Full-Scale 1903 Wright Flyer Wind Tunnel Test Results From the NASA Ames Research Center

Henry R. Jex, Jex Enterprises, Santa Monica, CA
Richard Grimm, Northridge, CA
John Latz, Lockheed Martin Skunk Works, Palmdale,CA
Craig Hange, NASA Ames Research Center, CA

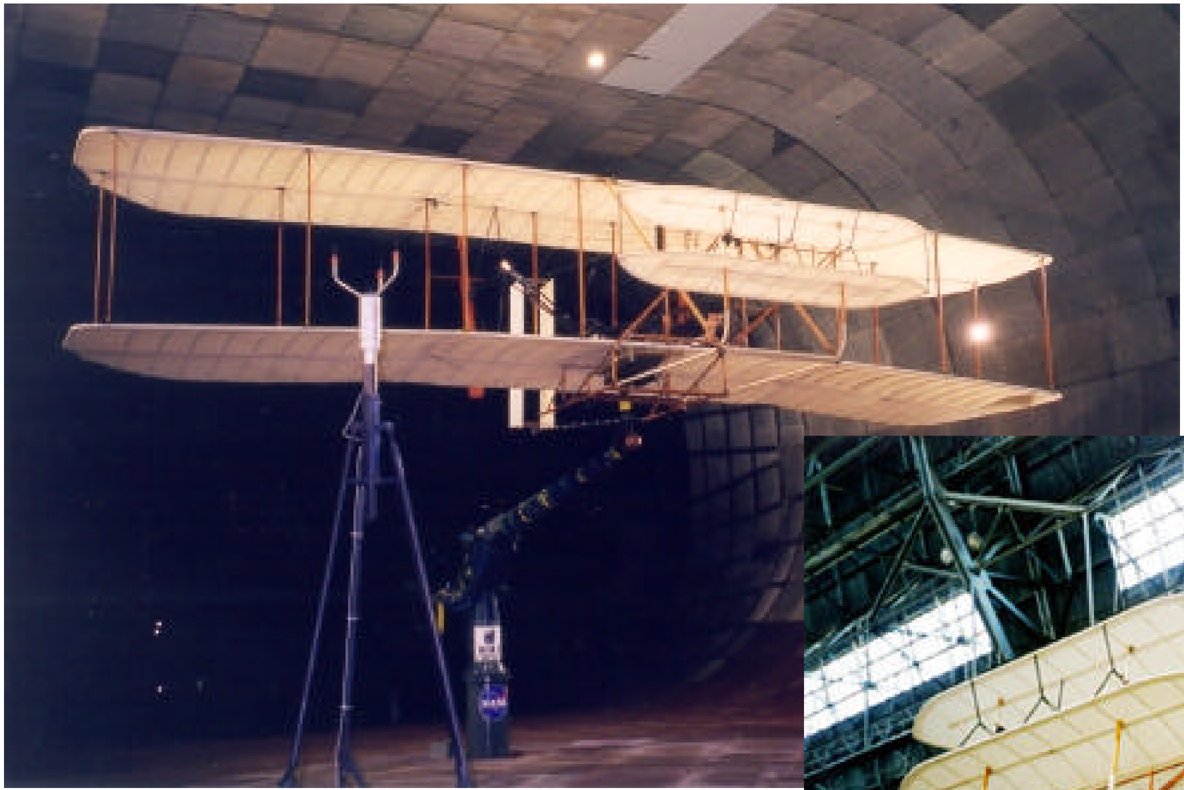
Synopsis

- Background
  - See prior paper: AIAA 2000-0511
    "The AIAA 1903 Wright Flyer Project; Prior to Full Scale Test at NASA Ames Research Center"
- Recent Tests @ NASA Ames National
  Full Scale Aerodynamics Complex
  40' x 80' Wind Tunnel
- Comparison with Previous Sub-scale Tests
- Main Conclusions and Implications

LA Section Wright Flyer Project

- Project Founded in 1979 with a $20,000 insurance claim for an earlier AIAA copy of the 1903 ‘Flyer’ destroyed in a fire at the San Diego Aerospace Museum
- Phase I: Full-Scale Replica tested at NASA Ames
  – Provide Engineering Data from Wind Tunnel Tests
  – Analyze Performance, Stability and Control
  – CFD to Augment Aerodynamic Analysis
  – Compute Test Loads and Structural Analysis
  – Simulation of Flight Dynamics

