The Legacy of Camillo Possio to Unsteady Aerodynamics

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Outline

- Introduction
- Aeroelastic problems
- Status of unsteady aerodynamic research at C. Possio's time
- The rising need to model compressibility in aeronautics
- Possio's first research work in 1937
- The Possio Equation (1938)
- Further contributions to unsteady aerodynamics (1938-1940)
- Contributions outside aircraft aerodynamics (1940-1943)
- Extension of C. Possio's work after World War II
- Conclusion : Legacy and research today

References

H.G. Küssner (1940) : *„The oscillating wing for $0<Ma<1$ has been investigated up to now in just a single investigation for the two dimensional problem [reference to C. Possio]”.*

Garrick, Reed III (1981) : *…….„There followed shortly afterward two short outstanding contributions by Camillo Possio in Italy. In 1938 he applied the acceleration potential to the two-dimensional nonstationary problem and arrived at an integral equation (Possio’s equation) the solution of which gives the loading over a flat plate airfoil in an airstream for a known motion of the plate, i.e., for a given downwash. …… Possio also gave an outline of the parallel problem for a supersonic mainstream. Possio’s brief brilliant career ended with his death during the war years.”*

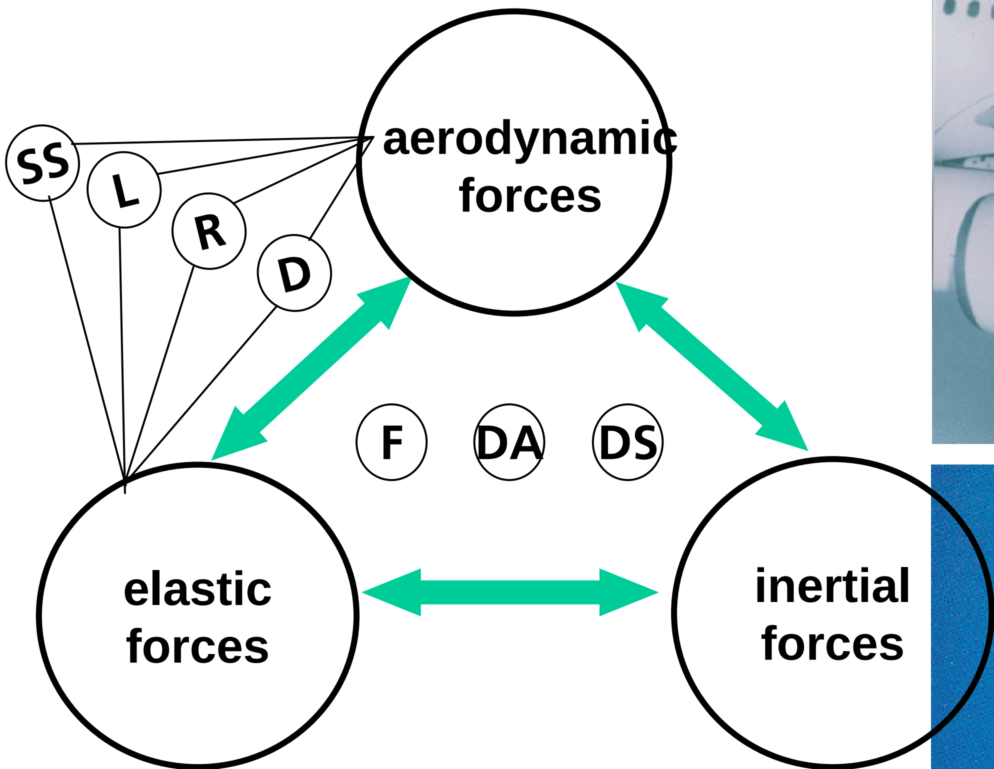
My experience : C. Possio’s 1938 paper *“ L’azione aerodinamica sul profilo oscillante in un fludio compressible a velocita iposonara” , (L’Aerotechnica),* is among the 5 most cited papers about unsteady aerodynamics.

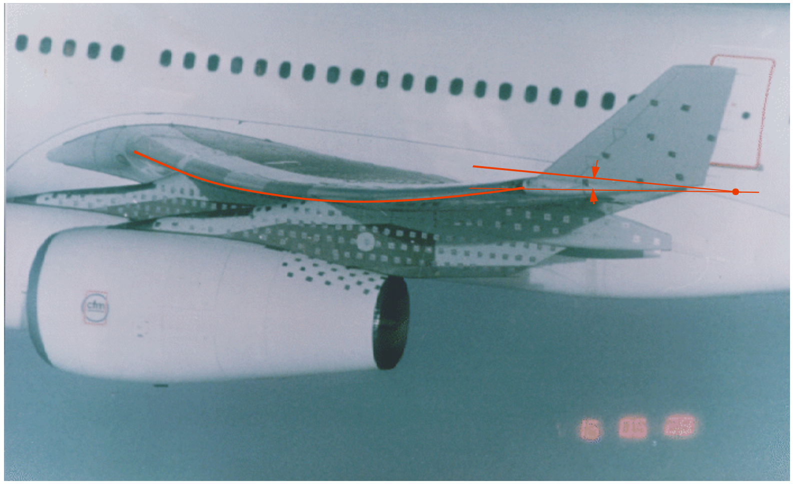
Camillo Possio – 1913 - 1945

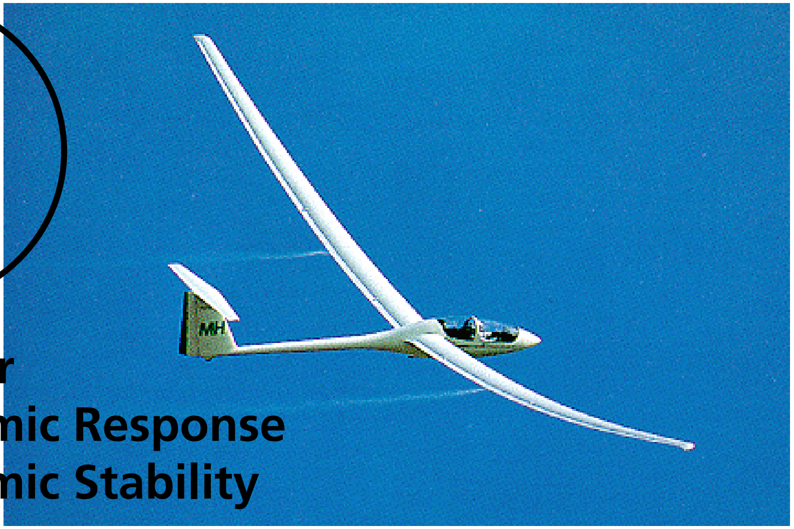
Born on October 30th 1913 in Torino
Student at Politechnico di Torino,
Teachers : Modesto Panetti and Carlo Ferrari
1936 laurea degree industrial engineering
1937 laurea degree aeronautics
1937 first scientific papers
1938 Possio's equation
Professor at Politechnico di Torino teaching
gas dynamics and thermodynamics
Military service until 1940 teaching at Torino
1939 3D unsteady flow and military research
1940–1943 : Further research on 3D unsteady
flow, on windtunnel interference,
hydrodynamic and acoustic problems
17 scientific publications

April 5th, 1945 : killed by an air attack on Torino

Aeroelastic Problems : The aeroelastic triangle







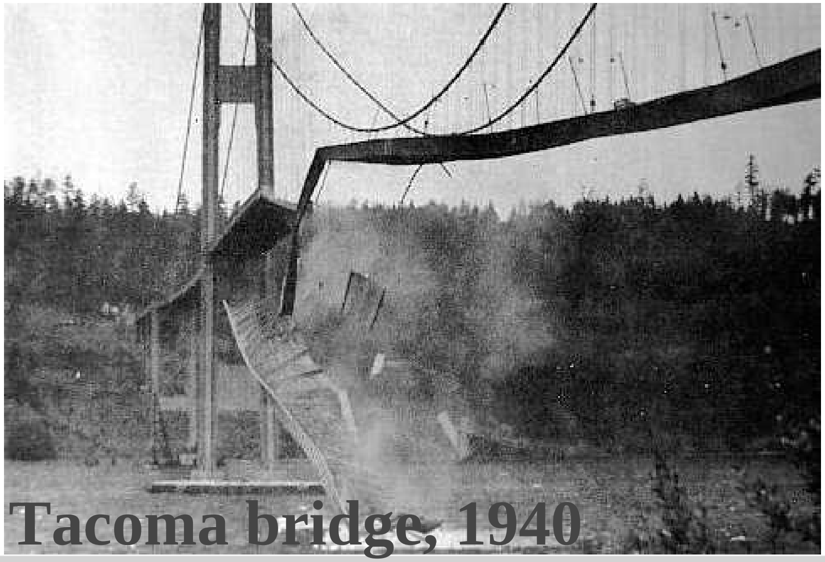
D	= Divergence	F	= Flutter
R	= Control Reversal	DA	= Dynamic Response
L	= Lift Distribution	DS	= Dynamic Stability
SS	= Static Stability		

