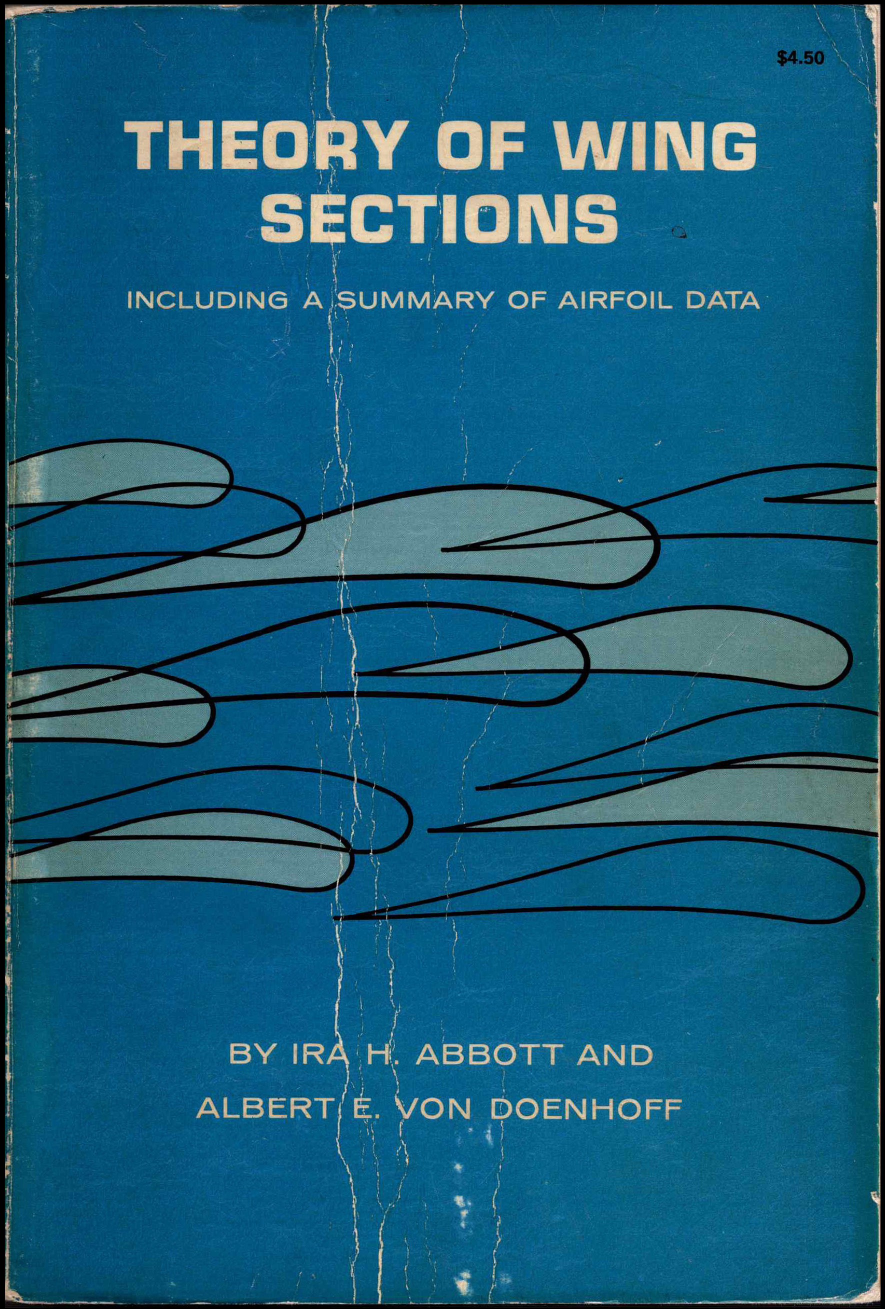
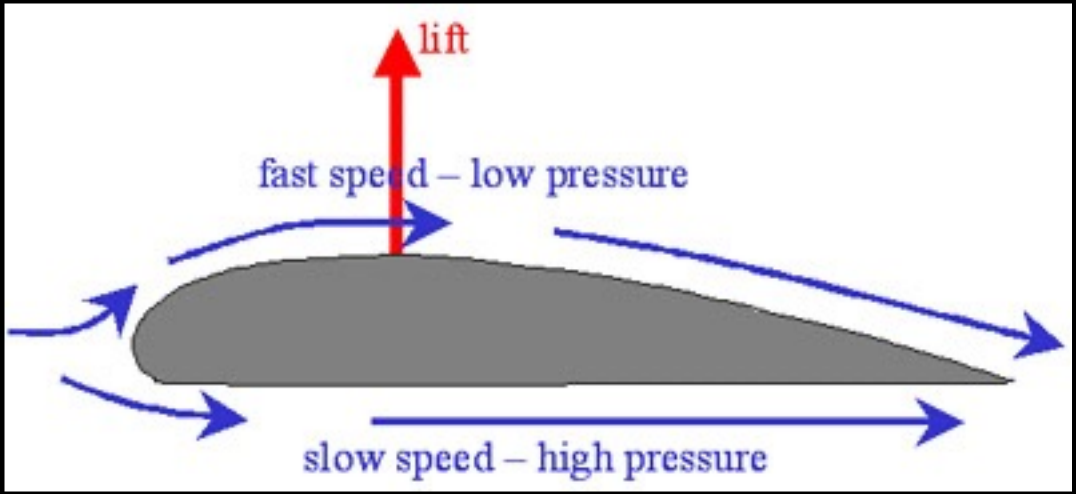


Maybe that title should reverse emphasis!

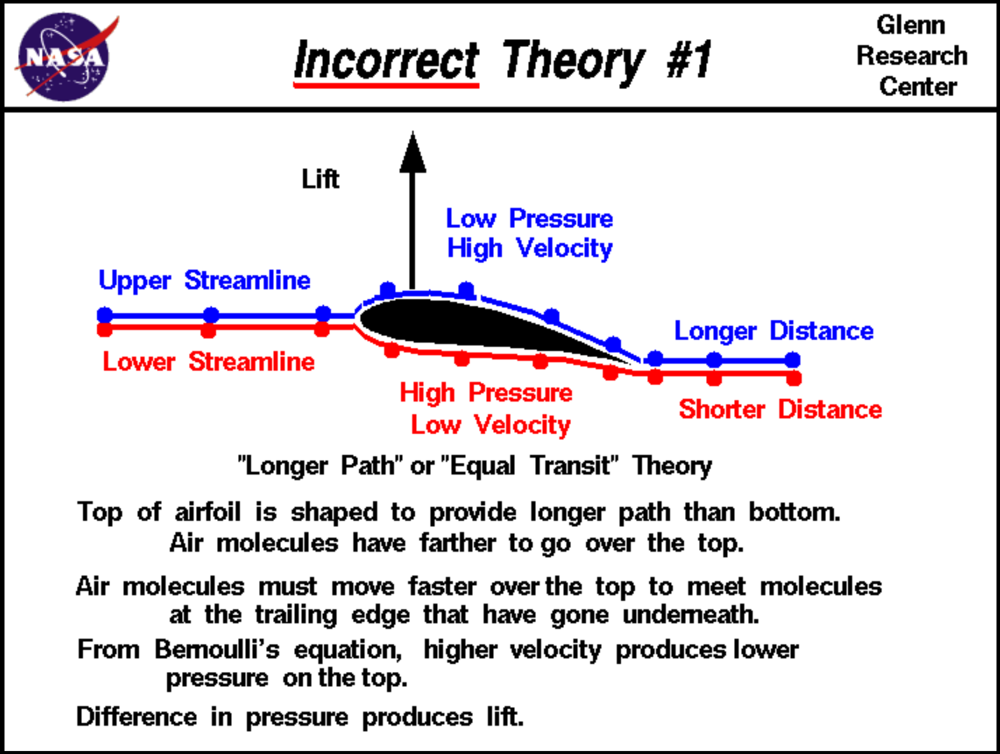
If any of you are young engineers, Note the price! When was the last time you bought an aero text for $4.50. It's really thick too!



HOW CONVENTIONAL LIFT IS GENERATED

Wing lift is NOT due to the Bernoulli Effect, despite many flight manuals and science museums claiming it is. The Bernoulli Effect is where a high speed fluid flowing over a surface reduces pressure. The Bernoulli Effect is a real phenomenon occurring elsewhere but not on wings.

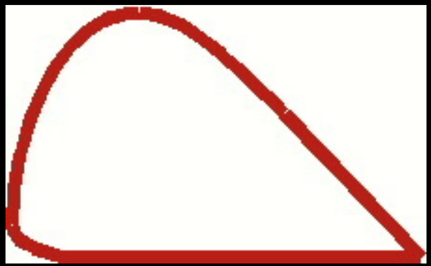
terry@vortex-dynamics.com.au



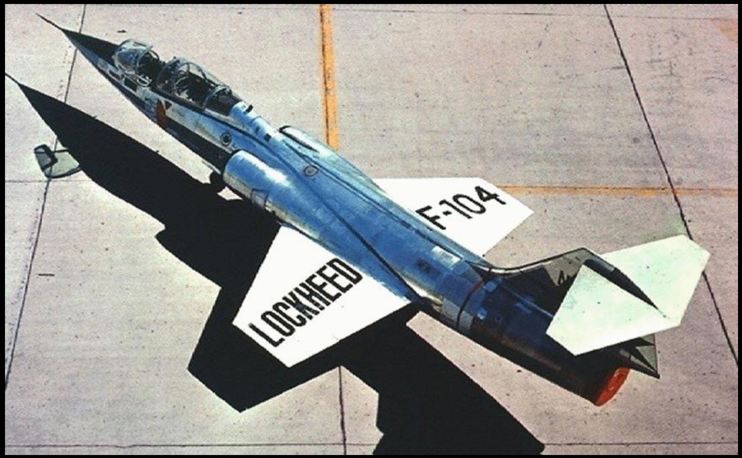
Problems With Bernoulli and equal transit time:

1) Nothing in Bernoulli's equations require equal transit time.
2) Does not explain Upwash ahead of the wing; Downwash behind the wing
3) Strength of tip vortices or the equation lift equals the product of air density x aircraft velocity x VORTEX STRENGTH

4) In order to generate the lift to support a small airplane the upper surface would need to be at least 150% as long as the lower surface. Typical cambered wings are 101% to 102.5%
A wing of the needed 150% would look like this:
I don't recall many airplanes whose wings look this way.
A Cessna 172 would have to fly with it's wing geometry would have to fly 400 mph to generate enough lift by the Bernoulli/equal transit time method.



5) How do symetrical airfoils work?
6) How do airplanes fly upside down?
7) How does a wing generate up to 9 times the lift pulling out of a steep dive? particularly when the airspeed is actually decreasing due to induced drag?
8) Actual airflow over the top is much faster than equal transit time would predict



Obviously neither of these airplanes can actually fly since the top surface and bottom surface are nearly the same length.

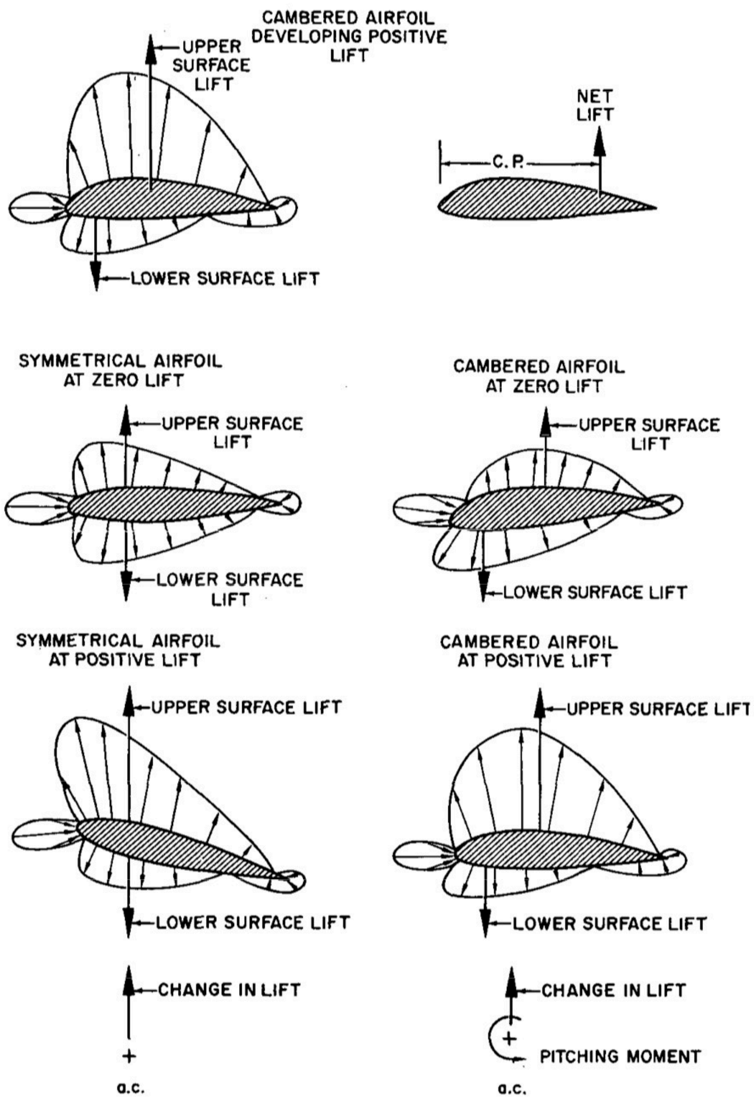
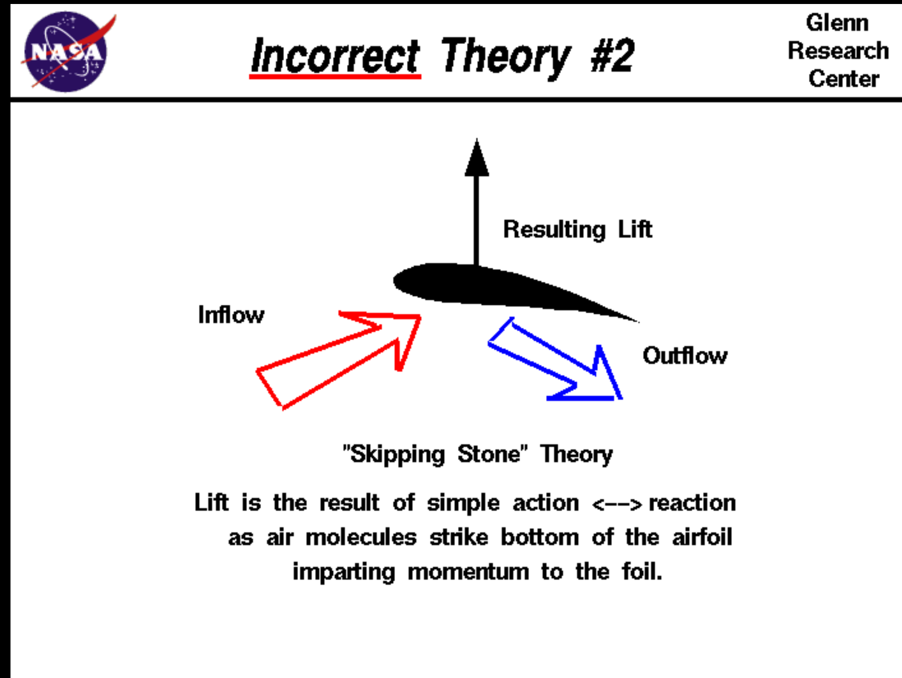
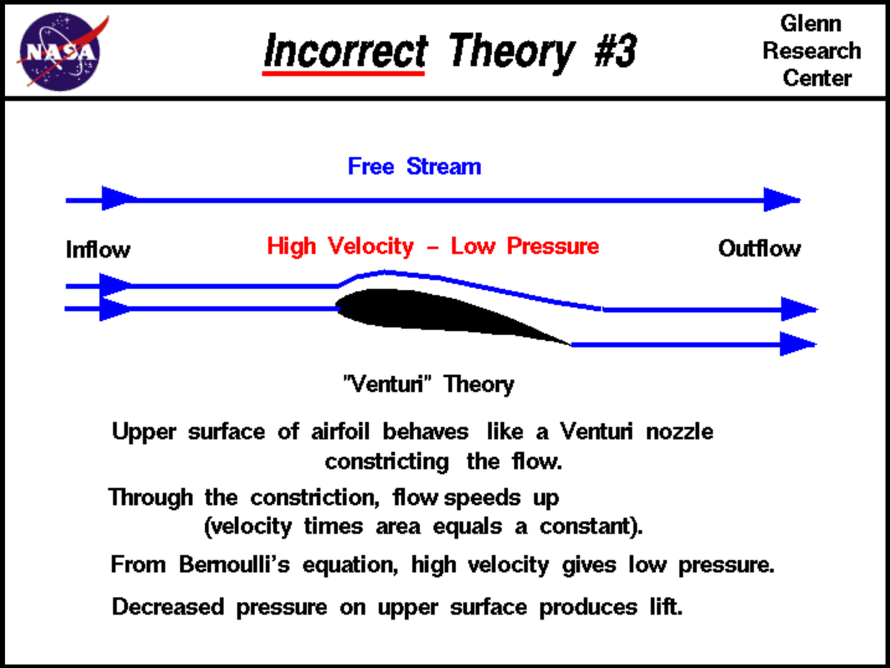