Wind Tunnel Test @ NASA Ames



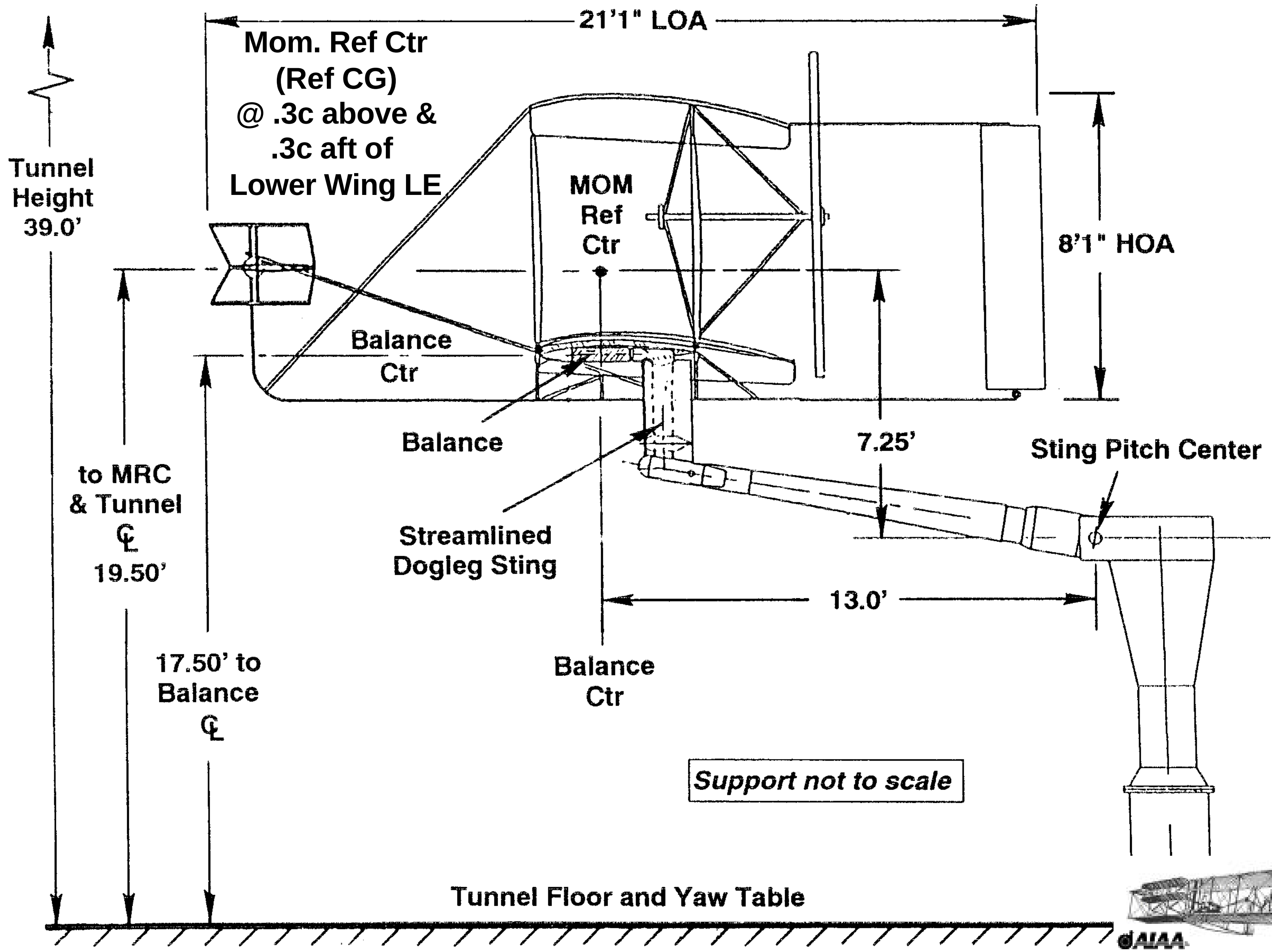
Wind Tunnel Model Design and Construction