Historical Flutter Accidents

Handley Page 0/400, tail+fuselage

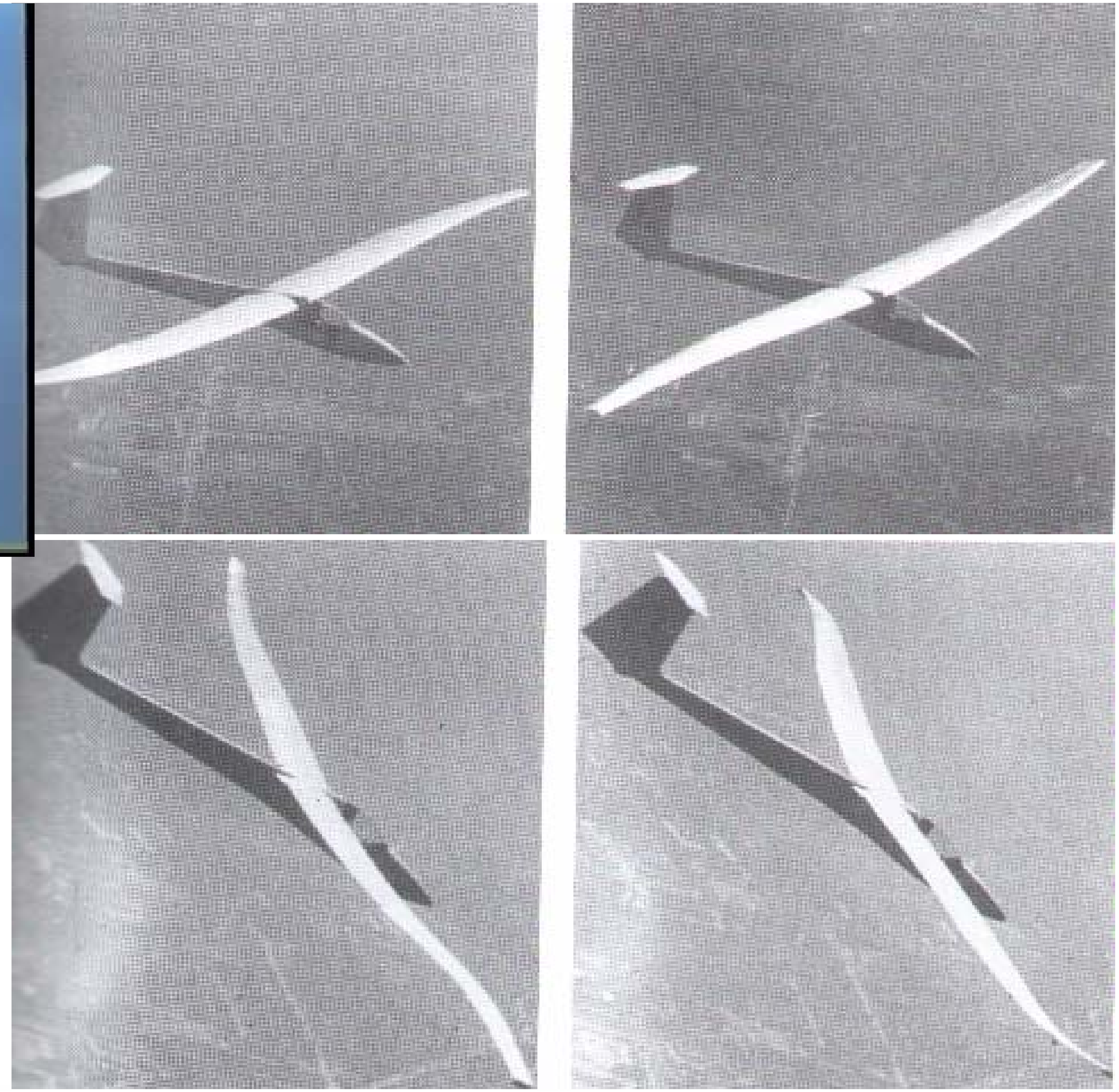
Junkers F13 – Stall (1930)

Junkers F90 (1938), tail



Tacoma bridge, 1940

Sailplane Flutter



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Flutter calculation as an Eigenvalue problem

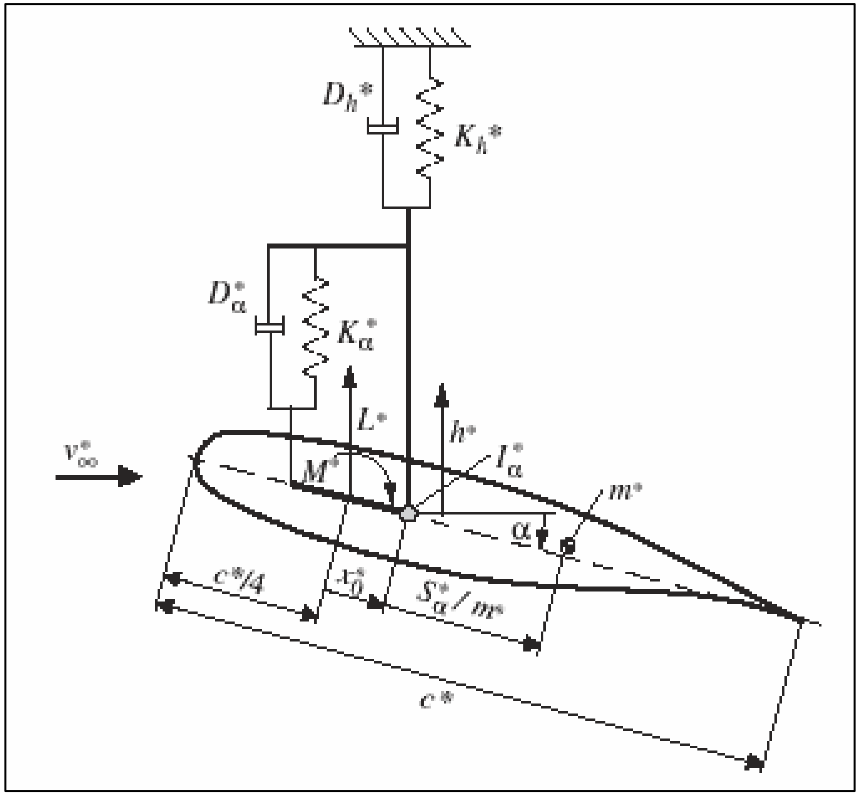
Lagrange's equation : $$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{q}_i}\right]-\frac{\partial L}{\partial q_i}=Q_i$$

$$\Rightarrow \begin{cases} m\ddot{h}+S_\alpha\ddot{\alpha}+k_h h=-L \\ S_\alpha\ddot{h}+I_\alpha\ddot{\alpha}+k_h\alpha=M \end{cases}$$

$$2\ldots DOFs\ldots.u(t)=\begin{pmatrix} h\ \ (t) \\ \alpha(t) \end{pmatrix}=u_0+u_{unst}(t)$$

Approach in frequency domain :

$$u_{unst}(t)=u_0+u\quad e^{i\omega\, t}$$



Eigenvalue problem, which needs knowledge of

- **structural dynamic oscillations (mass, stiffness, damping)**
- **aerodynamic lift and moment, induced by motion of the structure**

The Key Role of Modelling Unsteady Motion-Induced Aerodynamics

Modelling of the structure reached soon a sufficient capability, slender wings were treated as beam-like structures. Geometrically more complex modes were measured in Ground Vibration Tests, see figure.

