MULTIPHYSICS 2017

Design Evolution of Large Airliners

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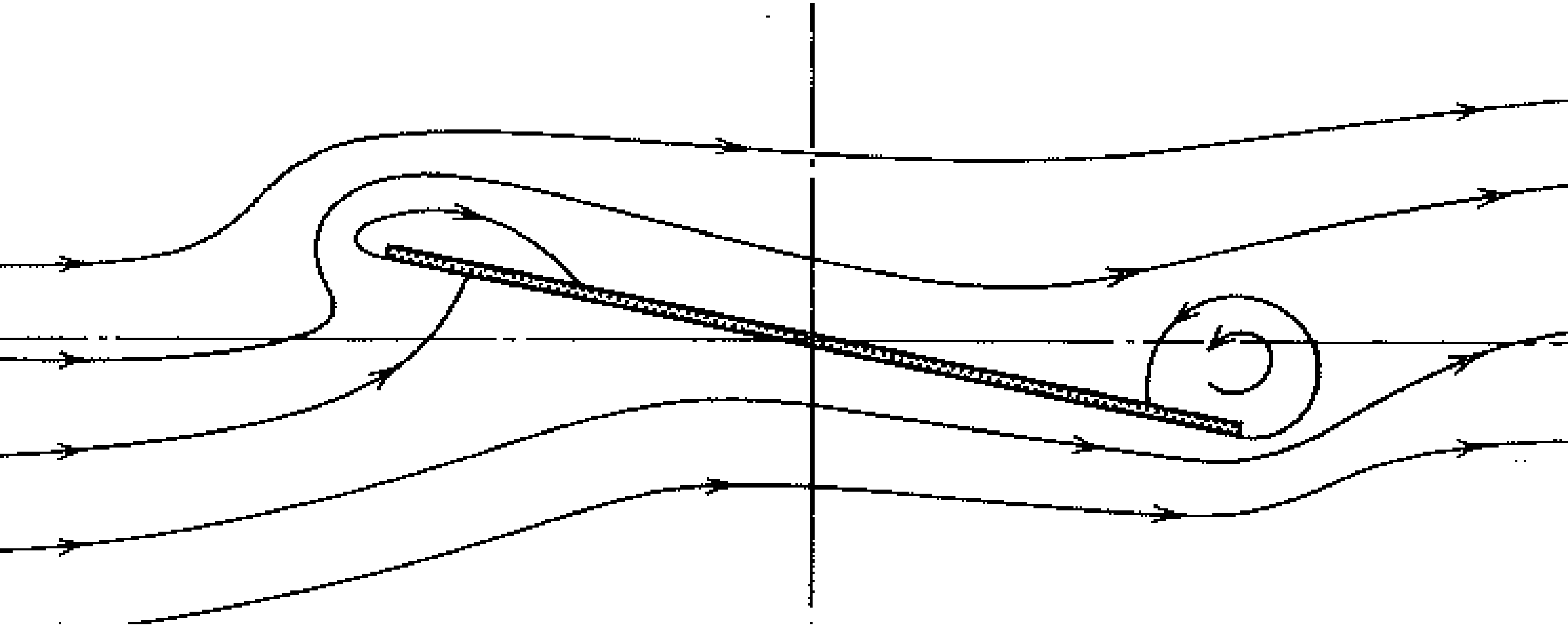
Beijing Institute of Technology

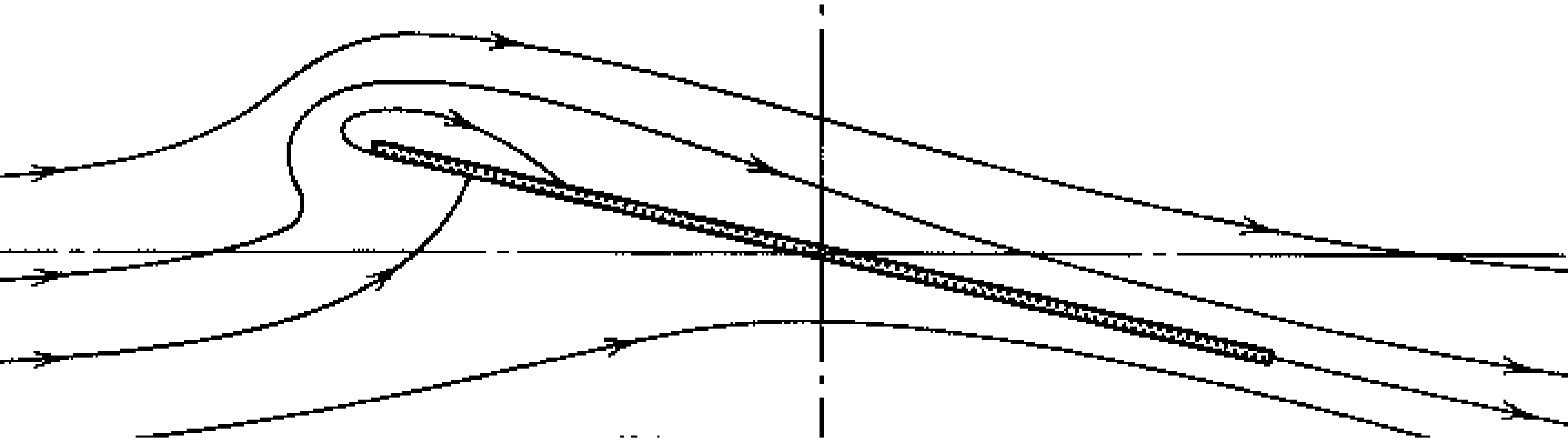
14th December 2017

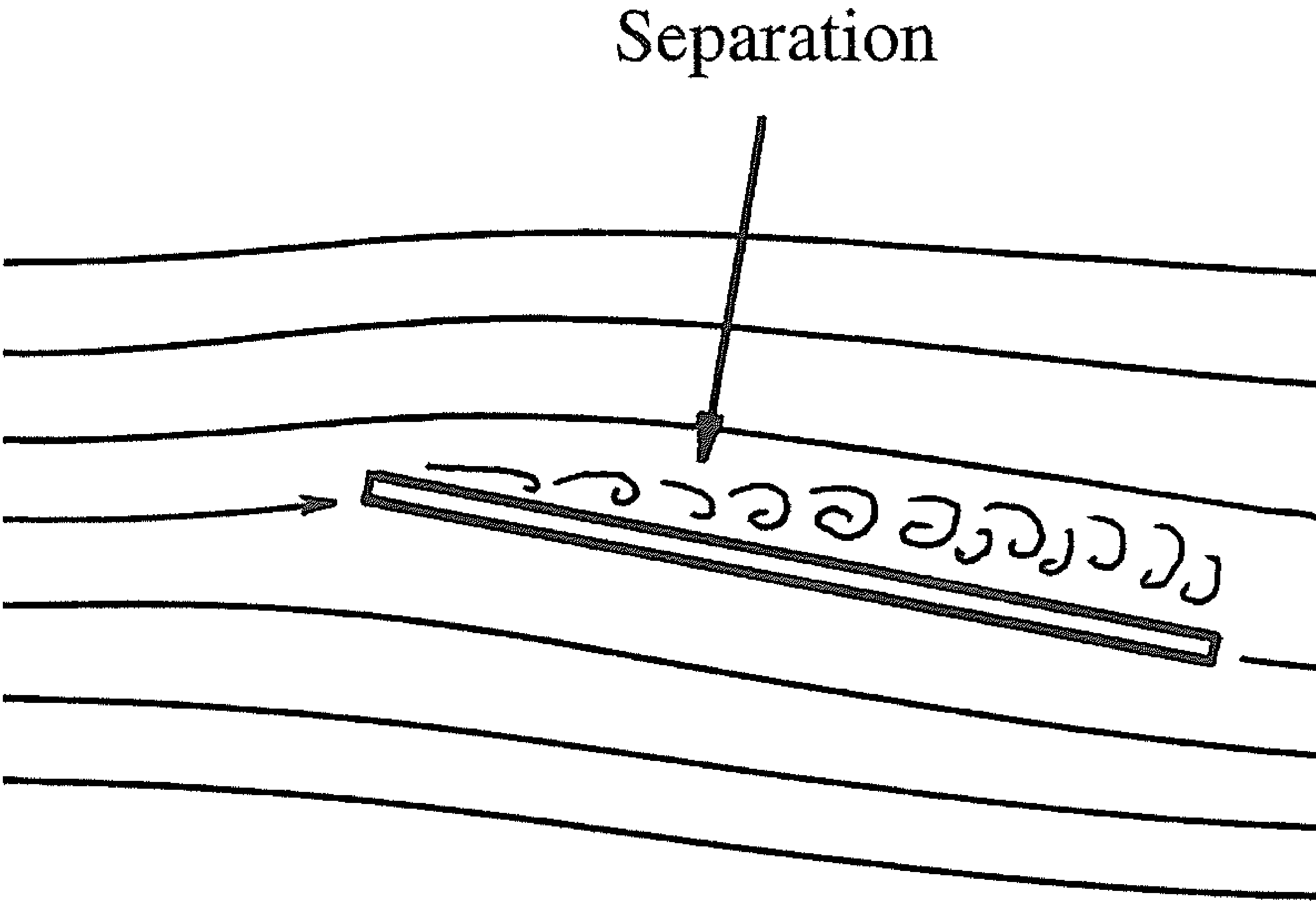

1809
George Cayley

1894 Lanchester: wing theory

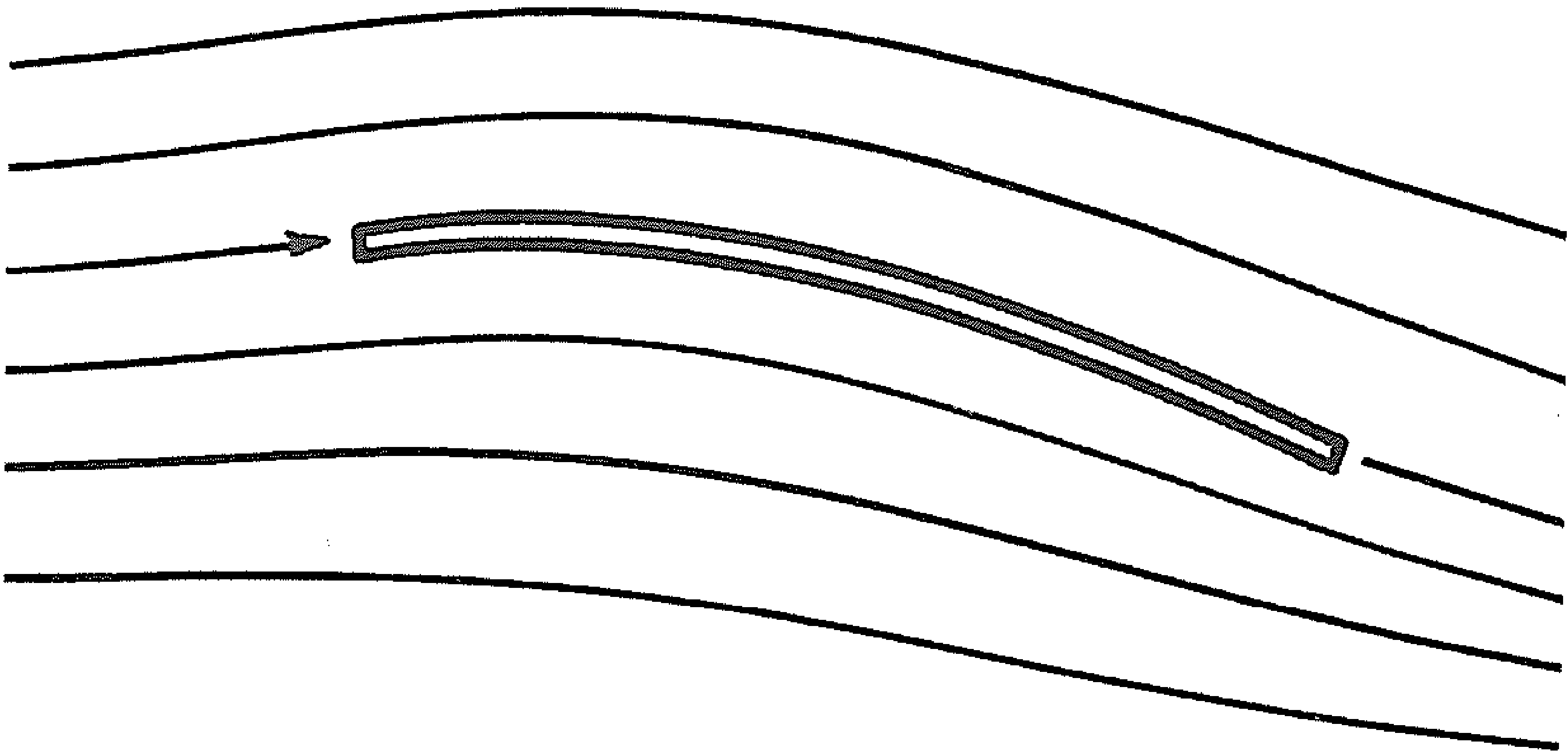


Kutta (1902) – Joukowski (1906) law

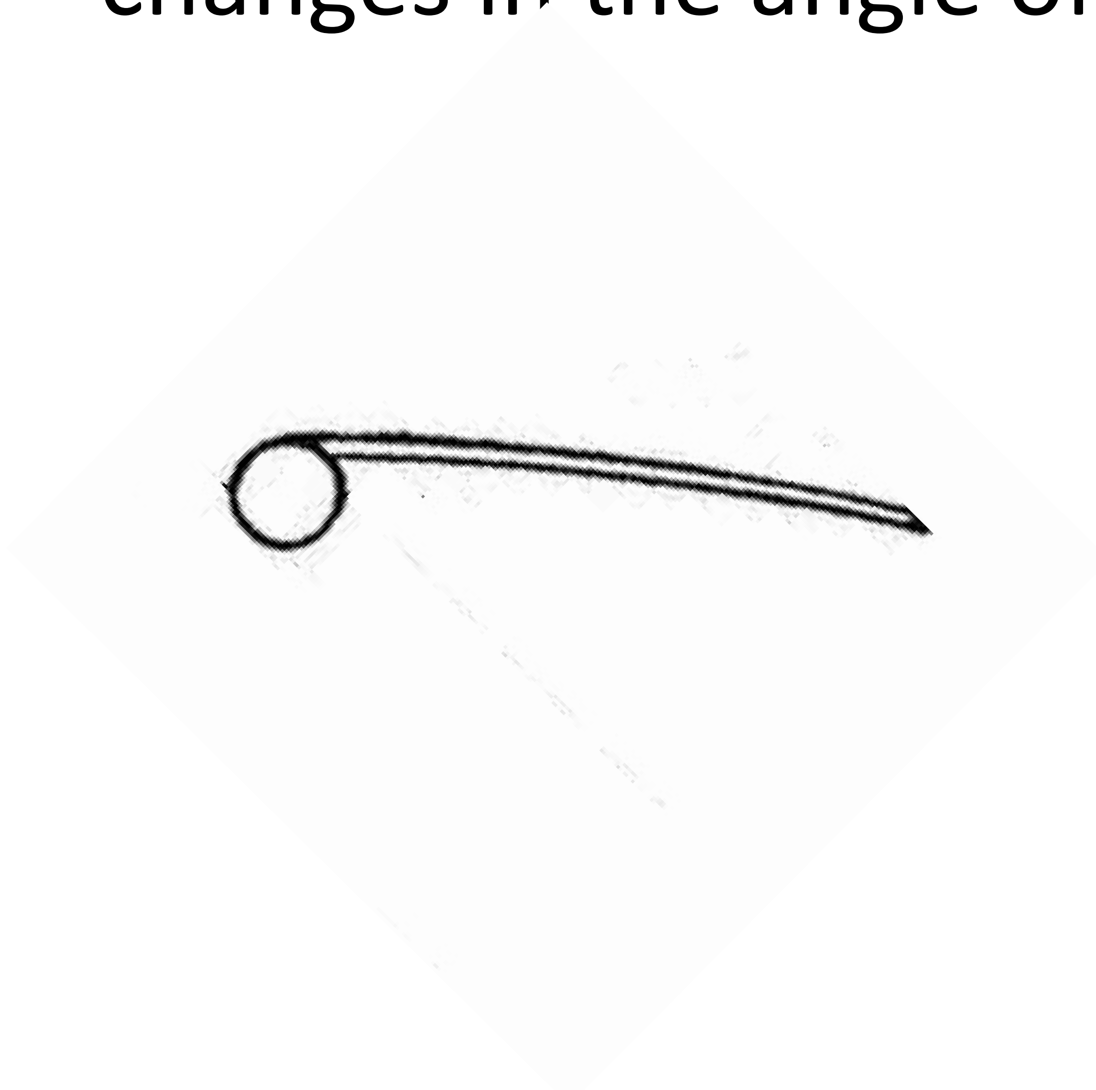



Separation

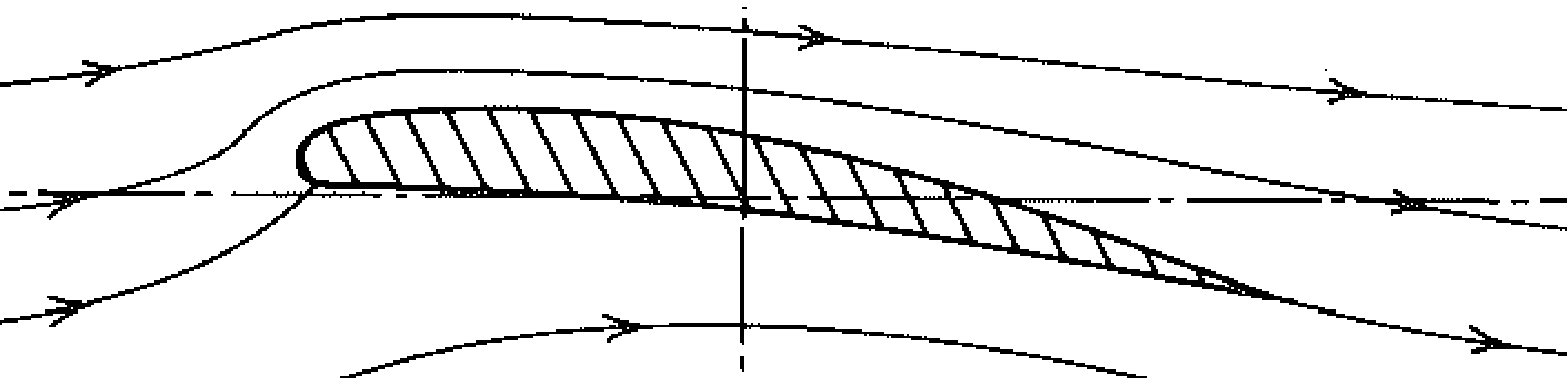
Curve (camber) wing to smoothen flow



Blunt leading edge to cope with changes in the angle of attack



Prandtl 1918: thick wing section

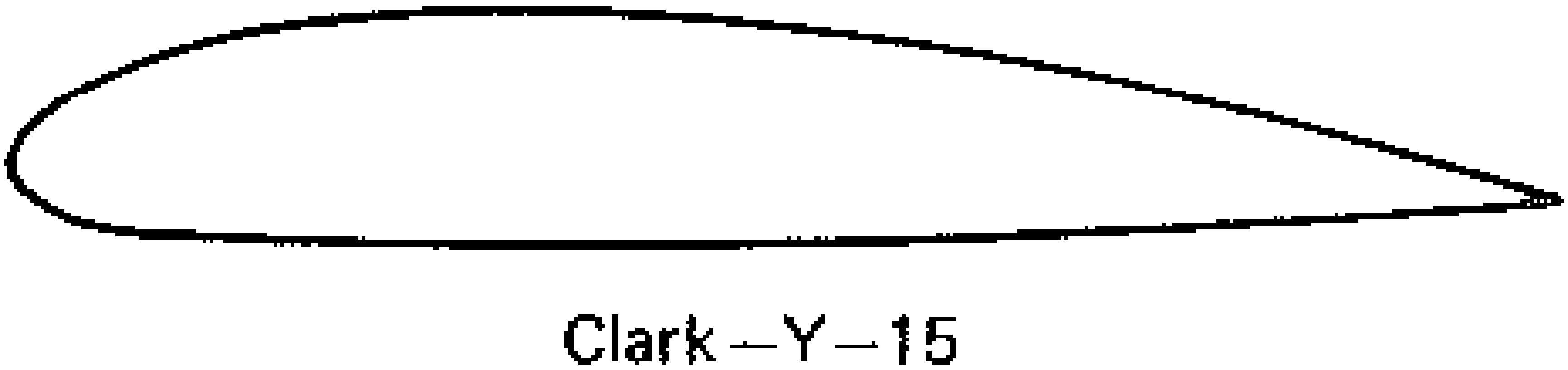


Founding of study agencies

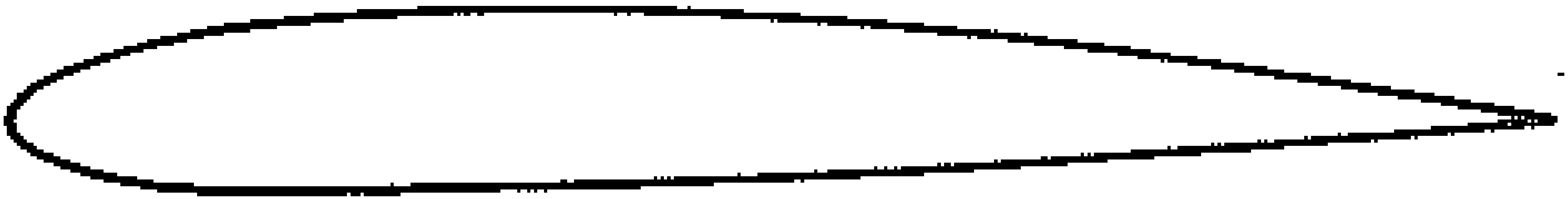
1915 National Advisory Committee for Aeronautics (NACA)