- Full-Scale 'Flyer' Built from 1950 Smithsonian Plans
  - Span 40.33 ft (Right Wing 0.33ft longer to compensate for engine weight)
  - Same construction with small structural reinforcements to accommodate sting mount, particularly in the center bay / lower wing
    - Untreated cloth covering, attached on 45° bias
    - Original chain drive and propellers
    - Original control surfaces, including flexible canard and wing warped by hip cradle (linear actuators)
  - Pilot mannequin
  - Powered by 45 HP electric motor 100-350 RPM

Wind Tunnel Model Installation

- Measurements and Instrumentation
  - 4.0” TASK 6-component balance mounted under center of lower wing (within undercamber)
  - Vertical strut (hockey stick) to sting below skids
  - No aero tares applied (deemed negligible)
  - Small upwash corrections to α & C_D (~ 1.2° @ C_L =1)
  - Commanded and achieved control settings recorded
  - Wing tip inclinometers for wing warp and incidence with respect to reference plane (skids)
  - 300 RPM for most powered runs,
limited data at 340 RPM (electric motor limitation)
    - 50 -> 340 RPM in static tests
  - Red-on-White tufts over wing and canards

Model Installation Diagram



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Wind Tunnel Test Conditions

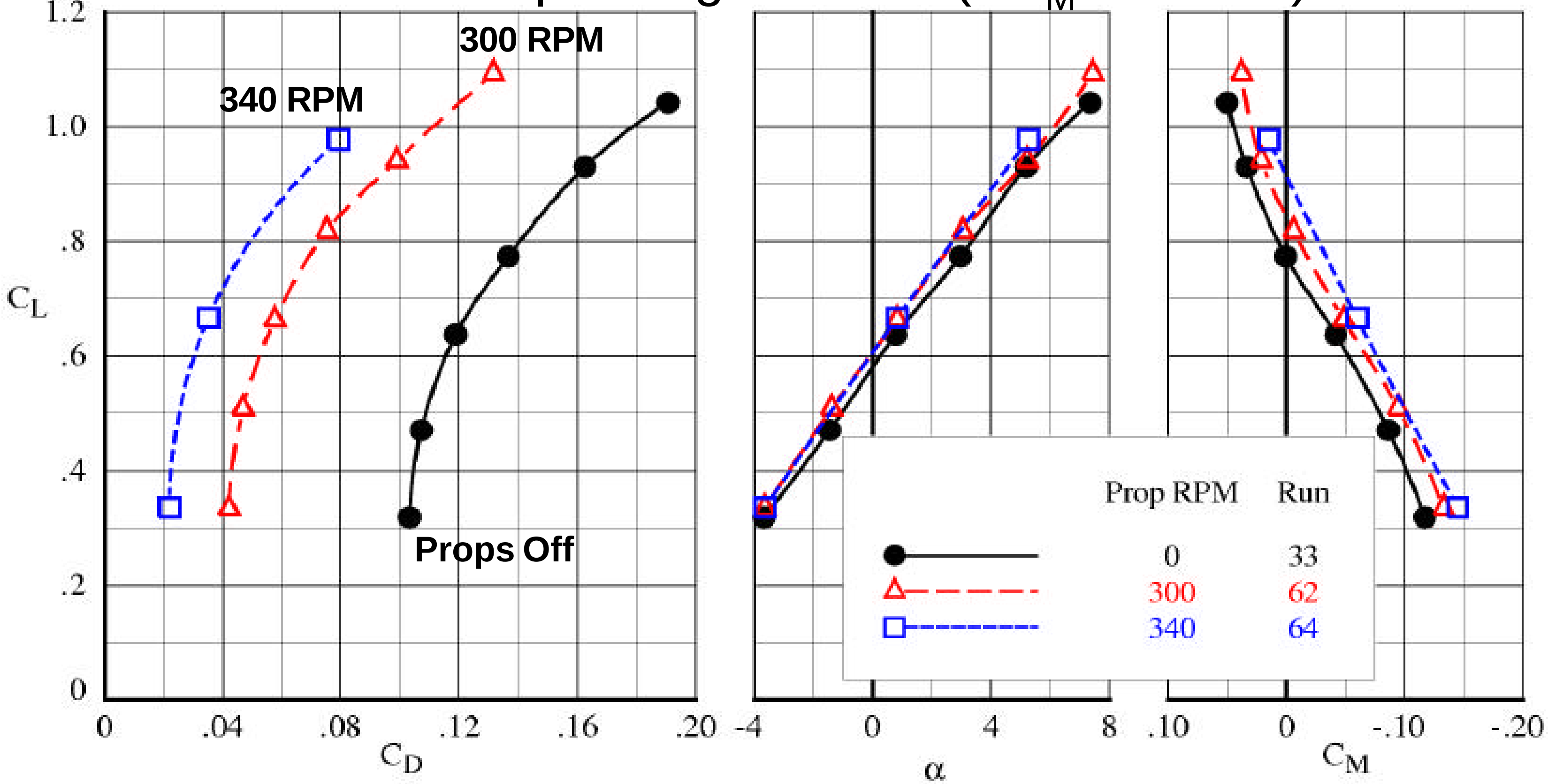
- Matched Wright's Flight Conditions
  – Airspeed: 25.0 kts (28.8 mph; 42.1 fps)
  – Dynamic Pressure: 2.0 psf
  – Reynolds Number: 1.8×10^6 (based on chord)
  – Mach Number: 0.04
  – α, β limited to $\leq \pm 8°$
- Tunnel: Rough Air at Low-Speed
  – At very low speeds, tunnel has low frequency turbulence due to off-design blade angles of fans
  – At low speeds, local α, β varied by |1°-4°| over 20-40 sec, shown by anemometers & streamers
  – Solution: average data over 2 minutes for each point
  – Most data fairly repeatable; some anomalies