Figure 1.21. Development of Pitching Moments

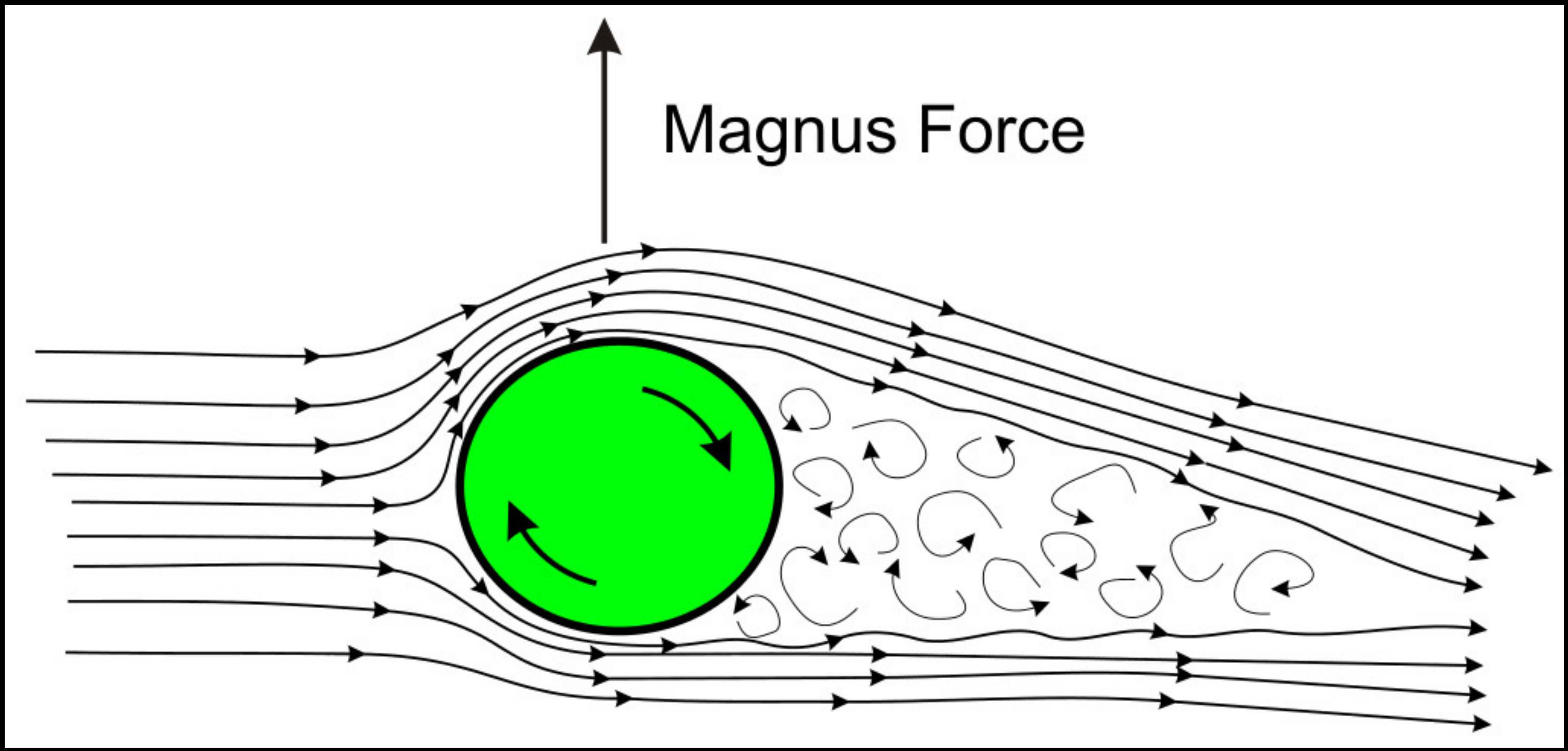


This theory also has some attractive features. It is correct in that lift is derived from a turning of the air flow, but is wrong on the face of it.

The shape of the upper surface is not considered, so why do we go to the considerable expense of building complex curved upper surfaces?



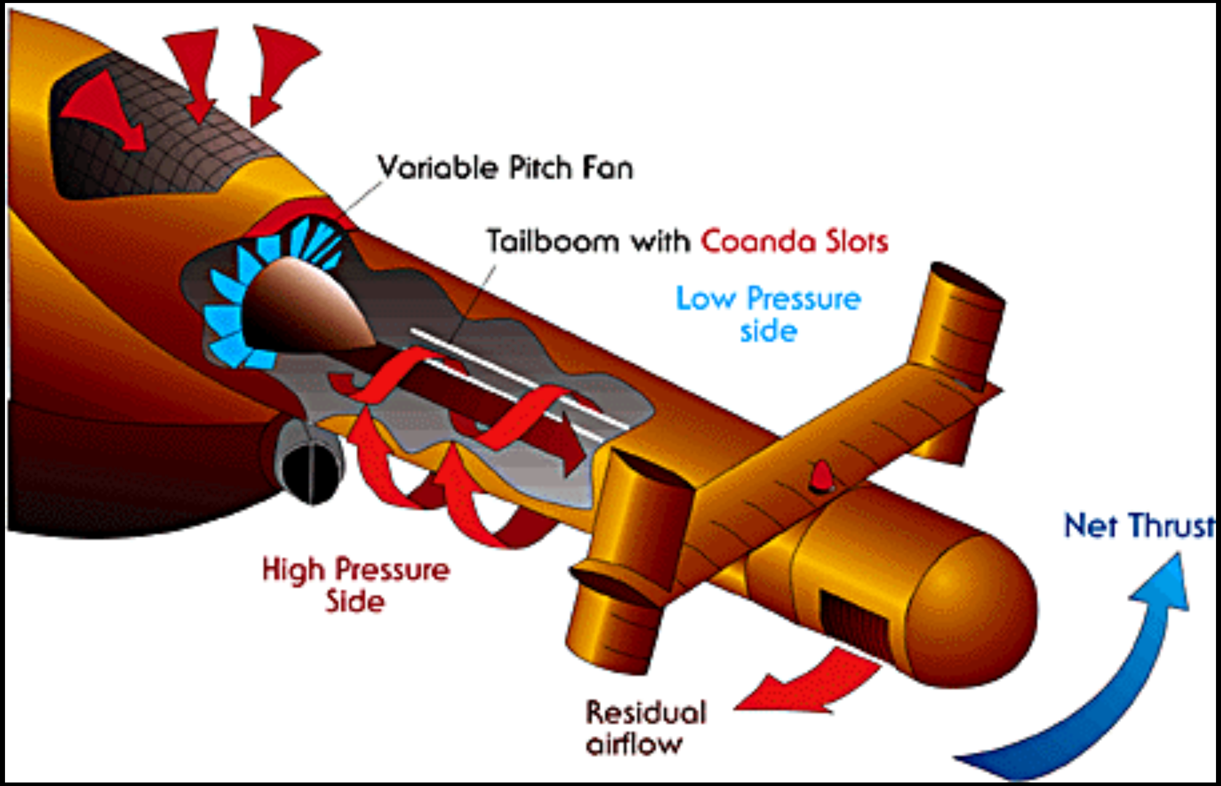
This theory has the same problems as incorrect theory #1 with the added complication that a venturi tube has an ACTUAL, not a virtual, other side. It is attractive because one can point out that fluids do not flow across a stream line. This is true. But the stream line does not form the boundary, the stream line is DEFINED by the flow not crossing a give line.



Curve balls work because of the Magnus effect. A rotating cylinder in a crossflow of air produces lift.

Maybe circulation of the air has something to do with lift!!

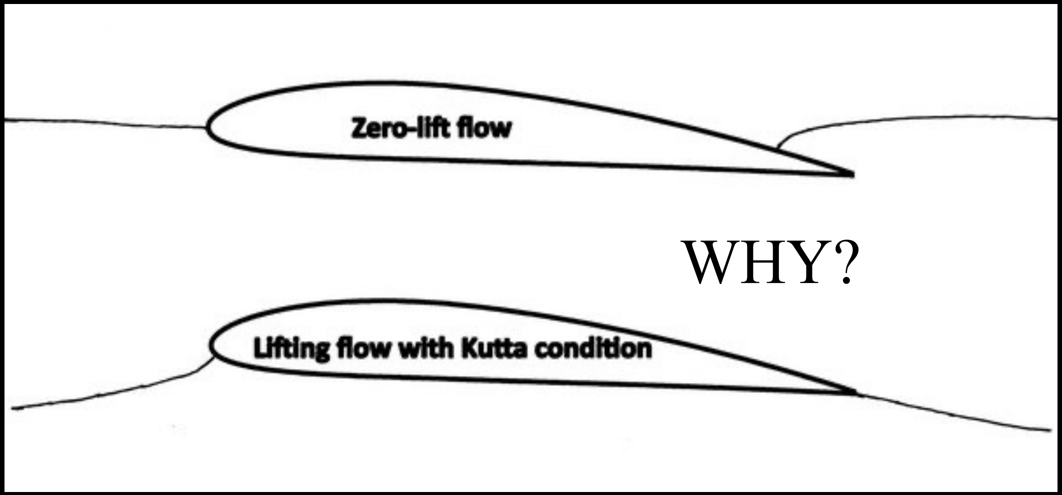
So how about that NOTAR



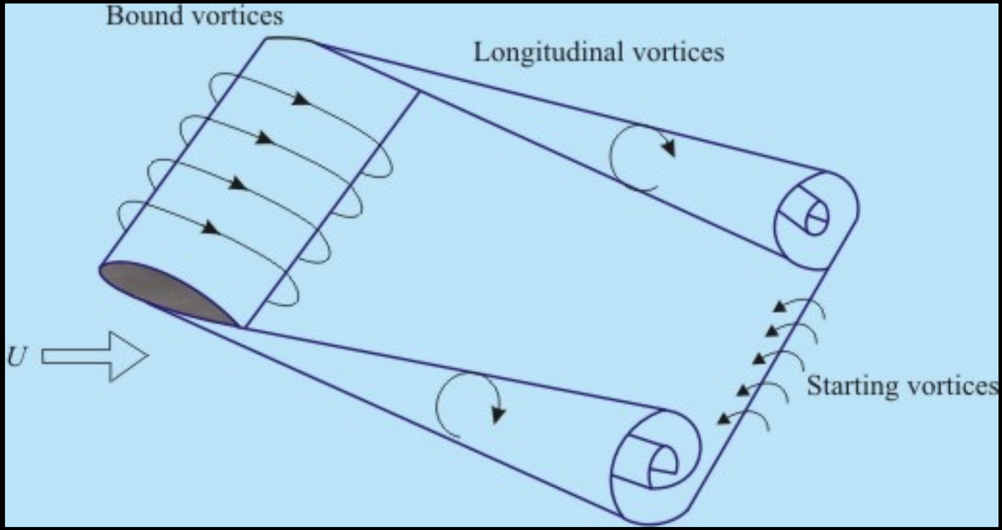
The Coanda effect says that a fluid stream (air is a fluid – it cannot resist shear stresses. Fluids may be gases or liquids) will try to attach to and follow a surface. A wings lift can be increased by a factor of up to three by utilizing the Coanda Effect, but Coanda must be externally applied. It does not occur naturally. i.e blown wings, slats etc

August Raspet, Mississippi State University Aero-physics Dept

Kutta/Joukowski Theorum

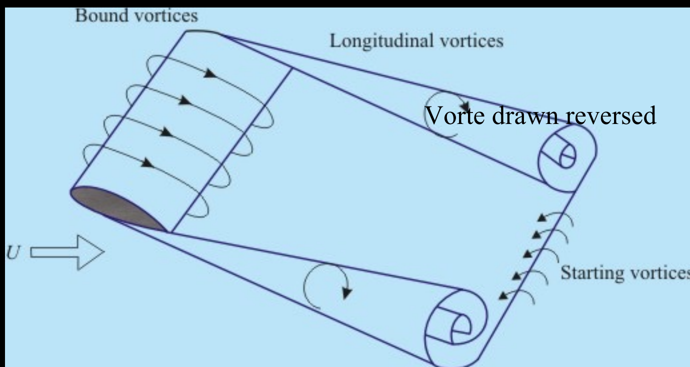


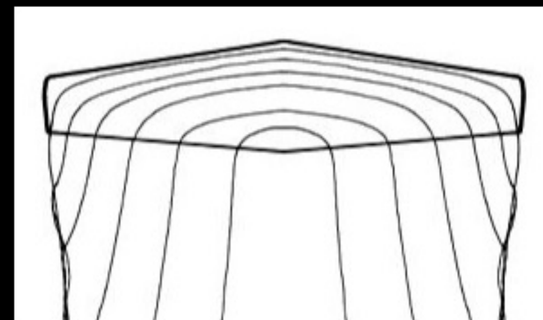
Also wrong, but it is the least wrongest



The Kutta/Joukowski Theorem

This theorem was originally proposed shortly after the airplane was invented.