1918 Royal Aircraft Establishment (RAE)

1920s: Flat-bottom section

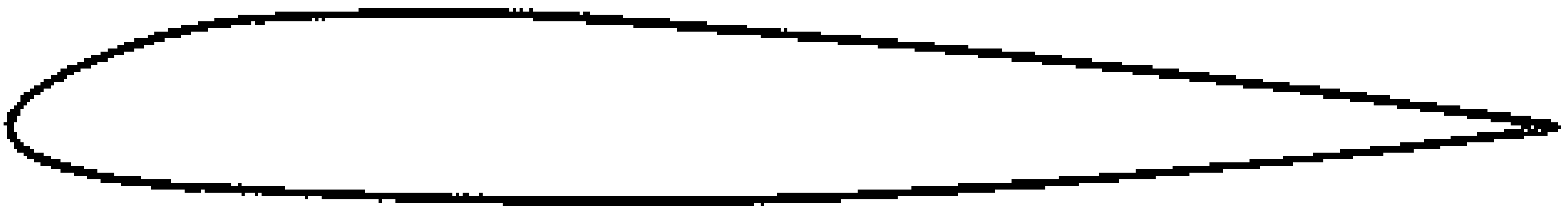


Four-digit section defined in 1932



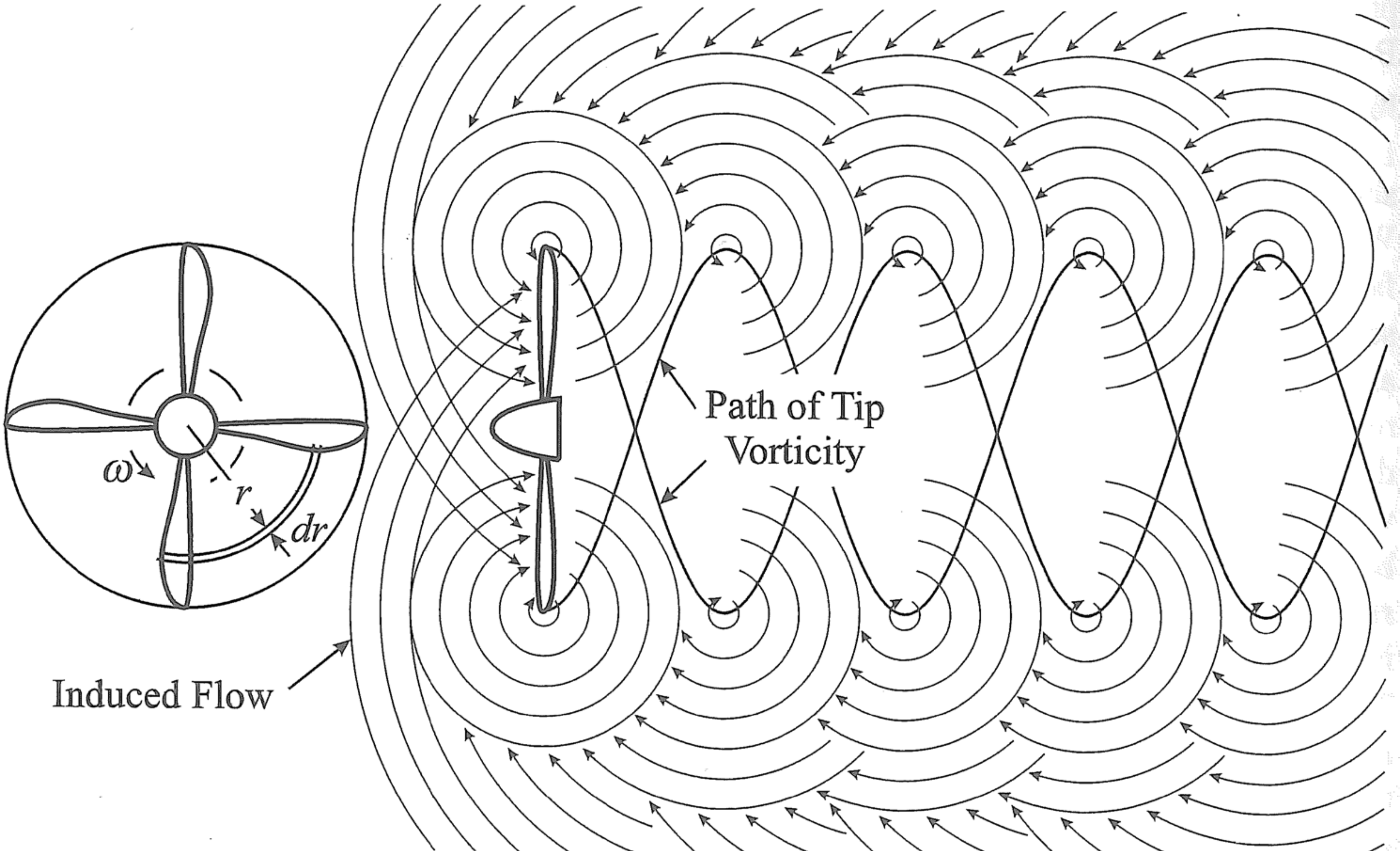
NACA 2412

Five-digit aerofoil (1935): max camber shifted forward for greater max lift

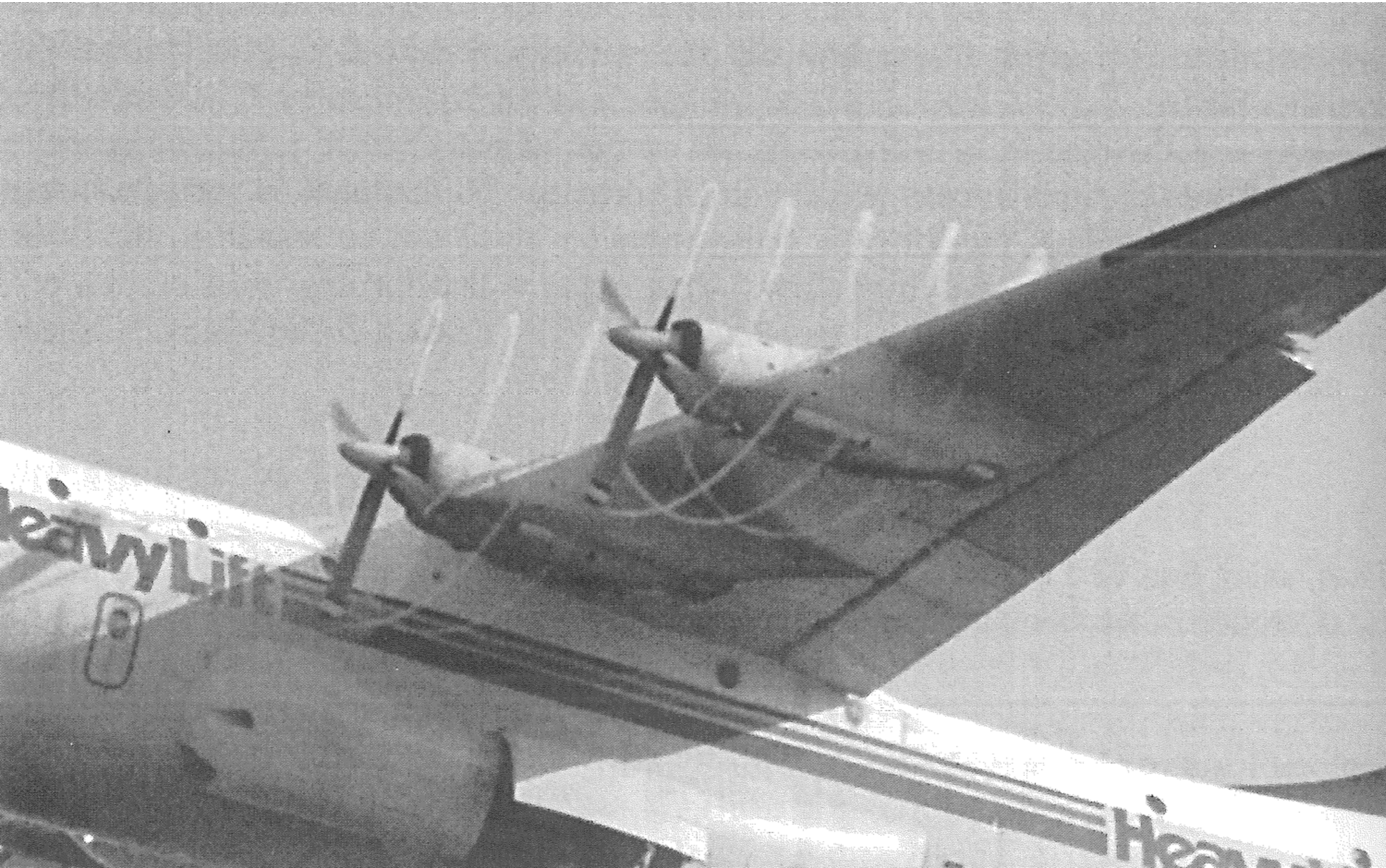


NACA 23012

1900 – 1940: engine W/N up by x 17



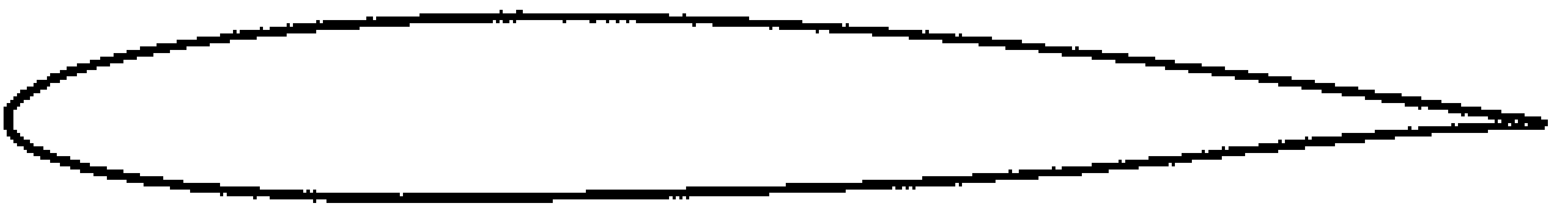
Short Belfast: helical blade tip vortices



1939: Theory applied aerofoil design 1-series (series-16) aerofoils to reduce shock wave & cavitation problems {aircraft & marine propeller design}

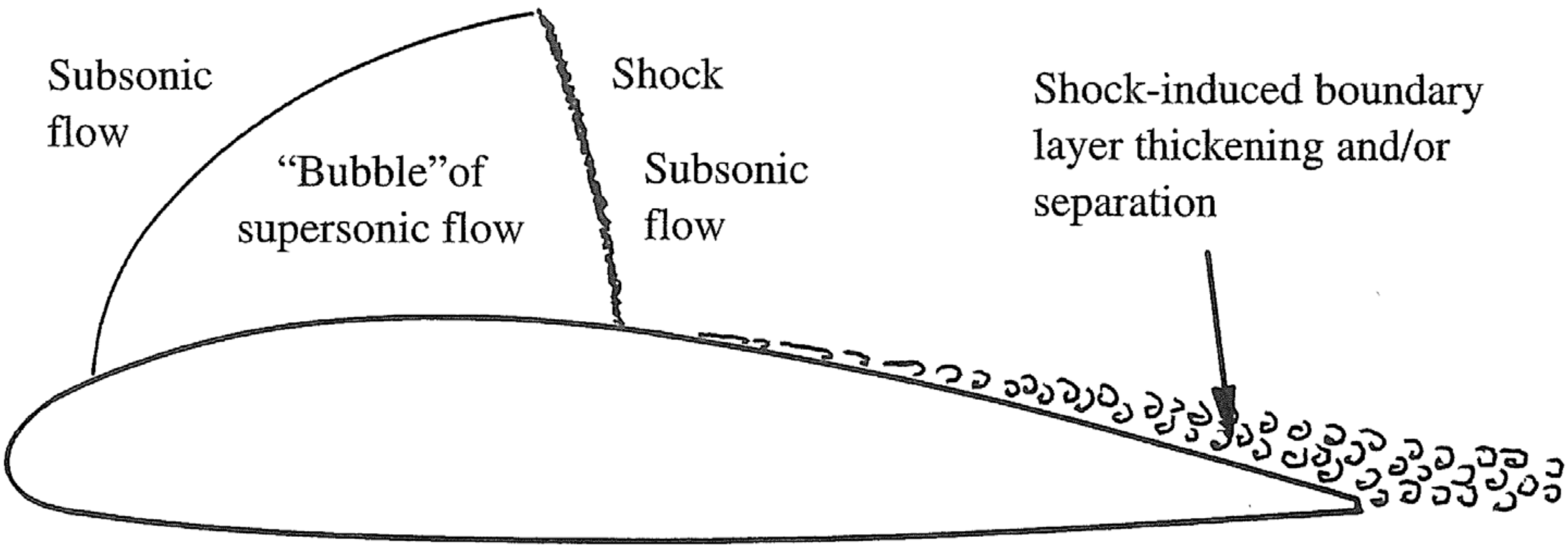
NACA 16–212

1942: 6-series aerofoils to maximise laminar flow (only if free of bugs & vibn)

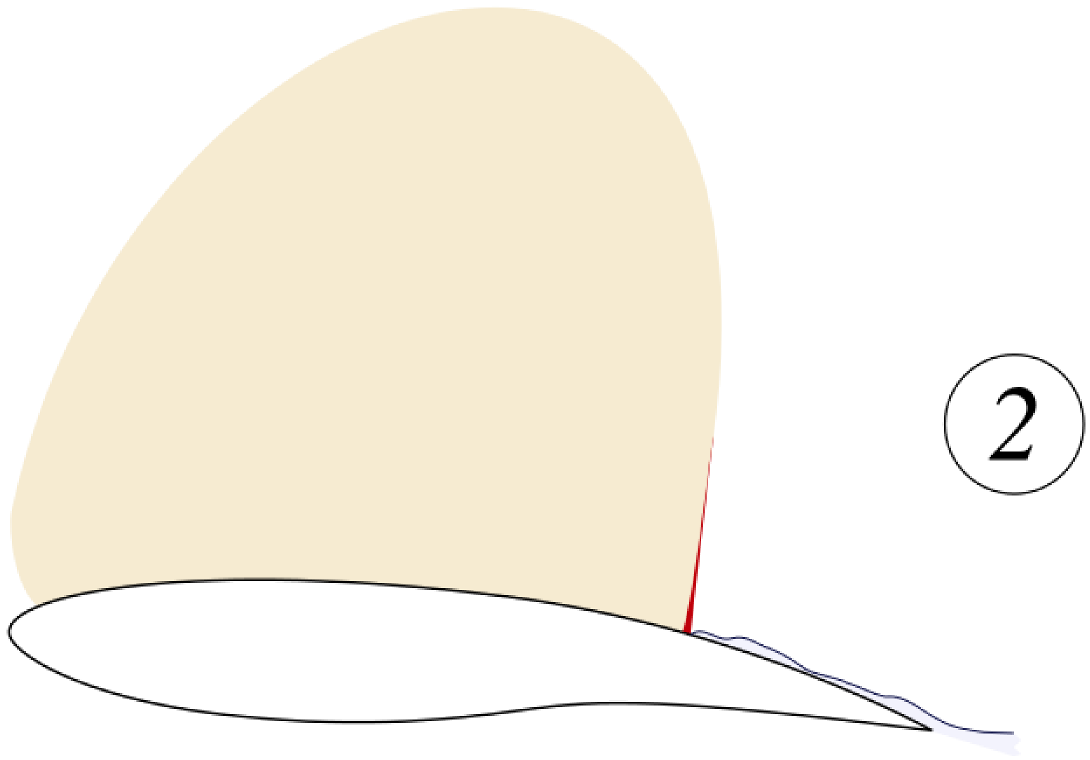


NACA 65,–212

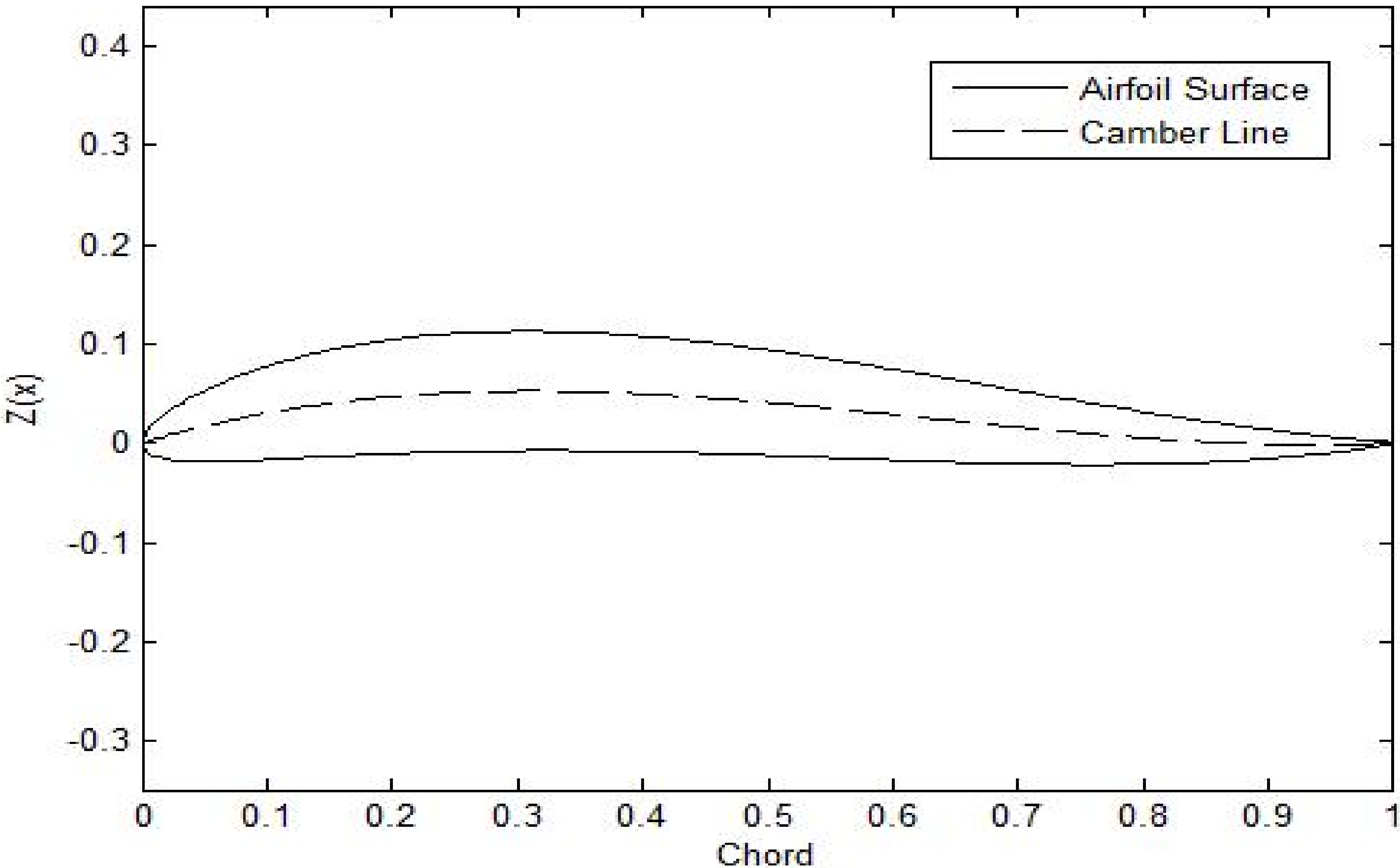
1950s: M=0.7, rapid decel thru strong shock wave, boundary layer separation



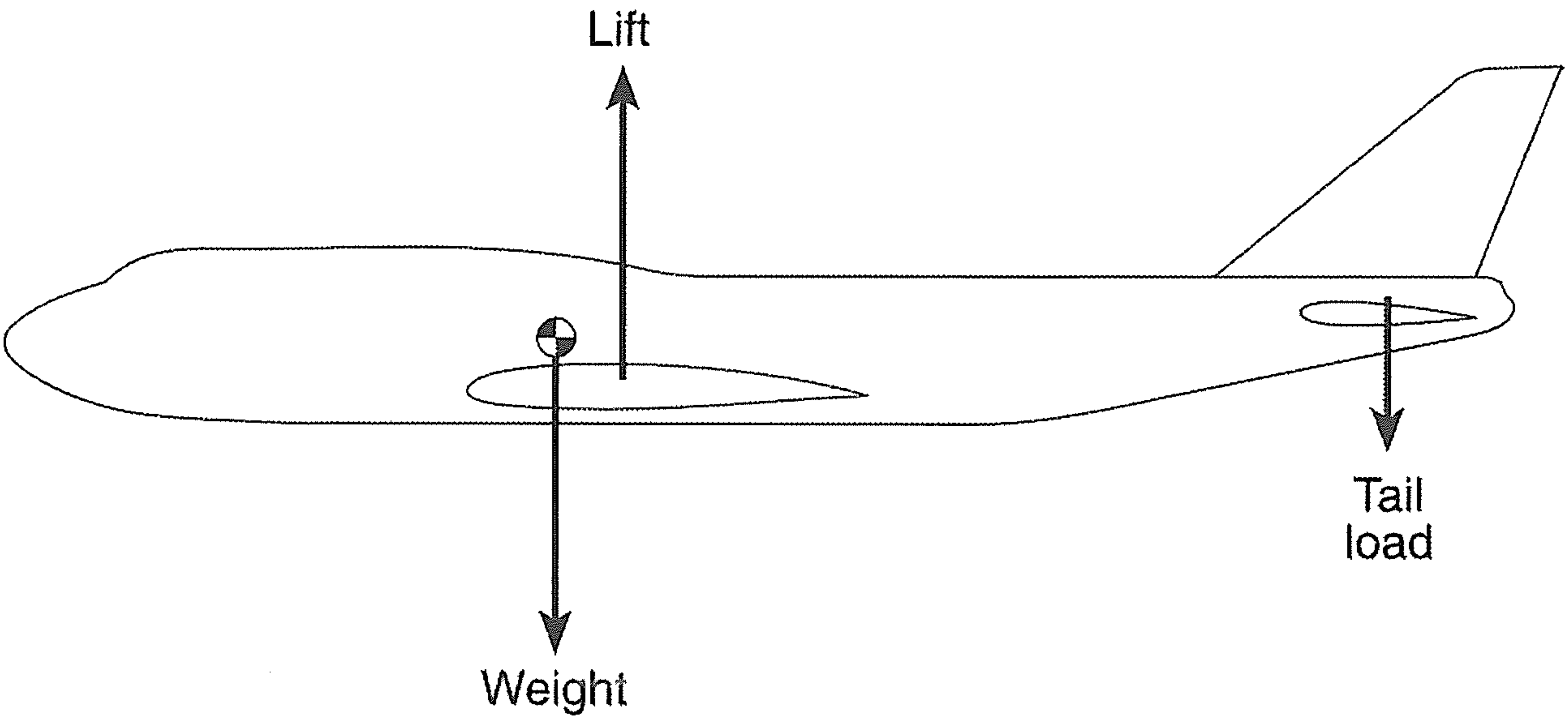
1970s: M~0.7, distributed decel thru stepped shock waves to delay drag rise (Kawalki 1940 and Whitcomb@NASA)



Reflexed trailing edge for stabitiy



Minimise the tail load by maximising the moment arm

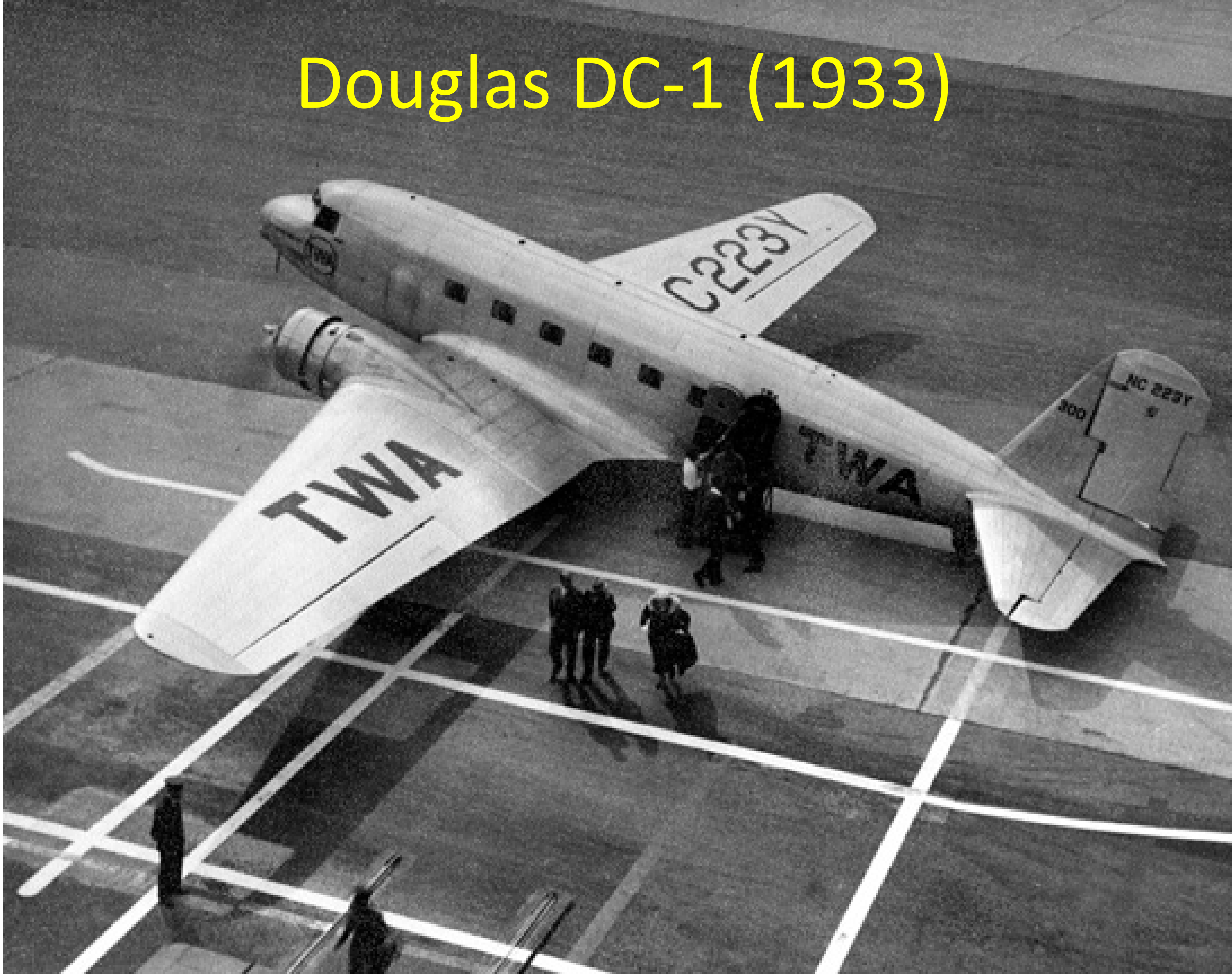


Beechcraft Starship (1986)