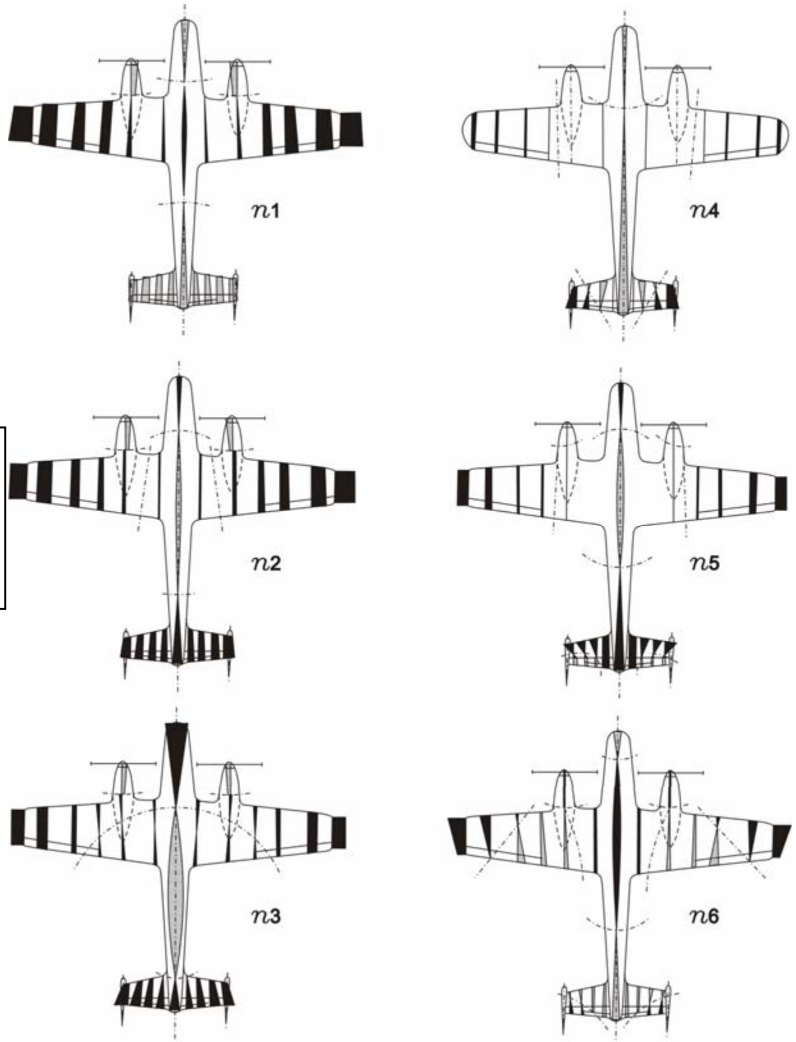
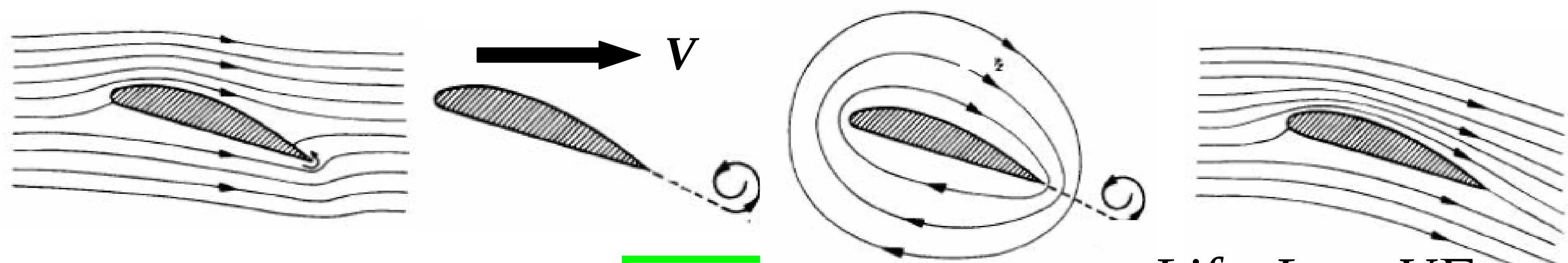


Figure : Ground Vibration Test (Do 17, 1942)

So for flutter calculations since 1920 the determination of forced oscillation-induced aerodynamic was the key problem.1937 -1943 C. Possio contributed to progress in this field.

First unsteady aerodynamic theories - incompressible



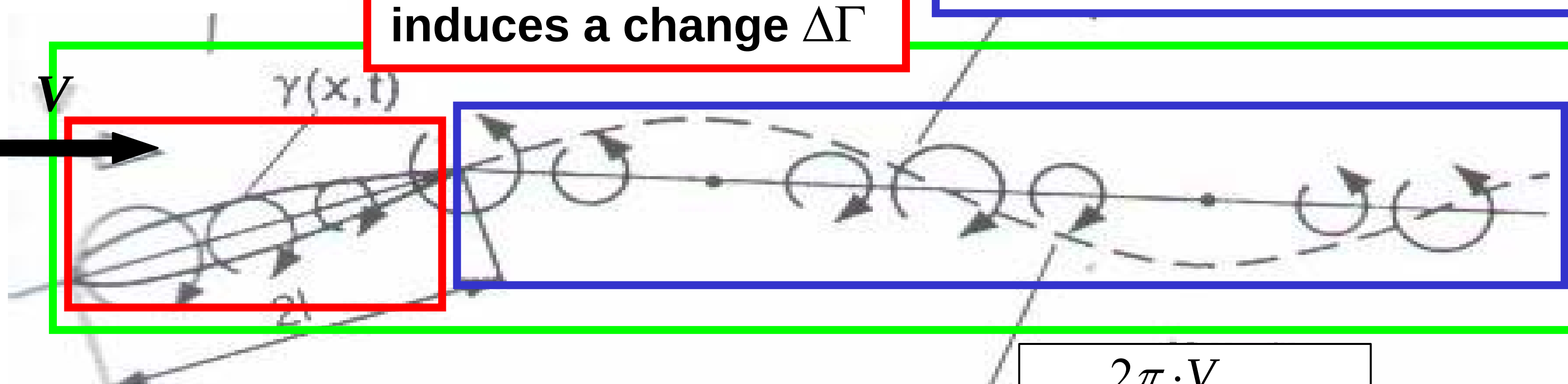
Prandtl 1918 Circulation $\Gamma = \int_C \vec{V} d\vec{s}$ is constant

$$Lift : L = \rho V \Gamma$$

Birnbaum 1922

Airfoil motion induces a change $\Delta\Gamma$

→ change $-\Delta\Gamma = \varepsilon$ in the wake



Reduced frequency :

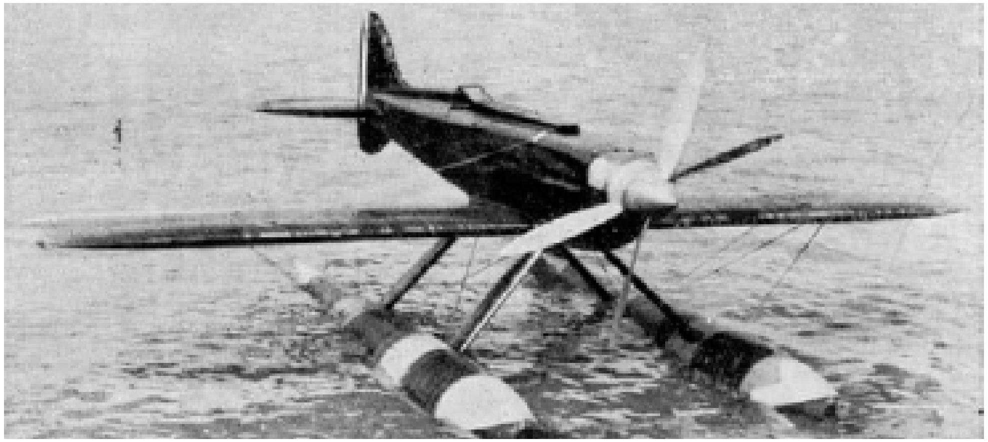
k* = *ω l* / *V

Wake vortices

$$L = \frac{2\pi \cdot V}{\omega} = V \cdot T$$

→ **Phase-shifts**

Increase of Speed in Aeronautics – a Grand Challenge with great influence and merit of C. Possio



1934 : Macchi-Castoldi MC72 water plane (709 kmh record flight)

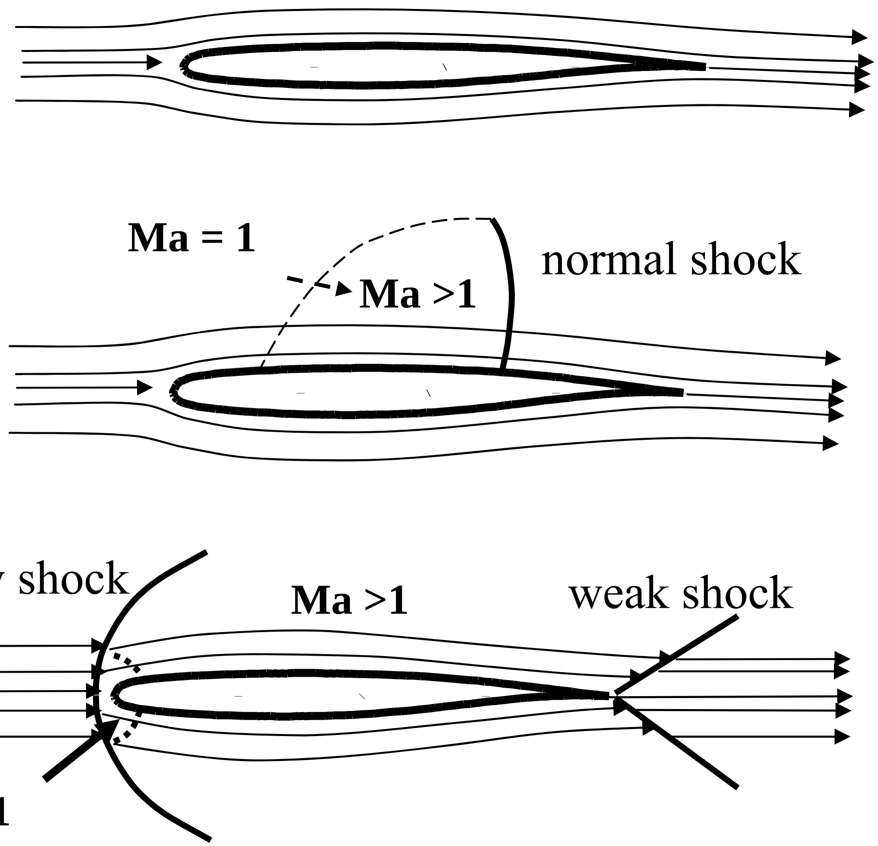
1939 : He178, 700 kmh, the world‘s first jet powered flight, 1942 : He280, 900 kmh