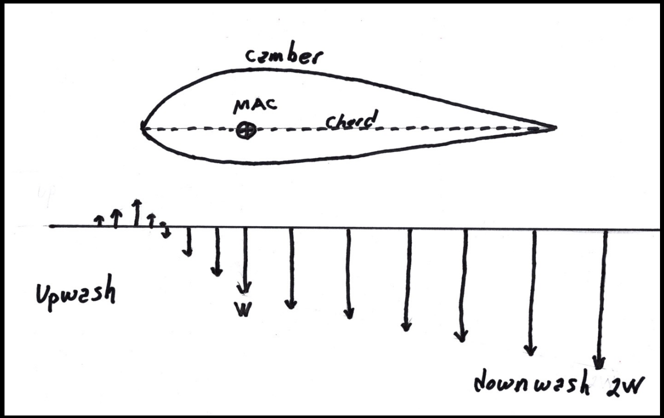




The theory used by most professional aerodynamicists, who have access to really big computers, because the mathematics are extremely difficult

Explains : upwash; downwash; tip vortices; and defines lift as a function of aircraft velocity x vortex strength x air density, ($- F = \rho V \Gamma$) A very powerful theory!! My Favorite

Problem is that it is also incomplete. The basis is the Kutta Condition which says:
"An airfoil with a thin trailing edge WILL produce about itself a vortex of such strength as to move the rear stagnation point to the trailing edge." But it gives no reason why this should be true. It is true but, not explained

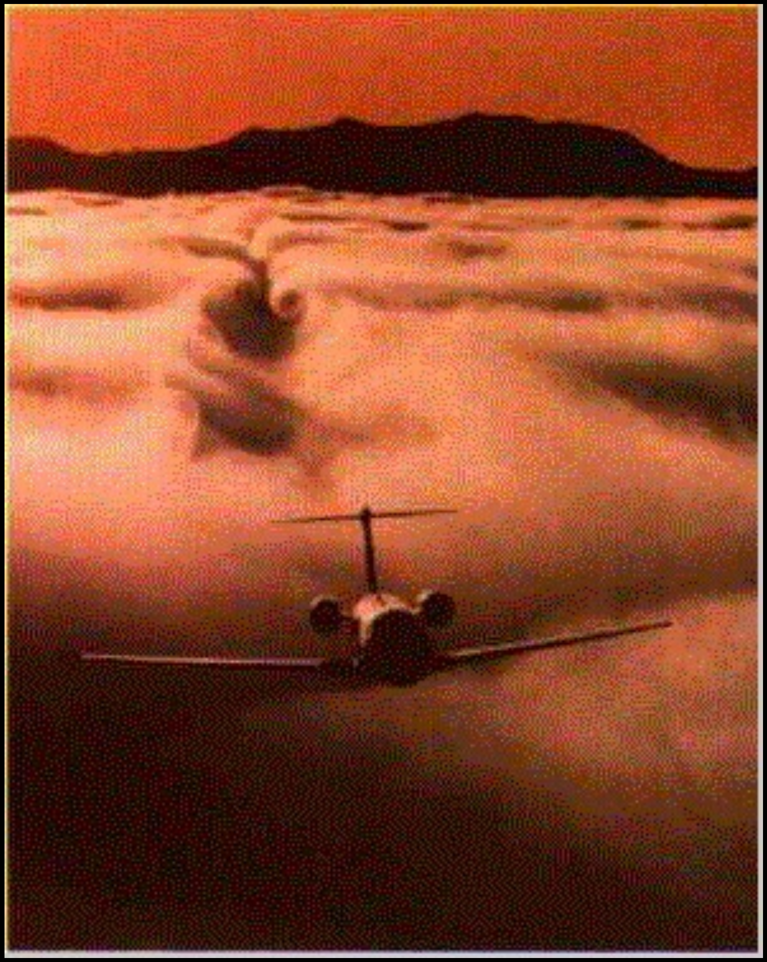


Trivial but correct lift theory:
Note that air is displaced downward by the wing at a velocity of 2W
Since the wing causes this downward flow of air, it sustains and equal and opposite force, lift, equal to the mass of the air displaced per unit time multiplied by 2W. This should not be a surprise since

$$T = \dot{m}\Delta V$$

(*BTW, this is the basic rocket thrust equation, propeller thrust equation, outboard motor thrust equation, helicopter rotor thrust equation (you get the picture*).)

Substitute L for T and 2W for delta V. It's one of the basic equations of physics, force equals rate of change of momentum!
The next slide shows this basic idea in action!



This aircraft is climbing out of a fog bank. Note how the downwash velocity is carving a canyon through the fog . Also note the wing tip vortices.

Now a question for the student:
When are the tip vortices strongest, at high speed flight at low altitude or during a landing approach?

How doest this knowledge affect air traffic control procedures?

Would the Bernoulli principle help you to understand this?

Understand that "wrong" is a relative thing. To say 2+2=3 is obviously wrong! To say 2+2=3.9999999 is also wrong, but not as wrong as 2+2=3. No matter how many descimal Places you use for "Pi" it will be wrong because Pi is an infinite, non-repeating decimal fraction. But we can get really REALLY close! But to say 2+2=purple is the wrongest yet because it indicates that you don't even understand the concept of addition.

"That we have written an equation does not remove from the flow of fluids its charm or mystery or its surprise." --Richard Feynman [1964]

Navier–Stokes Equations
3 – dimensional – unsteady

Coordinates: (x,y,z) Time : t Density: ρ Pressure: p Reynolds Number: Re

Velocity Components: (u,v,w) Stress: τ Heat Flux: q Prandtl Number: Pr

Continuity:
$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:
$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:
$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum:
$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Total Energy – Et:
$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z}$$
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$
$$- \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$

That we have written and equation also doesn't mean we can solve it. Solve the Navier-Stokes equations and you have a pretty good handle on fluid flow. Now you know why I became an experimental test pilot. I have been pretty good so far at cheating death by combat, by teaching kids how to fly helicopters, by flying aircraft that aren't housebroken yet, and by flying solo at 1,000,00 ft altitude at 17,500 mph, but the N-S equations scare me!

Flying is simple. All you have to do is hurl yourself at the Earth, and miss! Douglas Adams, The Hitchhikers Guide to the Galaxy

For the Space Shuttle, landing is what's hard because our Space Shuttle runway keeps moving at 800+ mph across our flight path, and the air (such as it is) keeps trying to roast us

Some Configuration Design Drivers

What must the vehicle do ?
- Deliver a specified (classified) payload to low Earth orbit
  - Sized the cargo bay and the lifting capacity (60’x15’, 50,000 lb)
  - USAF and DoD support essential politically

- Land on a hard surfaced runway on return
  - Drives wing planform through cross range requirement (Vandenburg once around) and entry heat load.

- Be returned from landing site to next launch site
  - Actually resulted in landing gear compromises
  - Bolt on engines, deployable engines or pure glider

Design must dissipate energy of a 250,000 lb vehicle traveling at 17,500 mph
- Energy dumped by re-radiated heat, Shock waves, and Aerodynamic drag
- Hot structure or cold structure (cold structure selected)

Fly back mode – glide or engines

Fully reusable or partially reusable – (Spoiler Alert – Partially Won)

Aerodynamic Considerations

Designed to dissipate the energy of a heavy vehicle traveling at orbital velocity & altitude

- Need high drag for energy control for ranging to runway
  - Aero heating
    - Too high AoA (to shorten range) means too high peak surface temperature
    - Too low AoA (to stretch range) means too high heat soakback to aluminum structure
    - Protect windows and vertical tail
    - Seals on landing gear doors (land upside down!!!!!)
    - Drove surface insulation and “color scheme”
- Solution: High angle of attack (40 degrees)
  - Skip out problem – Dump vertical component of L/D ratio through roll angle
    - Requires S-turn throughout (3 to 5 roll reversals). Leads to problem managing drag during roll reversals. Really do need 5 deg/sec roll rate, α modulation
  - Directional stability with tail blanked
  - Control mode (use sideslip angle – tenths of a degree)

Aero uncertainty: Large data scatter in wind tunnel data

- Management solution – Real data is the center of the scatter bands
  - Risk flight crew and entire program if you guess wrong
- Operator solution – Make FCS handle worst cases
- Aerodynamic variation sets – primarily lateral directional problem

Throughout the process we fail and, consequently, repeatedly discover or learn that we have exceeded our understanding of the problem by moving beyond the bounds of our prior assumptions.

Dr. Charles J. Camarda

Strings of successes can mask insidious failures that our simple models of behavior cannot predict. Success combined with a "can do" spirit can lead to arrogance. This can perpetuate an "overconfidence bias" or confirmation bias, resulting in the subjective interpretation of data to confirm what we want to be true rather than what is actually true.

Dr. Charles J. Camarda

Almost got me fired by NASA's chief engineer. But I had the data!

And he didn't have the authority!

STS-1 launched
April 12, 1981

U.S. Government
MEMORANDUM

Lyndon B. Johnson Space Center NASA

REFER TO: CB	DATE October 16, 1979	INITIATOR CB/RLStewart:mg:10/16/79:3856	ENCL

TO: Distribution

CC: Autostarting see?

FROM: CB/R. L. Stewart

SIGNATURE Bob Stewart
Robert L. Stewart

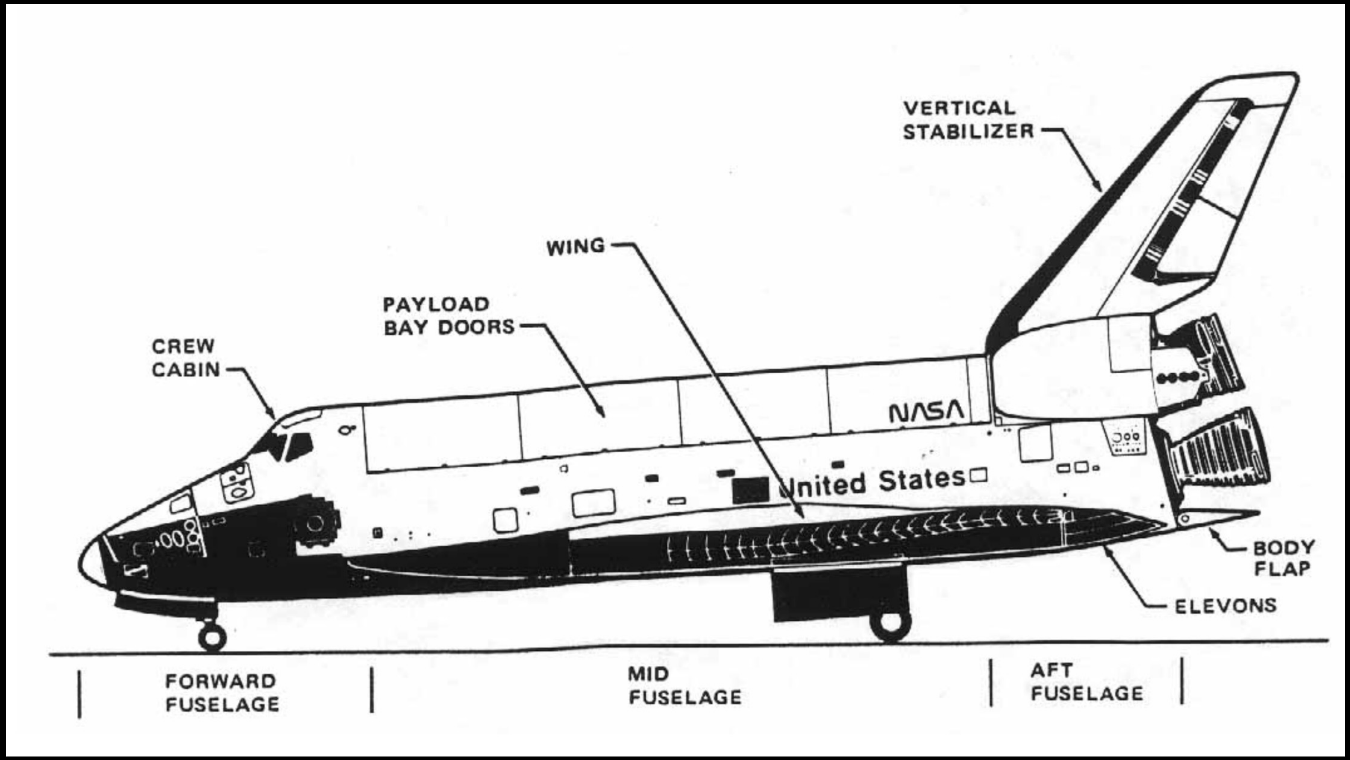
SUBJ: FSL Verification Status Overview

1. Entry verification was halted the first week in October to investigate previously observed anomalies. The conclusion drawn was that the FCS tolorance sets designed by Honeywell were much to severe and amounted to a 9σ FCS. Tolerances were added worst on worst rather than taking an RSS value. Many of the anomalies observed during verification may be attributed to this grossly degraded LRU and actuator error model. As presently formulated the FCS is not suitable for flight, but no redesign will be undertaken until Honeywell can compile and Rockwell test a legitimate 3σ FCS. As an interim measure RI resumed handling qualities tests on October 8 with two new trial tolerance sets; one combined the old "3σ" LRU's with "1σ" actuators, and the other combined "1σ" LRU's with "3σ" actuators. The actual error involved probably fell somewhere less than 9σ but greater than 3σ. This change was not noticable in the cockpit. Qualitatively no difference could be seen between the two tolerance sets and system performance was not noticably improved.

2. Handling qualities tests conducted through Wednesday Oct 10 produced no surprises. The sim went down on Oct 10, due to a failure of a D to A converter, and remained down Thursday and Friday.

3. On Monday Oct 15, I briefed Warren North and Ken Cox on my assessment of the current verification status. Other attendees were Milt Contella, Ernie Smith, Jon Harpold, Joe Gamble, and Ox van Hoften. The remainder of this memo will present the points discussed during this briefing. Issues generally fell into two categories: conduct of the simulation, and FCS problems as tested. The bottom line conclusion was that we are not making progress in verifying an entry FCS for STS-1 because several problems not shown on previous math model development sims make the "as tested" FCS unsuitable for flight. I feel that we should be investigating these problems rather than "filling in the squares" with completed verification runs. We are writing a bunch of TDR's on the test but you can't fly TDR's; they don't even make good SRB fuel.

4. The major difference noticed in performance of the E5 DAP as formulated by IBM and as designed on math model sims is the degraded roll damping. This degradation is evident in the larger values of roll angle overshoot with nominal FCS and unacceptably large roll angle overshoots with the present FCS tolerances (9σ). This degraded roll damping causes outright loss of control with variation set 12, in either Auto or CSS mode, at approximately M2.4 to M2.0. But poor roll damping is also responsible for trajectory control problems with other lateral variation sets as



Design changed during fabrication because of wind tunnel testing

- Shorten fuselage because of divergent nose up pitching moment
- Body flap/ Heat shield
- Nose landing gear shortened, main gear already made. (-5 degree α on roll out). Aero download almost same as vehicle weight! Brakes – tires.

Note approximately 5 degrees negative angle of attack on the ground during high speed rollout. Nearly doubles the landing gear and tire loads.