Bäumer Sausewind (1925)
elliptic wing planform

Republic XF-91 Thunderceptor 1949

Douglas DC-1 (1933)

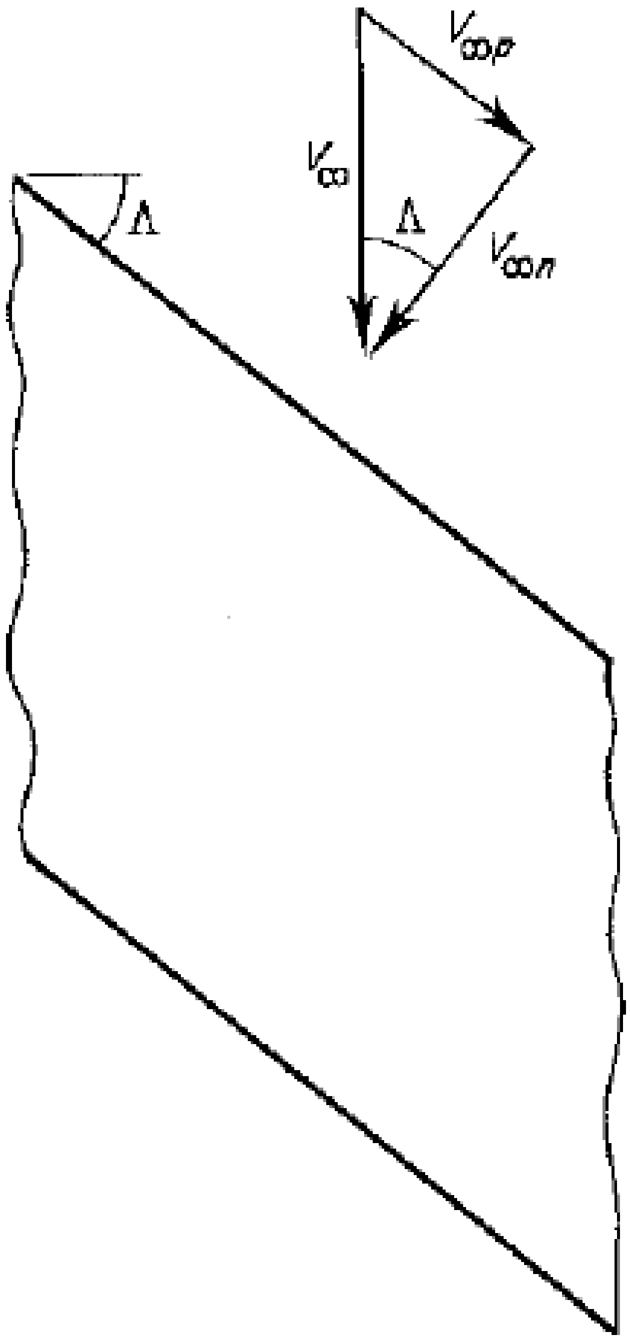


Adolf Buseman

Swept/Delta wing theory (1935)

Max Planck Institute
Gottingen University

(Theodore von Karman, Ludwig Prandtl, …)



Swept leading edge reduces normal velocity component

Enables flight closer to the sound barrier

But span-wise flow component problem

Polish PWS Z-47 "Sęp III"(LF)

Agust Zdaniewski 1936

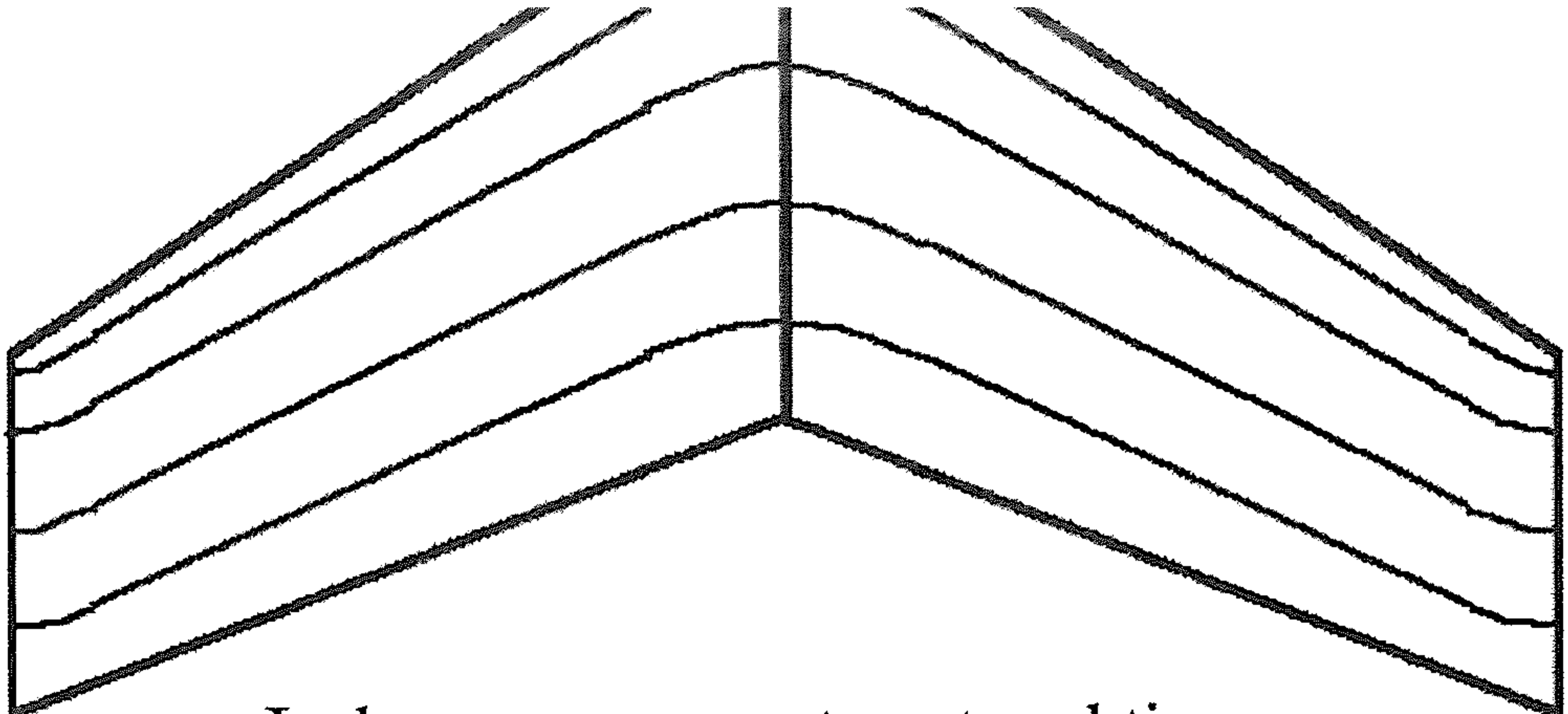
Alexander Lippisch

Thick winged highly swept wing theory

Me 163 Komet

01 Sep 1941

Avoid curve in lines of static pressure

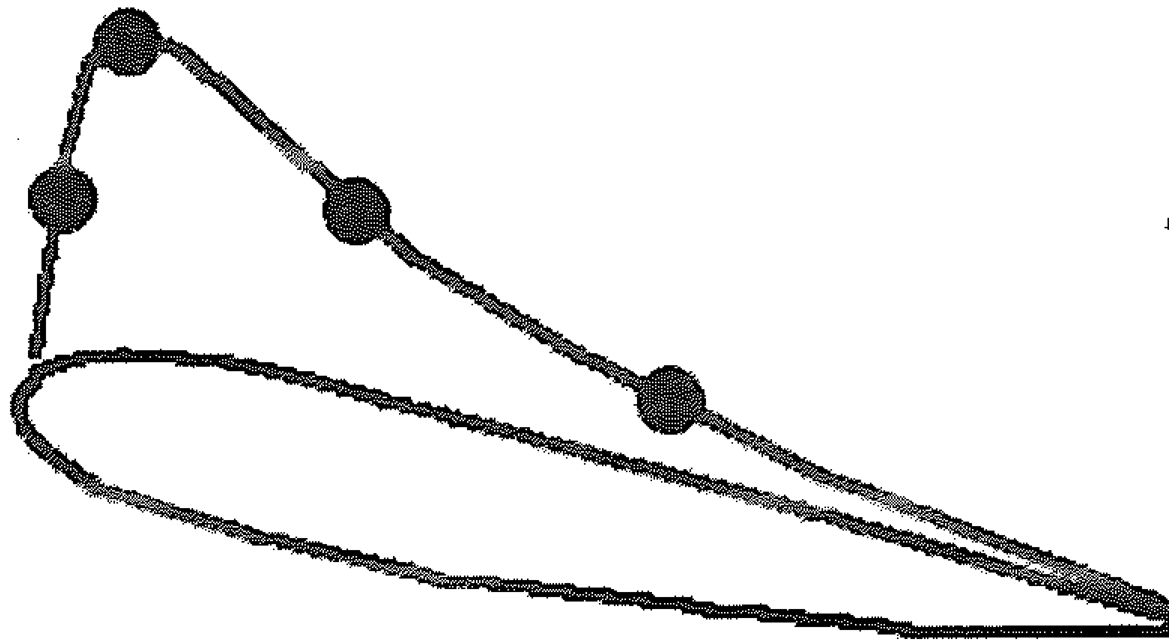


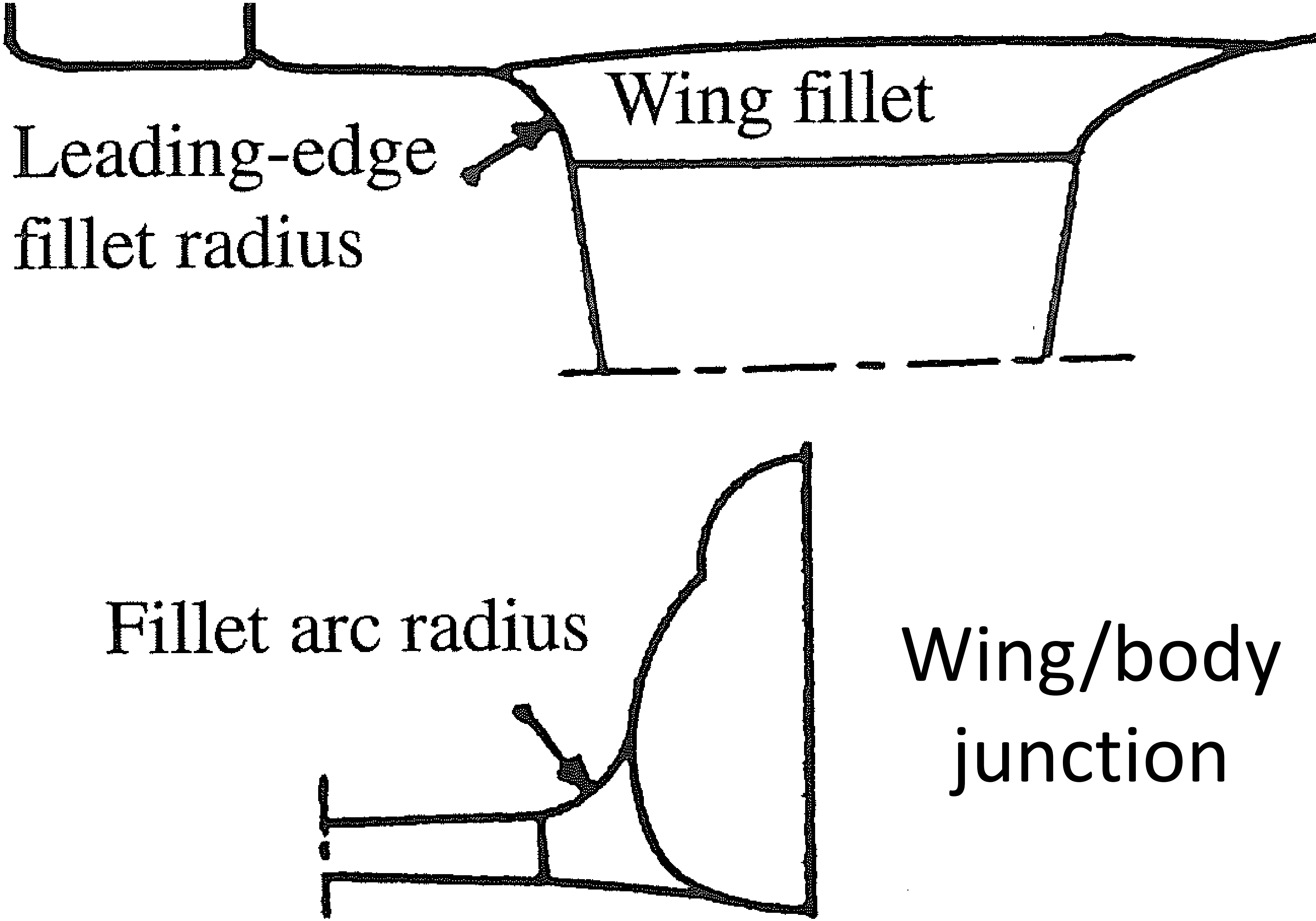
Isobars unsweep at root and tips

wing root nose section

thickened and zero or negative camber

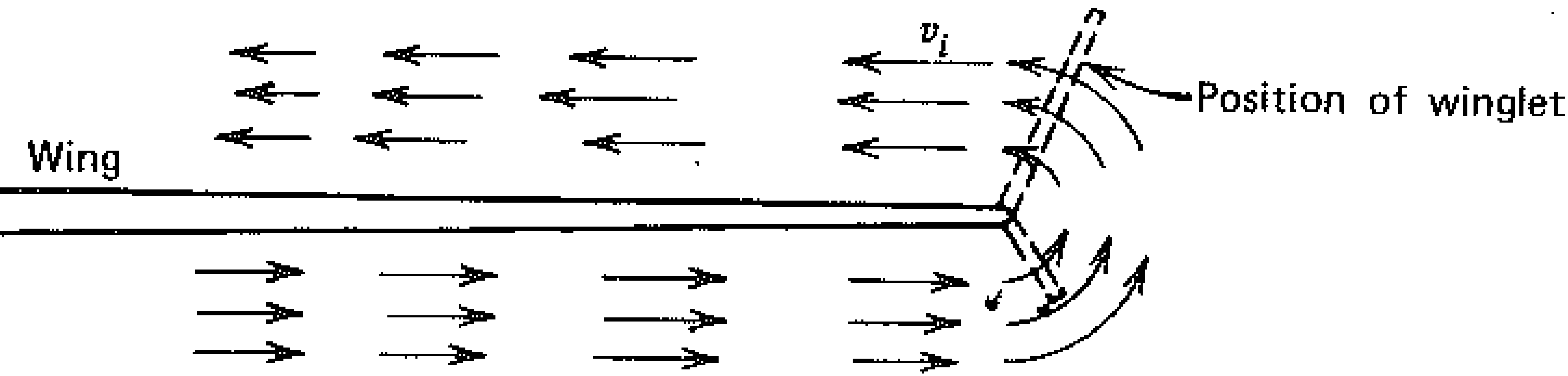
Restore isobar sweep with "peaky" root airfoil