Wind Tunnel Tests

- Data Acquisition and Reduction
  - Lab-View software on Apple Macintosh computer
  - Recorded at 10 sample/sec for 120 sec/point
    - Typically 10 points/run
  - Software included 6x27 balance matrix, weight tares, and wall corrections; averaged flow conditions & loads

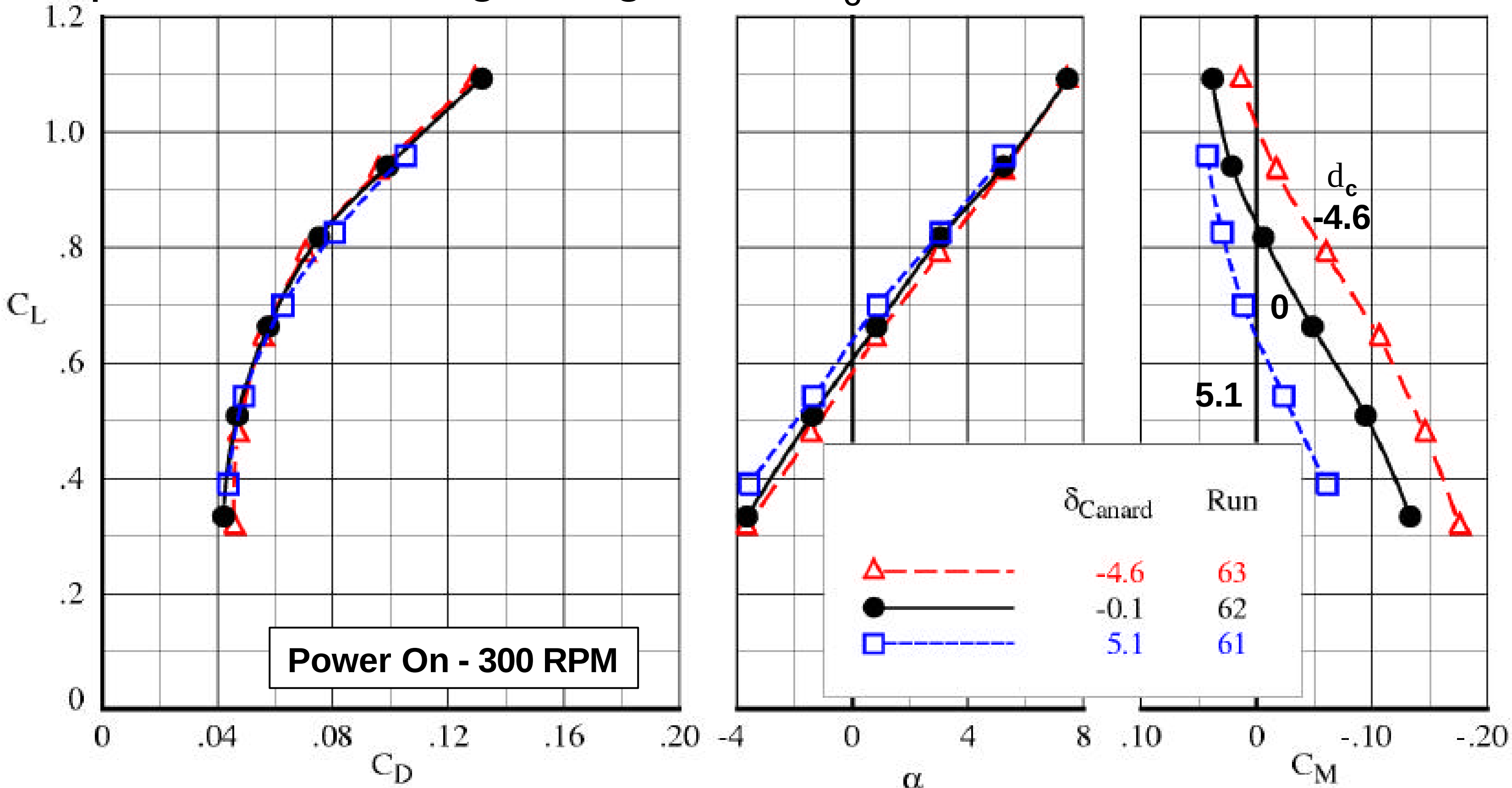
Wind Tunnel Data - Effects of Power

- Propeller efficiency insufficient to give T=D at 340 RPM
  - Historical value ˜ 340-360; power supply limited test data
- Slight lift increase due to prop slipstream ($\Delta C_L < 0.01\text{-}0.02$)
- Some nose-down pitching moment (ΔC_M ˜ -.025c)



Wind Tunnel Data - Effect of Canard Deflection

- Canard lift is always significant
- Adequate canard power to trim at operationally significant C_L's
- At δ_c = 5° & α ~ 6° canard showed separation and buffet: precluded testing at higher α / δ_c combinations