Vertical Tail blanked at 40 deg. AOA

$$\delta_{a_{trim}} = \frac{C_{l\beta}\left(C_A \frac{\Delta y}{b} - C_{n0}\right) + C_{n\beta}\left(C_N \frac{\Delta y}{b} + C_{l0}\right)}{C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a}}$$

AND

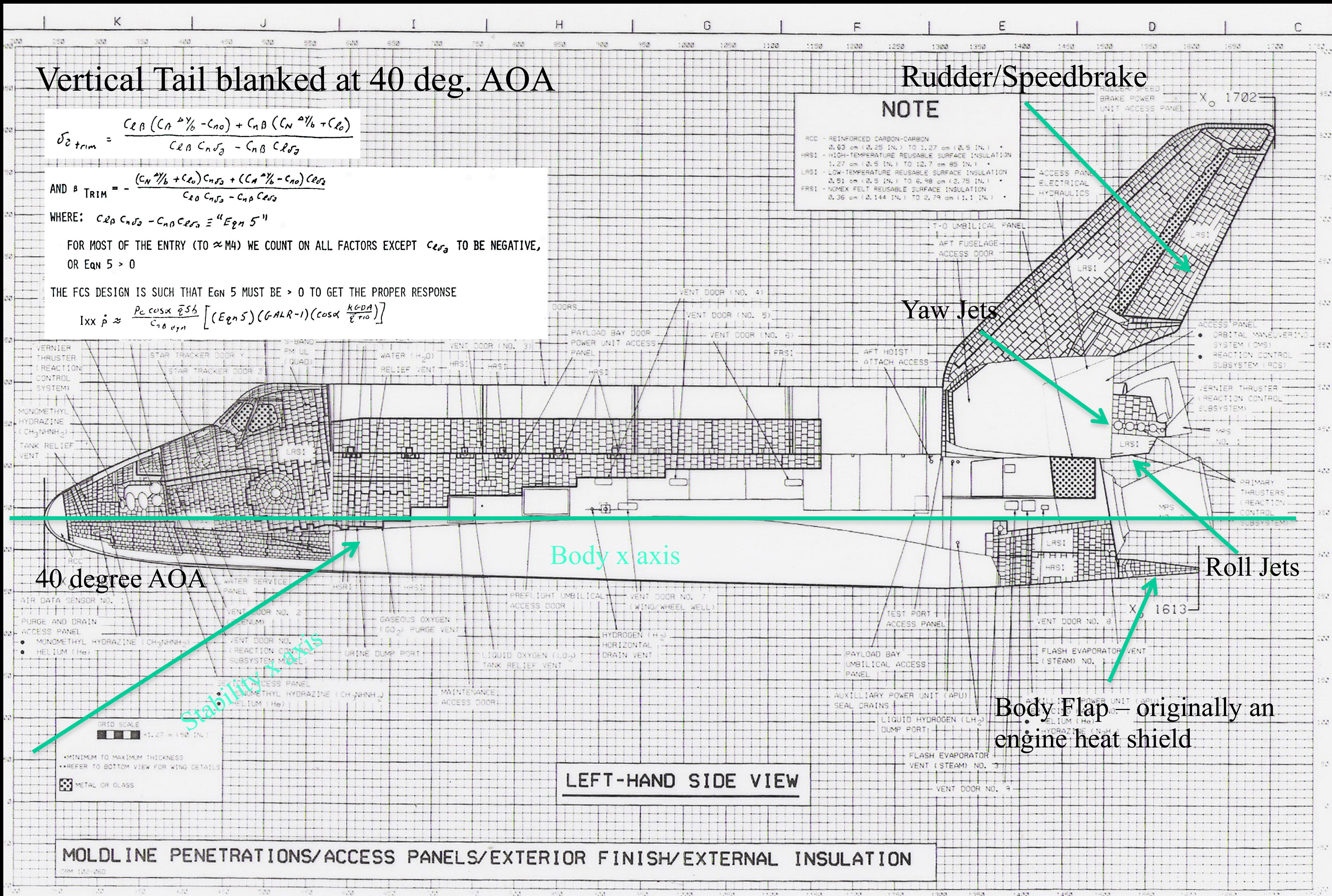
$$\beta_{TRIM} = -\frac{\left(C_N \frac{\Delta y}{b} + C_{l0}\right) C_{n\delta_a} + \left(C_A \frac{\Delta y}{b} - C_{n0}\right) C_{l\delta_a}}{C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a}}$$

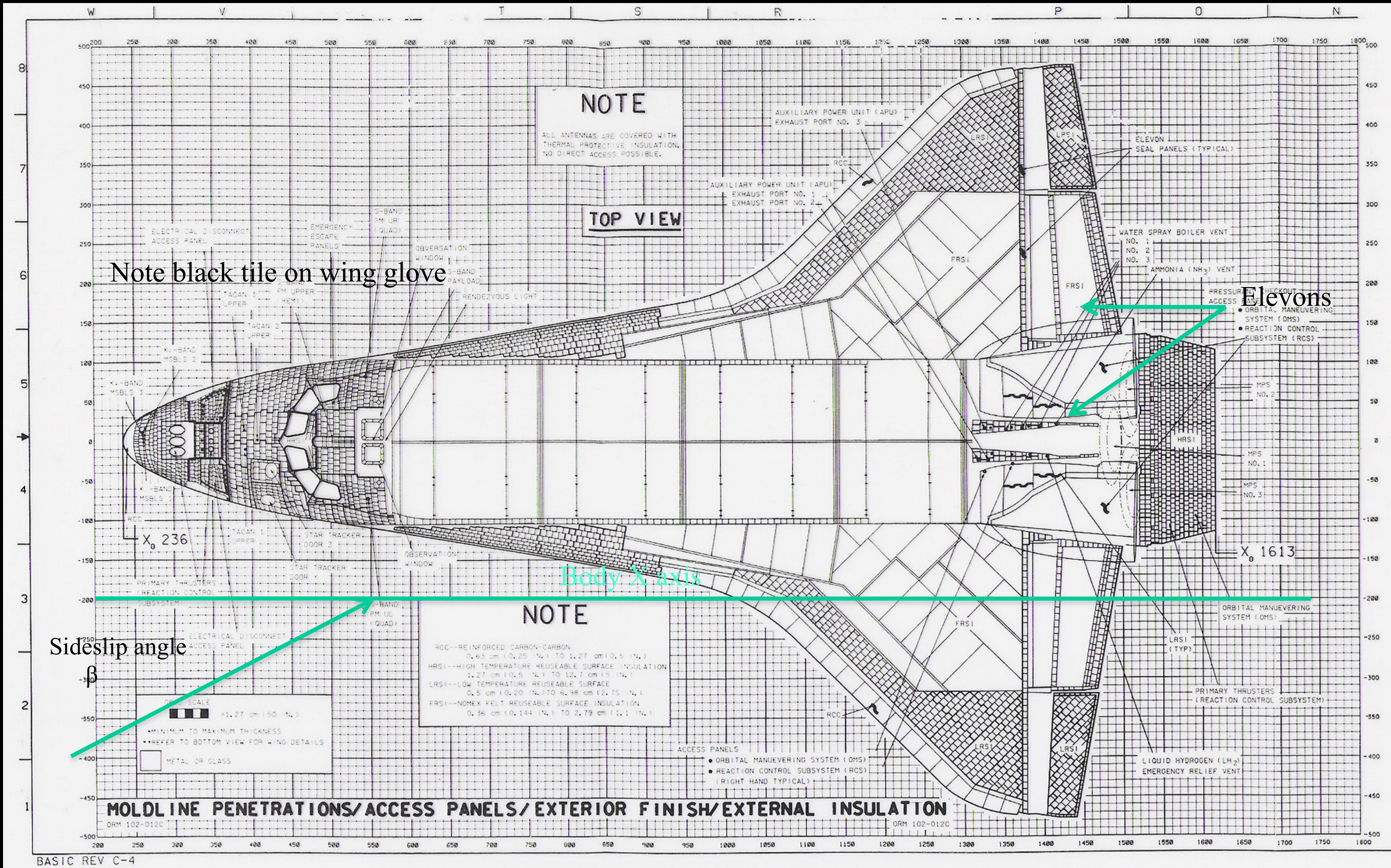
WHERE: $C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a} \equiv$ "Eqn 5"

FOR MOST OF THE ENTRY (TO ≈M4) WE COUNT ON ALL FACTORS EXCEPT $C_{l\delta_a}$ TO BE NEGATIVE, OR EQN 5 > 0

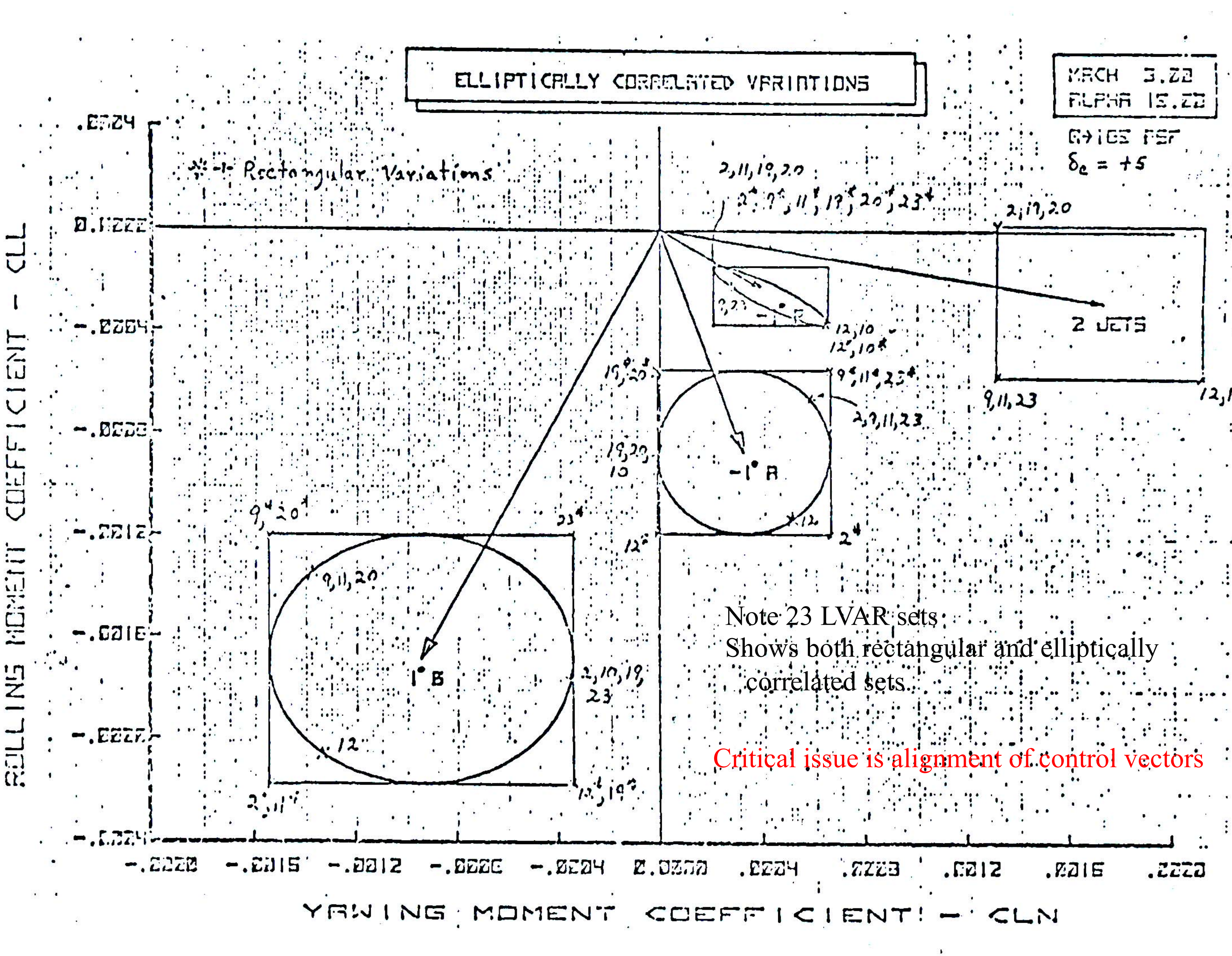
THE FCS DESIGN IS SUCH THAT EQN 5 MUST BE > 0 TO GET THE PROPER RESPONSE

$$I_{xx}\,\dot{p} \approx \frac{P_c \cos\alpha\ \bar{q}Sb}{C_{n\beta_{dyn}}}\left[(Eqn\,5)(GALR-1)\left(\cos\alpha\ \frac{KGDA}{\xi_{TIO}}\right)\right]$$





At 40 Deg AOA, You can roll in beta, and we do!



Note 23 LVAR sets

Shows both rectangular and elliptically correlated sets.

Critical issue is alignment of control vectors

DIVIDING THE MOMENT EQUATIONS BY $\bar{q}\,sb$ AND THE FORCE EQUATION BY $\bar{q}\,s$ YIELDS

$$C_n = C_{n\beta}\,\beta + C_{n\delta_a}\,\delta_a + C_{n\delta_r}\,\delta_r - \left(C_A \frac{\Delta Y}{b} - C_{n_0}\right) = 0$$

$$C_\ell = C_{\ell\beta}\,\beta + C_{\ell\delta_a}\,\delta_a + C_{\ell\delta_r}\,\delta_r + \left(C_N \frac{\Delta Y}{b} + C_{\ell_0}\right) = 0$$

$$C_Y = C_{Y\beta}\,\beta + C_{Y\delta_a}\,\delta_a + C_{Y\delta_r}\,\delta_r = 0$$

$$\begin{vmatrix} C_{n\beta} & C_{n\delta_a} & C_{n\delta_r} \\ C_{\ell\beta} & C_{\ell\delta_a} & C_{\ell\delta_r} \\ C_{Y\beta} & C_{Y\delta_a} & C_{Y\delta_r} \end{vmatrix} \begin{vmatrix} \beta \\ \delta_a \\ \delta_r \end{vmatrix} = \begin{vmatrix} C_A \frac{\Delta Y}{b} - C_{n_0} \\ -\left(C_N \frac{\Delta Y}{b} + C_{\ell_0}\right) \\ 0 \end{vmatrix}$$

IN THE "EARLY" SYSTEM RUDDER IS BLANKED BY THE WING AND IS NOT USED; SO $\delta_r \equiv 0$ AND THE EQUATIONS BECOME

$$\begin{vmatrix} C_{n\beta} & C_{n\delta_a} \\ C_{\ell\beta} & C_{\ell\delta_a} \end{vmatrix} \begin{vmatrix} \beta \\ \delta_a \end{vmatrix} = \begin{vmatrix} C_A \frac{\Delta Y}{b} - C_{n_0} \\ -\left(C_N \frac{\Delta Y}{b} + C_{\ell_0}\right) \end{vmatrix}$$

SOLVING FOR $\delta_{a\,trim}$ and β_{trim} BY CRAMERS RULE GIVES

$$\delta_{a\,trim} = \frac{C_{\ell\beta}\left(C_A \Delta Y/b - C_{n_0}\right) + C_{n\beta}\left(C_N \Delta Y/b + C_{\ell_0}\right)}{C_{\ell\beta}\,C_{n\delta_a} - C_{n\beta}\,C_{\ell\delta_a}}$$

$$\text{AND } \beta_{TRIM} = -\frac{\left(C_N \frac{\Delta Y}{b} + C_{\ell_0}\right) C_{n\delta_a} + \left(C_A \frac{\Delta Y}{b} - C_{n0}\right) C_{\ell\delta_a}}{C_{\ell\beta} C_{n\delta_a} - C_{n\beta} C_{\ell\delta_a}}$$

WHERE: $C_{\ell\beta} C_{n\delta_a} - C_{n\beta} C_{\ell\delta_a} \equiv$ "Eqn 5"

FOR MOST OF THE ENTRY (TO $\approx$ M4) WE COUNT ON ALL FACTORS EXCEPT $C_{\ell\delta_a}$ TO BE NEGATIVE, OR EQN 5 > 0

THE FCS DESIGN IS SUCH THAT EGN 5 MUST BE > 0 TO GET THE PROPER RESPONSE

$$I_{xx}\,\dot{p} \approx \frac{p_c \cos\alpha\, \bar{q} S b}{C_{n\beta\, dyn}} \left[(Eqn\ 5)(GALR - 1)\left(\cos\alpha\ \frac{KGDA}{\bar{q}\ r10}\right)\right]$$

DURING EARLY ENTRY GALR = 1.1 SO FAR A PROPER ROLL ACCELERATION, $\dot{p}$, IN RESPONSE TO ROLL COMMAND p_c, EGN 5 MUST BE > 0.