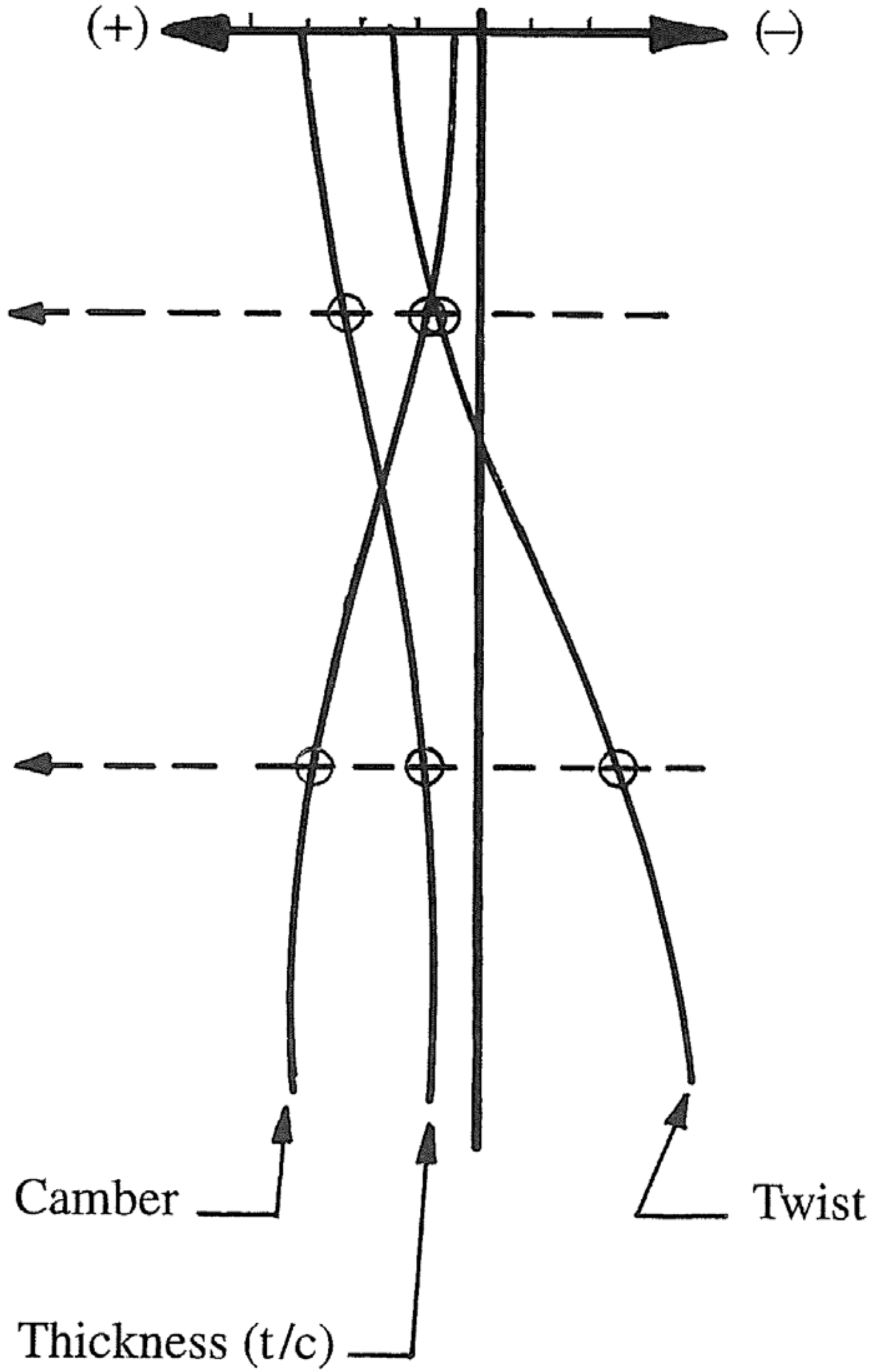



Wing fillet
Leading-edge fillet radius
Fillet arc radius
Wing/body junction

wing tip geometry

dip nose, increase camber, thin section





Auxiliary control lines

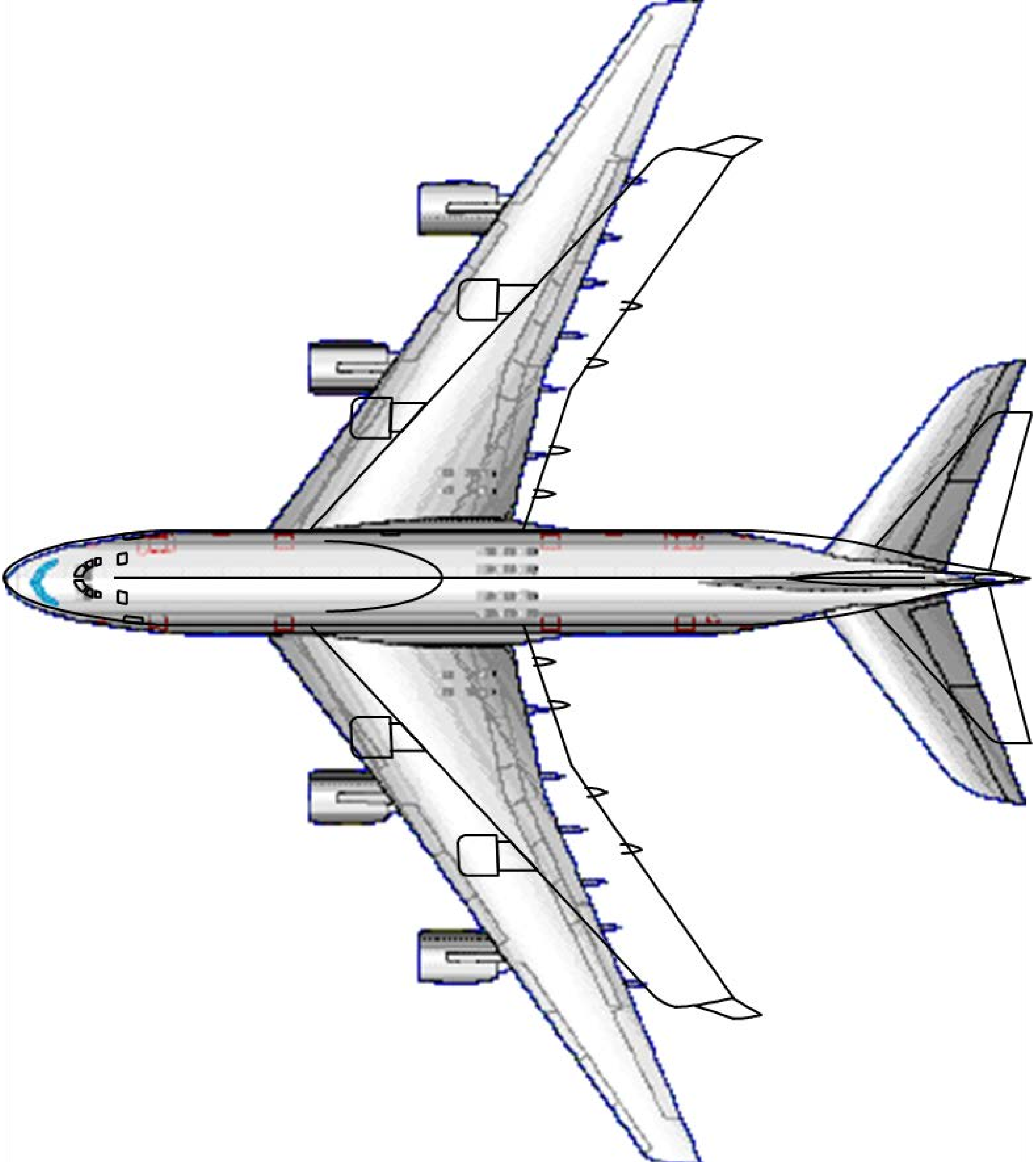
aerodynamic washout

thinner tip

geometric washout

chord taper

straight spars & hinges

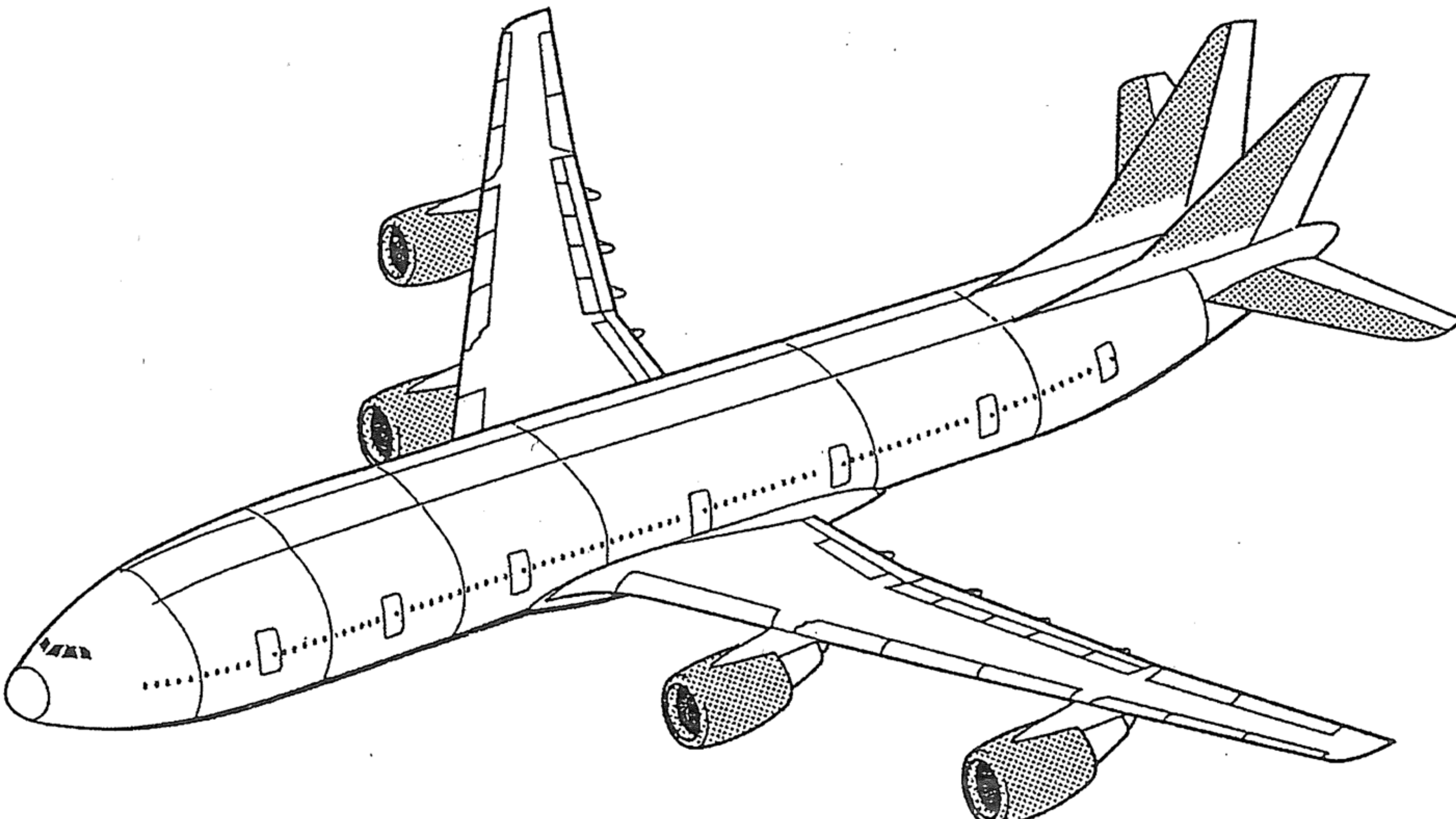


A380 / B747

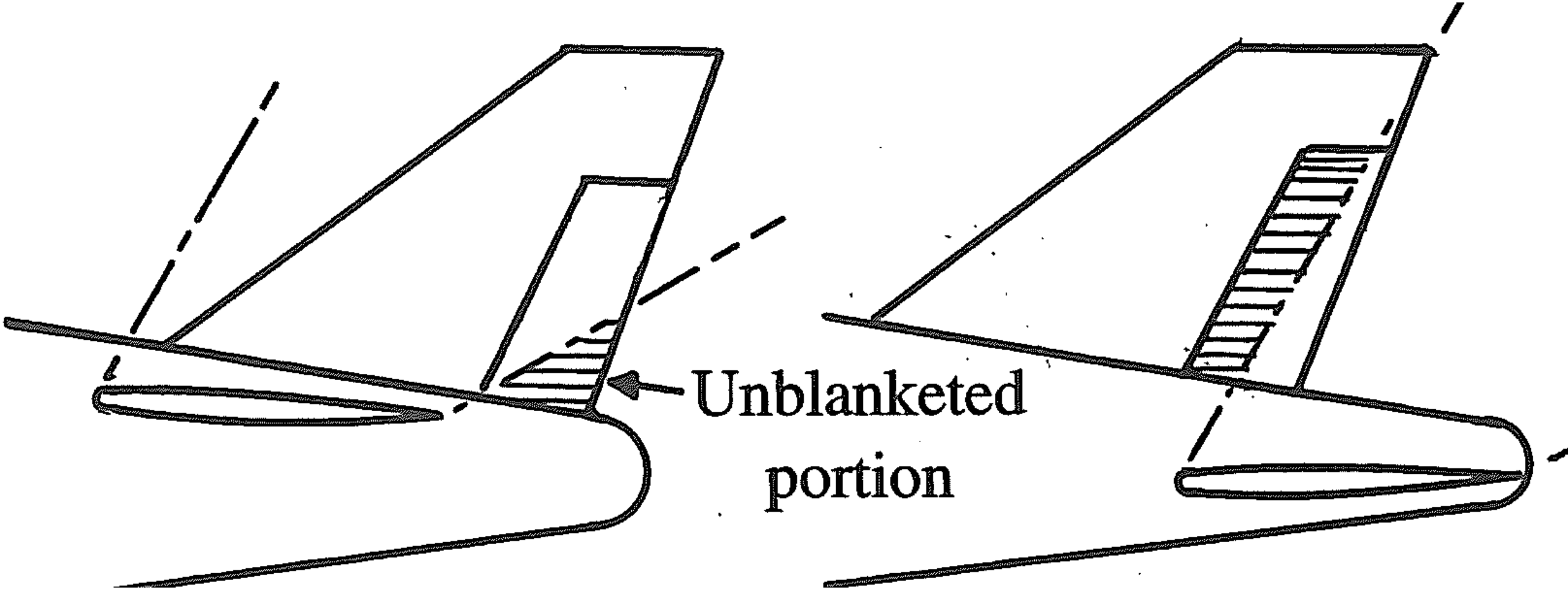
Plan form geometries

An-225 (1988): landing gear, ditching

Single deck tri/quad isle 16/19 abreast Emergency evacuation, pressurisation



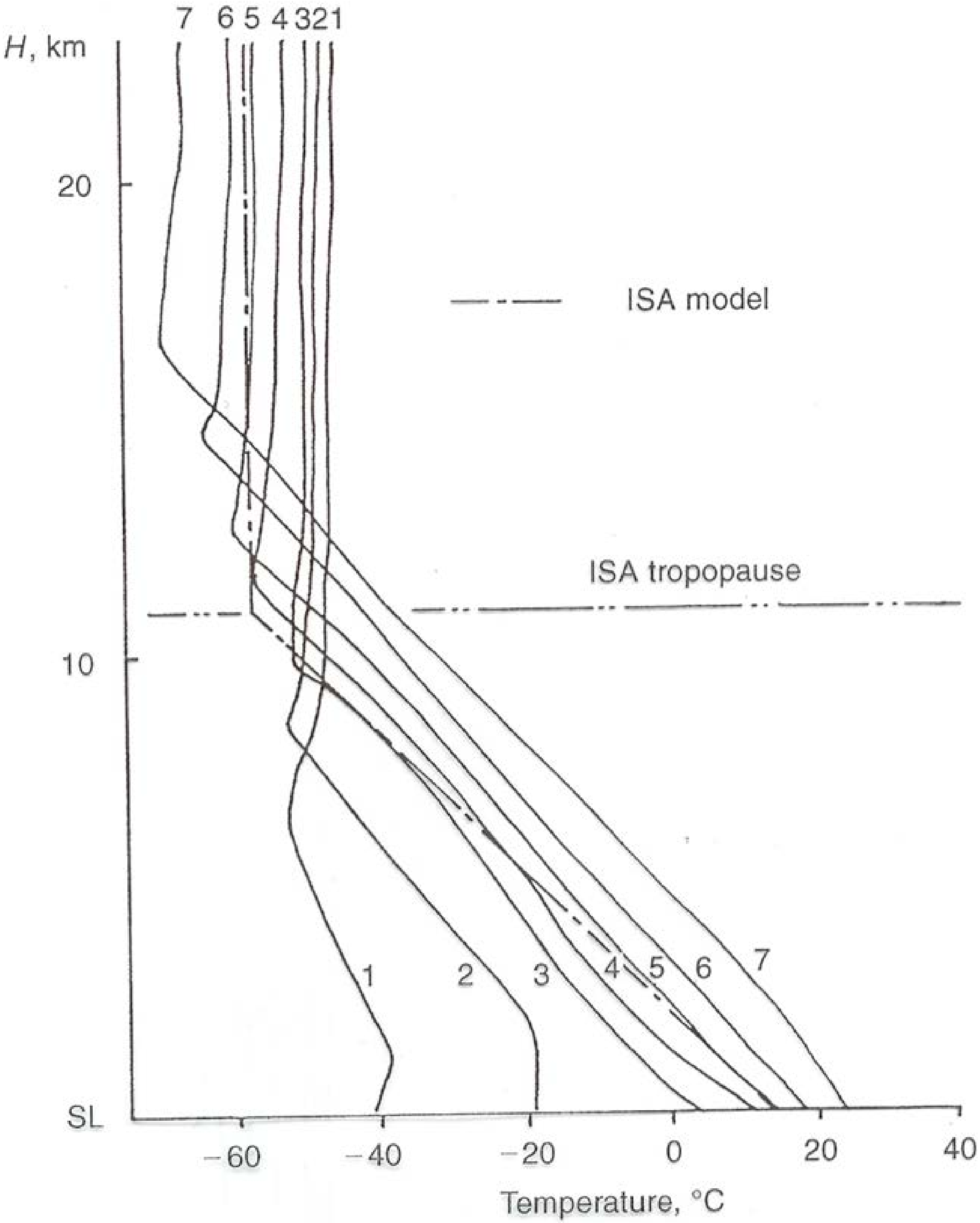
Fin positioning: 1/3 of rudder area be unblanketed from tailplane wake



Fin size

Big	Small
Dutch Roll Oscillation	Spiral Departure
High Altitude, Mach No	Cross-Wind Landing
Spin Recovery	Radio Wave Interference

International Standard Atmosphere 1993



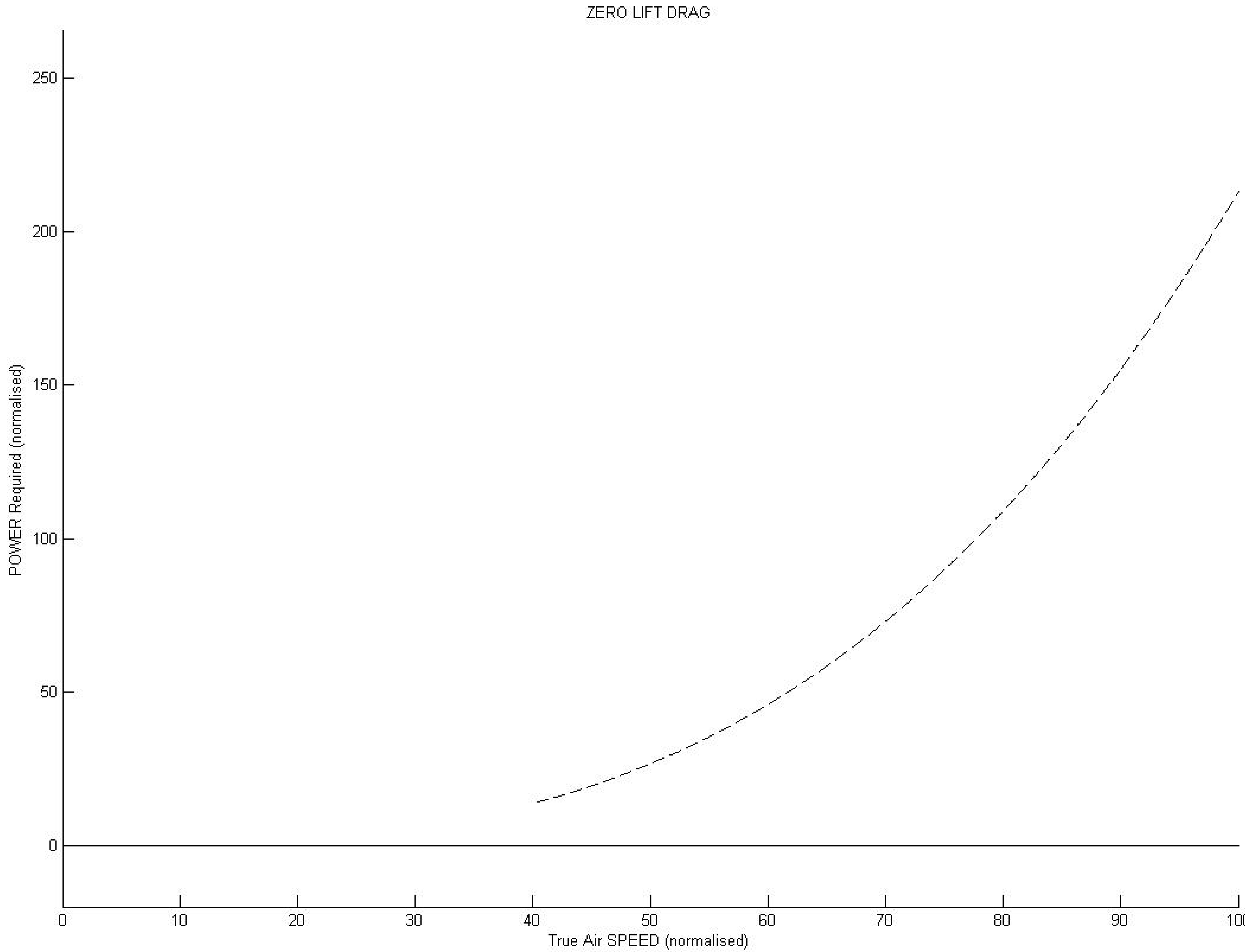
Variation of dry air temperature with altitude

Alt: cabin pressure (structure weight),
anoxia (low blood O_2, aggressive),
hypoxia (low tissue blood, comatose),
atelectasis (high O_2, low N_2, collapsed lung,
emergency descent – breathe normally)

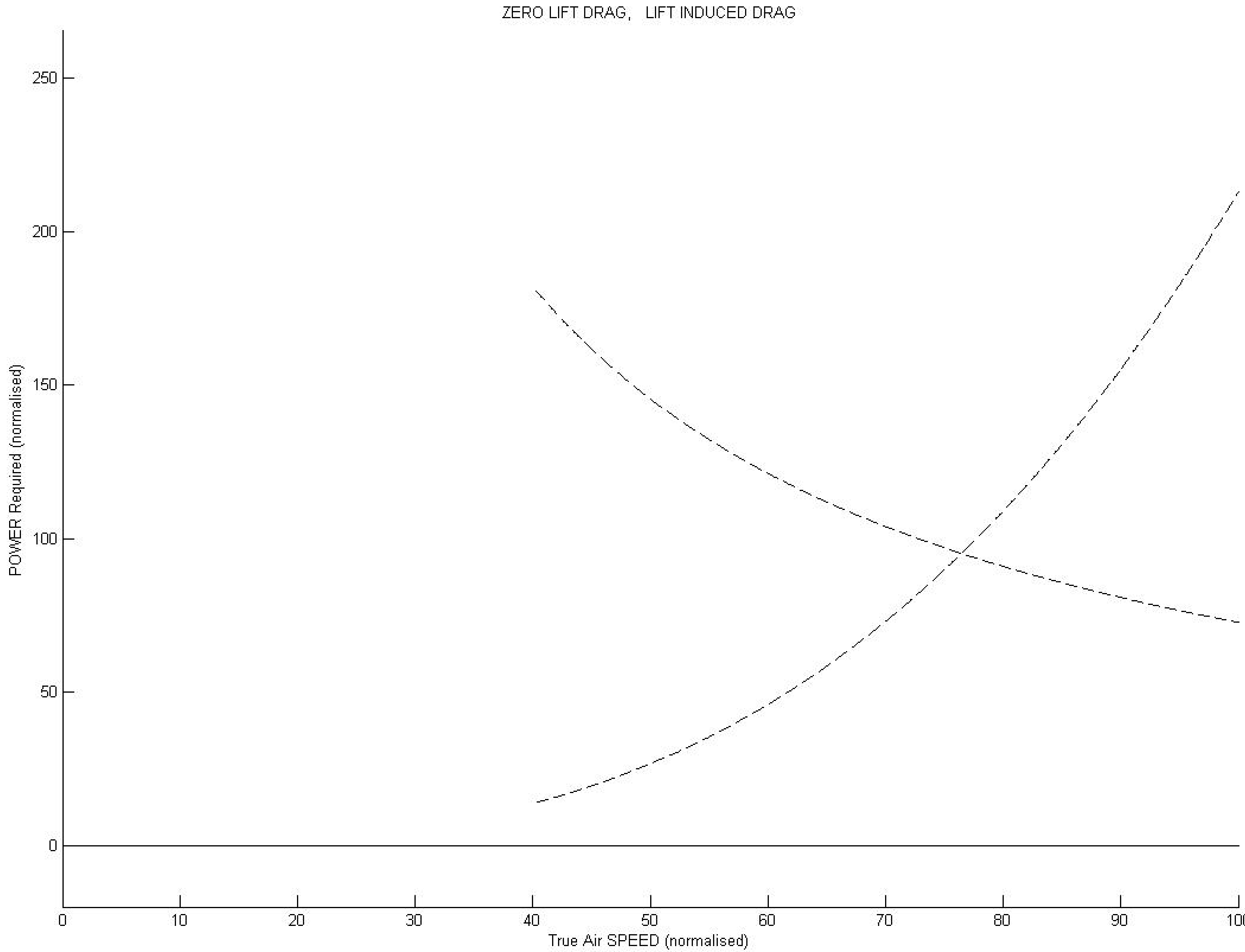
Thermal efficiency – max temp difference