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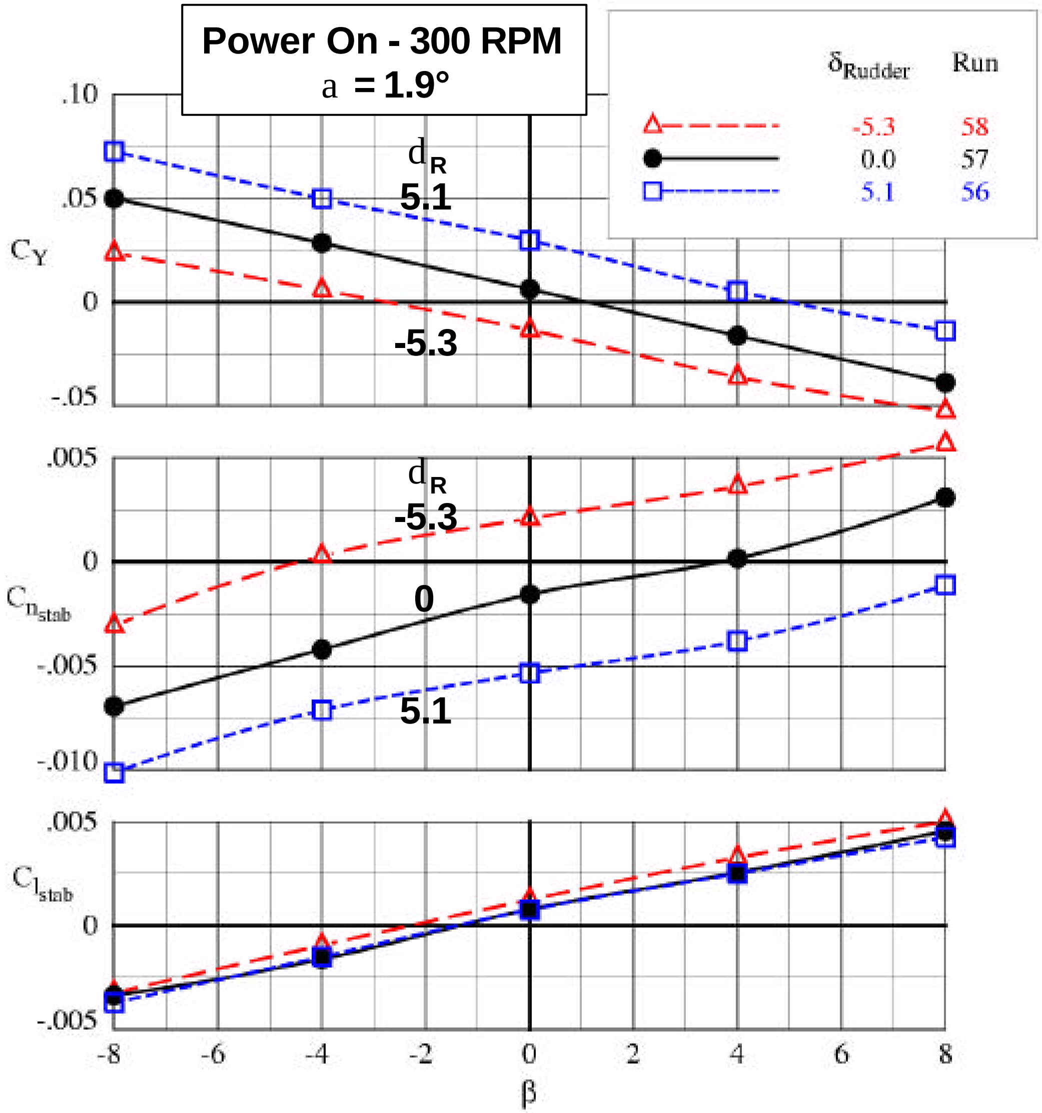