THE TERM $C_{n\beta\, dyn} = C_{n\beta} \cos\alpha - C_{\ell\beta} \sin\alpha \frac{I_{zz}}{I_{xx}}$ IS ORBITER DIRECTIONAL STABILITY DRIVER. THUS THE CRITERIA FOR STABLE $C_{n\beta\, dyn}$ IS:

$$\overset{(-)}{C_{n\beta}}\ \overset{(+)}{\cos\alpha} - \overset{(-)}{C_{\ell\beta}}\ \overset{(+)}{\sin\alpha}\ \overset{(+)}{\frac{I_{zz}}{I_{xx}}} > 0 \implies \frac{C_{n\beta}}{C_{\ell\beta}} < \tan\alpha\ \frac{I_{zz}}{I_{xx}}$$

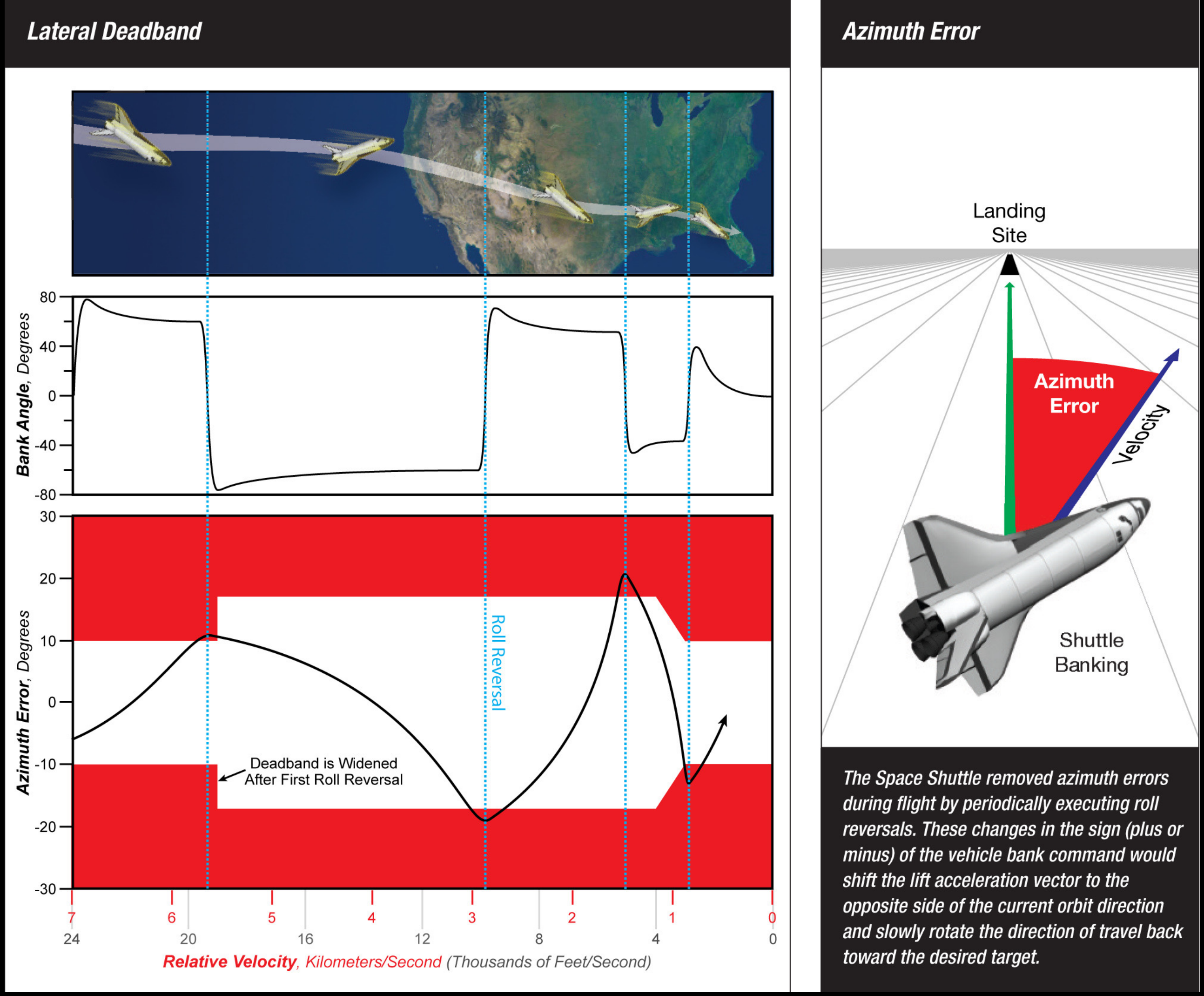
Actual values for the lateral directional control derivatives depend on Mach number, angle of attack, and SURFACE POSITION!

But primary job of elevons in pitch is to control pitch rate

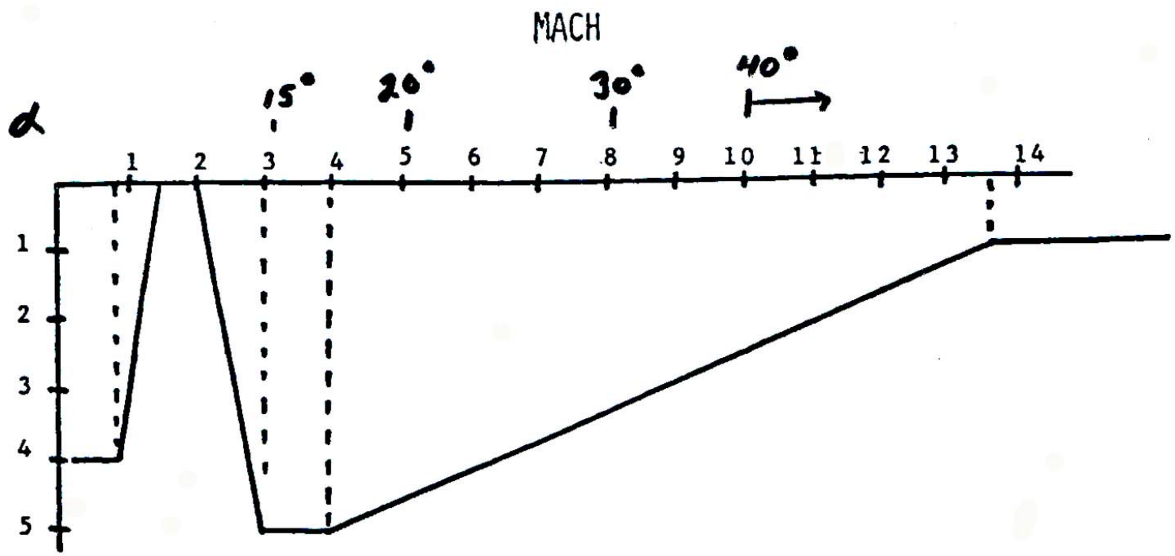
Must generate a pitch rate error so that elevons drive to desired position required by lateral directional requirement (Eqn 5>0)

This was accomplished by mechanizing the heat shield originally installed to keep the engines from melting during entry to be a big trim tab.

Also, when the speed brake becomes unblanked by the wing, it is deployed (heating constraints) to generate a nose up pitching moment to drive the elevons down to help the body flap. OK because it really doesn’t do that much to add drag anyway!



Guidance computes range to go and determines how much drag we need on the vehicle to get to the runway. S-turning across the ground track allows us to control drag without letting cross range distance diverge



ELEVON SCHEDULE

M>13.6 - HEATING CONSTRAINT

M 13.6 TO M 3 - ELEVON DRIVEN DOWN (AT A SCHEDULE WHICH CAN BE TRIMMED BY THE BODY FLAP) TO MAINTAIN NEGATIVE $c_{n\delta a}$ FOR YAW TRIM WITH AILERONS.

M 3 TO M 2 - ELEVON GOES UP SO THAN $c_{n\delta a}$ DOES NOT FIGHT THE RUDDER FOR YAW TRIM. ALSO C_m CHANGE REQUIRES IT FOR PITCH TRIM.

M 1.5 TO M 0.9 - ELEVON DRIVEN DOWN ALONG A NEAR ZERO HINGE MOMENT PROFILE TO AVOID POSSIBLE SURFACE RATE SATURATION.

What Could Possibly Go Wrong????

Looks like a streamlined locomotive, not a spaceship

Five time normal AOA to slow down & not melt windshield

Rolls by firing yaw jets. (Tenths of a degree of sideslip angle)

Runs ailerons backwards until slows to Mach 4

Uses its speed brake as a pitch control

Creates a pitch error to force elevons to a desired position

Must know its geographical location to maintain control

Guesses its aero environment because probes would burn off

Flies downwind leg at Mach 1

Ascent engineers accomplish their goal by brute force

Entry engineers must use strategy, guile and cleverness

Aerodynamic Conventions we will use:

Body axes: x - tail to nose, + is forward (use right thumb
y - out right wing, + is to the right
z - out bottom of fuselage, + is downward

Stability axes - same as above except x is aligned to the relative wind

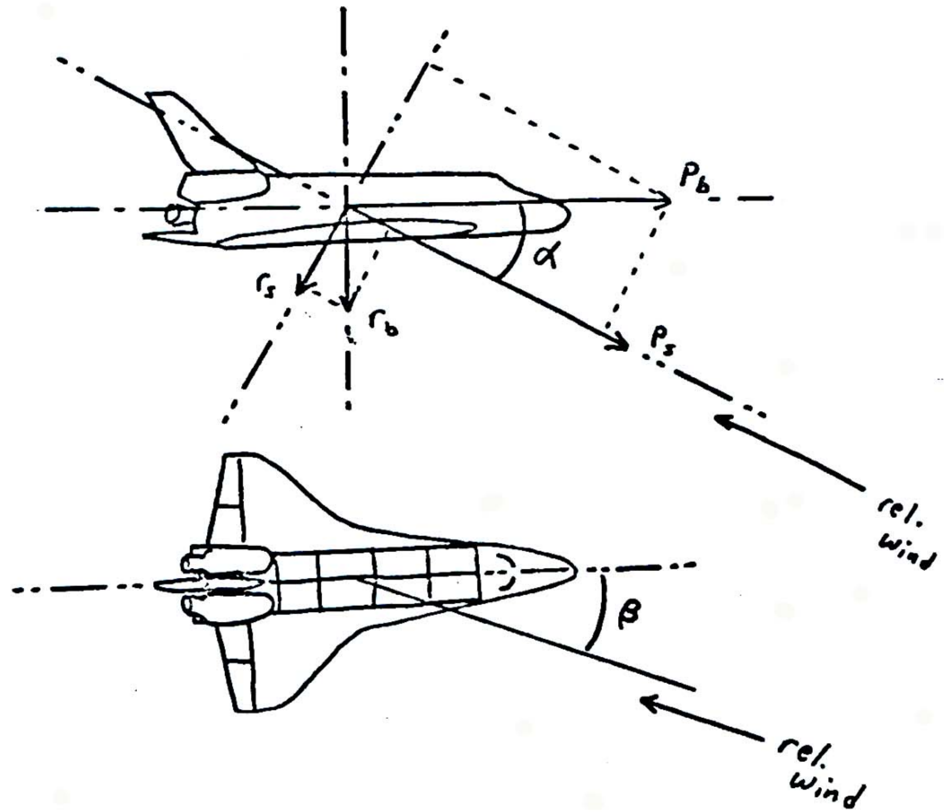
p, q and r are rates around the x, y and z axes

l, m and n are moments around x, y and z axes

α (alpha – angle of attack) – the angle of the relative wind to the body x axis in the xz plane

β (beta sideslip angle) – angle of the relative wind to the body x axis in the xy plane

C represents a non dimensional coefficient. i.e. $C_{n\beta}$ is the yawing moment due to sideslip - or the directional stability



FROM DEFINITION OF BODY AND STABILITY AXES:

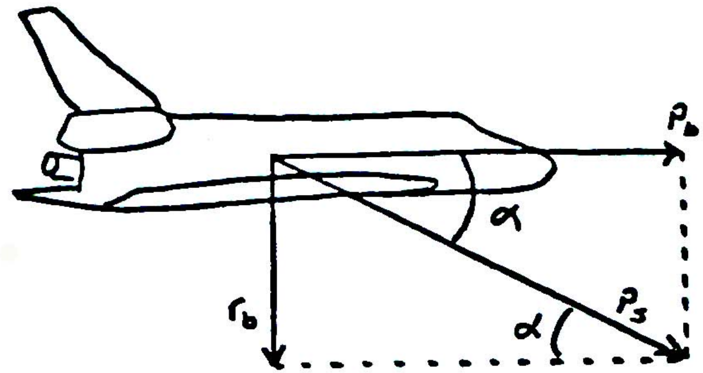
$$p_s = p_b \cos\alpha + r_b \sin\alpha$$

$$r_s = r_b \cos\alpha - p_b \sin\alpha \equiv -\dot{\beta}$$

FOR A PURE STABILITY ROLL: $r_s = 0$

$$r_b \cos\alpha - p_b \sin\alpha = 0 \qquad \boxed{p_b = r_b \,\mathrm{ctn}\alpha}$$

AND $p_s \equiv p_c$



IF $r_s \equiv -\dot{\beta} = 0$

$p_b = p_s \cos\alpha$ AND $r_b = p_s \sin\alpha$

FOR A ROLL RATE COMMAND, p_c, THE FCS WILL TRY TO DRIVE BODY RATES (SINCE THE RATE GYROS SENSE BODY RATES) DEFINED BY

$\boxed{r_b = p_c \sin\alpha}$ AND $\boxed{p_b = p_c \cos\alpha = r_b \operatorname{ctn}\alpha}$

FOR EXAMPLE $\alpha = 40^0$ $p_c = 5^0$/SEC

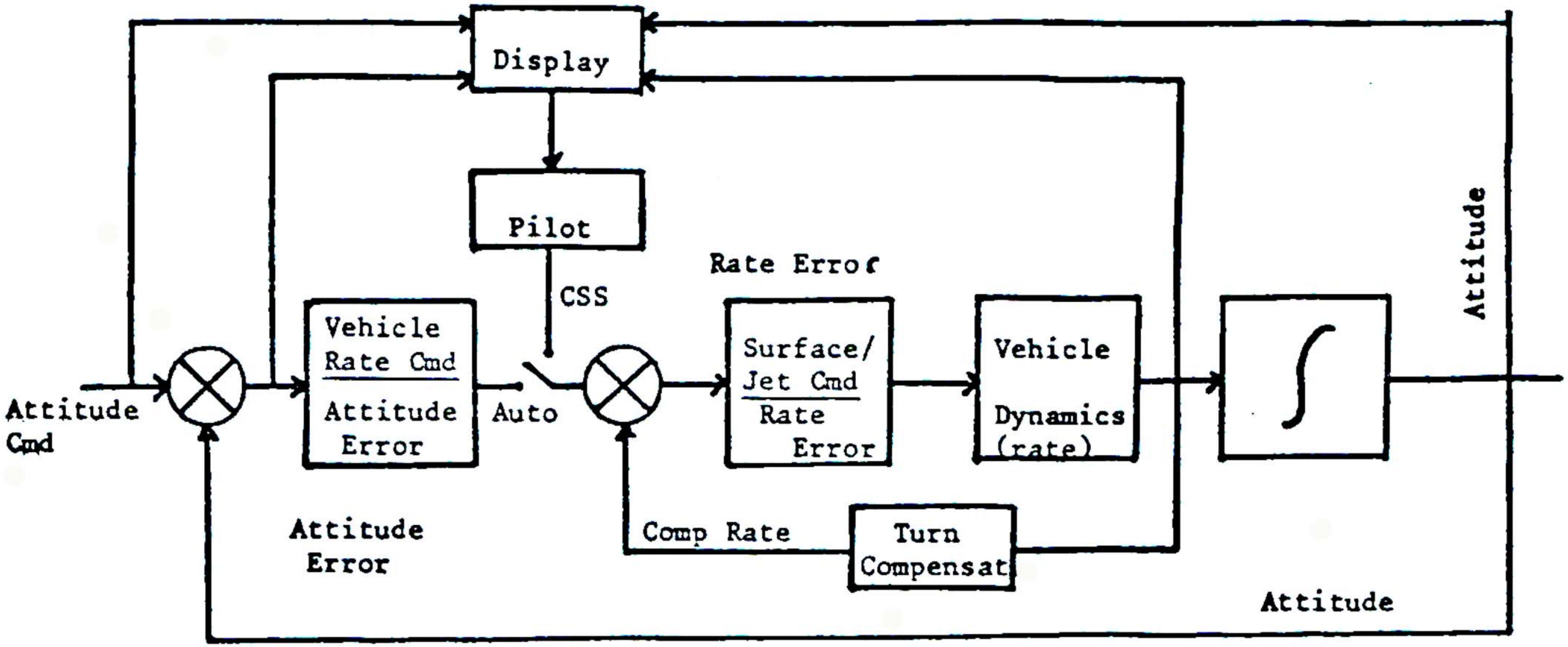
$r_b = 5 \sin 40 = 3.21^0$/SEC AND p_b $p_b = 3.21 \operatorname{ctn} 40 = 3.83^0$/SEC

IF THE FCS KNOWS $\alpha = 40^0$ AND ACTUAL $\alpha = 40^0$ THEN $\dot{\beta} = 0$

Why the necessity for these different axis systems?