1937 : Me109 (611 kmh)

Growing complexity of forced unsteady compressible flow – in the 1930 years

Ma < 0.3 — **Laplace equation**

Ma < 0.8 — **Wave equation**



Ma = 0.8 — **Mixed flow, no models**

Ma =1.2 — **Mixed flow, steady characteristic models**

Ma > 1.2 — **Wave equation, 2 retarded waves**

The 1935 Volta Conference
of the Royal Italian Academy of Sciences
(29 Sept. – 6 Oct. 1935 at Accademia dei Lincei, Roma).
A milestone for modern compressible flow research

- Knowledge about compressible fluids (gas dynamics) well developed before 1930
- Applications only for steam turbines and ballistic projectiles
- highest speeds for propeller blade tips

Topic : high speed in aeronautics

During a session at Villa Farnesina

With Conference president General Arturo Crocco

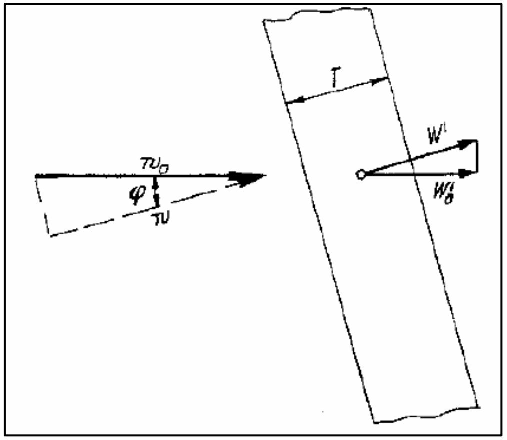
Some topics of the 1935 Volta Conference and their influence of C. Possio‘s work

- V. Karman calculated minimum wave drag shapes for axisymmetric bodies,
- Pistolesi derived Prandtl-Glauert- and other corrections for compressibility in subsonic and a similar rule for supersonic flows. But these were not applicable for unsteady flows.

$$c_L^{subsonic} \approx 2\pi\alpha / \sqrt{1 - Ma^2}$$

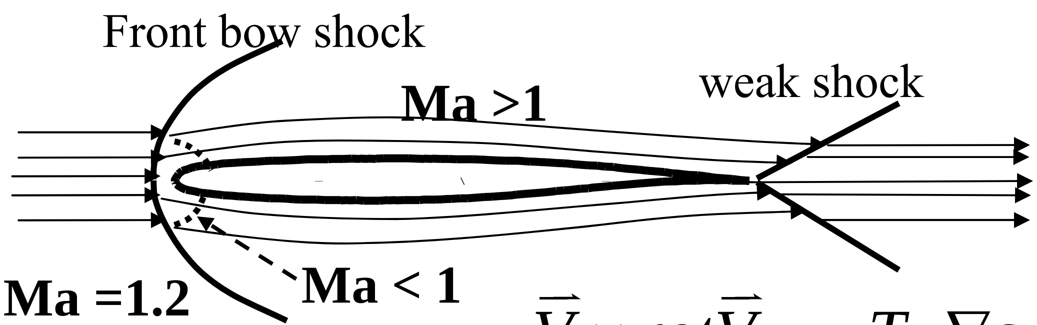
$$c_L^{supersonic} \approx 4\alpha / \sqrt{Ma^2 - 1}$$

- Busemann presented for the first time in history the concept of the swept wing as mechanism to reduce the large drag increase in high speed flight. Analysis of swept wings needs 3D theories, but Busemann’s concept was not significantly recognised.

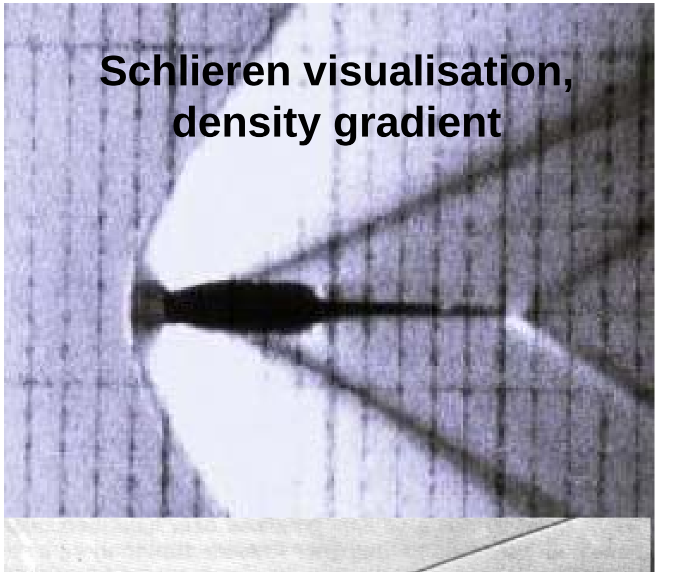


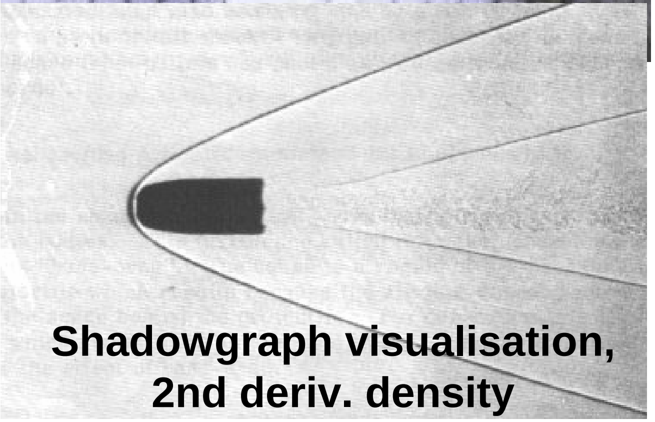
- Ackeret presented subsonic and supersonic windtunnel designs. Italian high-speed windtunnels in a new research center at Guidonia near Rome, were constructed under consultation of Ackeret. Possio later investigated windtunnel wall effects.
- Prandtl sketched a solution to attack the problems of compressible flow by the acceleration potential. The pressure jump across an oscillating lifting surface is directly proportional to the corresponding jump of the acceleration potential.This was very important for Possio’s work.

C. Possio's first scientific publications (1937) – Development of a 3D streamfunction formulation for rotational flows



$$\vec{V} \times rot\vec{V} = -T \cdot \nabla s$$





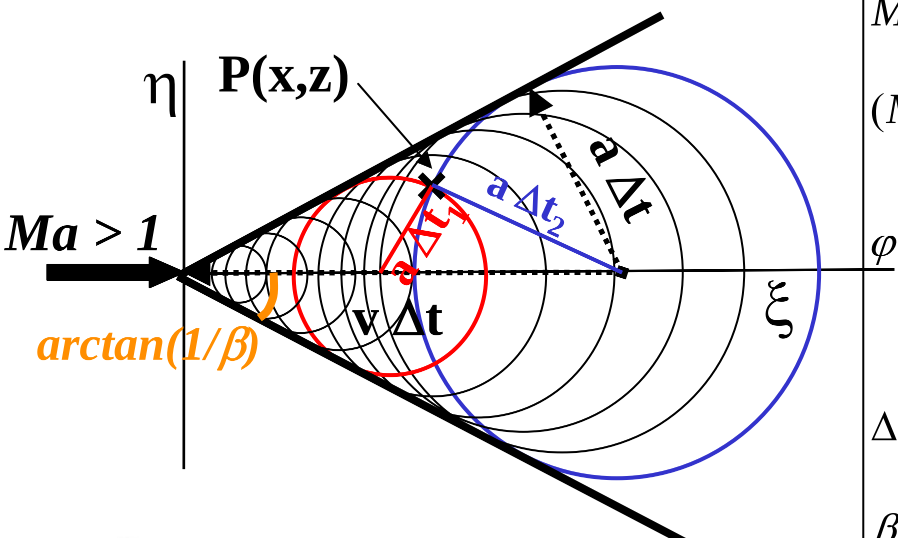
The supersonic flow is constant in front of the shock. For curved shocks, shock strength and thus entropy increase behind the shock differs.