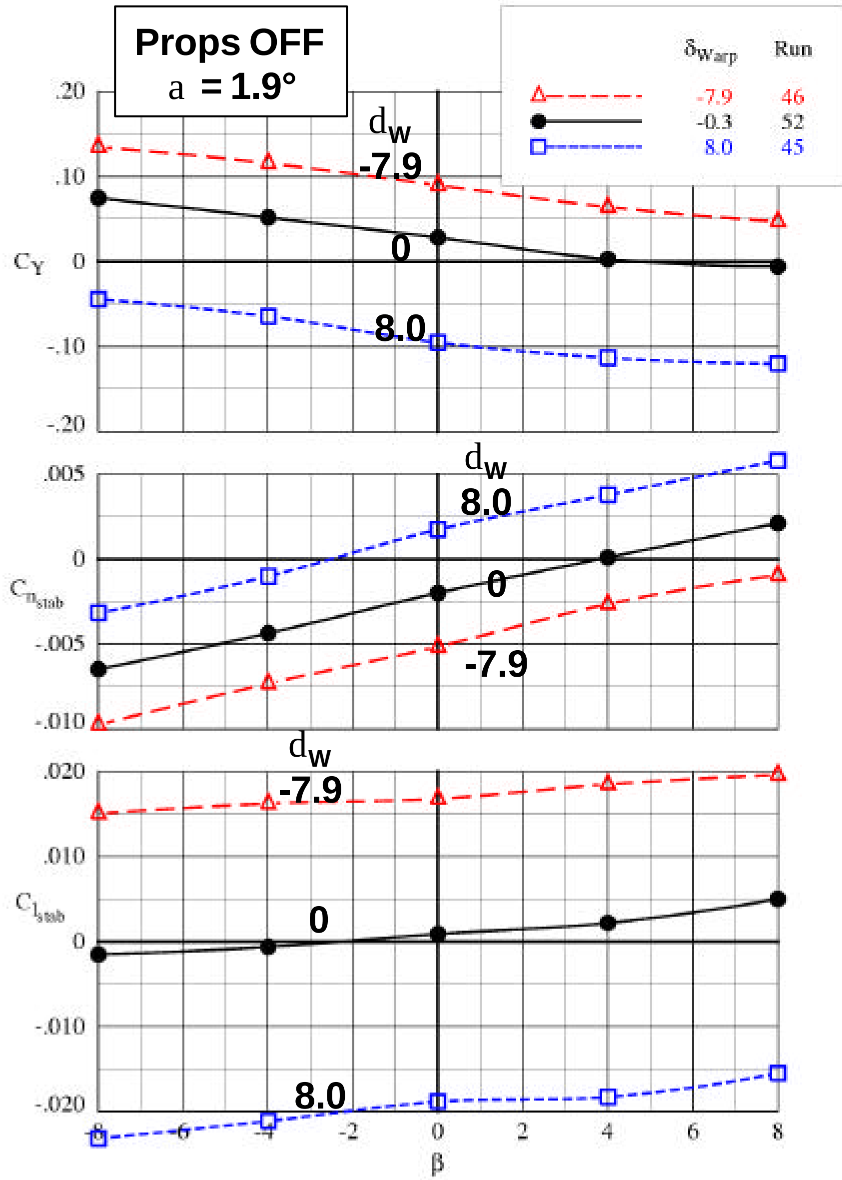
Wind Tunnel Data - Effect of Rudder Deflection



