CONTROL ASPECTS OF FLYING WINGS
WITH AFT - & FORWARD- SWEEP, Camber & Twist

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• Lastly it should be mentioned that any opinions expressed are those of the author.
Introduction

• Revival of Interest in Flying wings, Military & Civil
• More Efficient? More “Twitchy”
• Northrop B-2 & McDonnell Douglas (Boeing) Studies
• Some Commonality, Apart from STEALTH
• Short Moment arms & Low Inertia in Pitch

• Design for Well Behaved Pitch behaviour at all speeds & Cross-wind ability
• Intake, Propulsion Integration varies with Application
Northrop B-2, Essentially Optimised for Cruise
Military Flying Wings
Boeing (McDonnel Douglas)
Liebeck & Others
Transport/Civil Flying wing
This Presentation

• Based Originally from a Civil Viewpoint

• Flying Wings have:
• Special set of Different Constraints vs Conventional
• Consider Planforms Aft- & Forward- Sweep
• Stability & Control Important
  – Design of Camber & Twist, Mach no divergence
  – Low speed & high speed neutral points
  – Floor angle

• Address Lateral & Directional Issues
• Avenues for Further Work
Approach: Subsonic Theory & Euler

- Lifting Surface, Vortex Lattice Theory
  - first-Order Mach no Effects
- Attained Thrust & Vortex Estimates

- We tend to focus on S & C aspects first
  - longitudinal, Directional & Lateral Trim
  - Cruise & Field Performance
- Then detail design using Panel, CFD
  - Aerofoils, Shocks & Tailoring
Current Planform Studies
Many Feasible

ASW -A1
wing fw’d
on inner wing

FSW-F1
wing back

ASW -A2
wing back
on inner wing

High
sweep
Design Envelope

- **CL**: Conventional Mach No
- **BWB**: Mach No
- **Field**: Conventional
- **Cruise**: Conventional

Graph showing the design envelope for Conventional and BWB Mach Nos in the cruise and field conditions.
Practical “Highly” Swept Wings/portions at high lift

- Cranked LE poses difficulties
- local CL’s high
- Use attached flows as far as possible (L/D)
- Use LE/TE devices, if possible!
- Need to understand Vortex Breakdown enough to control it or design around it
- Multiple vortex fields exist, “peeling” off
About Neutral point

ASW-A1 PLANAR, FORCES & MOMENTS, Mach 0.8
PLANAR, SPANWISE LOADINGS WITH AOA VARIATION, LIFT, DRAG & AXIAL FORCE, Mach 0.8
DESIGNED with c/cref

STABLE

NEUTRAL

UNSTABLE

ASW -A1
DESIGNED
no c cref

Note Twist Req’d

ASW - A1

PLANFORM A1, DESIGNED CAMBER, SPANWISE LOADINGS WITHOUT c/c_a
FACTOR, STATIC MARGIN VARIES, 10%c_a Stable, Neutral & 10%c_a Unstable, Mach 0.8

STABLE

NEUTRAL

UNSTABLE
DESIGNS
Neutral & Stable

ASW - A1
DESIGNS
Neutral & Stable

ASW - A1
PLANFORM A1, COMPARING FORCES, DESIGNED CAMBER, SPANWISE LOADINGS, STATIC MARGIN VARIES, 10% \( c_a \) Stable, Neutral, Mach 0.8
DESIGNS
Neutral & Unstable
DESIGNS Neutral & Unstable

PLANFORM A1, COMPARING FORCES, DESIGNED CAMBER, SPANWISE LOADINGS, STATIC MARGIN VARIES, 10% $c_a$ Unstable, Neutral, Mach 0.8
Longitudinal

• Short Moment Arms, Low Pitch Inertia
• go for longer inner wing (fuselage !)
  – thickness important at root
• Cabin floor angle restriction
• Twist required, increases for stable flight
  – affects CD0
• Neutral pt. shifts forward for low speed 3%, Trim!
• “armpit” control “fights” “tip” control, moment arms geometry cuts effectiveness by 1/2
• Need to continue Planform Work
About Neutral point

FSW-F1, PLANAR, FORCES & MOMENTS, Mach 0.8
FSW - F1, PLANAR, SPANWISE LOADINGS WITH AOA VARIATION, LIFT, DRAG & AXIAL FORCE, Mach 0.8
DESIGNED with c/c_ref