<u>L. Crocco</u> derived a relation between curl of velocity and entropy gradient behind the shock, and introduced a stream function for calculation of 2D and axisymmetric rotational flows.

<u>C. Possio</u> extended this concept to 3D flows.

Unsteady Supersonic Flow

C. Possio derived a wave equation for the velocity potential and as a basic solution the potential of an acoustic source of pulsating strength moving rectilinear with supersonic velocity. In supersonic flow, due to disturbance propagation, the effect of a single source pulse is felt at two different retarded times $t_{1,2}$



$$\frac{\partial\rho}{\partial t}+div(\rho v)=0$$

$$\frac{D\vec{v}}{Dt}=\frac{\partial\vec{v}}{\partial t}+\vec{v}(\nabla\vec{v})=-\frac{1}{\rho}\nabla p,\cdot\cdot and\cdot\cdot rot\vec{v}=0$$

$$\rho=\rho(p)$$

$$\Delta\Phi-\frac{1}{a^2}\left\{\frac{\partial^2\Phi}{\partial t^2}+\frac{\partial}{\partial t}(\nabla\Phi)^2+\nabla\Phi*\nabla\frac{(\nabla\Phi)^2}{2}\right\}=0$$

$$Linearisation:\vec{v}=\nabla\Phi=V\vec{i}+\nabla\varphi,\cdots thus\cdots\Phi=\varphi+Vx$$

$$Ma=V/a$$

$$(Ma^2-1)\frac{\partial^2\varphi}{\partial x^2}-\frac{\partial^2\varphi}{\partial y^2}+2\frac{Ma^2}{V}\frac{\partial^2\varphi}{\partial x\partial t}+\frac{Ma^2}{V^2}\frac{\partial^2\varphi}{\partial t^2}=0$$

$$\varphi(x,y,t)=\frac{a(\xi,\eta,\tau)}{\sqrt{a^2(t-\tau)^2-\left[(x-\xi)-V(t-\tau)\right]^2-(y-\eta)^2}}$$

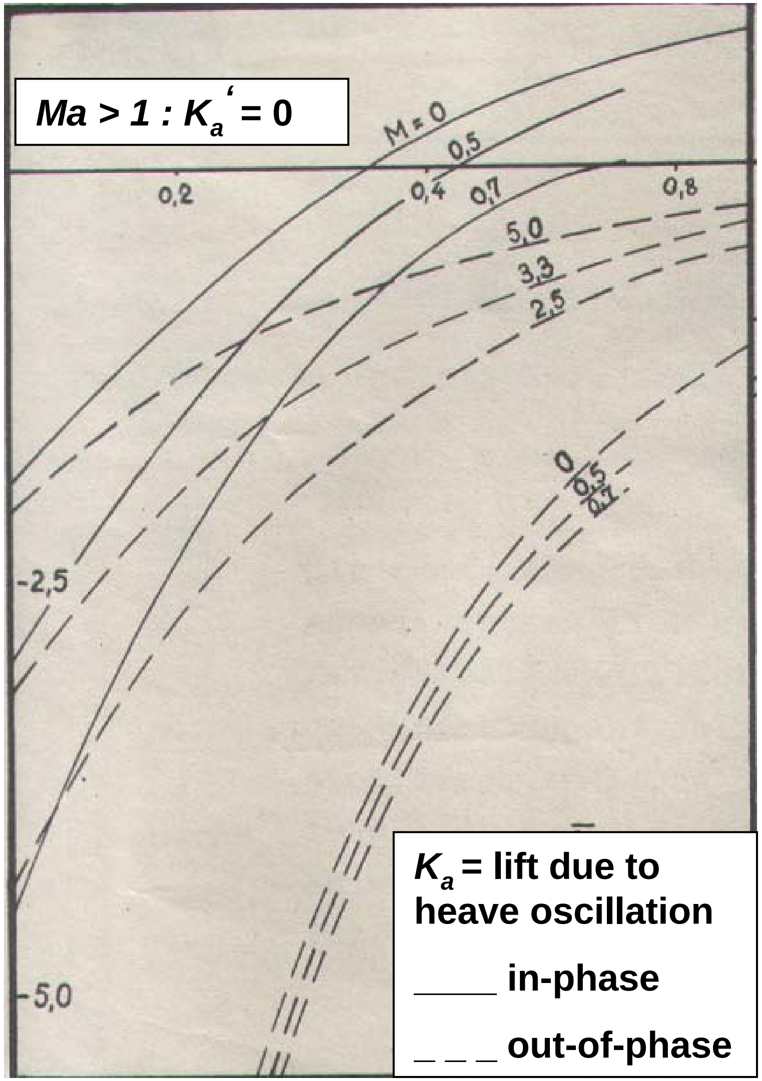
$$\Delta t_{1,2}=\frac{Ma(x-\xi)\mp\sqrt{(x-\xi)^2-\beta^2(y-\eta)^2}}{a\beta^2}$$

$$\beta^2=Ma^2-1$$

Unsteady Supersonic Flow

By derivation he obtained the induced velocity component w normal to the flat plate, representing the thin airfoil. He combined the effects of two sources with infinitesimal small distance to the upper and lower side of the plate, and thus obtained the effect of a doublet singularity of pulsating strength. The unsteady supersonic flow was then modelled by a doublet distribution of varying strength along the flat plate chord.

Possio's paper on this topic was published in "Pontificia Accademia Scientiarium Acta ", and the summary was written in Latin. Perhaps this is one reason, that - unlike others of his papers - it is not among those which have soon been reviewed or even translated in Germany. It appeared **already in 1937**, but it was referenced only 5 years later for the first time by v. Borbely 1942 in a different method. Results are from Schwarz and Jordan, 1944.



Unsteady Subsonic Compressible Flow Possio‘s Equation

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SOMMARIO

RENDICONTI DEL CONVEGNO DI AEROTECNICA
Torino, 14–17 ottobre 1937–XV

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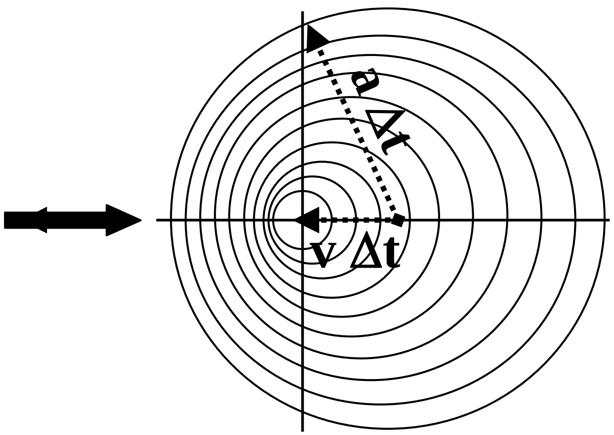
Unsteady Subsonic Compressible Flow – Wave Equation for Velocity Potential φ

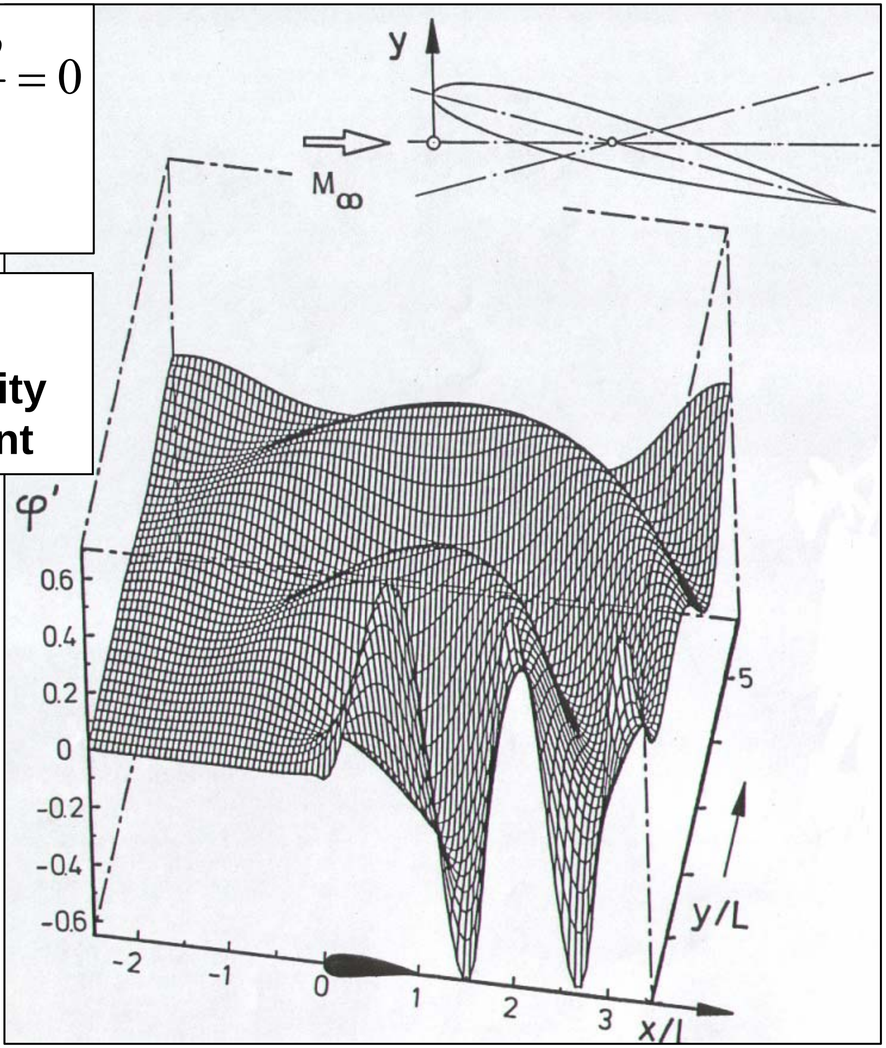
$$\beta^2 \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} - 2\frac{Ma^2}{V}\frac{\partial^2 \varphi}{\partial x \partial t} - \frac{Ma^2}{V^2}\frac{\partial^2 \varphi}{\partial t^2} = 0$$