- Control Increments are fairly linear
- Flyer can trim to $\beta \sim \pm 8°$ with $\pm 10°\ \delta_R$
- Negligible roll due to rudder

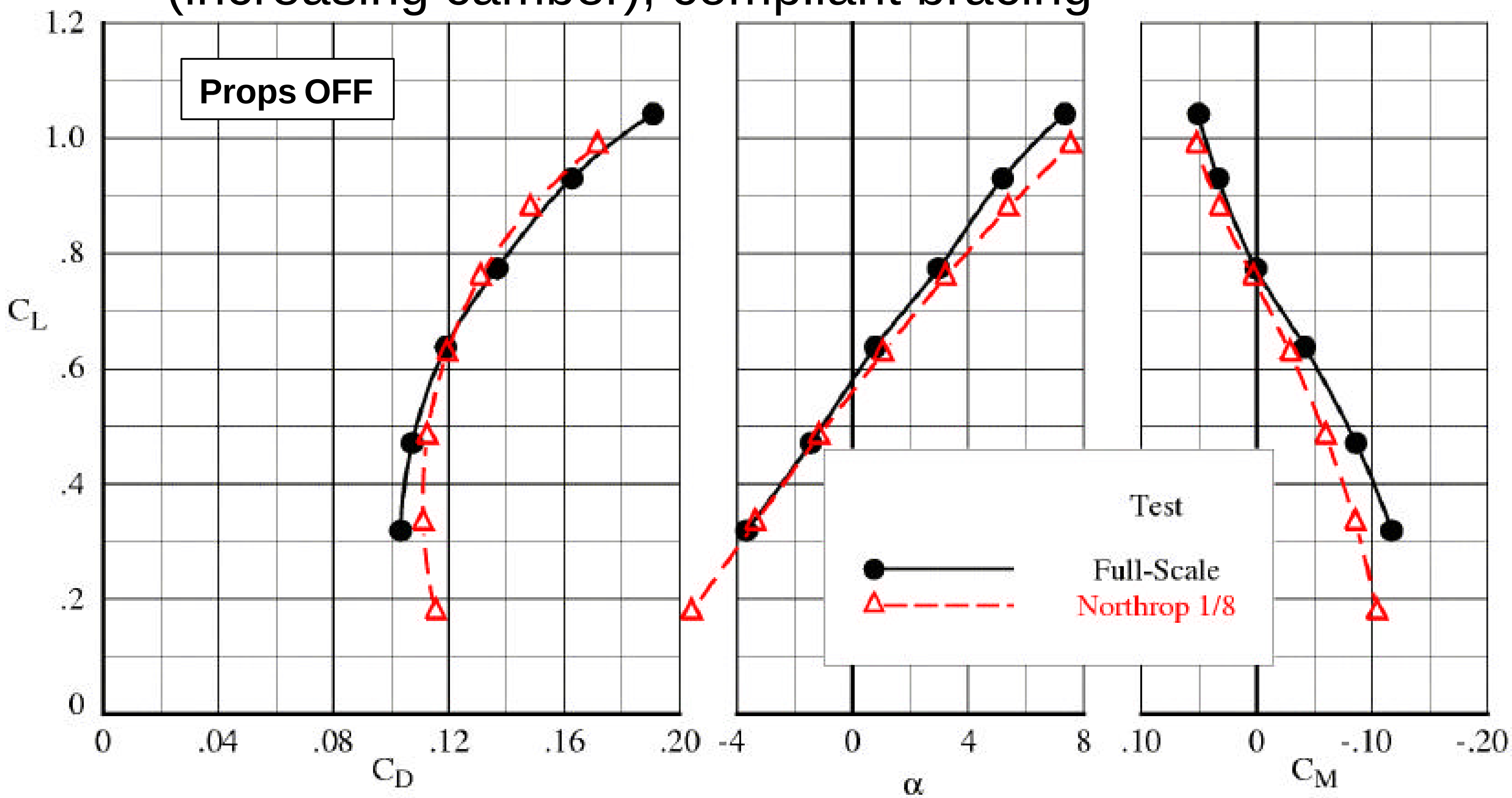
Wind Tunnel Data - Effect of Wing Warp



- Warp Defined as:
  $$\delta_W = i_{right} - i_{left}$$
- Rudder / wing warp interlink disconnected for test
- Large adverse yaw:
  $$\left.\frac{C_n}{C_l}\right|_{d_w} = -\frac{.007}{.035} \cong -.2$$
- Some non-linearity in control derivatives
- Small anhedral effect
- Roll control not affected by power

Wind Tunnel Data - Comparisons with Prior Data

- Model Differences
  - Northrop model had “fat” bracing wires; higher C_{D_O}
  - Full-scale model had aeroelastic effects: fabric “billowing” (increasing camber), compliant bracing



Comparison of Longitudinal Data

- Full-scale model showed increased lift curve slope at higher C_L's
  - Billowing of fabric causes increased camber with increasing α
- Due to accurate modeling of the variable camber canard, pitching moment effectiveness is higher than Northrop (1/8) and GALCIT (1/6) models
- Canard is close to stall at cruise conditions due to strong upwash from wings: $\frac{de}{da} \approx -.5$
- Aircraft is very unstable in pitch. Historical cg at ~30% chord
- Neutral Points:

  Full-scale: 0.05c; GALCIT: 0.01c;

  Northrop: 0.08c; Theory: 0.07c

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Summary: Significant Findings of Full-Scale Test

- Original vehicle structure, bracing, controls, covering, and flight conditions were closely matched
- Rough flow in tunnel required data averaging and reduction
- Comparisons (props-off) with previous wind tunnel tests of smaller models showed fairly close agreement