The aircraft flies in the stability axis system but the sensors measure quantities in the body axis system.

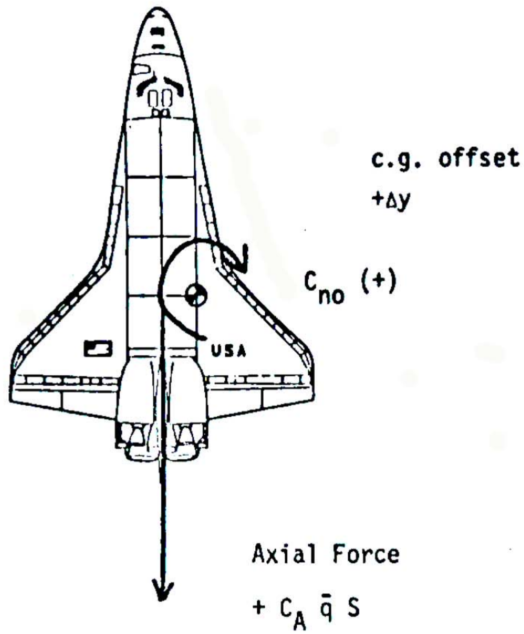
- Inertial Measurement units
- Rate gyros - body mounted, oil-canning
- Bent airframe
- Offset y - cg

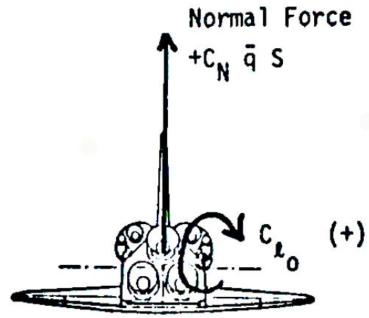


OUTER LOOP: ATTITUDE ERROR CONVERTED TO RATE COMMAND BY THE PILOT OR THE AUTO SYSTEM (PITCH - α OR N_Z; ROLL - ϕ; YAW - β OR N_Y)

INNER LOOP: CONVERTS RATE ERROR TO SURFACE COMMAND OR/AND JET COMMAND: PROVIDES AUTOMATIC STABILITY AND TURN COORDINATION

DEPENDENT ON NAV FOR: FCS MODING (M, $\bar{Q}$); GAIN SCHEDULING (M, $\bar{Q}$); TURN COORDINATION (θ, ϕ, TAS)





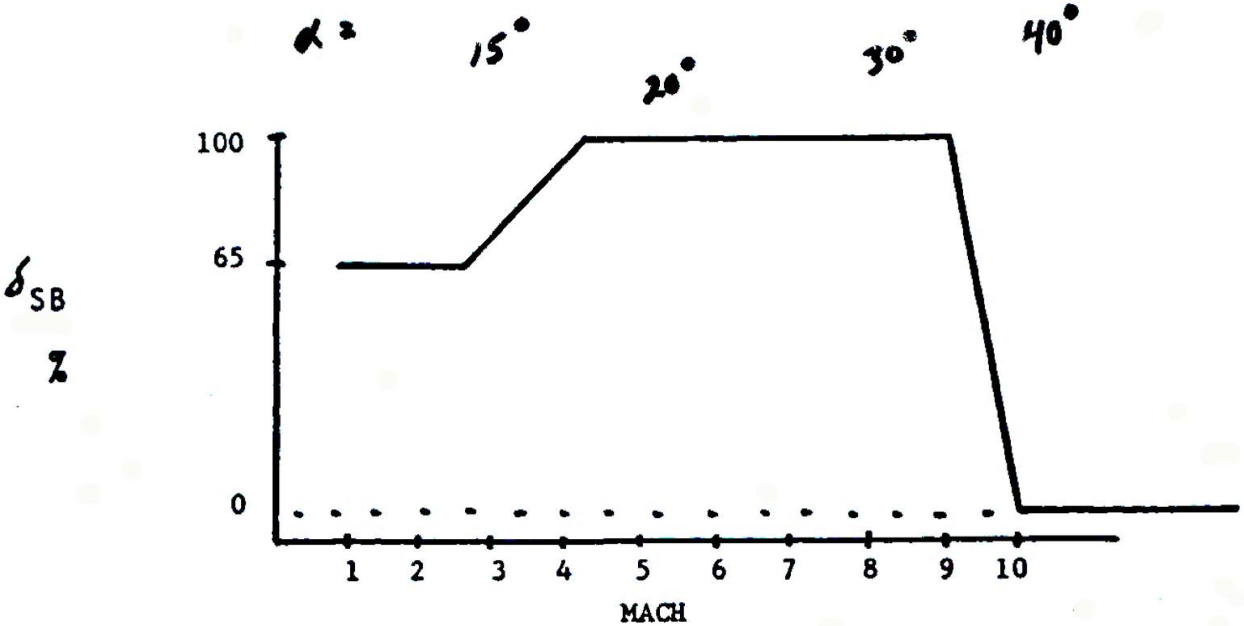
A RIGHT c.g. OFFSET PRODUCES A POSITIVE ROLLING MOMENT, $C_N \bar{q} S \Delta y$, AND A NEGATIVE YAWING MOMENT, $-C_A \bar{q} S \Delta y$

FOR TRIM: TOTAL ROLL MOMENT, C_ℓ, AND TOTAL YAW MOMENT, C_n, MUST BE ZERO. IT IS DESIRABLE THAT TOTAL SIDE FORCE ALSO BE ZERO.

YAWING MOMENT $= C_n \bar{q} S b = (C_{n_\beta} \beta + C_{n_{\delta_a}} \delta_a + C_{n_{\delta_r}} \delta_r + C_{n_o}) \bar{q} S b - C_A \bar{q} S \Delta y$

ROLLING MOMENT $= C_\ell \bar{q} S b = (C_{\ell_\beta} \beta + C_{\ell_{\delta_a}} \delta_a + C_{\ell_{\delta_r}} \delta_r + C_{\ell_o}) \bar{q} S b + C_N \bar{q} S \Delta y$

SIDE FORCE $= C_y \bar{q} S = (C_{y_\beta} \beta + C_{y_{\delta_a}} \delta_a + C_{y_{\delta_r}} \delta_r) \bar{q} S$



SPEEDBRAKE SCHEDULE

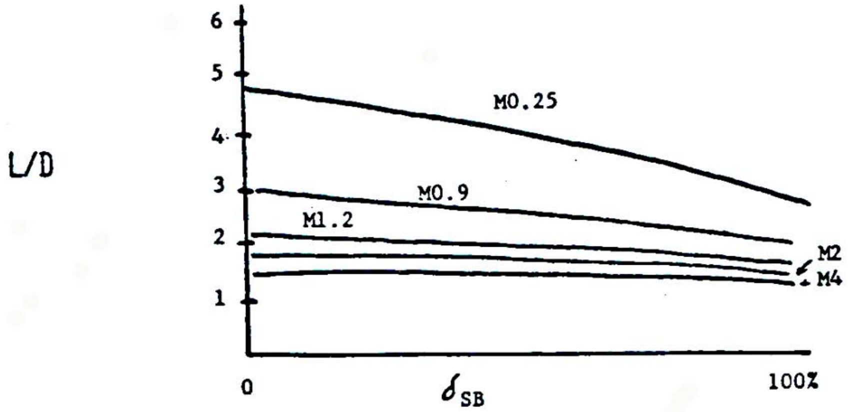
M>10 - HEATING, INEFFECTIVE DUE TO BLANKING

M10 TO M4 - PROVIDES NOSE UP PITCHING MOMENT TO ALLOW TO TRIM DOWN 5° WHILE MAINTAINING UNSATURATED BODY FLAP

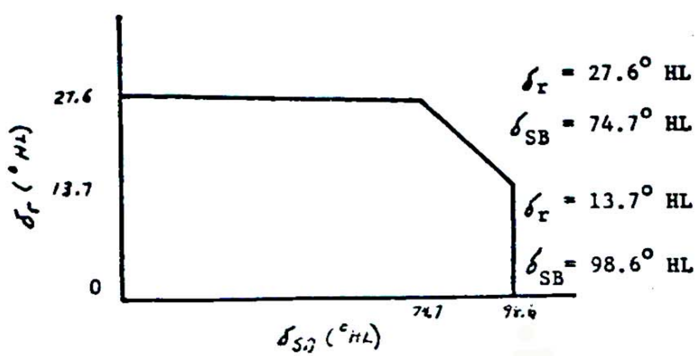
M4 TO 2.5 - RAMP TO 65% FOR RUDDER EFFECTIVENESS.

M2.5 TO 0.9 - 65% FOR COMPROMISE BETWEEN RUDDER EFFECTIVENESS AND TRIM

M<0.9 - MODULATES TO CONTROL $\bar{q}$.



SPEEDBRAKE EFFECT ON L/D



MECHANICAL EFFECT OF SPEEDBRAKE ON RUDDER

It’s Over! Was it worth it?

A question that will be open to debate for years to come

What did we try to do?

- Cheap access to space.
- Safe access to space
- Routine access to space

We reached far and dared much

Commenting on future courses of a technology is always hazardous.

- "Heavier than air flying machines are impossible" Lord Kelvin, 1895
- "There is not the slightest indication that nuclear energy will ever be obtainable." Albert Einstein, 1935
- "Fooling around with alternating current is just a waste of time. No one will ever use it." Thomas Edison, 1889
- "A rocket will never be able to leave the Earth's atmosphere" NY Times, 1936
- "Who would ever need more than 640K…" Bill Gates, unk

You can even be correct for the wrong reasons.

- Gen John "Blackjack" Pershing was a supporter of the military airplane as a new and efficient way to deliver oats to the horses in the field.

What did it cost?

Over 40 years, 10 of development and 30 of flying – $209B

Where was it spent? Right here in in creating high tech jobs, solving engineering problems undreamed of even in proposing the concept.

By contrast, we paid $210B IN INTEREST on the national debt in 2013. Where did that go? Who holds our debt?

NASA's share of the federal budget peaked in 1966 at 4.4%
Today it is 0.5%!

Most likely historical assessment, and mine personally.

It was a technological triumph, BUT it cost too much and we flew it much too long.

Progress in material and genetic science here on Earth far outstripped projected achievements, negating much of what we wanted to do with space manufacturing.

From “gumdrops” we came and to “gumdrops” we shall return.

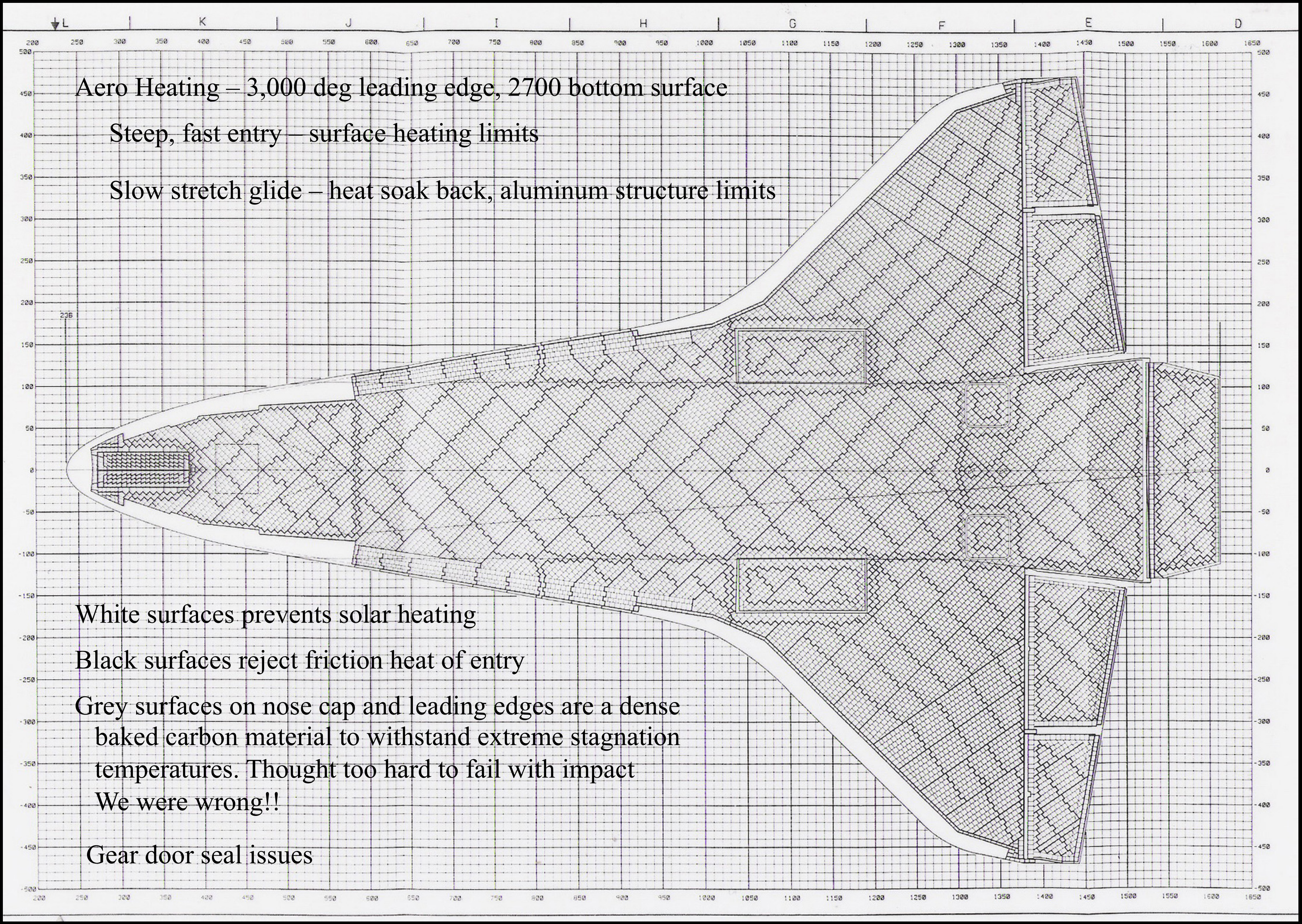
NASA’s job is exploration, not operating an airline.