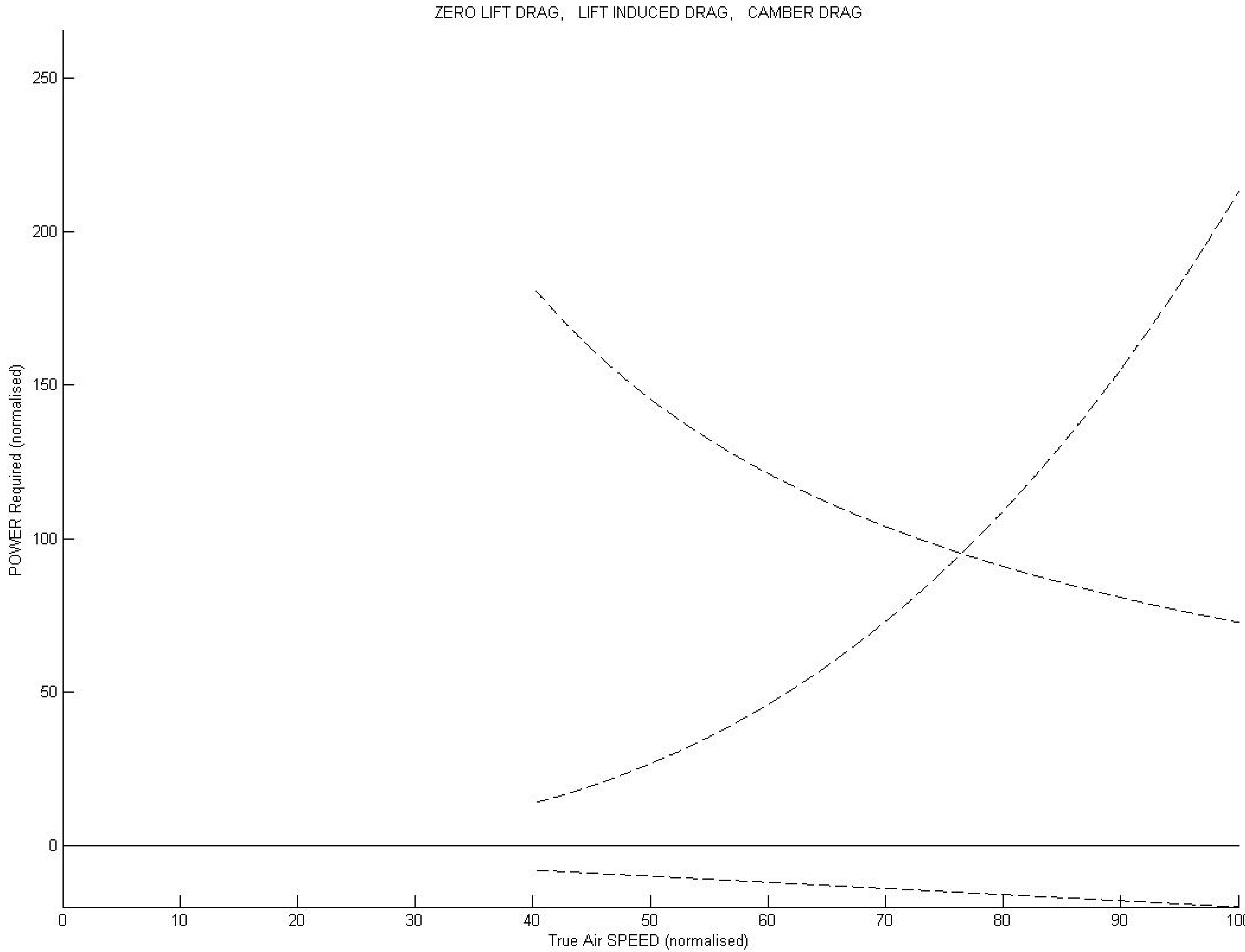
@ 11 km: 217K, 23 kN/m^2, 0.36 kg/m^3

Max L/D & fastest @ 0.85 x 295 m/s

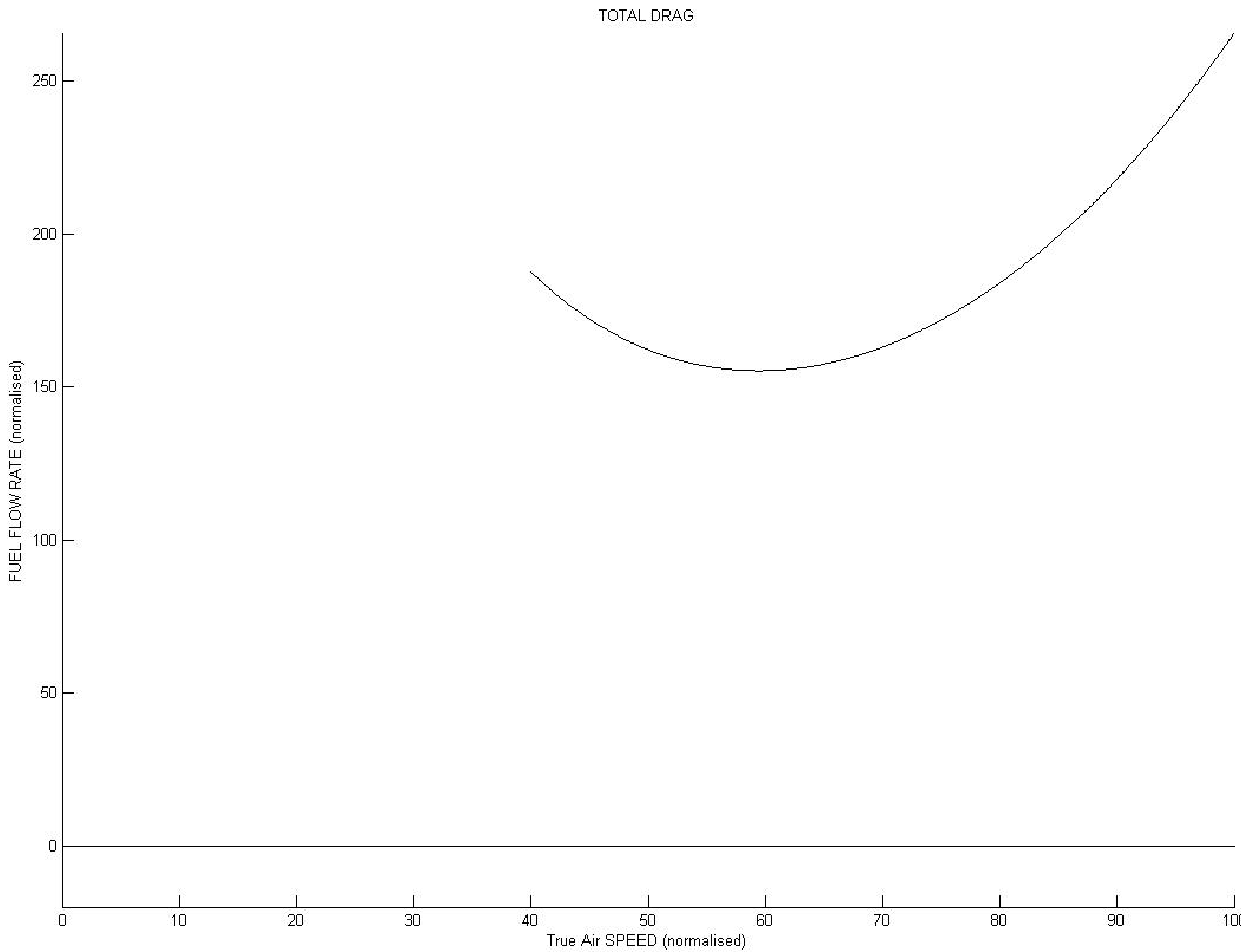


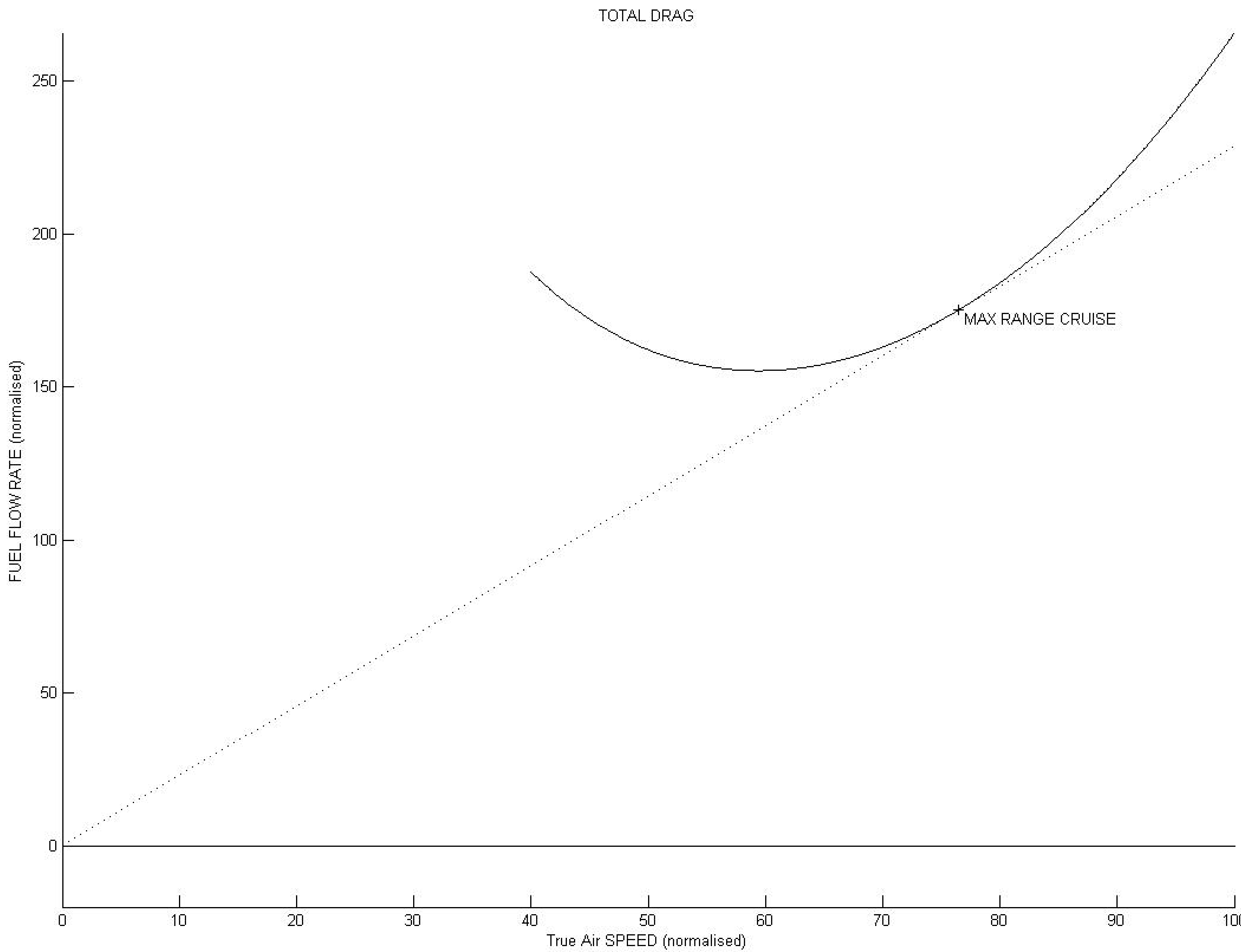
ZERO LIFT DRAG
POWER Required (normalised)
True Air SPEED (normalised)
0
50
100
150
200
250
0
10
20
30
40
50
60
70
80
90
100

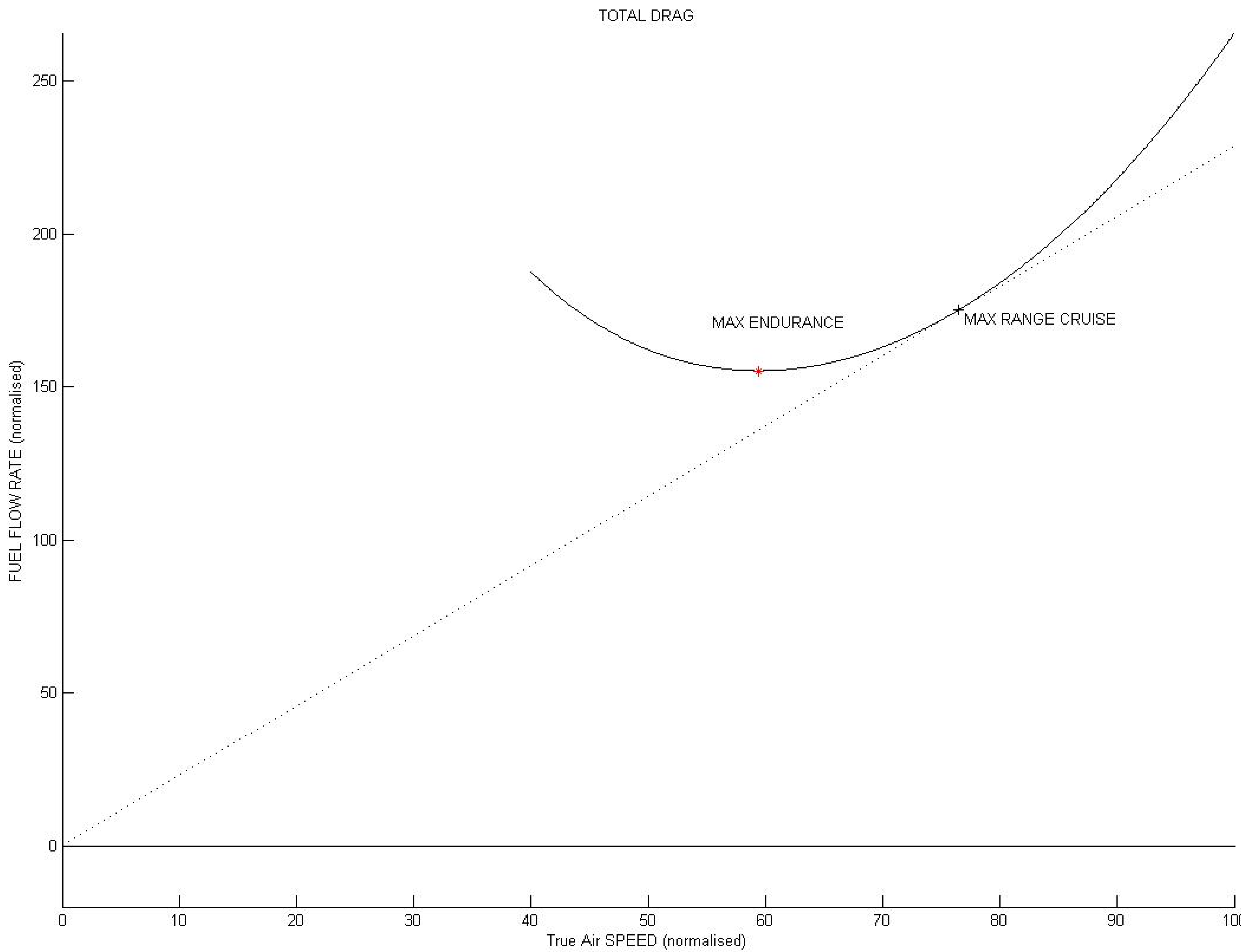

ZERO LIFT DRAG, LIFT INDUCED DRAG
POWER Required (normalised)
True Air SPEED (normalised)
0
50
100
150
200
250
0
10
20
30
40
50
60
70
80
90
100

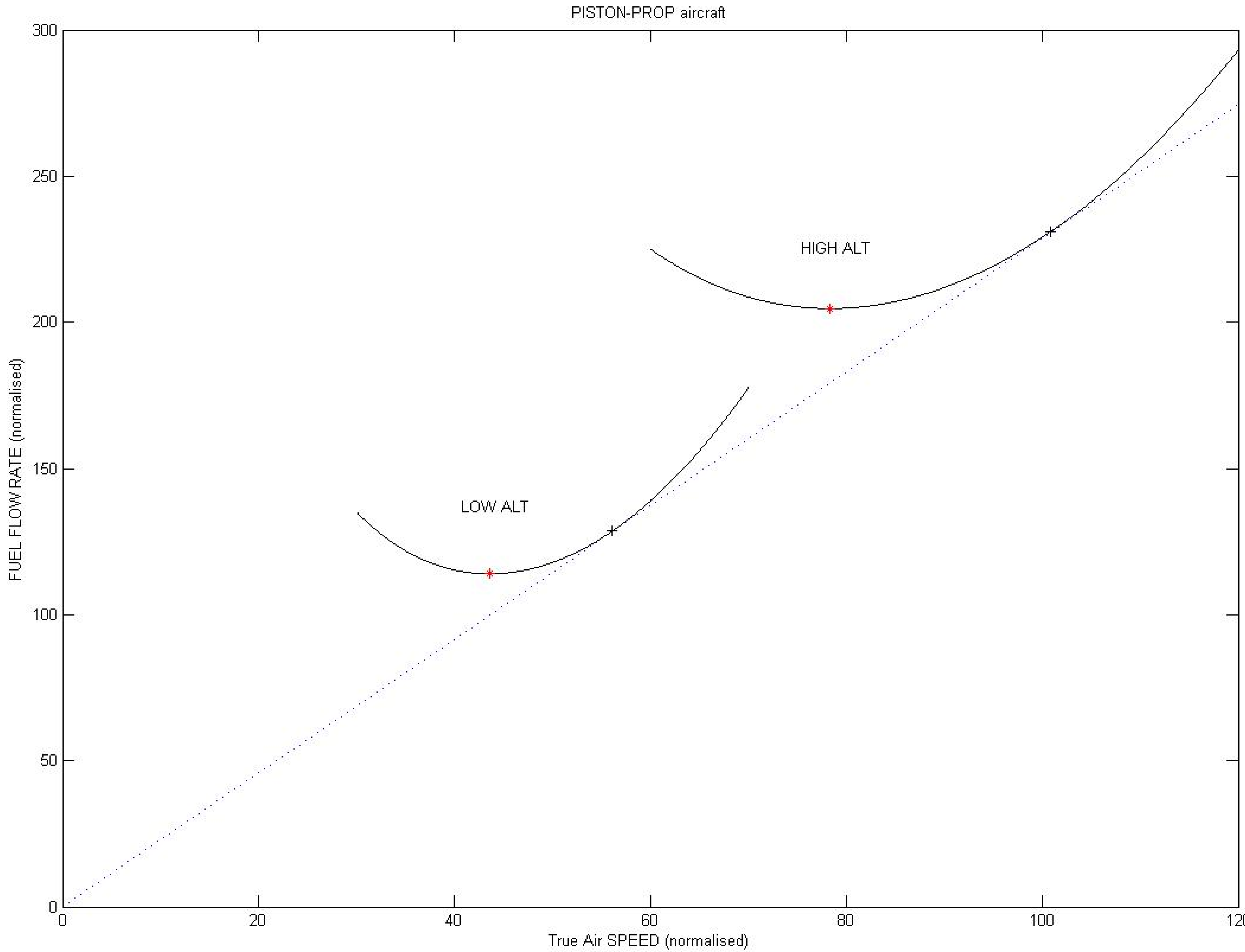


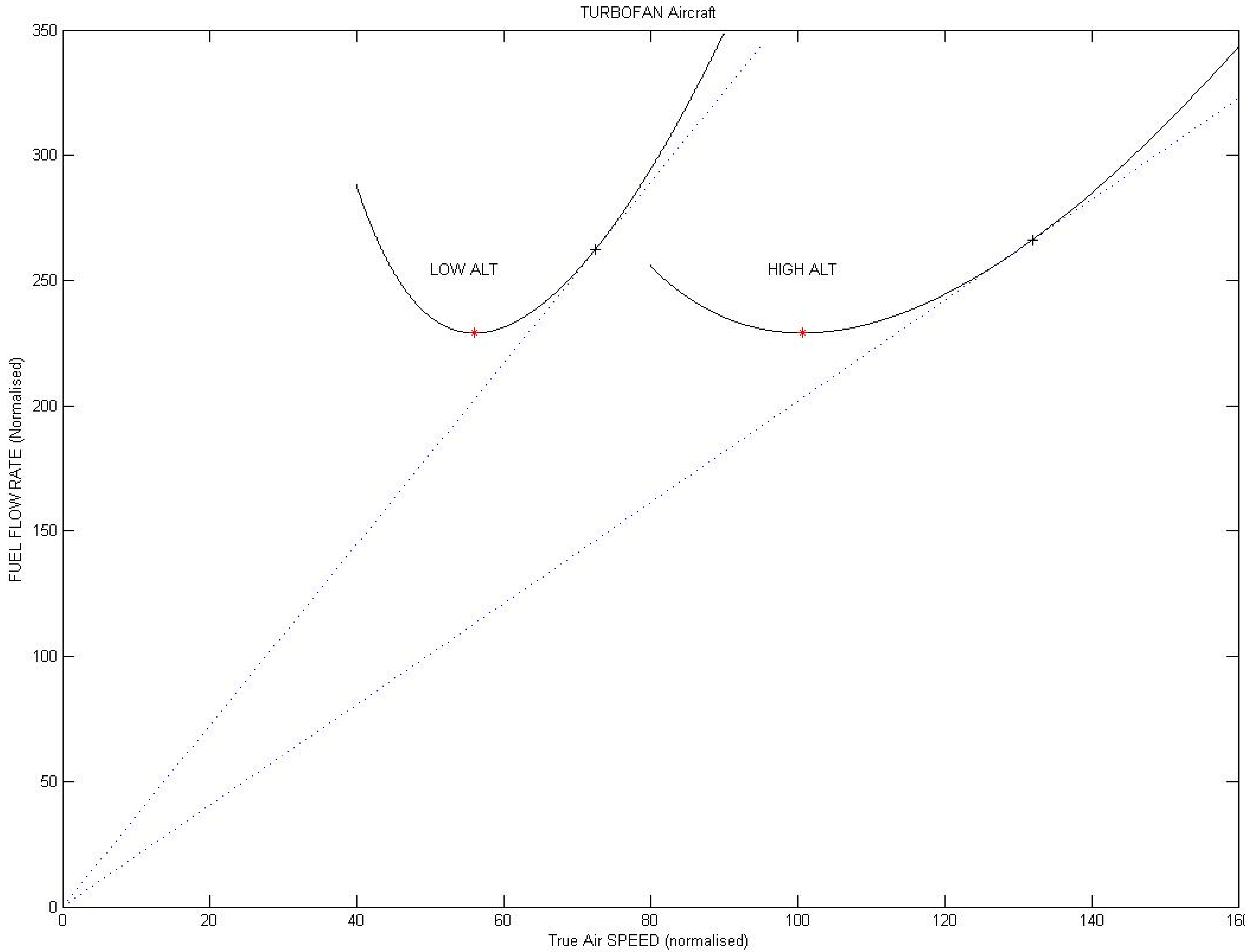
ZERO LIFT DRAG, LIFT INDUCED DRAG, CAMBER DRAG
POWER Required (normalised)
True Air SPEED (normalised)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100


TOTAL DRAG
FUEL FLOW RATE (normalised)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
True Air SPEED (normalised)


TOTAL DRAG
MAX RANGE CRUISE
FUEL FLOW RATE (normalised)
True Air SPEED (normalised)
0
50
100
150
200
250
0
10
20
30
40
50
60
70
80
90
100


TOTAL DRAG
FUEL FLOW RATE (normalised)
250
200
150
100
50
0
MAX ENDURANCE
MAX RANGE CRUISE
0
10
20
30
40
50
60
70
80
90
100
True Air SPEED (normalised)


PISTON-PROP aircraft
HIGH ALT
LOW ALT
FUEL FLOW RATE (normalised)
True Air SPEED (normalised)
0
50
100
150
200
250
300
0
20
40
60
80
100
120


TURBOFAN Aircraft
FUEL FLOW RATE (Normalised)
True Air SPEED (normalised)
LOW ALT
HIGH ALT
0
50
100
150
200
250
300
350
0
20
40
60
80
100
120
140
160

Lockheed Constellation (1943)

Boeing 377 Stratocruiser (1947)

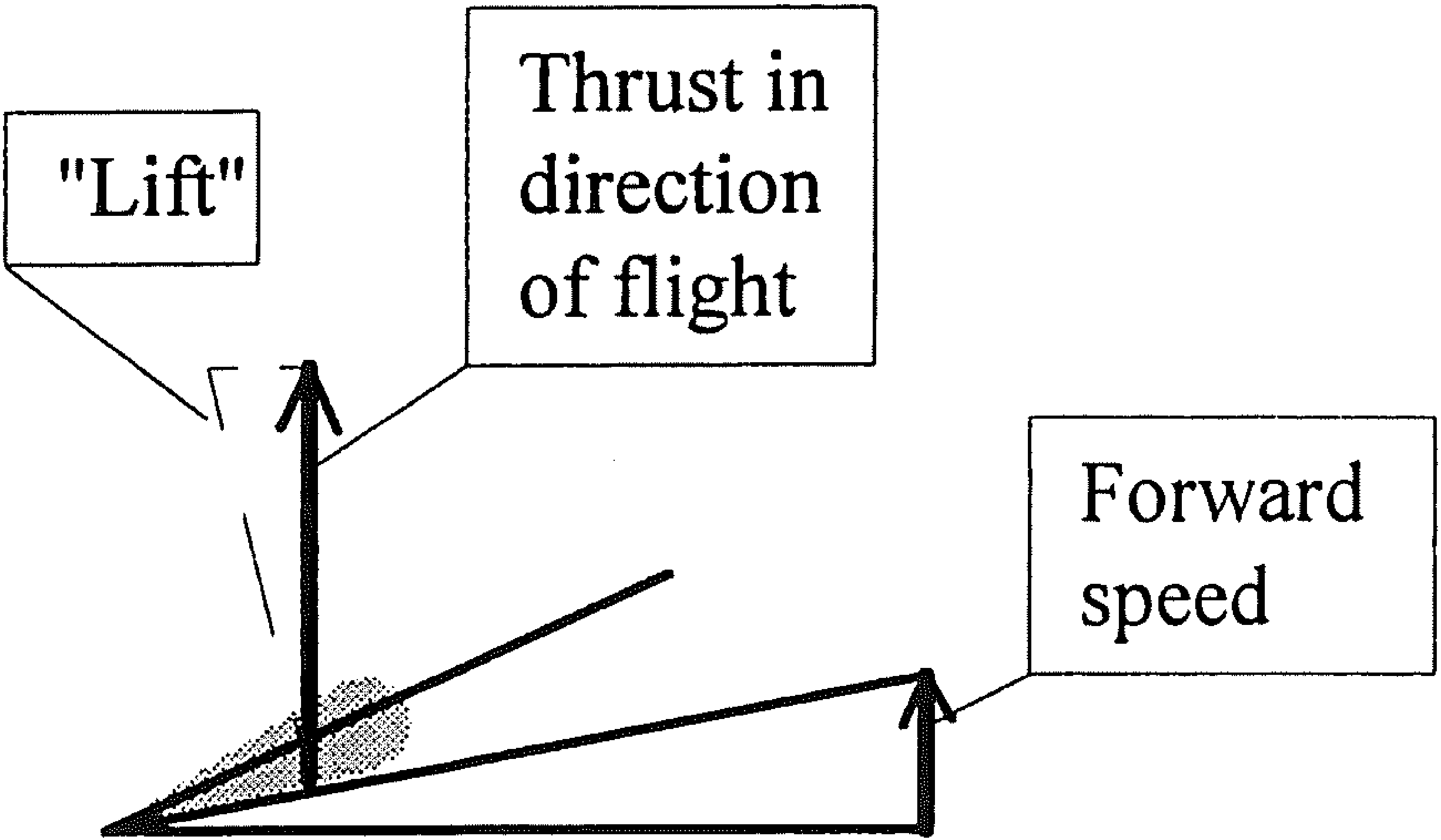
Douglas DC-7 (1953)

Ilyushin Il-18 (1957)

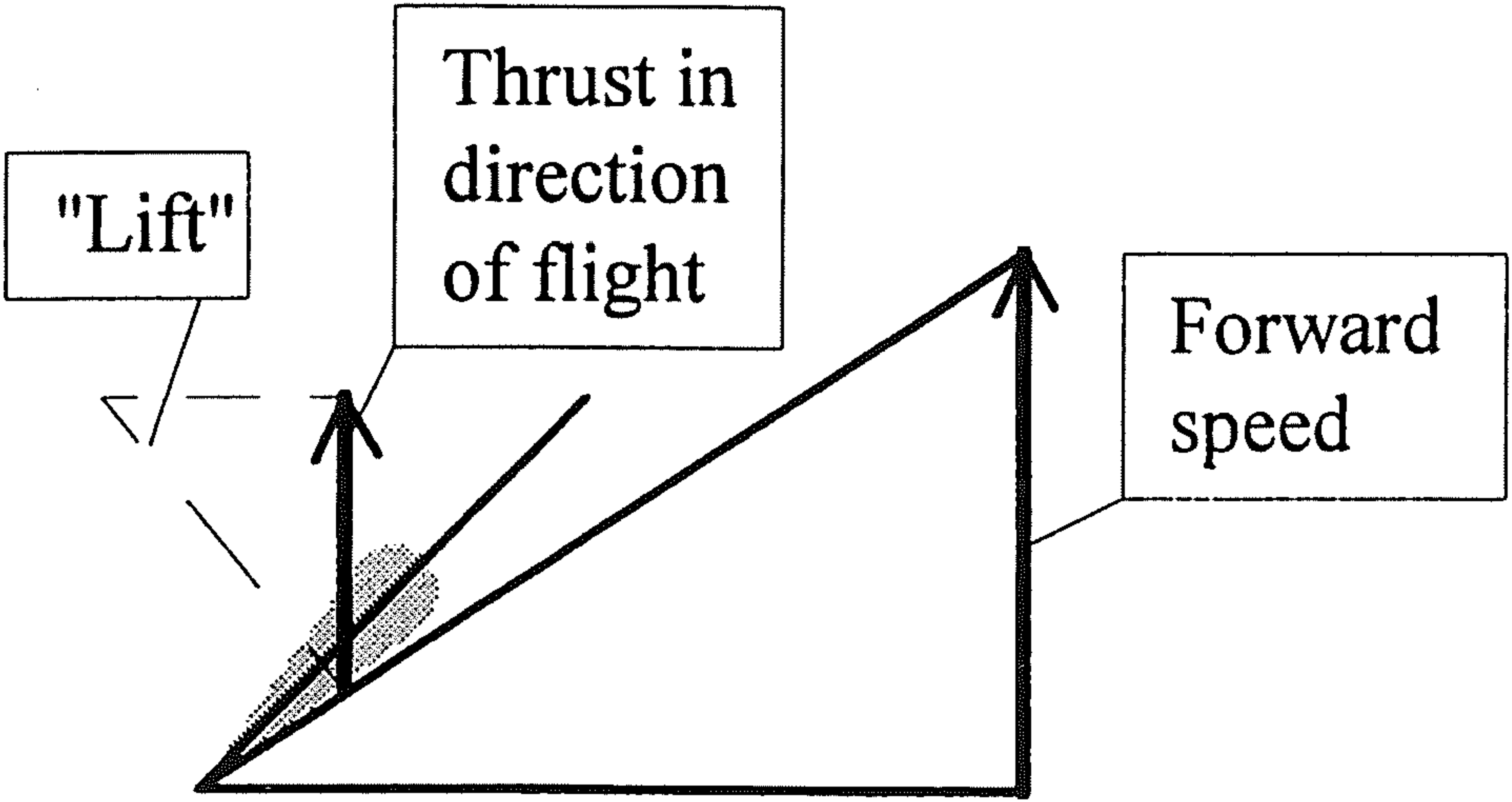
Fastest prop Tupolev Tu-114 (1957)

