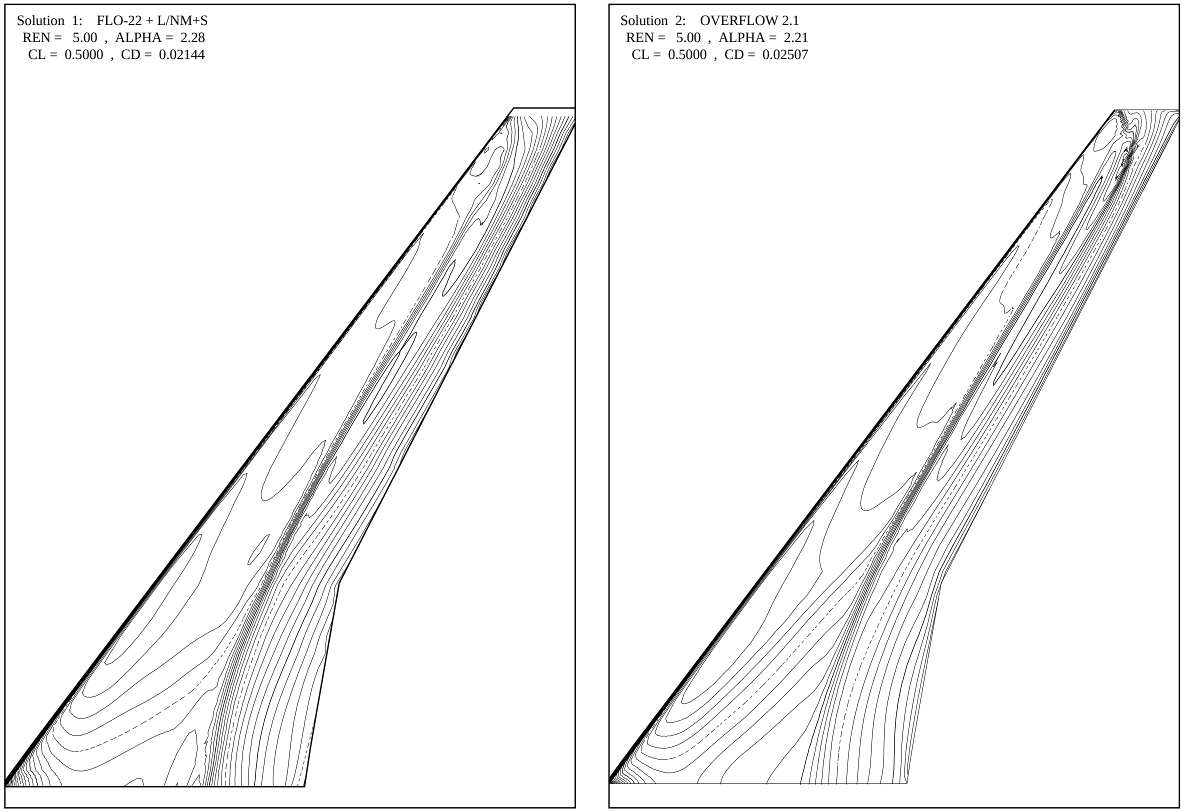
COMPARISON OF SPANLOAD DISTRIBUTIONS
NASA COMMON RESEARCH MODEL WING/BODY CONFIGURATION
MACH = 0.850