IF mankind is to venture outward into the solar system, the space program must be de-politicized, and alliances developed.

Aero Heating – 3,000 deg leading edge, 2700 bottom surface

Steep, fast entry – surface heating limits

Slow stretch glide – heat soak back, aluminum structure limits



White surfaces prevents solar heating

Black surfaces reject friction heat of entry

Grey surfaces on nose cap and leading edges are a dense baked carbon material to withstand extreme stagnation temperatures. Thought too hard to fail with impact We were wrong!!

Gear door seal issues

Vertical Tail blanked at 40 deg. AOA

$$\delta_{a\,trim} = \frac{C_{l\beta}\left(C_A \frac{\Delta Y}{b} - C_{n0}\right) + C_{n\beta}\left(C_N \frac{\Delta Y}{b} + C_{l0}\right)}{C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a}}$$

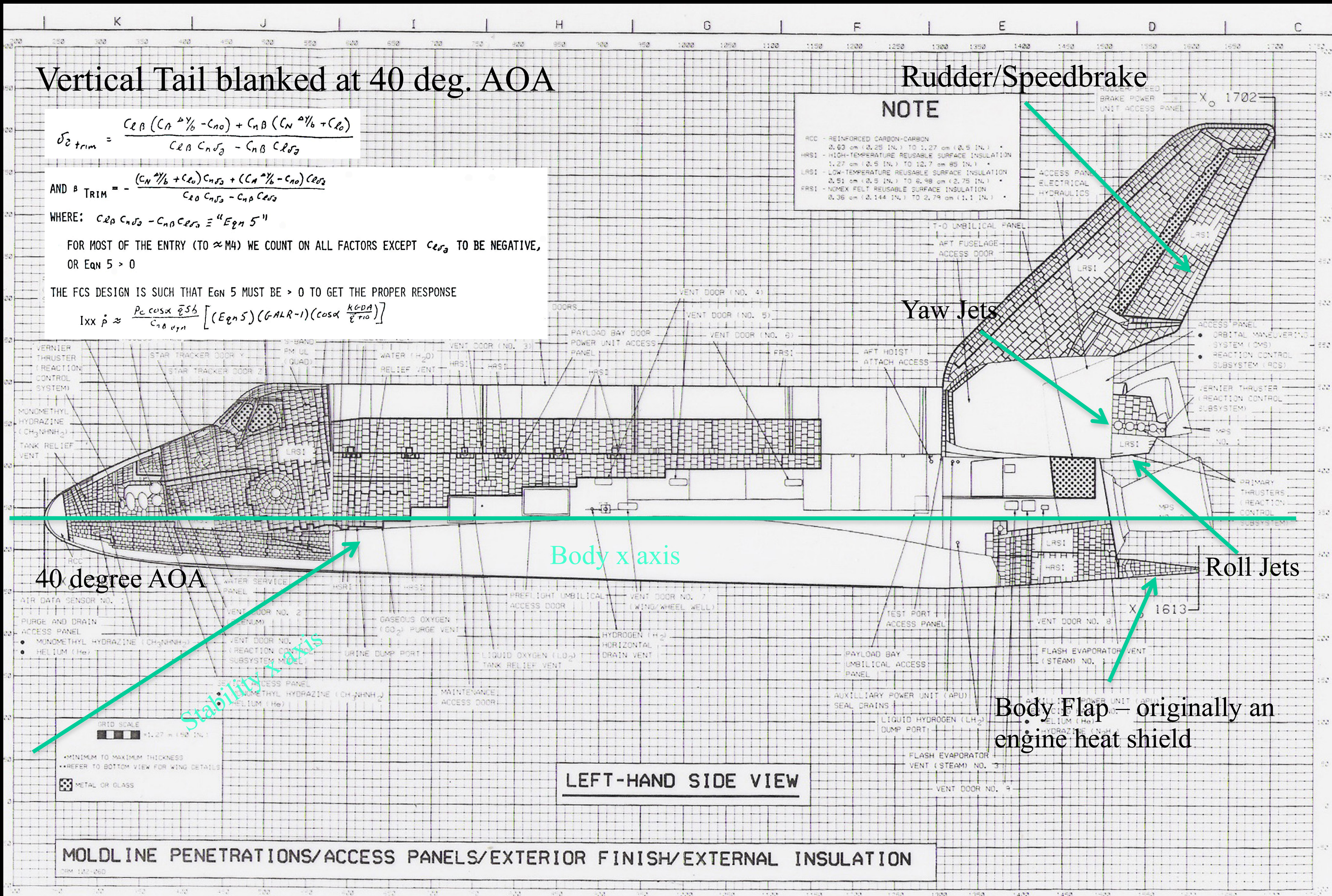
AND $\beta_{TRIM} = -\dfrac{\left(C_N \frac{\Delta Y}{b} + C_{l0}\right) C_{n\delta_a} + \left(C_A \frac{\Delta Y}{b} - C_{n0}\right) C_{l\delta_a}}{C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a}}$

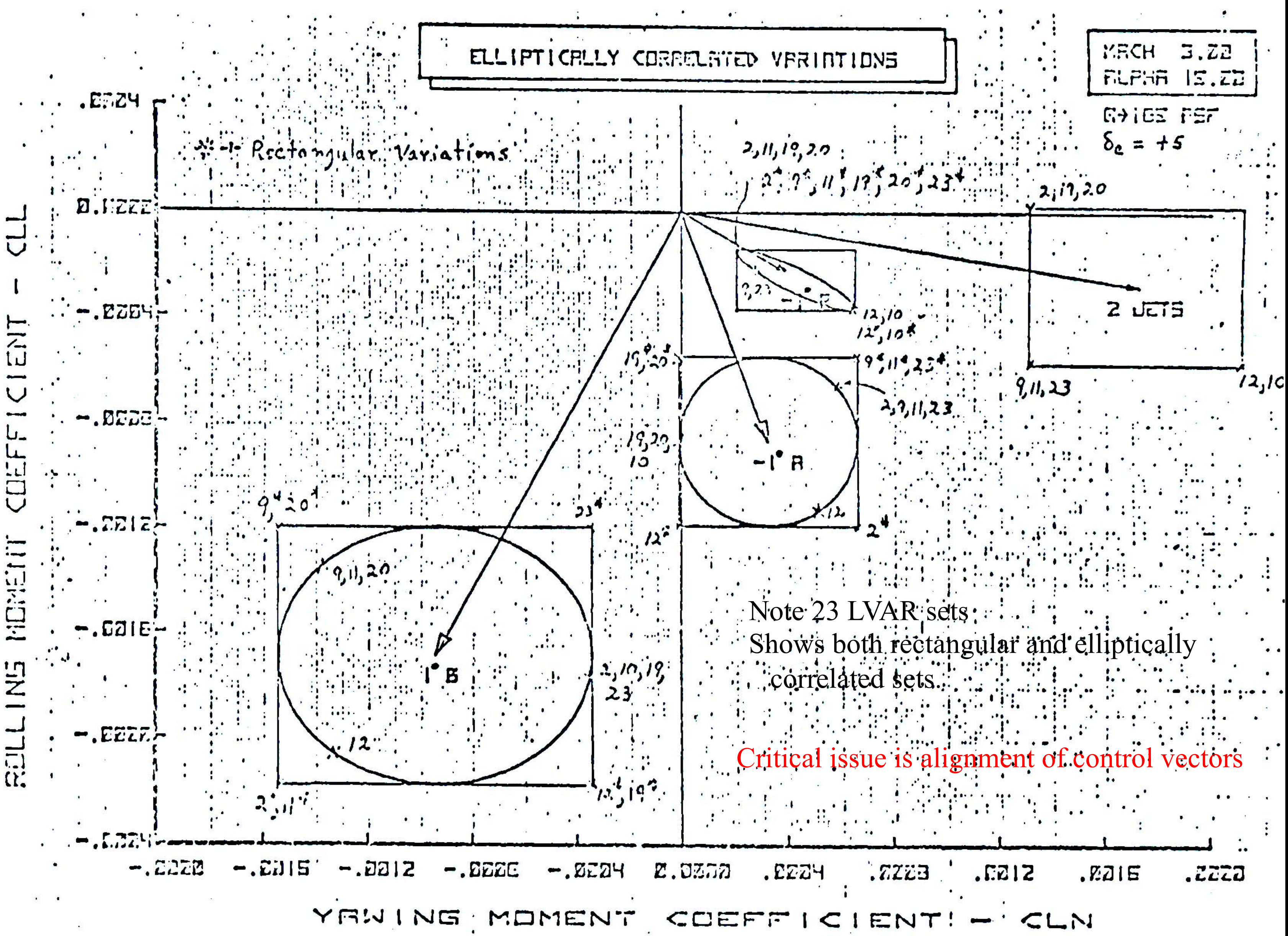
WHERE: $C_{l\beta} C_{n\delta_a} - C_{n\beta} C_{l\delta_a} \equiv$ "Eqn 5"

FOR MOST OF THE ENTRY (TO $\approx$ M4) WE COUNT ON ALL FACTORS EXCEPT $C_{l\delta_a}$ TO BE NEGATIVE, OR EQN 5 > 0

THE FCS DESIGN IS SUCH THAT EGN 5 MUST BE > 0 TO GET THE PROPER RESPONSE

$$I_{xx}\,\dot{p} \approx \frac{P_c \cos\alpha\, \bar{q} S b}{C_{n\beta\,dyn}} \left[(Eqn\,5)(GALR-1)\left(\cos\alpha \frac{KGDA}{\bar{q}\,T10}\right) \right]$$

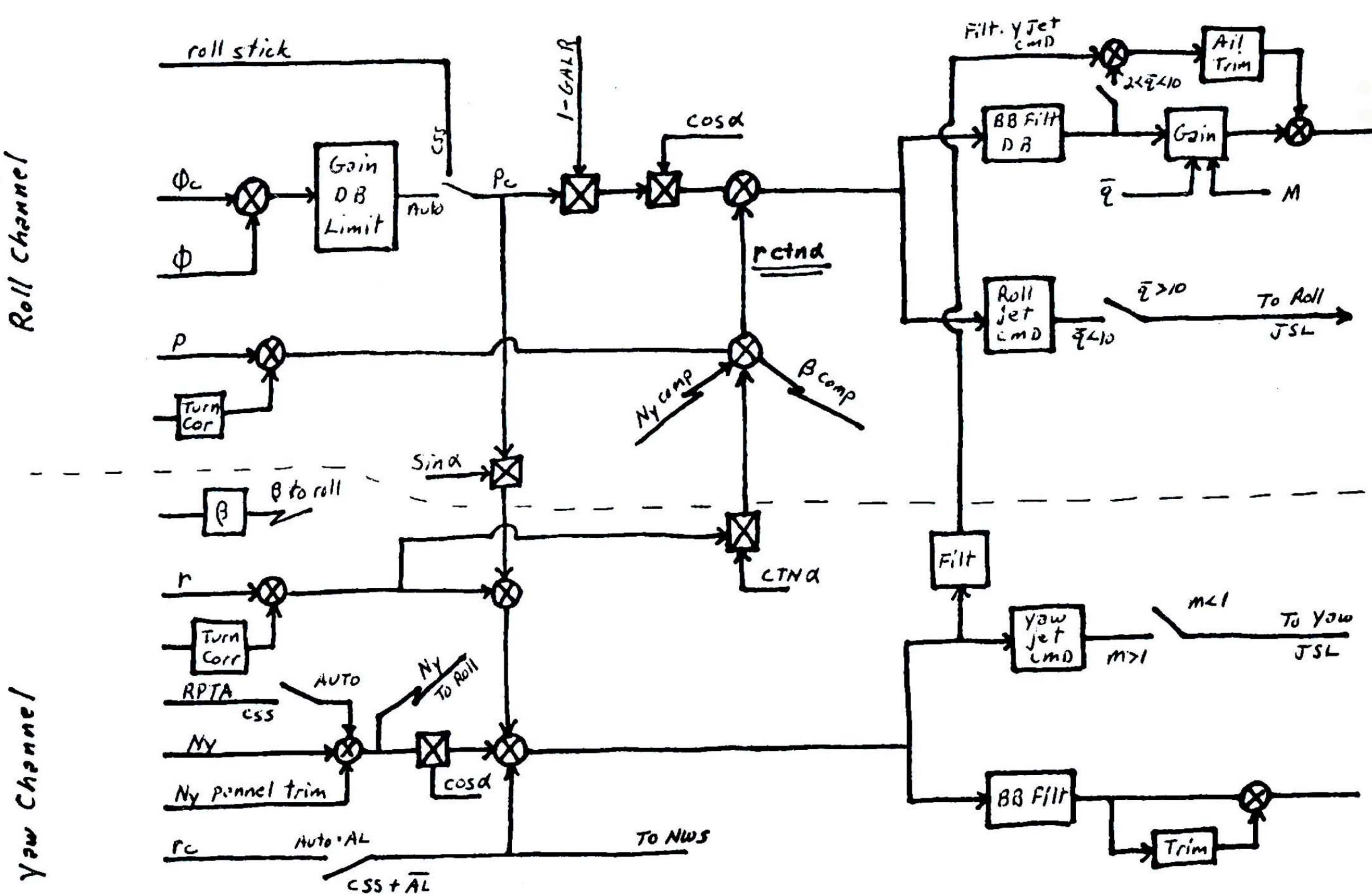




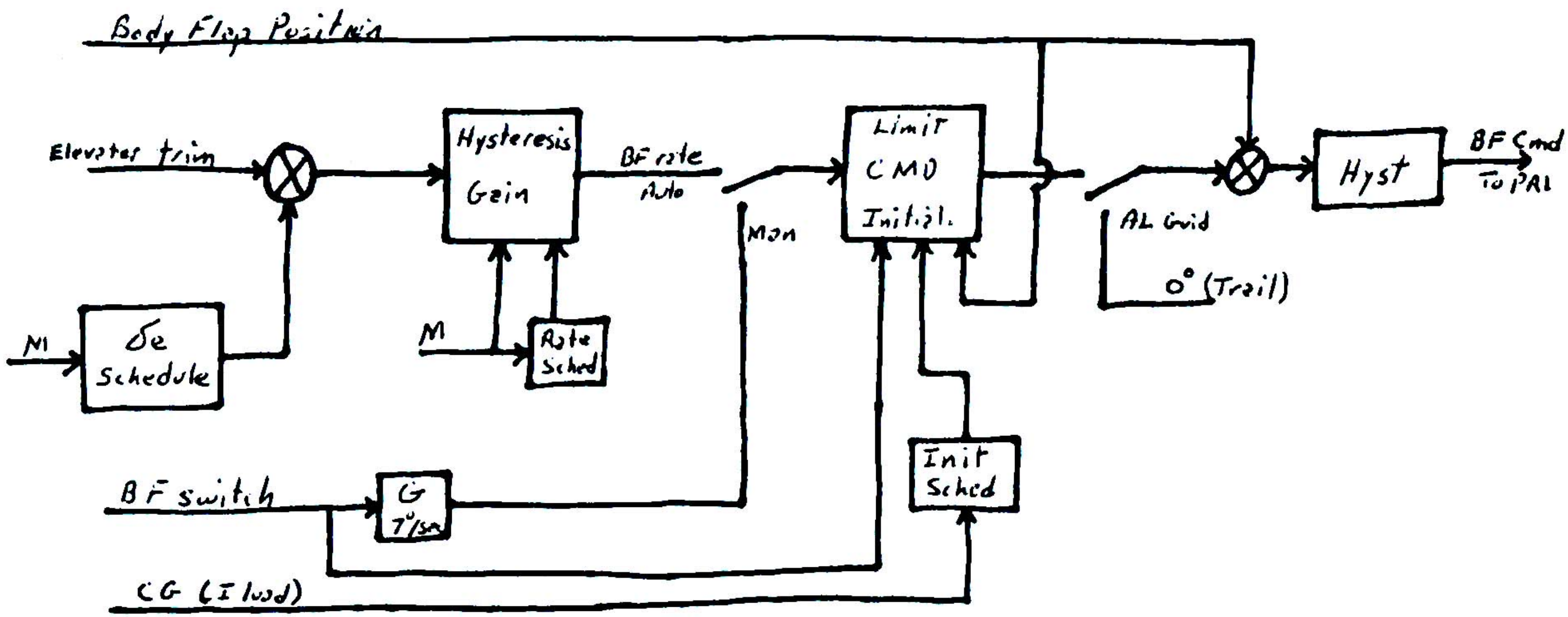
Note 23 LVAR sets
Shows both rectangular and elliptically correlated sets.