$$\beta^2 = \sqrt{(1 - Ma^2)}$$

Ma = 0.79, ω* = 2.0,

φ = unsteady velocity potential component





Possio‘s Equation – Acceleration potential

vortex singularity can <u>not</u> be used as basic solution for compressible flow → Prandtl‘s acceleration potential ψ

$$\rho \frac{Dv}{Dt} = -\nabla p \Rightarrow \frac{Dv}{Dt} = -\nabla \int \frac{dp}{\rho} = \nabla \psi$$

$$\psi = \frac{\partial \Phi}{\partial t} + V^2 = -\frac{p - p_\infty}{\rho_\infty}$$

in a shock-free flow field, ψ is continuous, in contrast to φ

$$(1 - Ma^2)\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} - 2\frac{Ma^2}{V}\frac{\partial^2 \psi}{\partial x \partial t} - \frac{Ma^2}{V^2}\frac{\partial^2 \psi}{\partial t^2} = 0$$

$$\frac{\partial^2 \psi}{\partial \bar{x}^2} + \frac{\partial^2 \psi}{\partial \bar{y}^2} - \frac{1}{a^2}\frac{\partial^2 \psi}{\partial \bar{t}^2} = 0, \ldots. Transformation : x = \bar{x} - Vt, \ldots. y = \bar{y}, \ldots. t = \bar{t}$$

$$\psi_D(x, y) = a(\xi, \eta) V^2 \frac{4}{\beta} \exp i\left(\omega t + \frac{\omega^* Ma}{\beta^2}\frac{x - \xi}{l/2}\right) \cdot i \frac{\partial}{\partial \eta} H_0^{(2)}(R)$$

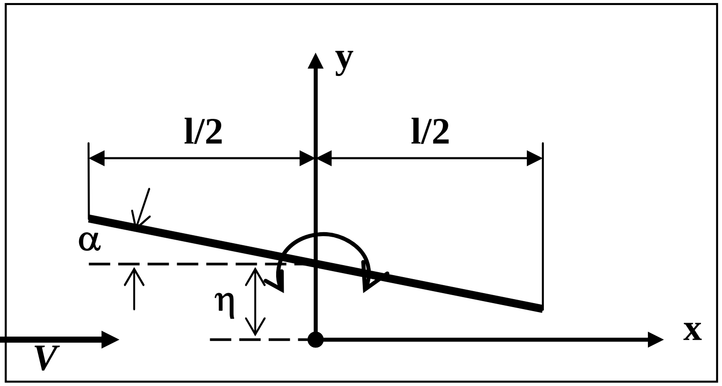
$$\omega^* = \frac{\omega \cdot l/2}{V}, \ldots. R = \frac{\omega^* Ma}{\beta^2}\frac{\sqrt{(x-\xi)^2 + \beta^2 (y - \eta)^2}}{l/2}, \ldots. \beta = \sqrt{1 - Ma^2}$$

Possio's Equation

$$\overline{w}(x) = w(x,0,t)\cdot e^{-i\omega t} = \frac{\omega}{\rho V^2}\int_{-l/2}^{+l/2} \Delta p(\xi)\cdot K\left(Ma,\frac{\omega^*(x-\xi)}{l/2}\right)\cdot d\xi,$$

$$K = \frac{1}{4\beta}\left\{e^{i\frac{\omega^* Ma^2(x-\xi)}{\beta^2\cdot l/2}}\left[i\cdot Ma\frac{|x-\xi|}{x-\xi}H_1^{(2)}\left(\frac{\omega^* Ma|x-\xi|}{\beta^2\cdot l/2}\right) - H_0^{(2)}\left(\frac{\omega^* Ma|x-\xi|}{\beta^2\cdot l/2}\right)\right]\right\}$$

$$+\frac{i\omega^*}{4\beta}\left\{e^{-i\frac{\omega^*(x-\xi)}{l/2}}\int_{-\infty}^{x-\xi} H_0^{(2)}\left(\frac{\omega^* Ma|x-\xi|}{\beta^2\cdot l/2}\right)e^{i\frac{\omega^* u}{\beta^2\cdot l/2}}du\right\}$$



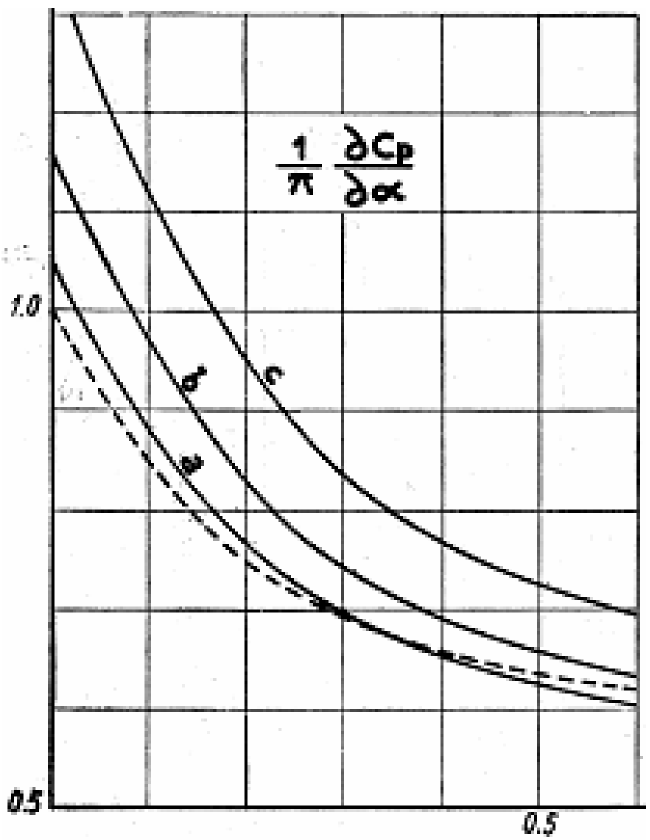
Possio's Equation

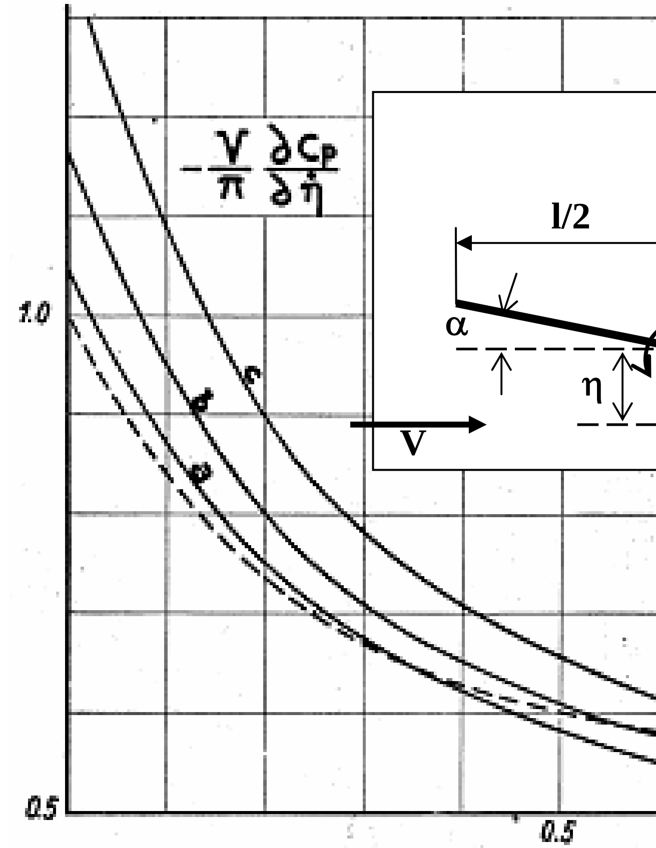
- Name „Possio's Equation" was introduced by H.G. Küssner
- Possio presented the equation in real- and imag. part, not in complex form
- the Kernel function, involving Hankel cylindrical functions, is singular for $x = \xi$, Possio computed the Kernel for a reduced spectrum of frequencies and for the Mach numbers 0,25, 0,50, 0,70
- first numerical solutions by using only 3 coefficients A_0, A_1, A_2
- series expansion for Δp in chordwise direction :