COMPPLOT
Ver 2.01

John C. Vassberg
12:27 Sat
7 Nov 09

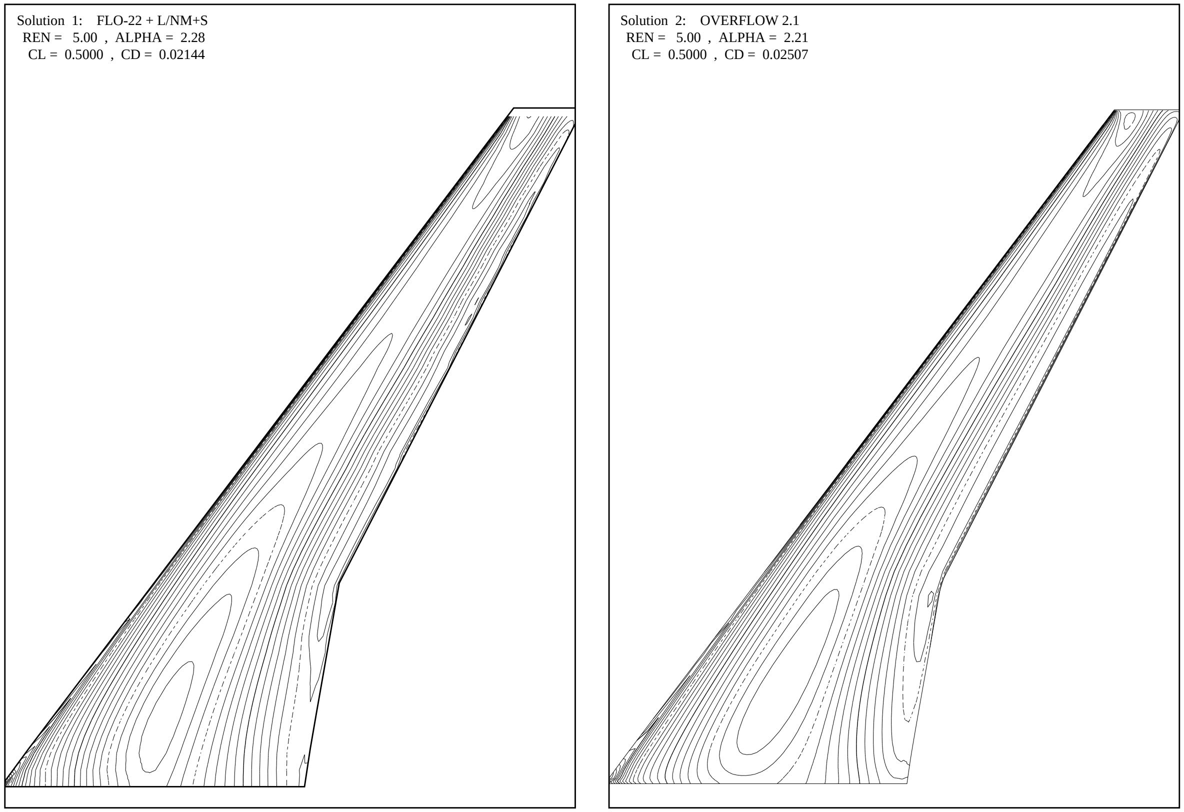
COMPARISON OF UPPER SURFACE CONTOURS
NASA COMMON RESEARCH MODEL WING/BODY CONFIGURATION
MACH = 0.850
(Contours at 0.05 Cp)



COMPPLOT
Ver 2.01

John C. Vassberg
12:27 Sat
7 Nov 09

COMPARISON OF LOWER SURFACE CONTOURS
NASA COMMON RESEARCH MODEL WING/BODY CONFIGURATION
MACH = 0.850
(Contours at 0.05 Cp)