- Power-on data (300 RPM) showed small effects due to induced slipstream over wing and near vertical tail: $\Delta C_L \sim 0.02$, ~20% more rudder effectiveness
- Canard control effectiveness was roughly doubled over the smaller, rigid models; due to variable camber design
- Lift progressively increased versus the rigid models due to fabric billowing and resulting increased wing camber

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Summary (cont'd)

- Lateral control effectiveness due to wing-warp was comparable to GALCIT test, as was strong adverse yaw
- Overall stability of the full-scale model (power-on) demonstrated:
  – Very severe pitch instability (static margin = -25% c), but adequate canard control power to trim and control the instability
  – Sever spiral mode instability due to anhedral, but adequate warp control to cope with it
  – Vehicle was marginally stable directionally, with enough rudder control power to cope with adverse yaw due to warp and initiate banked turns
  – Use of warp-to-rudder interlink would be effective in canceling most of the adverse yaw due to warp

Summary (cont'd)

- In the wind tunnel, the reproduced propeller fell short of T=D @ 28 mph test condition when operating at the maximum permitted speed of 340 RPM. These data are being analyzed
- All of the unique aerodynamic features incorporated by the Wright Brothers worked as intended (cambered canards, pilot control of roll via wing warp, rudder crossfeed to control adverse yaw, and large contra-rotating propellers)

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1903 Wright Flyer - FAA Flight Deck