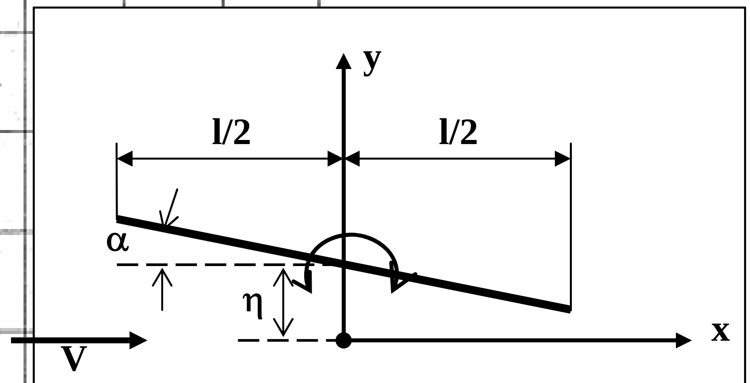
$$\Delta p(\theta) = A_0 \cot\frac{\theta}{2} + \sum_{n=1}^{\infty} A_n \sin n\theta, with : \cos\theta = \xi / l$$

$$c_L = \frac{L}{\rho l V^2} = \frac{\pi}{2}\left(A_0 + \frac{1}{2}A_1\right), c_M = \frac{M}{\rho l^2 V^2} = \frac{\pi}{16}\left(A_1 + \frac{1}{2}A_2\right)$$

Possio's first results – from the original paper







--- : Ma=0,

(a) : Ma=0.25,

(b) : Ma=0.50,

(c) : Ma=0.70

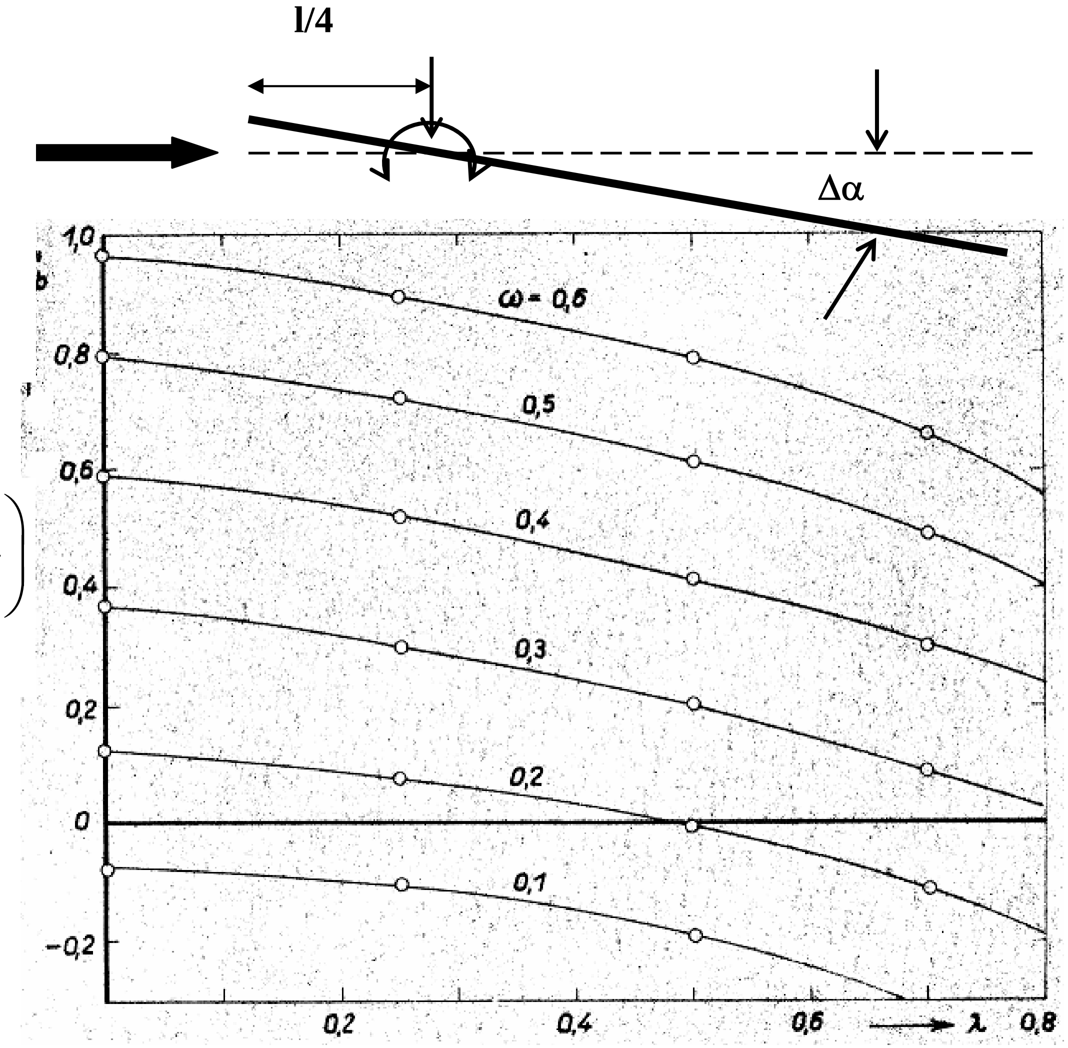
$$c_L = \left(\frac{l}{\pi}\frac{\partial c_P}{\partial \eta}\right)\pi\frac{\eta}{l} + \left(\frac{V}{\pi}\frac{\partial c_P}{\partial \eta^\bullet}\right)\frac{\pi}{V}\frac{d\eta}{dt} + \left(\frac{1}{\pi}\frac{\partial c_P}{\partial \alpha}\right)\alpha\pi + \left(\frac{V}{\pi l}\frac{\partial c_P}{\partial \alpha^\bullet}\right)\frac{\pi l}{V}\frac{d\alpha}{dt}$$

Transfer of Possio's original results to German Coefficients (Schwarz 1939)

Soon after Possio's break-through, also in Germany research on unsteady compressible aerodynamics started (not in other countries), but first his results were simply used for flutter analysis

$K_b^{//}$ = imag. Lift due to pitching

$$k_b^{//} = -\omega\left(\frac{V}{\pi}\frac{\partial c_P}{\partial \eta^{\bullet}}\right)\frac{\pi}{V}\frac{d\eta}{dt} + 4\omega\left(\frac{V}{\pi l}\frac{\partial c_P}{\partial \alpha^{\bullet}}\right)$$

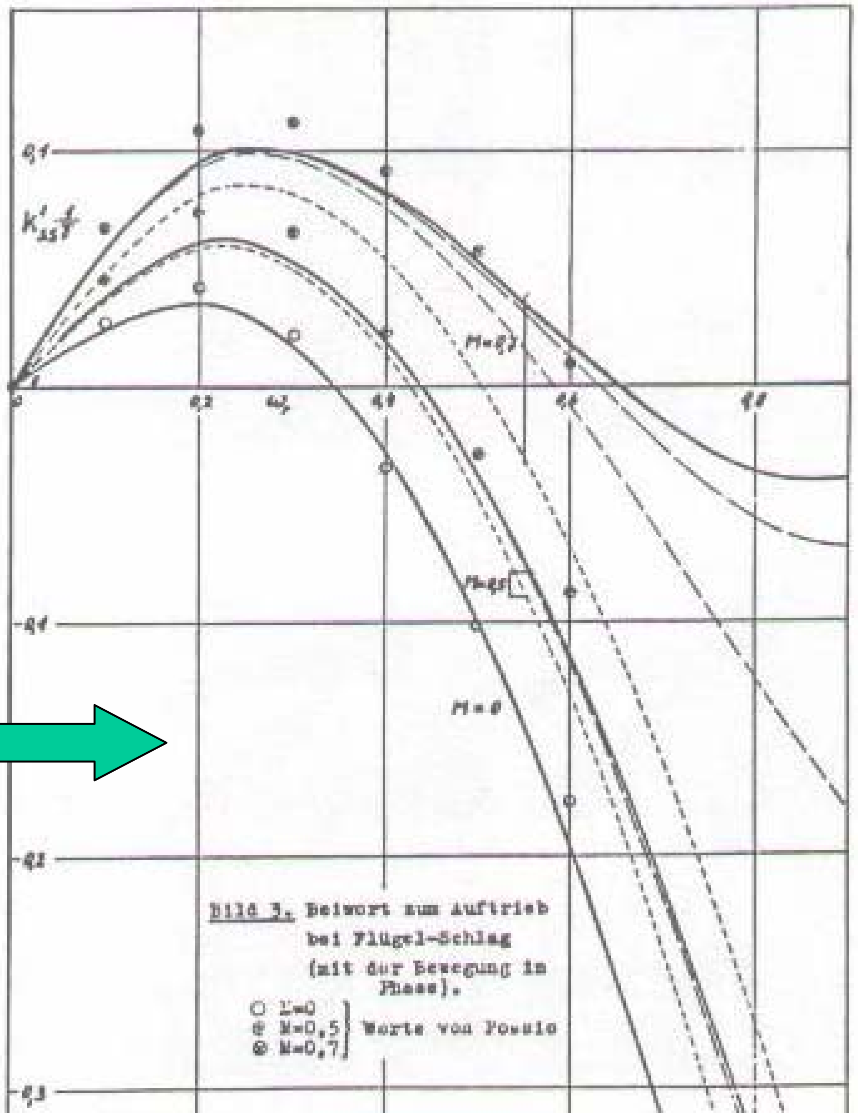


Possio's solution was restricted in frequency range.