Solution 1: FLO-22 + L/NM+S
REN = 5.00 , ALPHA = 2.28
CL = 0.5000 , CD = 0.02144

Solution 2: OVERFLOW 2.1
REN = 5.00 , ALPHA = 2.21
CL = 0.5000 , CD = 0.02507

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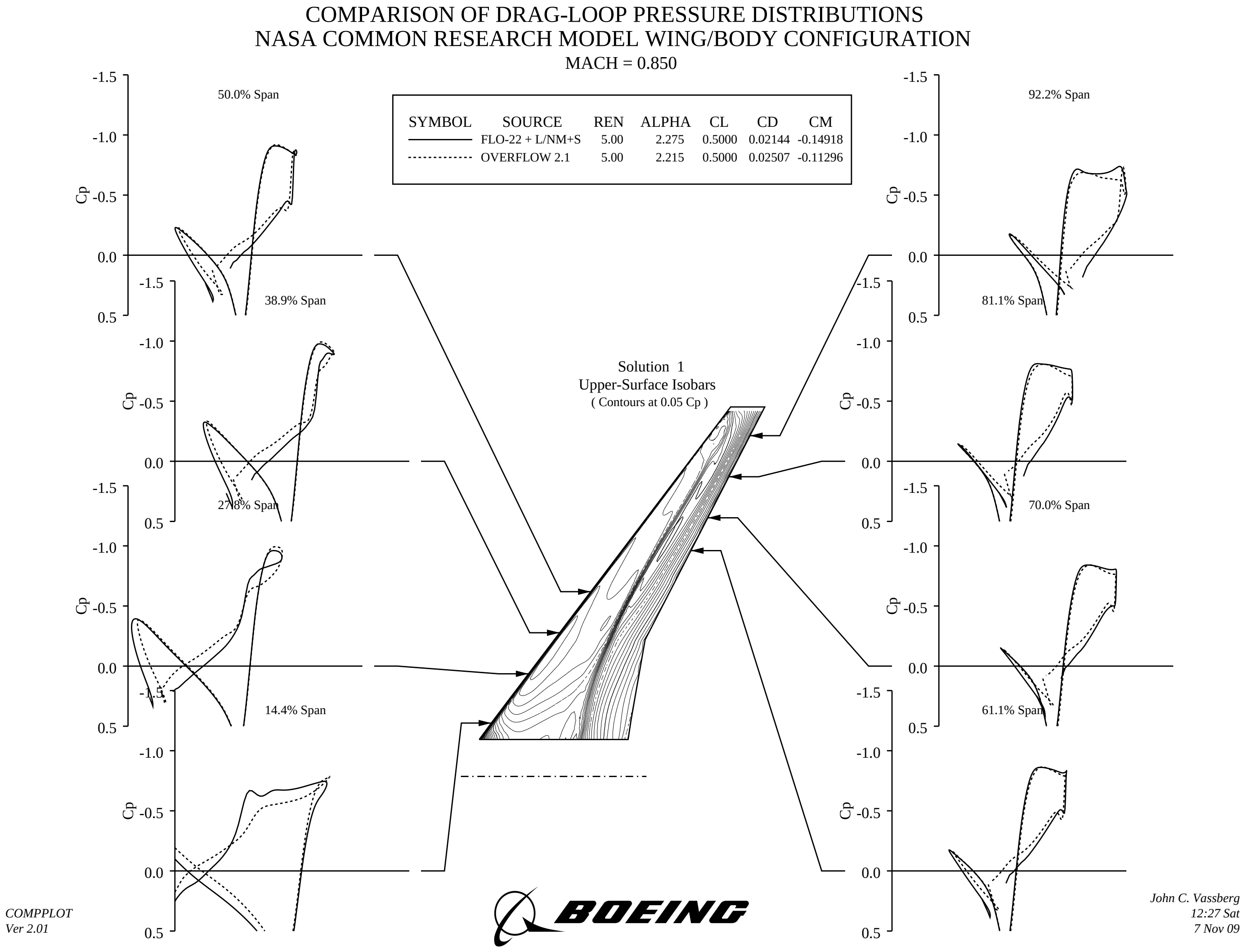
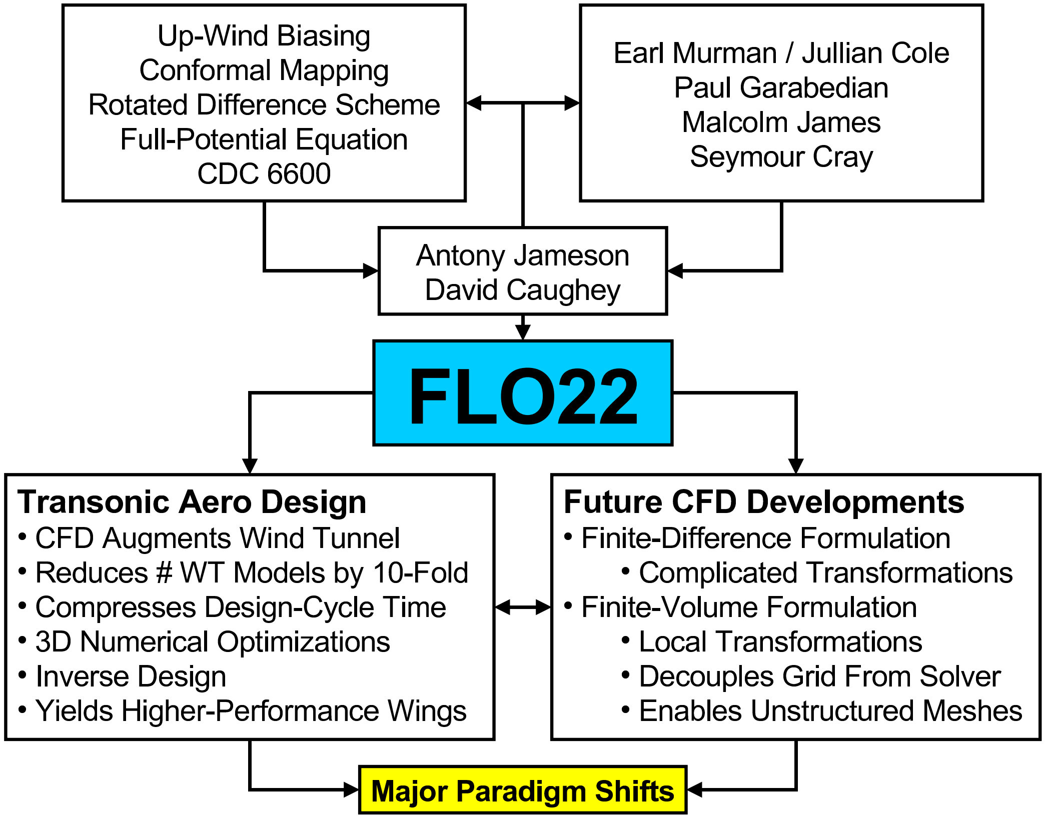
7 Nov 09