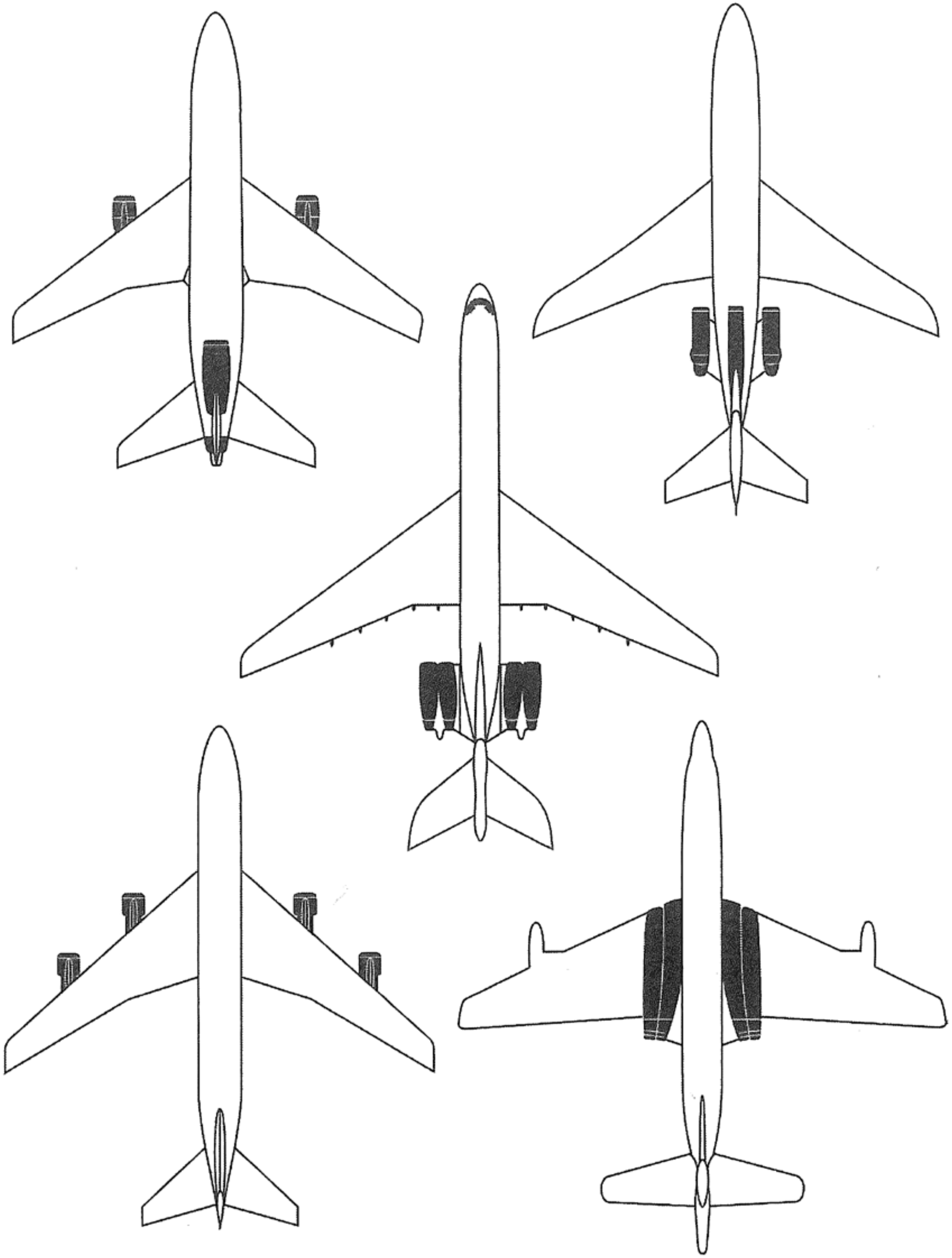
Largest turboprop Antonov An-22 (1965)

Low-speed flight: fine blade pitch



High-speed flight: coarse pitch





Engines

What type(s)?

How many?

Where?

Why?

Ilyushin Il-62 (1963)

Lockheed L-1011 TriStar (1970)

McDonnell Douglas MD-11 (1990)

De Havilland Comet (1949)

VFW-Fokker 614

1971

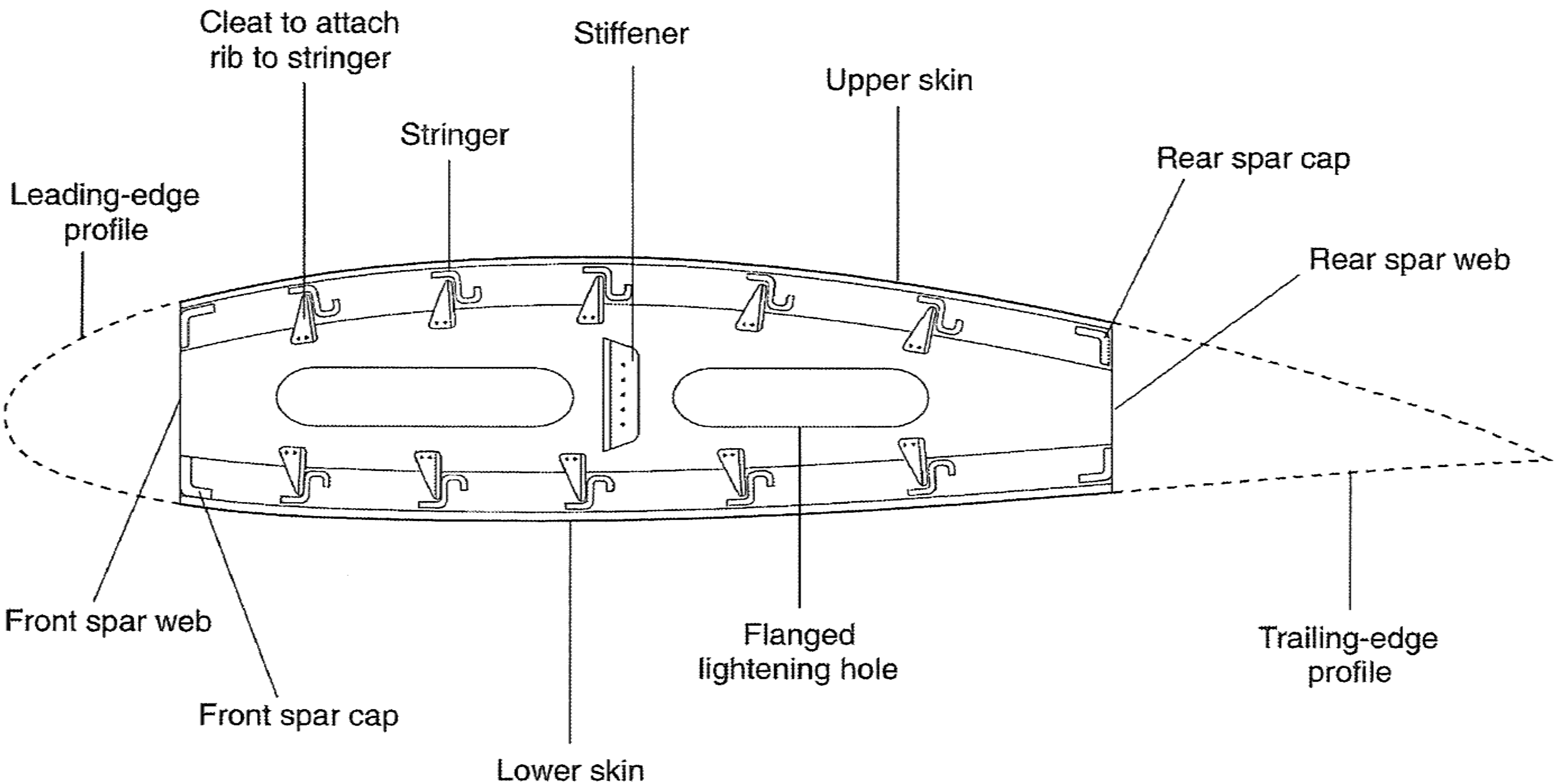
reduced FOD
shorter legs
lighter wing

But …
wing aerodyn
maint access

Take-off thrust 60 units

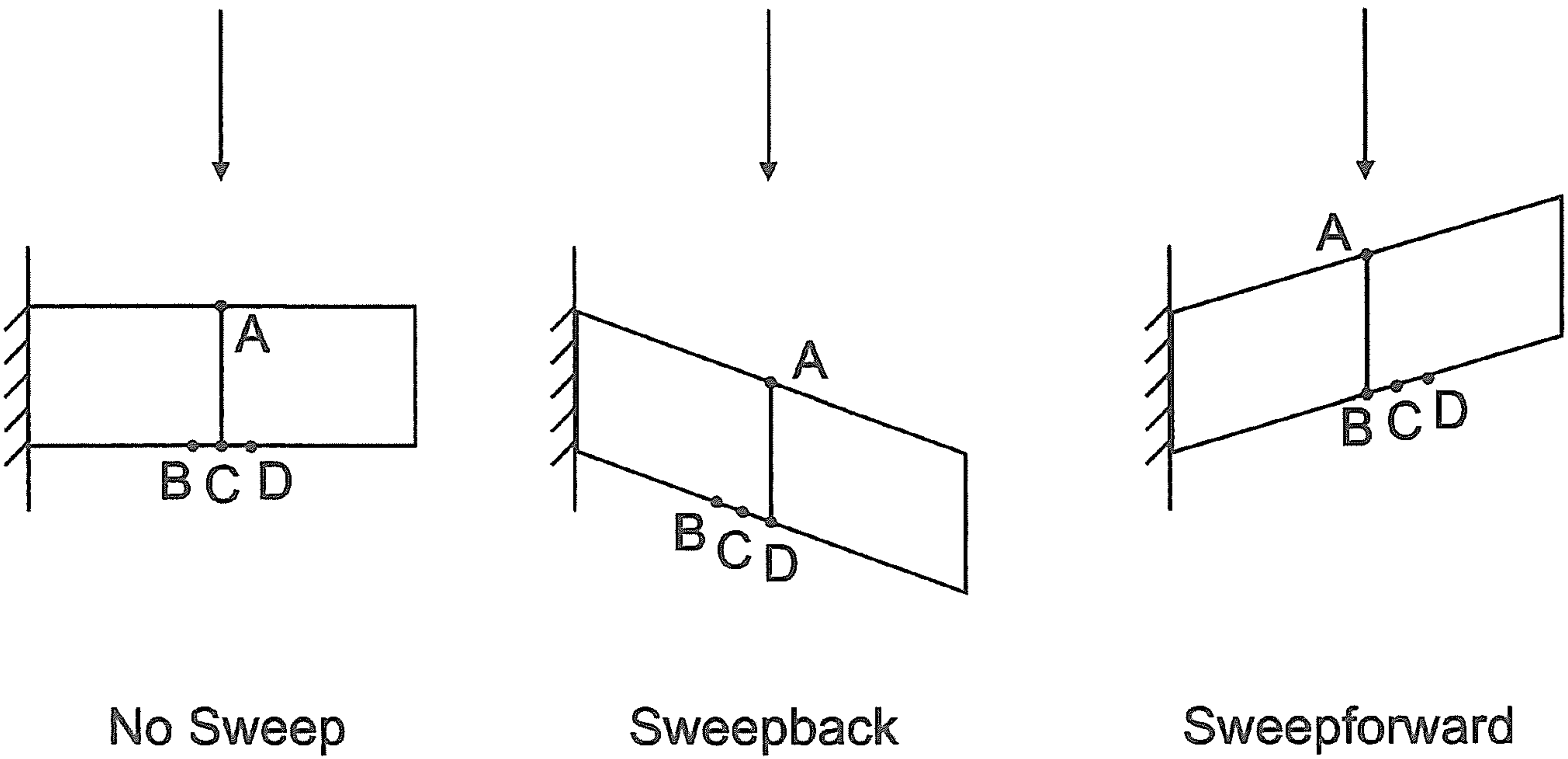
	2 Engines	4 Engines
T / E	60/(2-1) = 60	60/(4-1) = 20
total T	60x2 = 120	20x4 = 80
W / E	60/5 = 12	20/5 = 4
total W	12x2 = 24	4x4 = 16

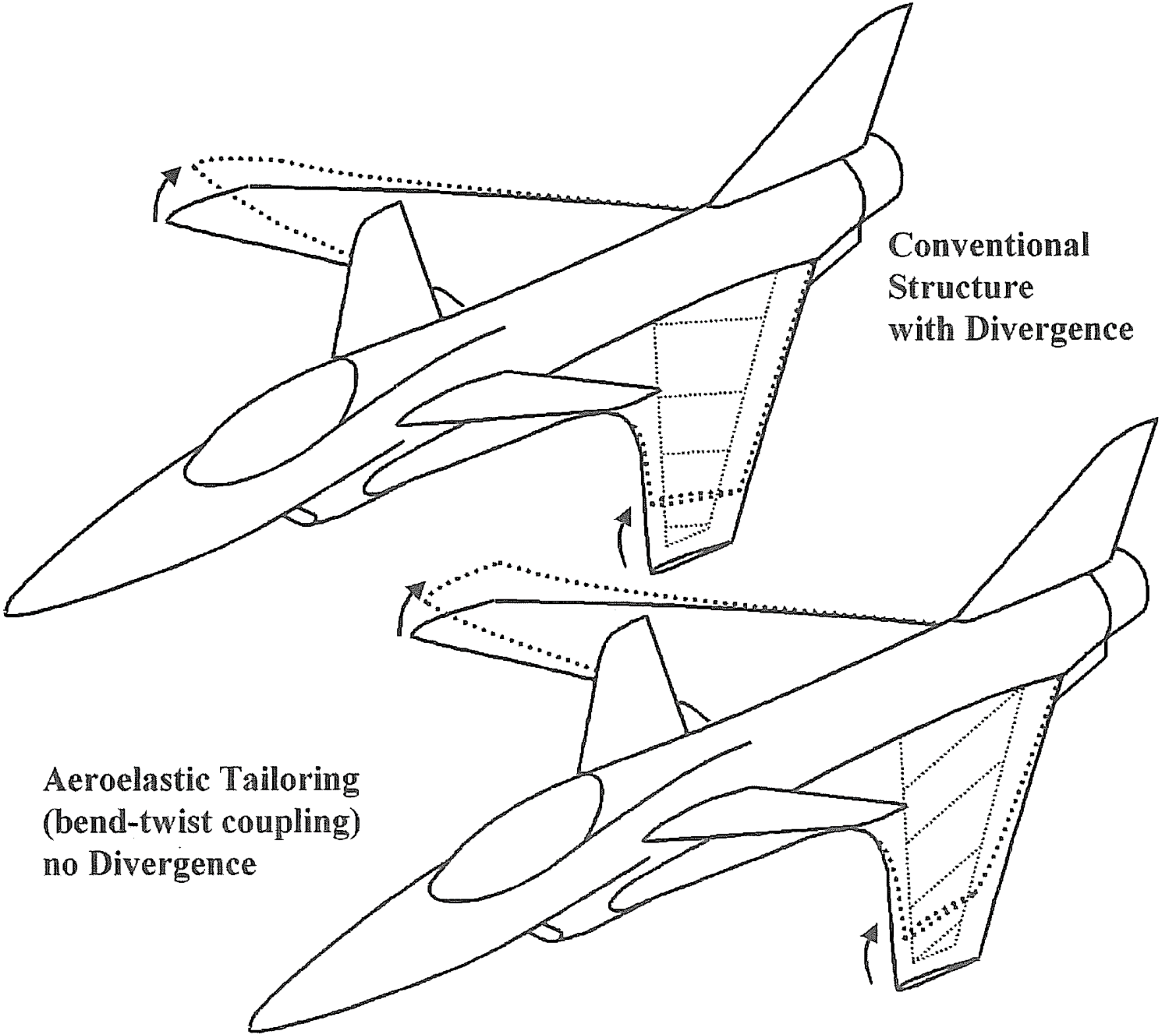
Wing torsion box



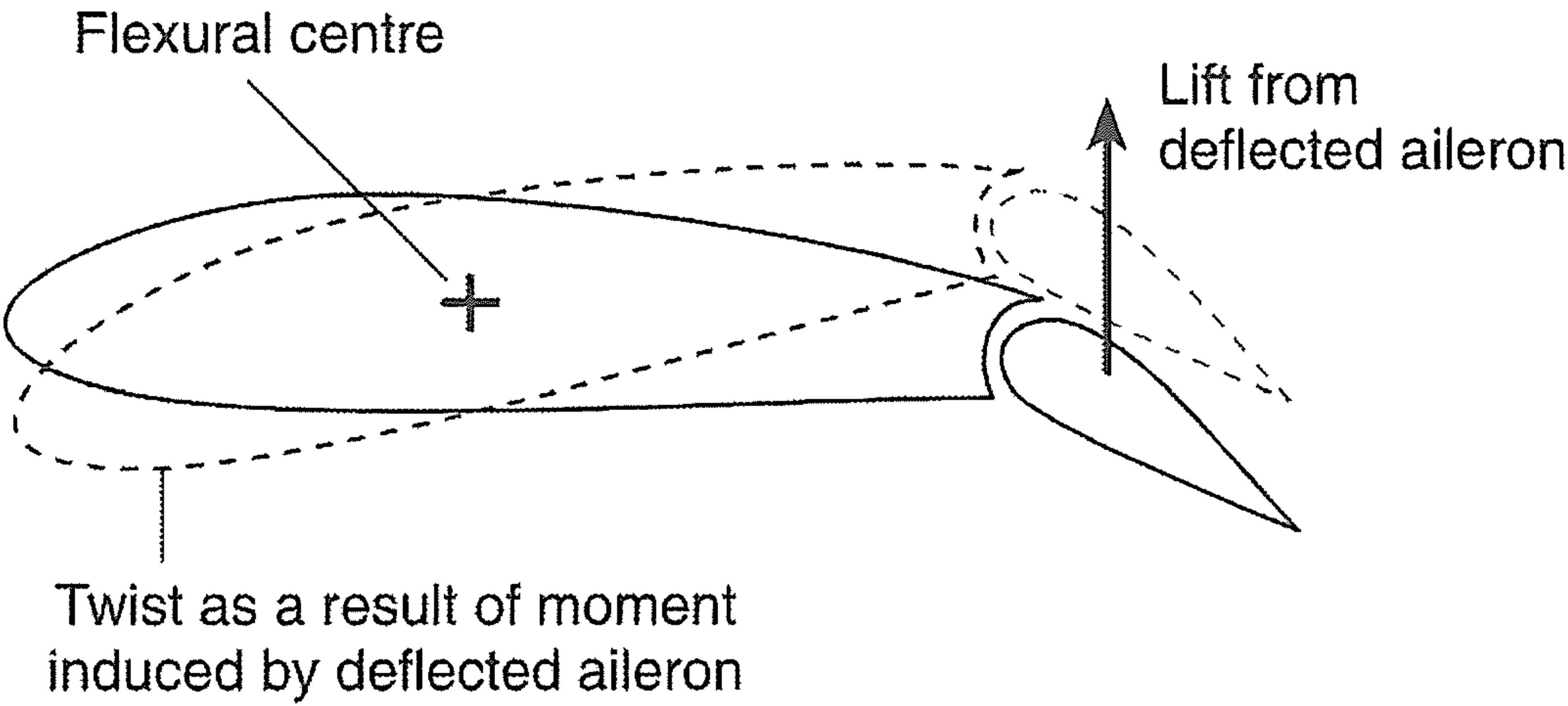
Wing torsional divergence problem

sweep it backwards to reduce weight




Conventional
Structure
with Divergence
Aeroelastic Tailoring
(bend-twist coupling)
no Divergence