FSW -F1

PLANFORM F1, DESIGNED CAMBER, SPANWISE LOADINGS WITH c/c_a
FACTOR, STATIC MARGIN VARIES, 10%c_a, Stable, Neutral & 10%c_a, Unstable, Mach 0.8
DESIGNED
no c/cref

Note Lack of Twist Req’d

STABLE

NEUTRAL

UNSTABLE

FSW - F1

PLANFORM F1, DESIGNED CAMBER, SPANWISE LOADINGS WITHOUT c/cD
FACTOR, STATIC MARGIN VARIES, 10%c, Stable, Neutral & 10% c Unstable, Mach 0.8
DESIGNS Neutral & Stable

FSW -F1
DESIGNS Neutral & Stable

with $c/cref$

no $c/cref$

FSW - F1

PLANFORM F1, COMPARING FORCES, DESIGNED CAMBER, SPANWISE LOADINGS, STATIC MARGIN VARIES, 10%$c_a$ Stable, Neutral, Mach 0.8
DESIGNS Neutral & Unstable

with c/cref
no c/cref

FSW - F1
PLANFORM F1, COMPARING FORCES, DESIGNED CAMBER, SPANWISE LOADINGS, STATIC MARGIN VARIES, 10%c_a Unstable, Neutral, Mach 0.8
DESIGNS Neutral & Unstable

Cabin floor

stable

neutral

FSW -F1, COMPARING DESIGNED CAMBER, STATIC MARGIN VARIES, 0% Neutral & 10%c_{ay} Unstable, Mach 0.8
Design Inferences

• Stable Static margin leads to TE down (higher local Incidence) camber.

• Camber & Twist can be controlled over regions
  **Aft- Swept Wings, Usual**
  - Outer Wings are more heavily loaded
    - which have to be off-loaded for trim
    - leading to aero centre shifts off-design.

  **Forward- Swept Wings, A Contender**
  - Outer Wing are lightly loaded, more in sympathy with planform sweep & chord as well as root BM
  - Capitalise on FSW laminar flow
  - With Aero-elastic tailoring, structural divergence should be less of a problem on wings of 9% t/c, X-29 was 4% thick.
Transports, Directional, Lateral

- Critical - One Engine-Off during take-off or at low-speeds (30 kt cross-wind). Large Aircraft, 80m span
- Ability to hold a 10 deg heading at 75% control power
- Vertical fins exist, low moment arms.
- Can’t have Anhedral
- Balancing by Split Ailerons produces drag
  - Low L/D, Climb Gradient affected
- Rudders+Split ailerons
- Initially, side-force dominates before yawing effects come in (high inertia in yaw)
  - No more than 30 m “drift” permitted on runways
- Continual Research needed.
Lateral Characteristics

Dihedral / Anhedral introduced over outer 70% semi-span, PRELIMINARY

Clβ based on semi-span, MACH 0.2
Military Lateral, Directional

- B-2 (No Vertical fins) appears Directionally unstable with Active Control system and sophisticated side-slip measurement

- Adequate Thrust available on Military Aircraft
- Thrust can be deflected / vectored!
- Split Ailerons / Drag rudders for Yaw moment
- Clβ at low speeds, Dihedral/Anhedral Effect
Boeing BOP

Note canted Tips
Stealth + CIβ !
Future Work

• More Parametric Studies including FSW
• Combining with Euler for detailed Transonics
• Low-Speed pitch trim using LEF / TEF
• Control Requirements, small moment arms
• Roll & Yaw Coupling, Fins, Dutch Roll
• Off-design effects
• Intakes / Propulsion
Concluding Remarks

• Revival of Interest in Flying Wings for Military & Civil, different set of Constraints summarised, e.g. Low CL
• Appreciation of Solvers, Linear Theory, Euler
  – Understanding & Quick turn-around needed
• Strategy: Appropriate Solvers with Stability Constraints
• Aft- & Forward- swept planforms Designed & studied with lifting surf. theory (Mach & Re. & Attained thrust) ts
• Capitalise on FSW laminar flow
• With Aero-elastic tailoring, structural divergence should be less of a problem 9% t/c wings (X-29 was 4% t/c).
• Preliminary work on Laterals, FSW permits Dihedral
*** Thank You for Listening ***

Barely touched the surface of this vast subject, plenty more to do!

There are Experts in the Audience
Shall we try Comments and Discussion

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