COMPARISON OF DRAG-LOOP PRESSURE DISTRIBUTIONS
NASA COMMON RESEARCH MODEL WING/BODY CONFIGURATION
MACH = 0.850

SYMBOL	SOURCE	REN	ALPHA	CL	CD	CM
———	FLO-22 + L/NM+S	5.00	2.275	0.5000	0.02144	-0.14918
- - - - -	OVERFLOW 2.1	5.00	2.215	0.5000	0.02507	-0.11296

FLO22 IN A NUTSHELL



Up-Wind Biasing
Conformal Mapping
Rotated Difference Scheme
Full-Potential Equation
CDC 6600

Earl Murman / Jullian Cole
Paul Garabedian
Malcolm James
Seymour Cray

Antony Jameson
David Caughey

FLO22

Transonic Aero Design

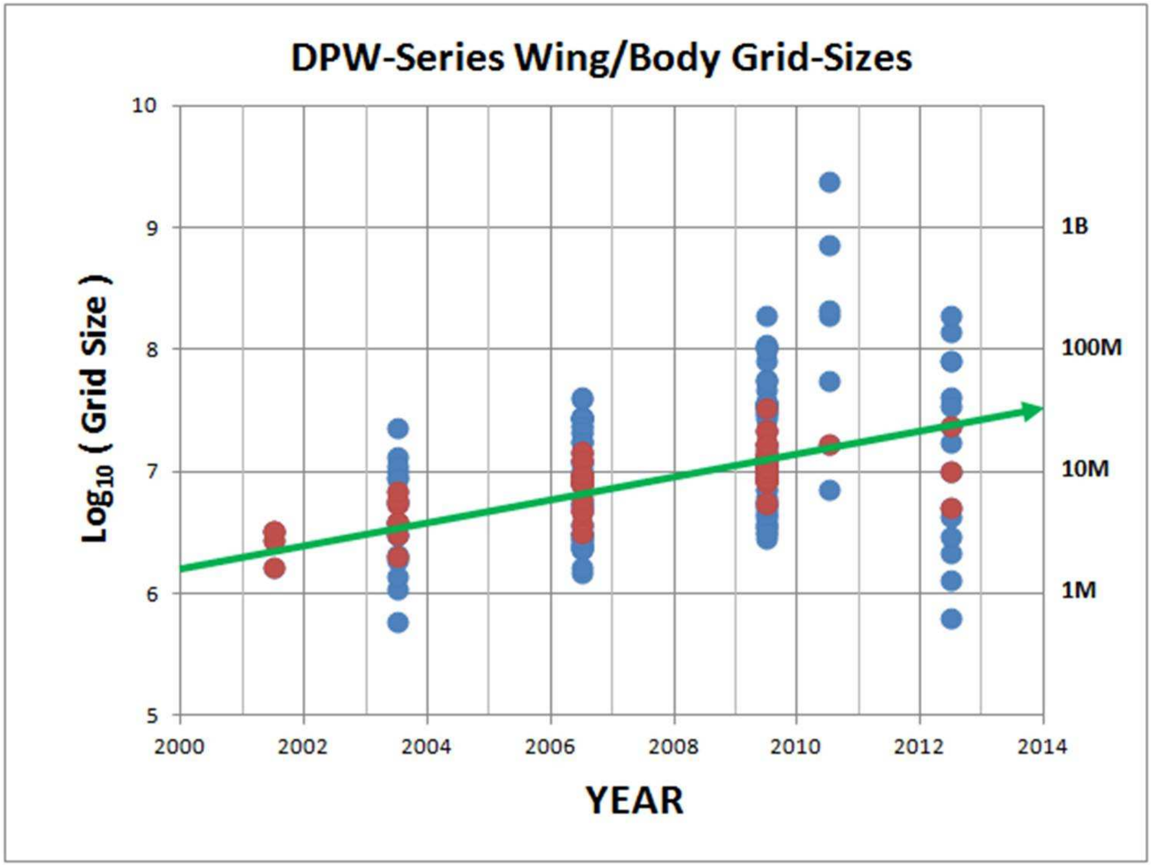
- CFD Augments Wind Tunnel
- Reduces # WT Models by 10-Fold
- Compresses Design-Cycle Time
- 3D Numerical Optimizations
- Inverse Design
- Yields Higher-Performance Wings