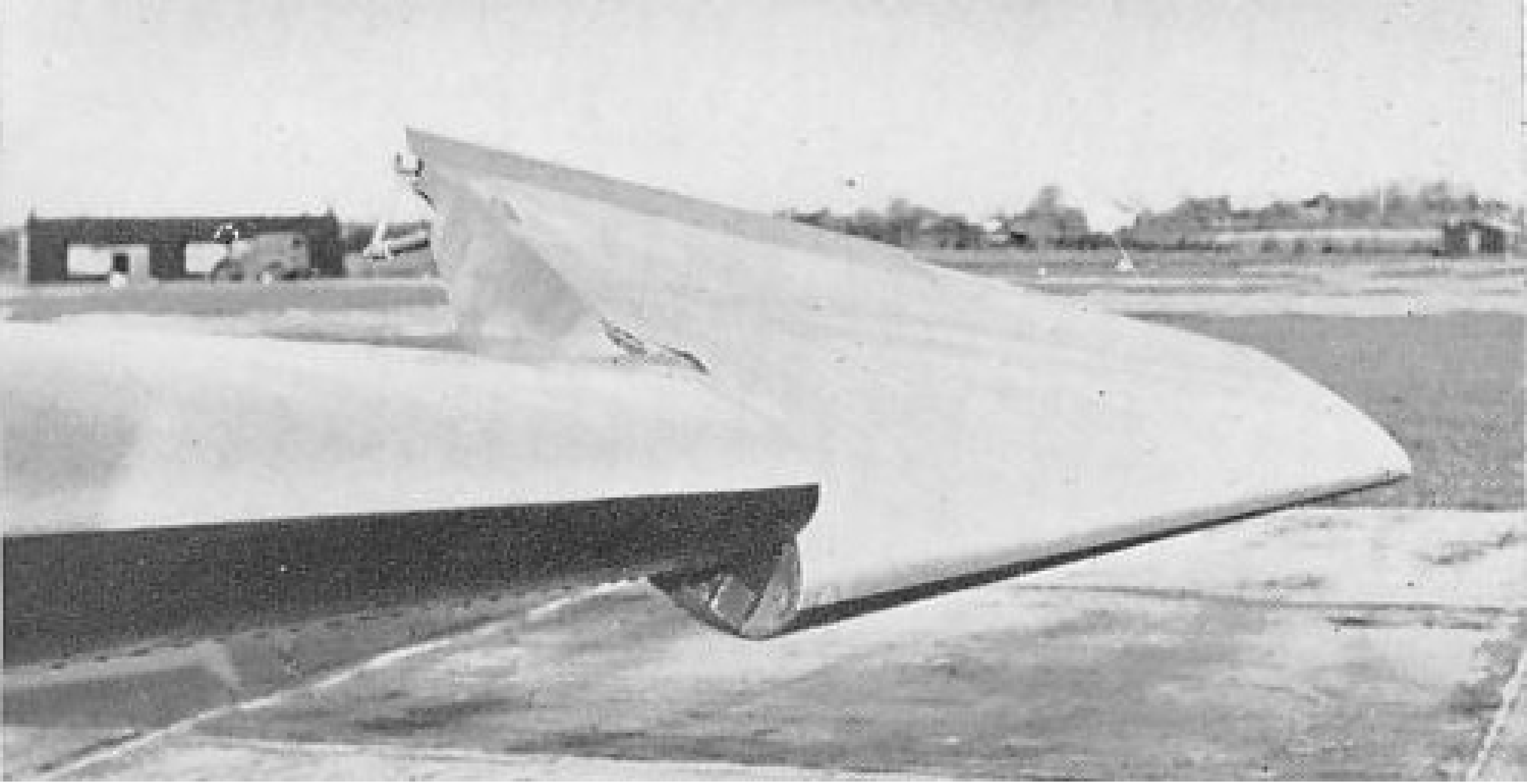
Control effectiveness and reversal



Short SB.1 aero-isoclinic winged tailless glider with elevons 1951

Short SB4 Sherpa, twin jet 1953

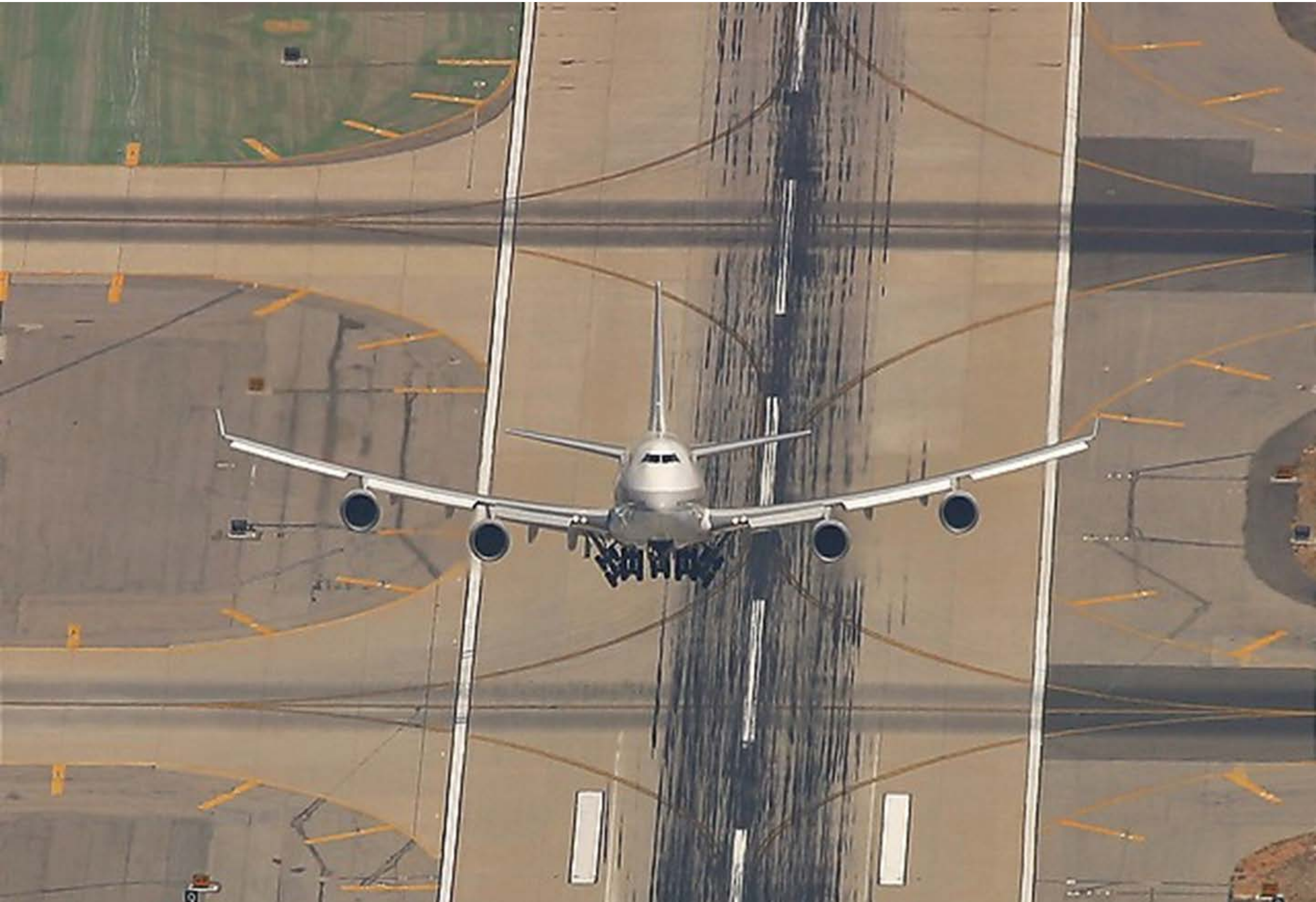
B.35/46 specification driven design



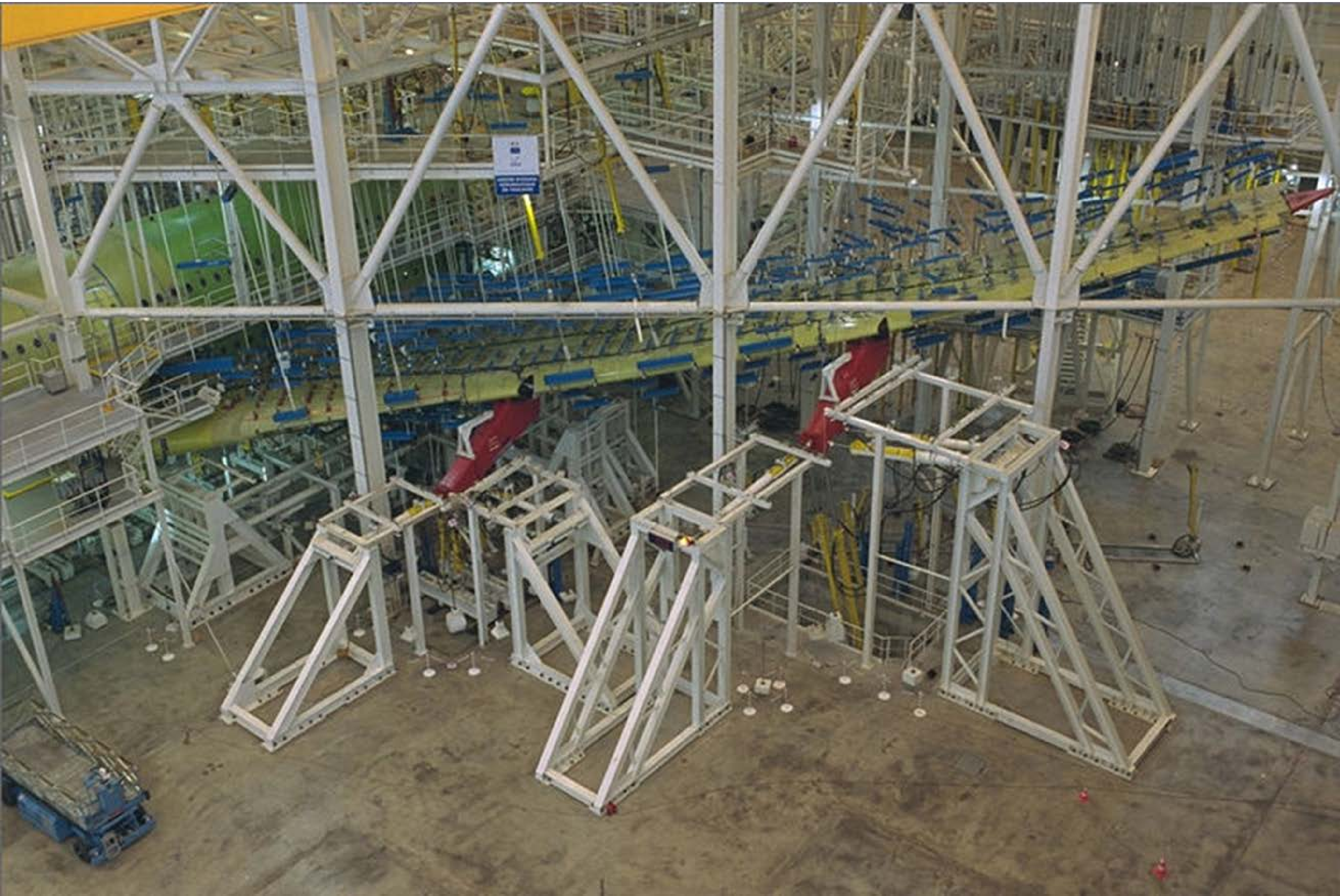
Rotating wing tip (20% wing area)

Boeing B-47 Stratojet (1947)

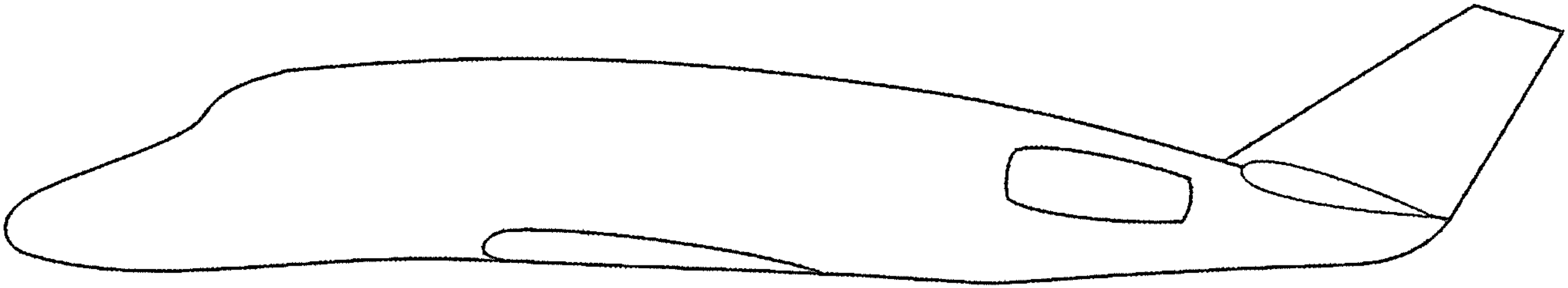
Structural distortion due to aerodynamic loads



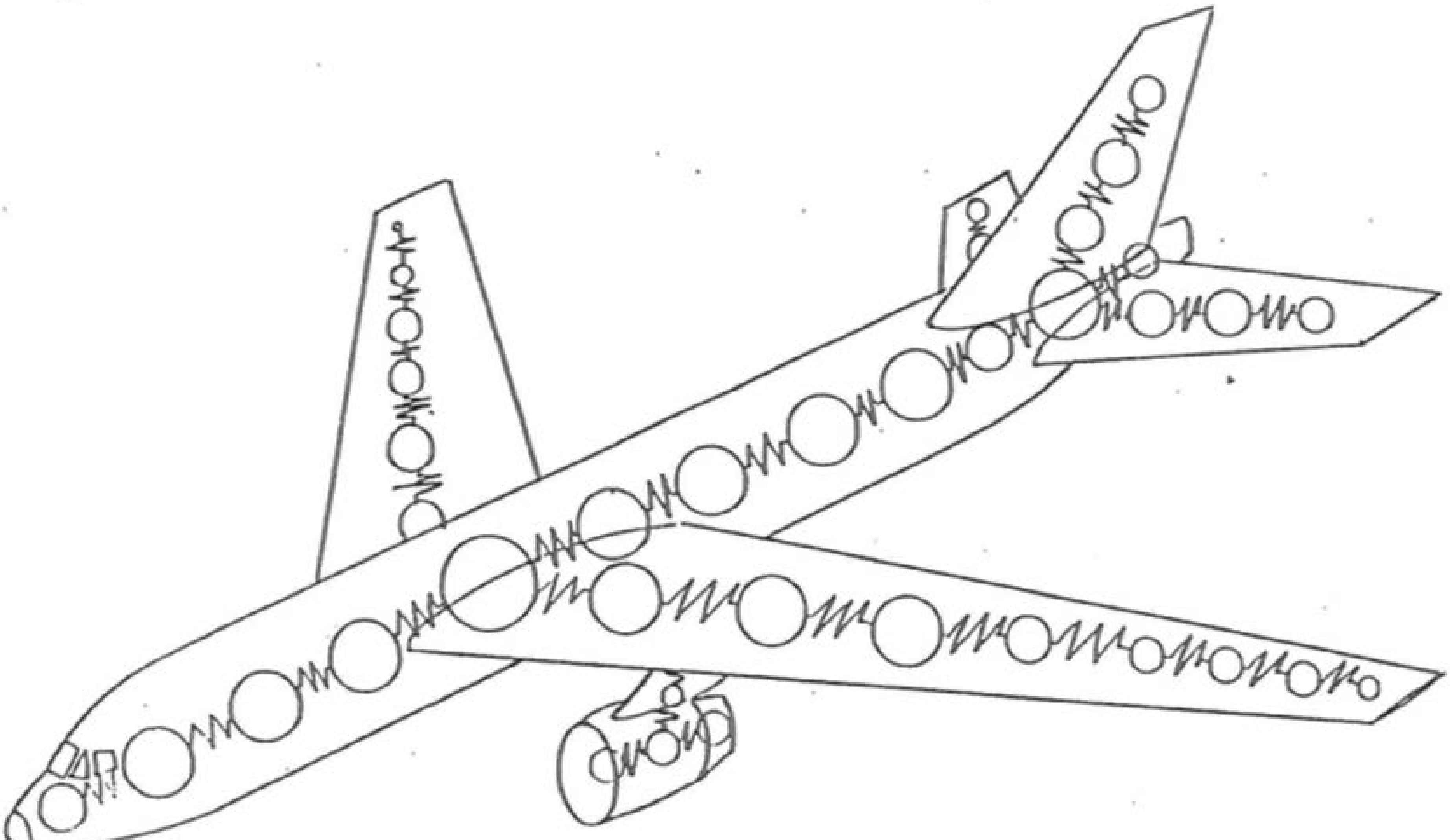
A380 wing static test, Toulouse, 25 May 2004
300 jacks, 2815 loading points, 8000 strain gauges, wing tip 8m peak-to-peak