Critical issue is alignment of control vectors

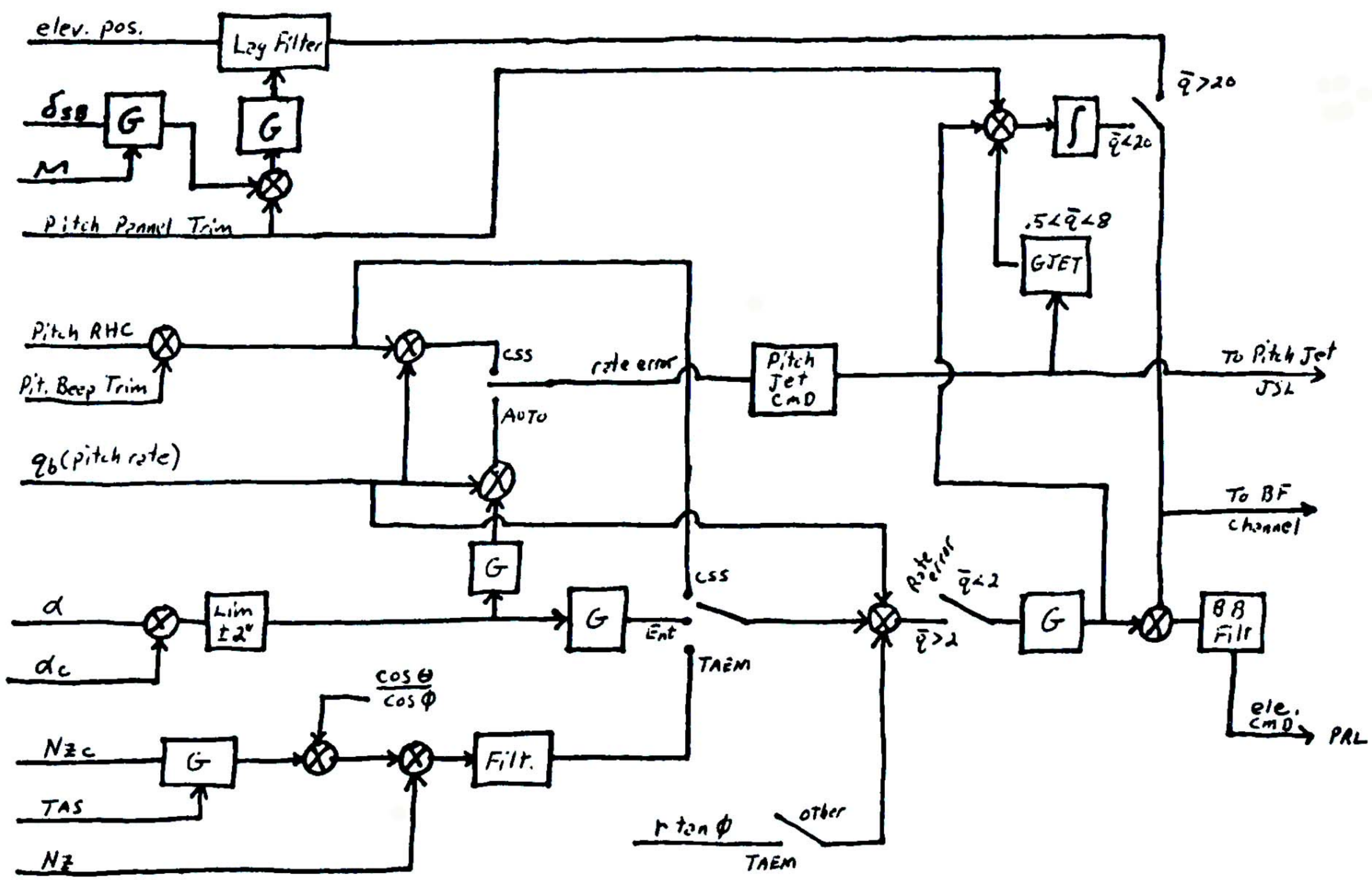
Roll and Yaw FCS



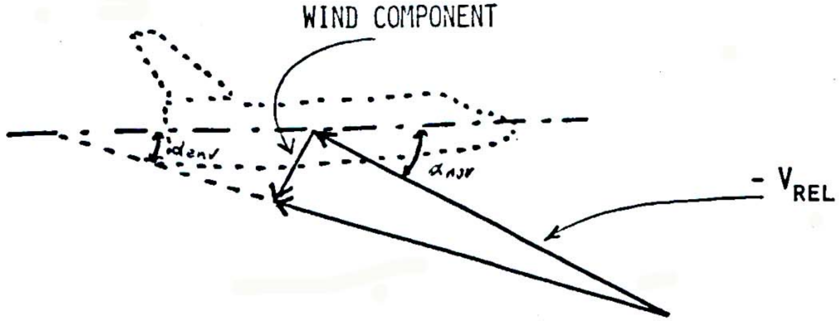
Body Flap Channel



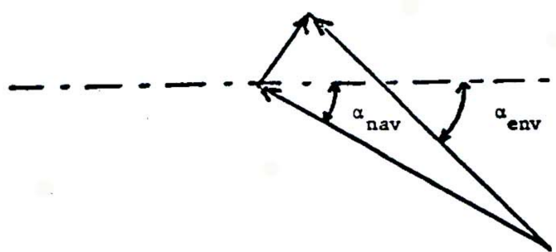
Pitch FCS



elev. pos.
Lag Filter
$\bar{q}$>20
δ_{SB}
G
G
M
$\bar{q}$<20
Pitch Pannel Trim
.5<$\bar{q}$<8
GJET
Pitch RHC
CSS
rate error
Pitch Jet CMD
To Pitch Jet
JSL
Pit. Beep Trim
AUTO
q_b(pitch rate)
To BF
channel
G
CSS
Rate error
$\bar{q}$<2
α
Lim ±2°
G
G
BB Filt
Ent
$\bar{q}$>2
α_c
TAEM
cos θ / cos φ
ele. CMD
PRL
Nzc
G
Filt.
TAS
r tan φ
other
Nz
TAEM



IF THE VEHICLE ENCOUNTERS A WIND COMPONENT FROM THE "TOP" (I.E. BANKED INTO THE WIND) THE ACTUAL α WILL BE LESS THAN NAV COMPUTES



IF THE WIND COMPONENT IS FROM THE BOTTOM (I.E. BANKED AWAY FROM THE WIND) THE ACTUAL α WILL BE GREATER THAN NAV ESTIMATES

THE FCS IS SENSITIVE TO SITUATIONS WHERE THE ACTUAL α IS LOWER THAN THE NAV ESTIMATE BECAUSE OF THE COMPUTATION OF BODY RATES TO ACHIEVE A STABILITY ROLL RATE WITH $\dot{\beta} = 0$

In the FCS, which controls perturbations around body axes, and steady state rate components must be allowed. Thus the rate error signals are computed by subtracting the computed steady state rates from the measured body sensed rates from the rate gyros.

$$\text{Roll error signal} = P_b - \frac{g \tan\phi \sin\theta}{V}$$

$$\text{Yaw error signal} = r_b - \frac{g \sin\phi \cos\theta}{V}$$

$$\text{Pitch error signal} = q_b - r_b \tan\phi$$

Navigated air data (NAVDAD) is at best a SWAG

α = ∠ between Velocity vector and FRL
does not consider wind!

$M = V_{rel}/1000$

$\bar{q}$ (M>2.5) based on F=ma
Drag Force = mass × acceleration
(known) (measured)

$D = C_D \bar{q} S$ and $C_D = f(\alpha)$ and α is "known"

$\therefore \bar{q} = D / f(\alpha) S$

Now since nav thinks it knows $\bar{q}$ it tries to establish altitude based on $\bar{q}$ and velocity by $\bar{q} = \frac{1}{2} \rho V_{rel}^2 \Rightarrow \rho = 2\bar{q} / V_{rel}^2$ and altitude = $f(\rho)$. This is called Drag altitude and is used to stabilize the altitude covariance matrix (80,000 ft edit criteria)

$\bar{q}$ $(M<2.5) = \frac{1}{2} \rho V_{rel}^2$ where ρ = function of NAV altitude (seasonal I loads)

Below M 1.5 FCS needs better data than NAVDAD
∴ Default air data (to FCS only)
α = constant 7.5°
$\bar{q}$ = canned function of V_{rel}

WHY DO WE NEED AIR DATA?

ASSUME STRETCHING A GLIDE TO EDW WITH A 99.5% TAILWIND AT 40,000 FT

ACTUAL CONDITIONS (ASSUMED READ BY ADTAS)

$$200 \text{ KEAS} = \frac{200}{\sqrt{.246}} = 403 \text{ KTAS} = 681 \text{ FT/SEC THRU AIR MASS}$$

$$\text{TRUE } M = \frac{681}{980} = 0.69 \quad \text{TRUE } \bar{q} = \left(\frac{200}{17.16}\right)^2 = 136 \text{ PSF}$$

WITH THE EDW TAILWIND, 220 FT/SEC NAV WOULD SEE:

$$V_{REL} = 681 + 220 = 901 \text{ FT/SEC}$$

$$\bar{q}_N = 1/2\ (.0005857)\ (901)^2 = 238 \text{ PSF}$$

$$M_N = \frac{901}{980} = 0.92$$

$$EAS_N = 17.16\sqrt{238} = 265 \text{ KEAS}$$

$$TAS_N = V_{REL} = 901 \text{ FT/SEC} = 533 \text{ KNOTS.}$$

NAVDAD ERRORS:

102 PSF $\bar{q}$ (75%), 130 KTAS (32%), 65 KEAS (33%) 0.23M (33%)

JUST FOR FUN, ASSUME YOU BANK 50° INTO THE CROSSWIND.

α ERROR WOULD BE ARCTAN $\frac{220 \sin 50^\circ}{681} = 13.9^\circ$

ALPHA ERROR

SUPPOSE $\alpha_{NAV} = 40^0$ BUT $\alpha_{ENV} = 37^0$

WHEN THE FCS GETS $p_c = 5^0$/SEC (RIGHT ROLL)
IT WILL TRY TO ESTABLISH BODY RATES GIVEN BY THE PREVIOUS EXAMPLE

$$p_b = 3.83^0/\text{SEC} \quad \text{AND} \quad r_b = 3.21^0/\text{SEC}$$

BUT IF ACTUAL $\alpha = 37^0$ $\dot{\beta}$ WILL NOT BE Φ

$$-\dot{\beta} = r_b \cos\alpha - p_b \sin\alpha$$
$$= 3.21 \cos 37^0 - 3.83 \sin 37^0$$
$$= 2.56 - 2.30 = .25^0/\text{SEC}$$

$\therefore \dot{\beta} = -.25^0$/SEC

IN A RIGHT ROLL, β WILL GROW TO THE LEFT ACCELERATING THE ROLL RATE.

IF α_{ENV} WERE 43^0 WE WOULD FIND

$\dot{\beta} = + .26^0$/SEC

AND THE β WOULD GROW TO THE RIGHT IN A RIGHT ROLL
THUS DAMPING THE ROLL RATE.

A SECONDARY EFFECT OF ALPHA ERROR IS AN INDUCED $\bar{q}$ ERROR BECAUSE OF THE NAV $\bar{q}$ ALGORITHM ABOVE M1.4

$$F = MA \qquad C_D \bar{q} S = MA$$

$$\bar{q}_{NAV} = \frac{MA}{C_D S}$$

MASS IS KNOWN
ACCELERATION IS MEASURED
C_D IS COMPUTED AS $f(\alpha)$

IF ACTUAL α IS LOWER THAN NAV α, THE COMPUTED VALUE OF C_D WILL BE HIGHER THAN IT SHOULD BE. NAV $\bar{q}$, WITH A LARGER C_D IN THE DENOMINATOR WILL BE SMALLER THAN ACTUAL $\bar{q}$.

FCS GAINS WILL BE SET BASED ON THE SMALLER NAV $\bar{q}$ AND WILL BE TOO HIGH FOR THE LARGER ACTUAL $\bar{q}$ THAT THE VEHICLE IS EXPERIENCING

CONVERSELY, IF ACTUAL α IS HIGHER THAN NAV α, NAV $\bar{q}$ WILL BE HIGH, GAINS DECREASED.

SO THE CRITICAL α ERROR FROM BOTH A $\bar{q}$ AND $\dot{\beta}$ STANDPOINT IS ENVIRONMENT $\alpha <$ NAV α.

A better but extremely difficult lift theory also one of the first

The most successful modeling of flow around an airfoil is the Kutta-Joukowski theorem which states that the forces acting on a body are determined wholly by the circulation around it and the free stream velocity! The force is given by the equation:

$$- F = \rho V \Gamma$$

where ρ is the fluid density, V is the free stream velocity and Γ is the circulation strength. This theorum explains: wing tip vortices, up-flow ahead of a wing, down-flow behind a wing, why wing vortices are stronger when an airplane is slow (i.e. during landing and right after takeoff). It is generally the most successful theory to date, but it too doesn't tell us WHY circulation occurs.

This theory indicates that the geometry of the body and the free stream velocity do not uniquely determine circulation. We have to go to experimentally determined data in airfoil design.

So how do we determine the circulation? Empirical Observation, i.e test, observe, apply lessons learned!

Computational fluid dynamics , using iterative calculations using a super-computer are getting close.

Best explanation of circulation is the Kutta Condition which states that a body with a sharp trailing edge WILL establish a circulation about itself which moves the stagnation point to the trailing edge. Why?

I don't know! Nor does anyone else! It just DOES, OK!