Future CFD Developments

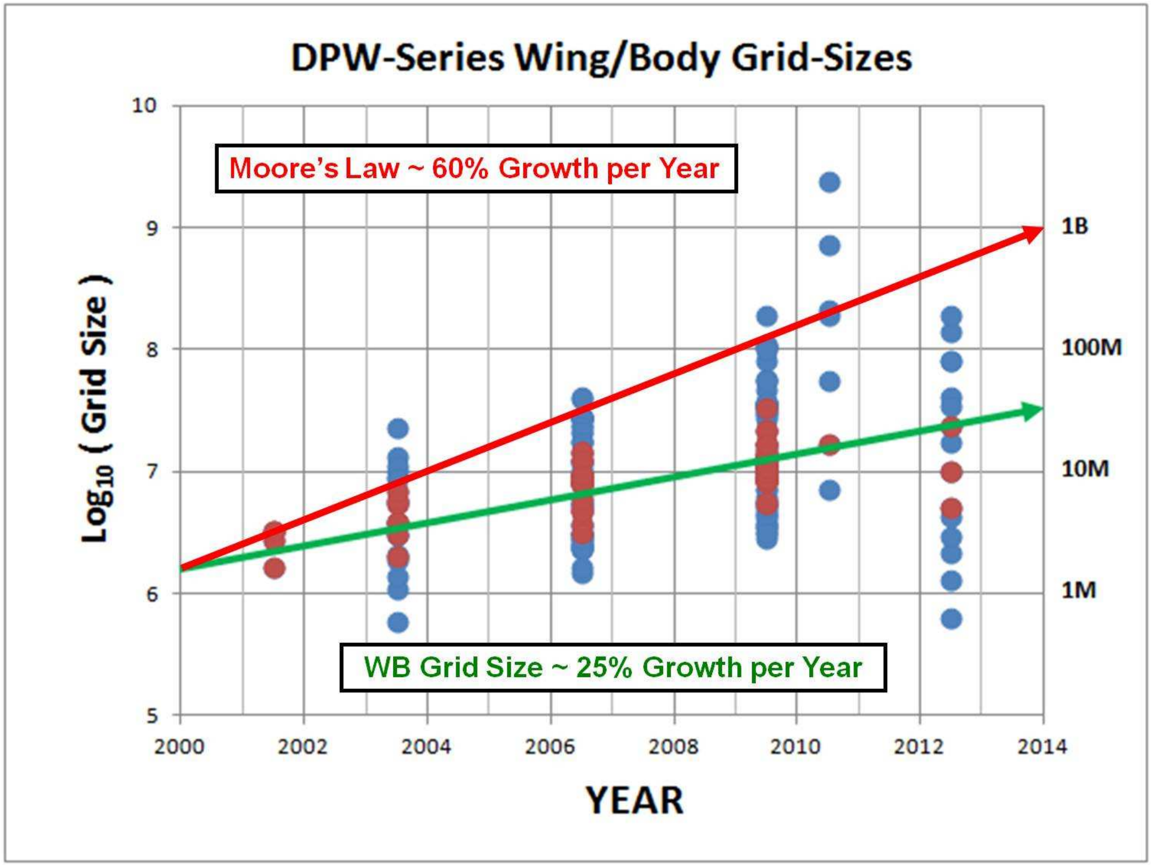
- Finite-Difference Formulation
  - Complicated Transformations
- Finite-Volume Formulation
  - Local Transformations
  - Decouples Grid From Solver
  - Enables Unstructured Meshes

Major Paradigm Shifts

GRID GROWTH TREND



GRID GROWTH TREND



FLO22 REAL-TIME RUN

- **NASA Common Research Model**
- $M = 0.85$, $C_L = 0.5$
- **Grid: (3,073 x 194 x 258)**
- **Nodes: 153,809,796**
- **CPU: $\sim$50 Minutes**
- **Apple MacBookPro Laptop**


7H 16 66
CALIFORNIA