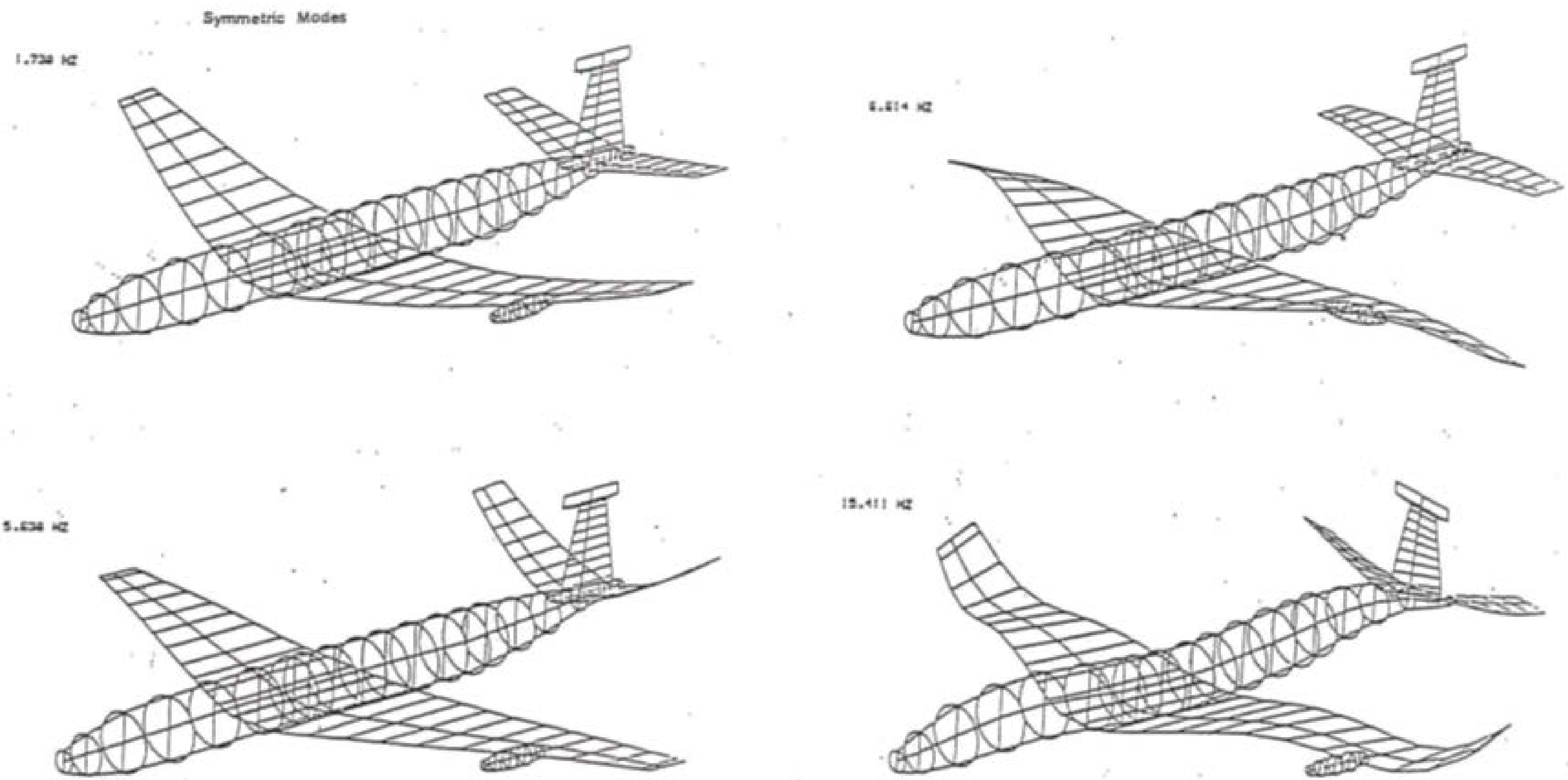
Fuselage bending: stability margins



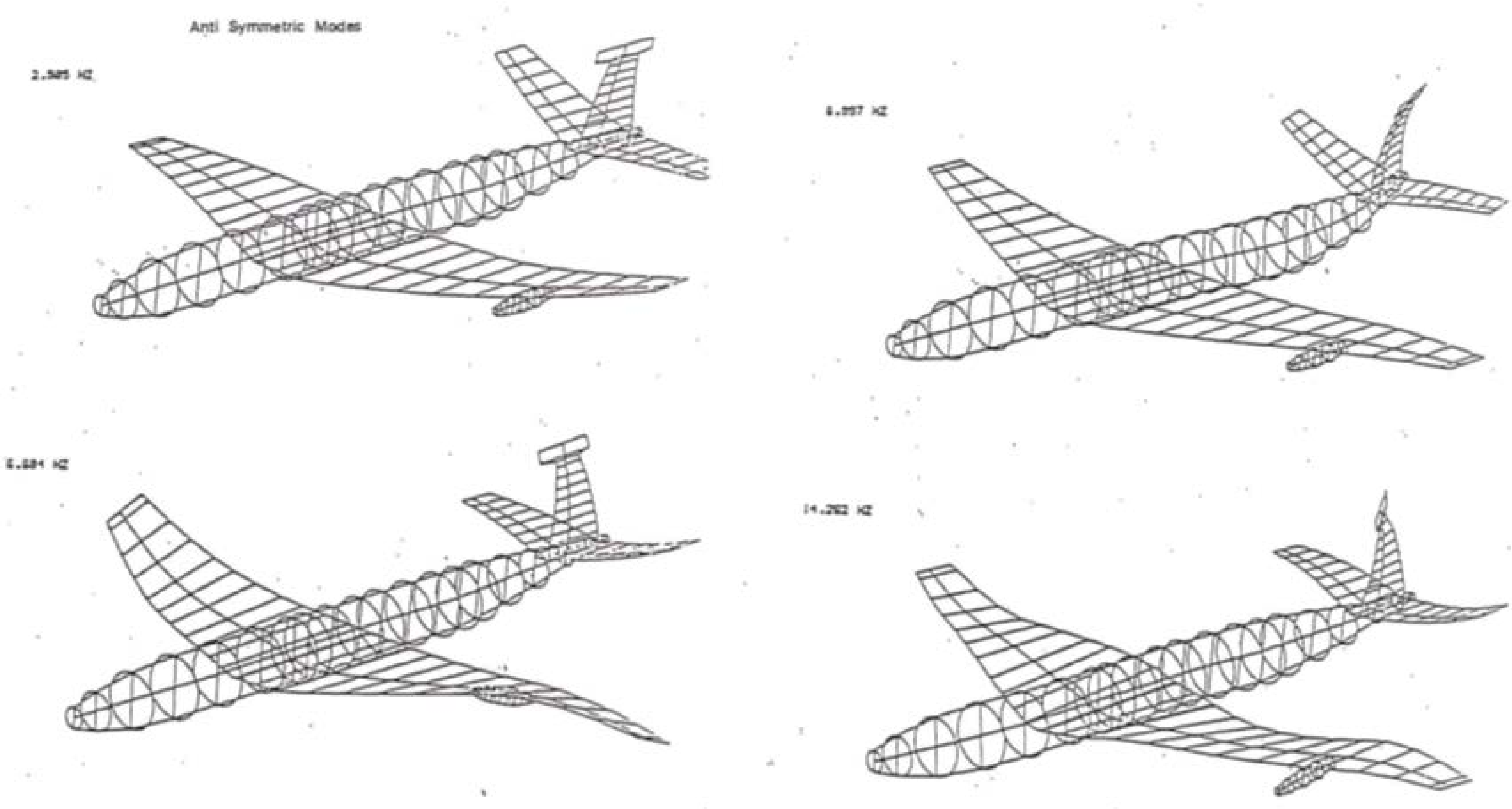
Modelling to study structural dynamics

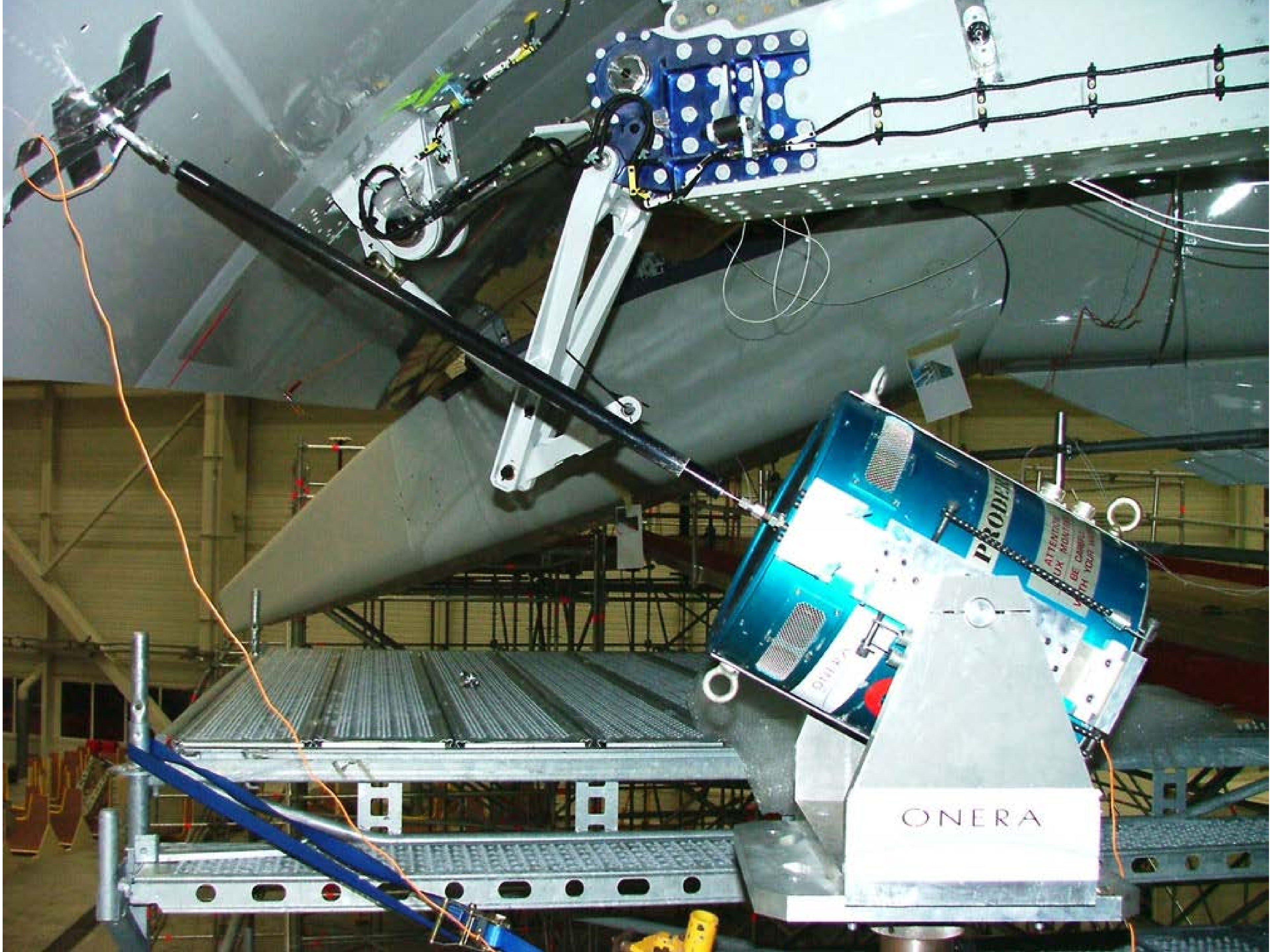


1.7 Hz,   5.6 Hz,   6.6 Hz,   15.4 Hz

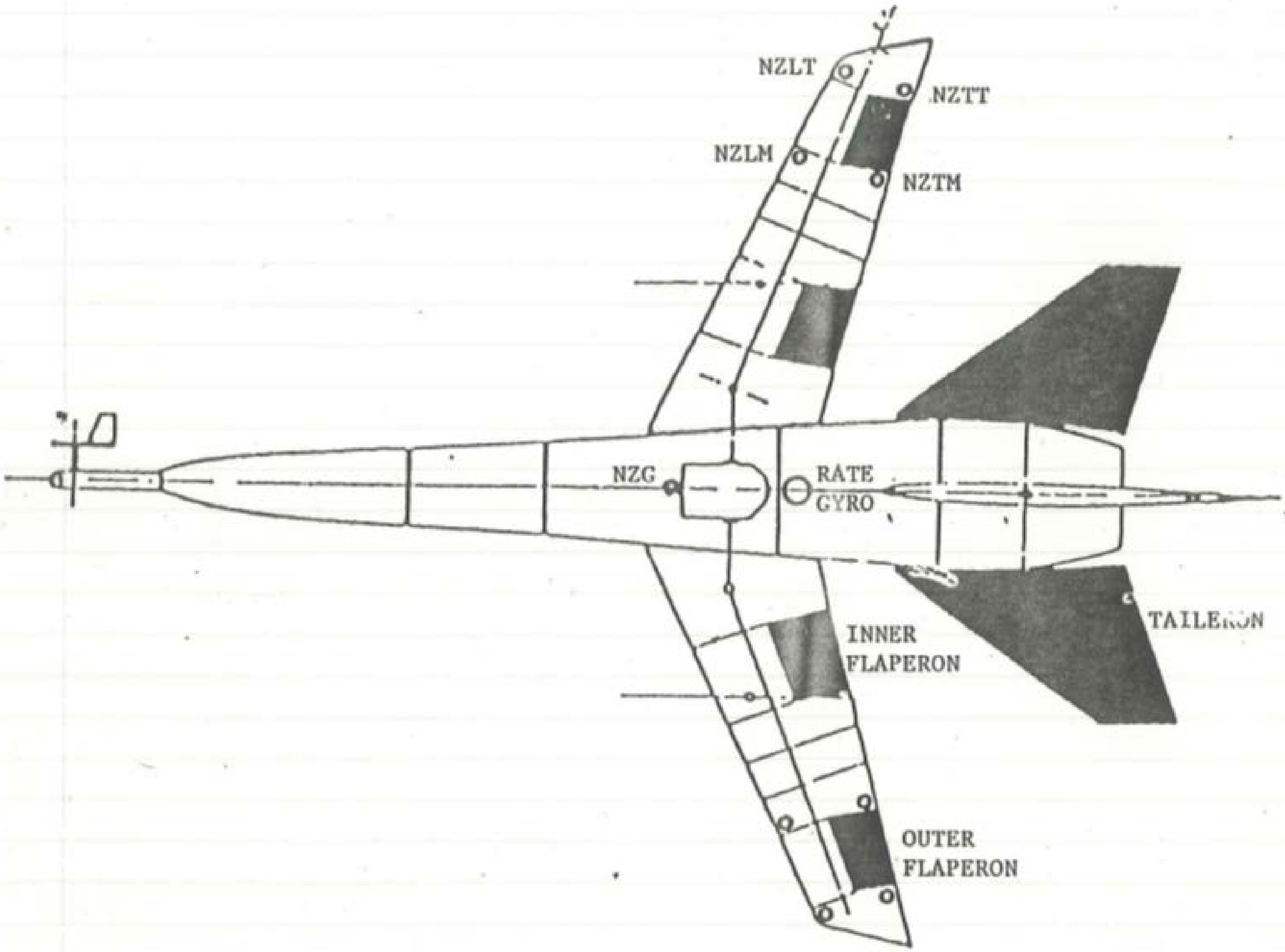


2.9 Hz,   6.7 Hz,   9.0 Hz,   14.3 Hz




ONERA

GVT: 17 exciters and 850 accelerometers
Six weeks of testing to refine math model

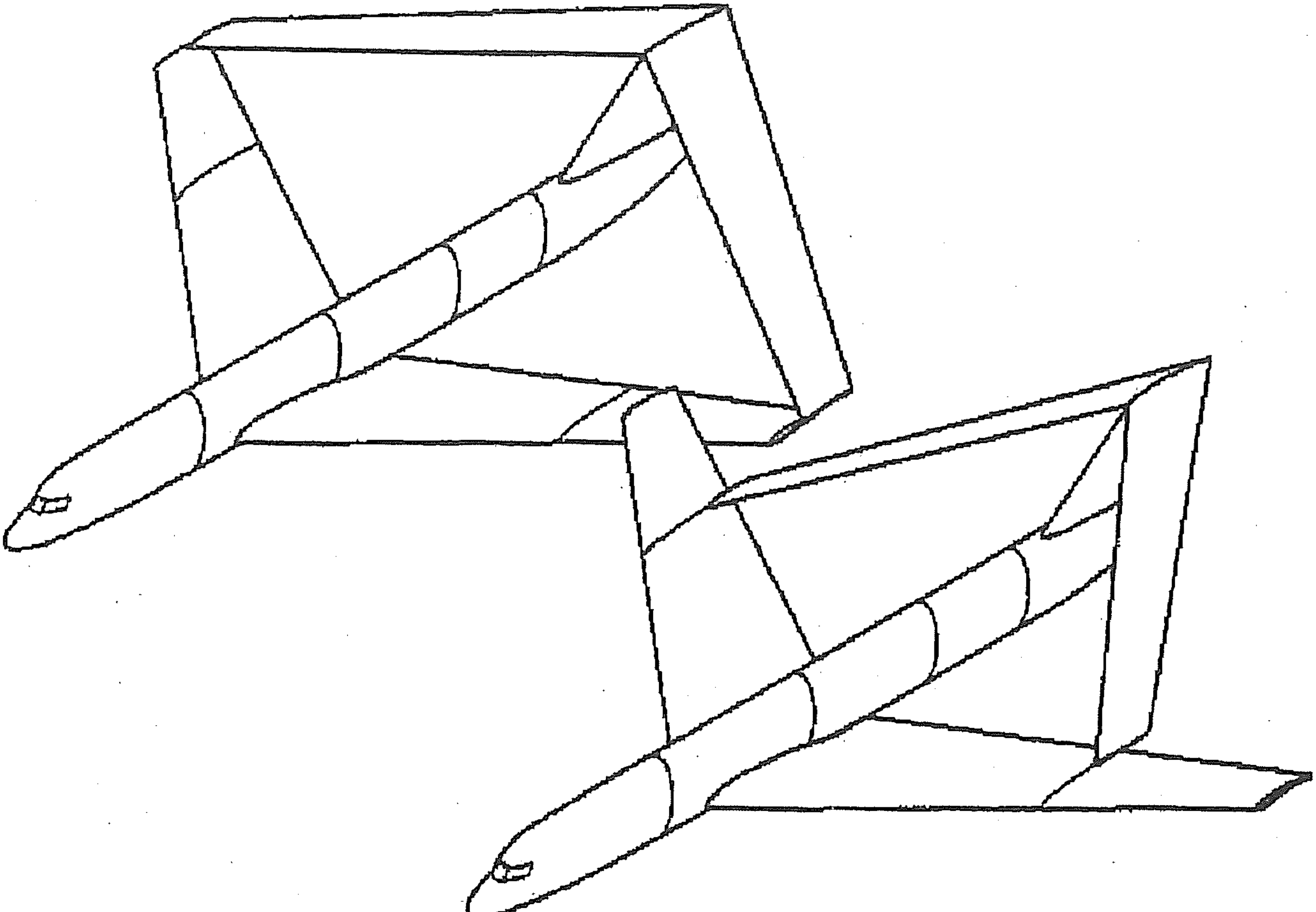


THE GARTEUR WIND TUNNEL MODEL

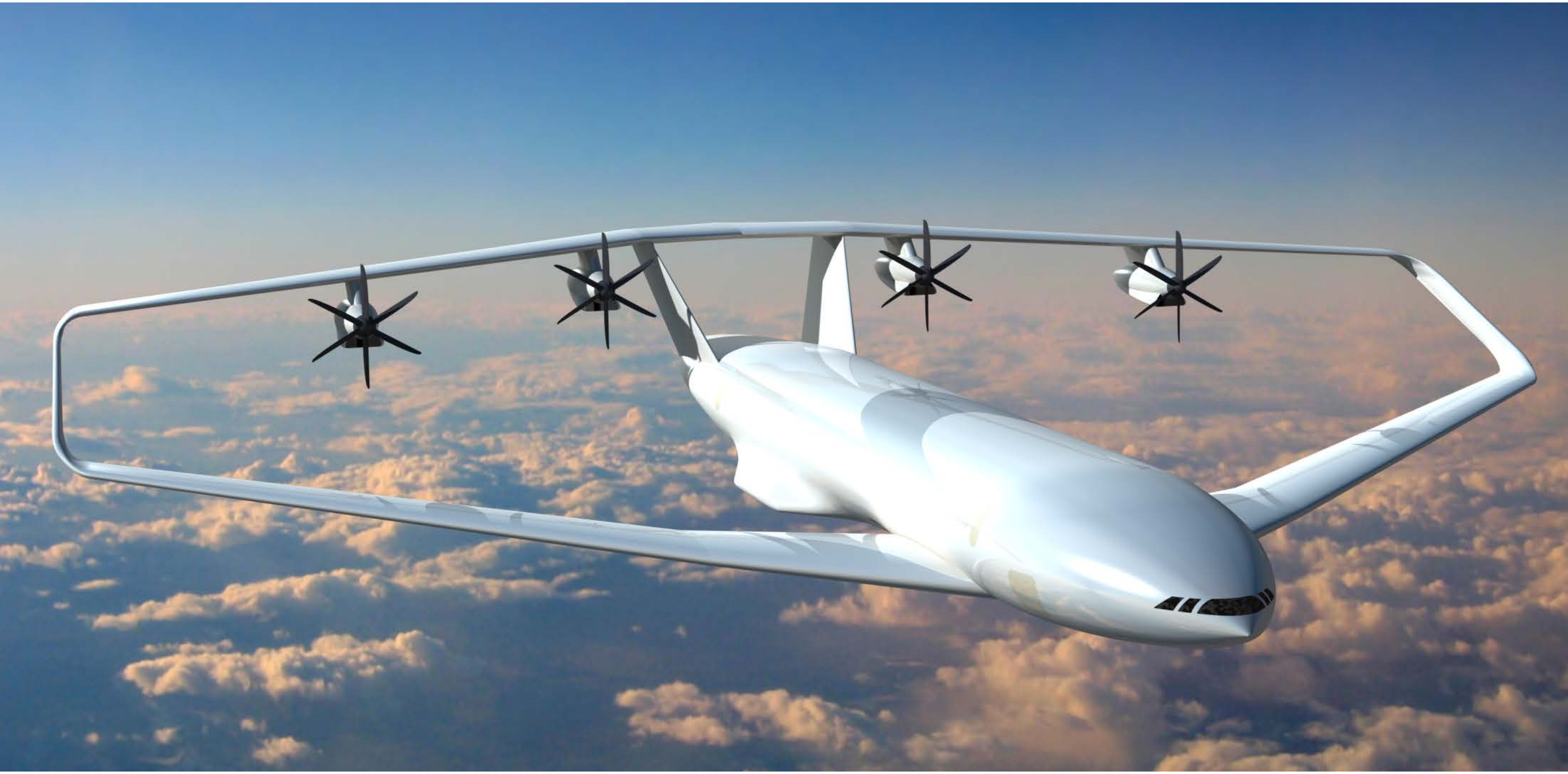
Feedback Control Loop

Sense, Process, Instruct, Actuate

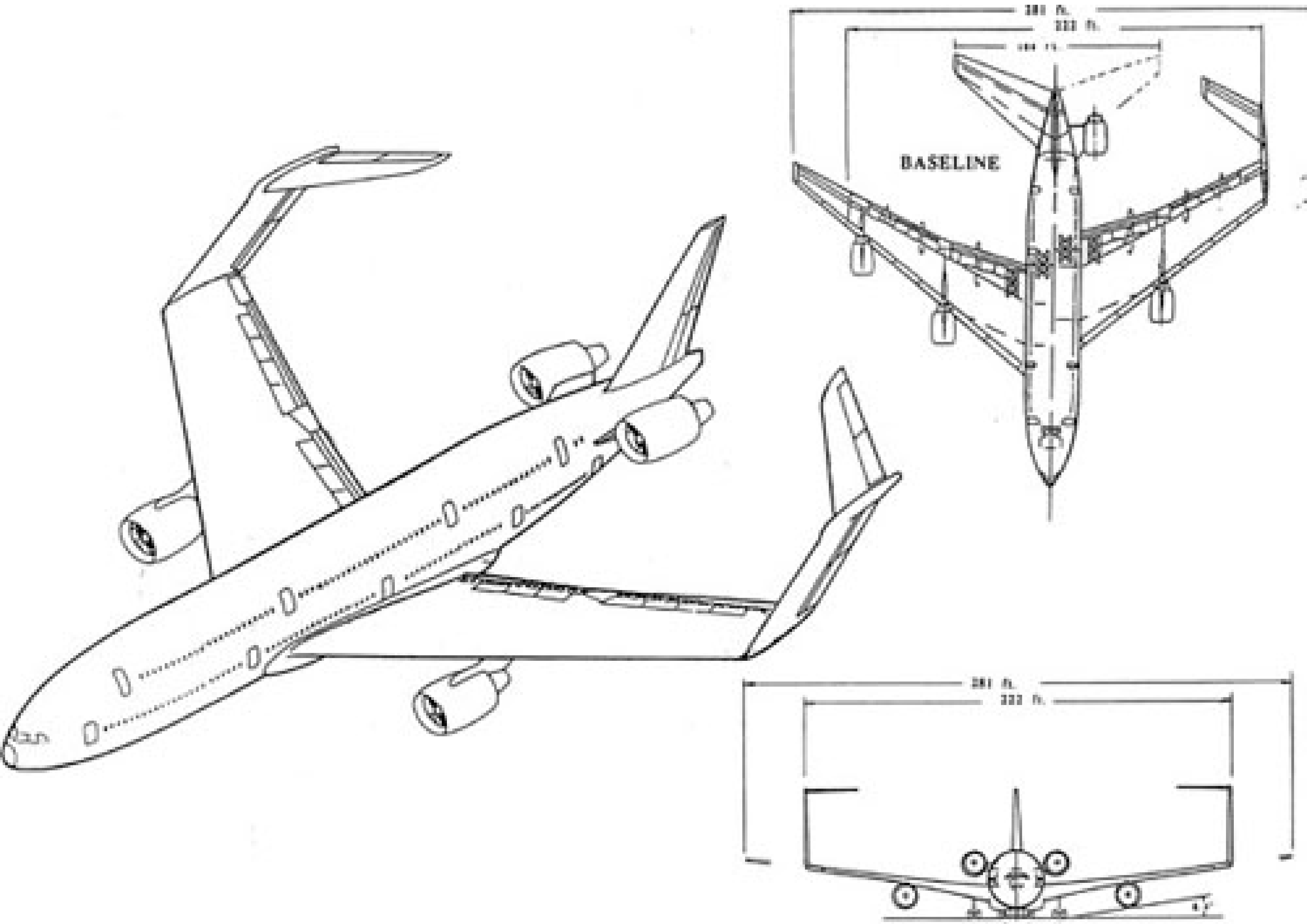
Joined wing configurations



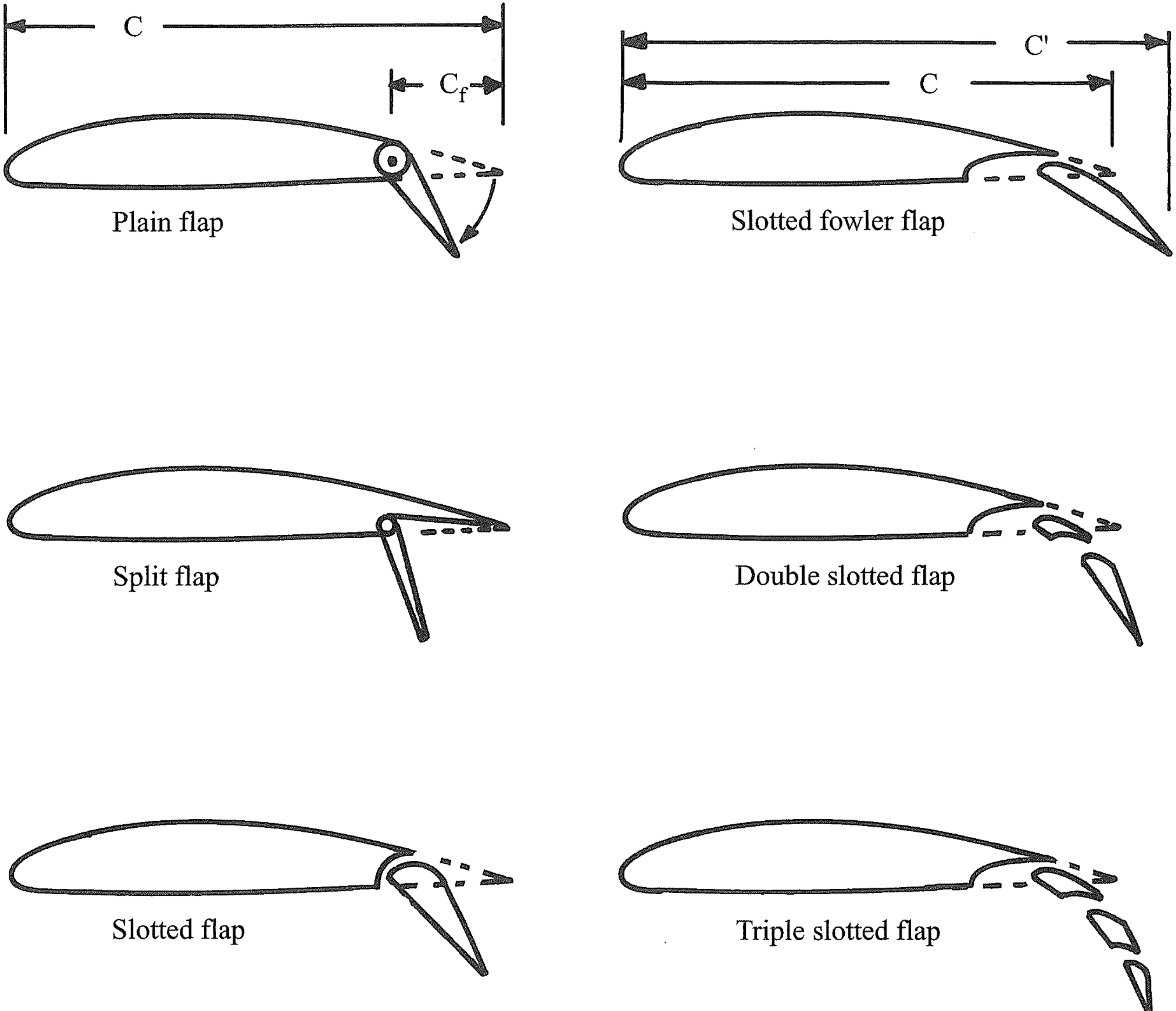
Box, closed, circular, annular, ring wing

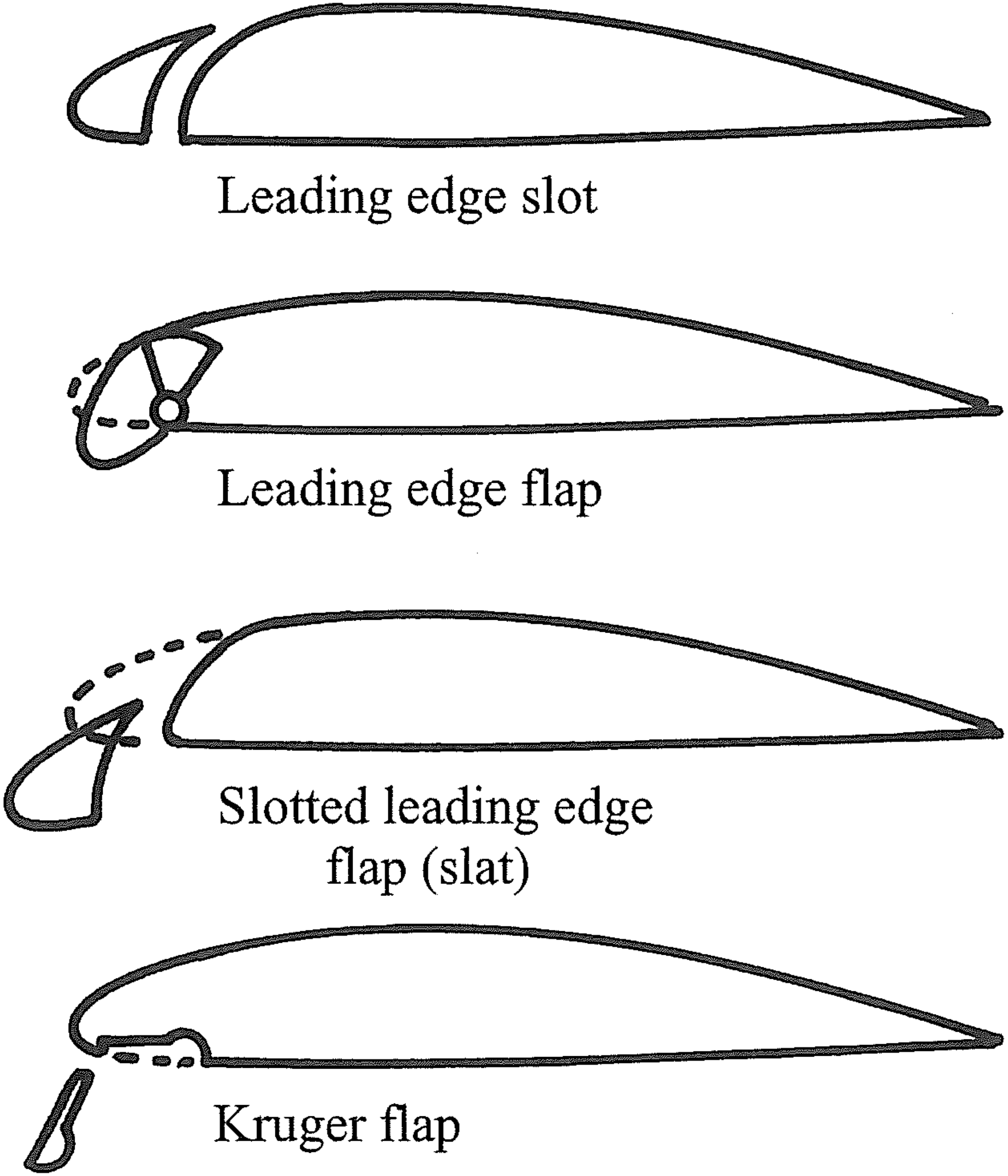


Built by Cranfield Aerospace for Boeing/NASA (2007)



ALTERNATIVE C-WING CONFIGURATION FOR A VERY LARGE SUBSONIC TRANSPORT AIRPLANE


C
C_f
Plain flap
C'
C
Slotted fowler flap
Split flap
Double slotted flap
Slotted flap
Triple slotted flap



Must be used
if equipped

buys rotation
tolerance

Auxiliary systems

Hydraulics:	346 Bar (5000 psi)
Electrics:	115 V, 400 Hz, three phase
Pneumatics:	cold air unit, compressed air
Avionics:	radar, nav, comms, lighting
Landing gear:	500 C service landing, 14 atm
APU:	IC engine, fuel cell or LiPo?

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Fair Winds and Happy Landings

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