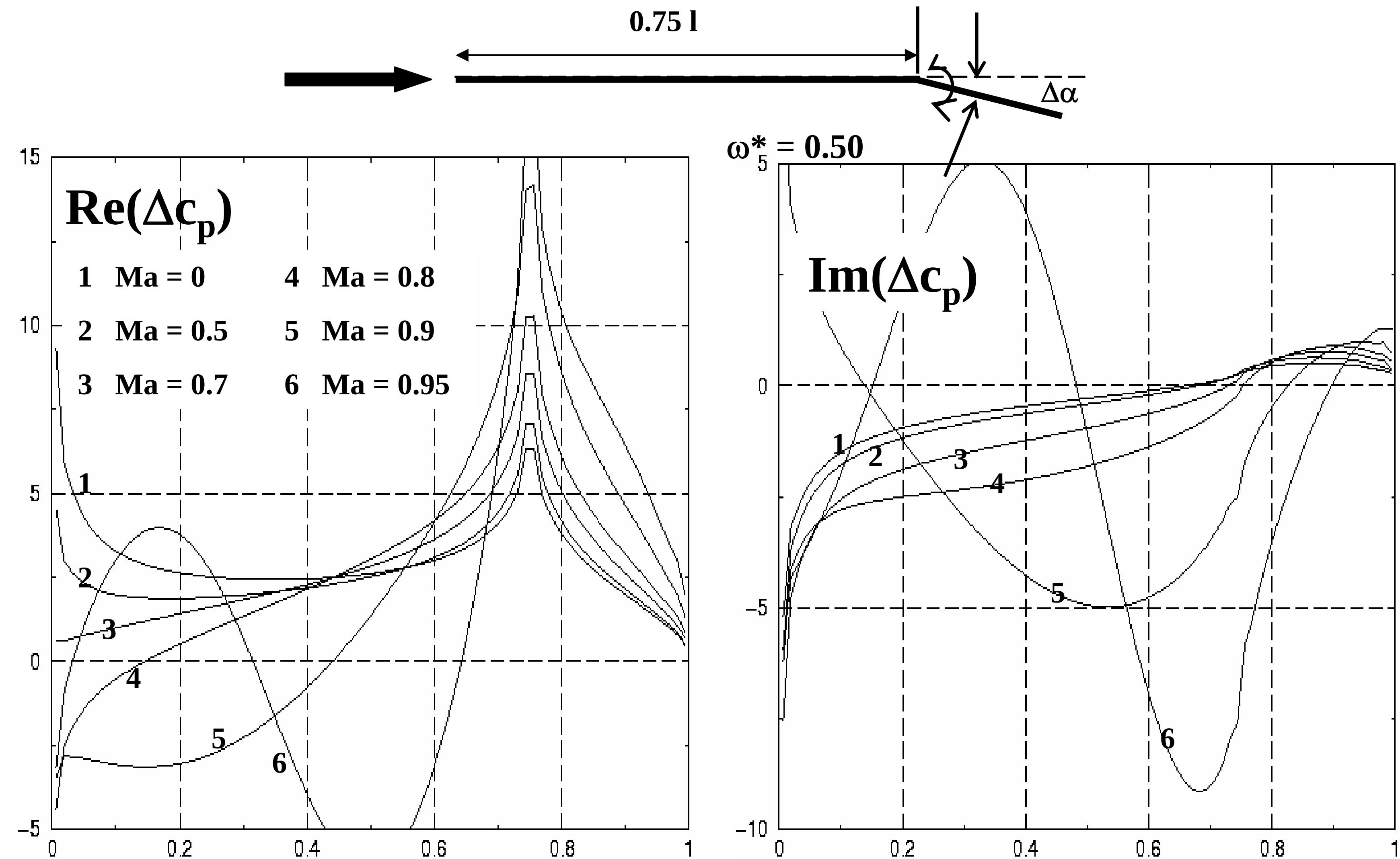
More complex modes, like flap oscillations need more than 3 A-coefficients

Improved Solution Procedures for Possio‘s Equation

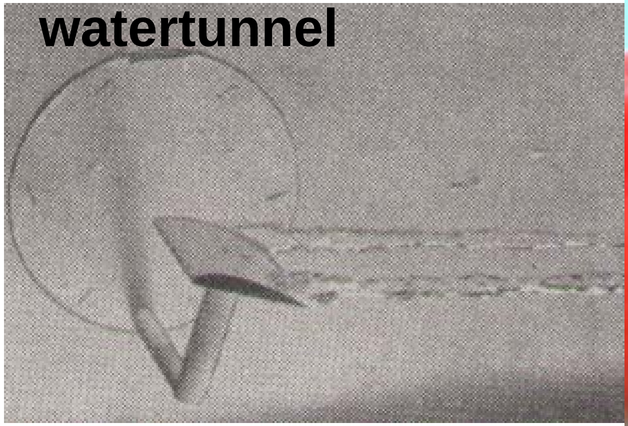
Dietze in 1942 developed the kernel function in terms of its relatively simple counterpart from incompressible flow, which had been presented by Possio in his paper too (mainly determined by tabulated Sine- and Cosine integrals). Starting from the incompressible solution, he derived an iteration procedure, consisting of successive approximations to an integral equation, the kernel of which is the difference *ΔK* between compressible and incompressible kernels. His results <u>compare well with Possio’s original ones</u> (symbols in figure). Convergence is improved, but *ΔK* is still singular. This disadvantage was later overcome by Fettis in 1952, by splitting the kernel into singular and a remaining part.

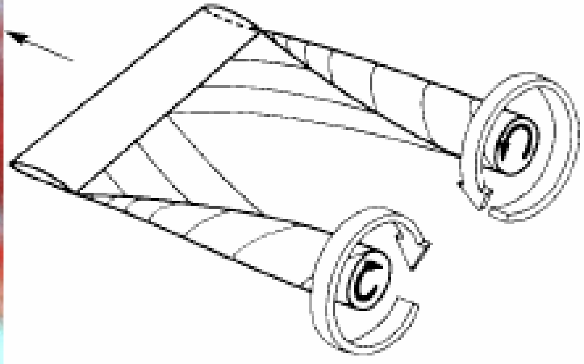


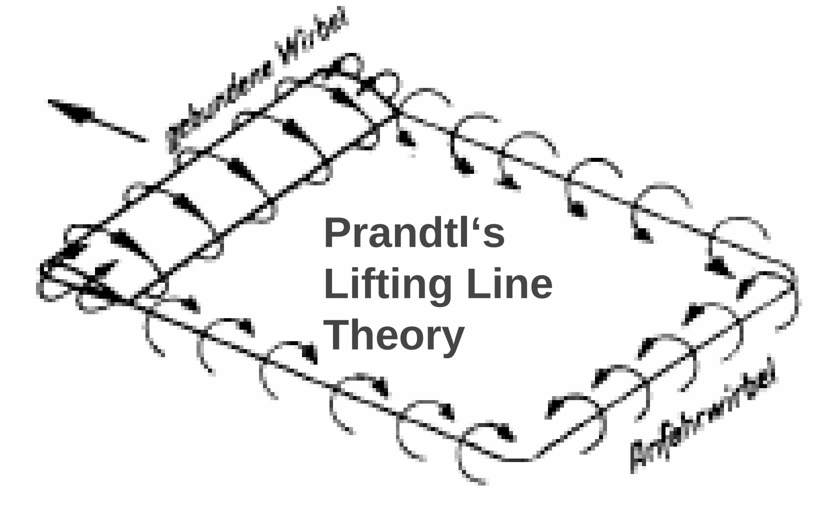
Possio's Equation – Computation of control surface oscillations using improved numerical methods



The Need to include 3D Effects for Oscillating Wings







Until 1930 flutter calculations were applied adopting stripwise 2D unsteady aerodynamic loads.

This became questionable for :

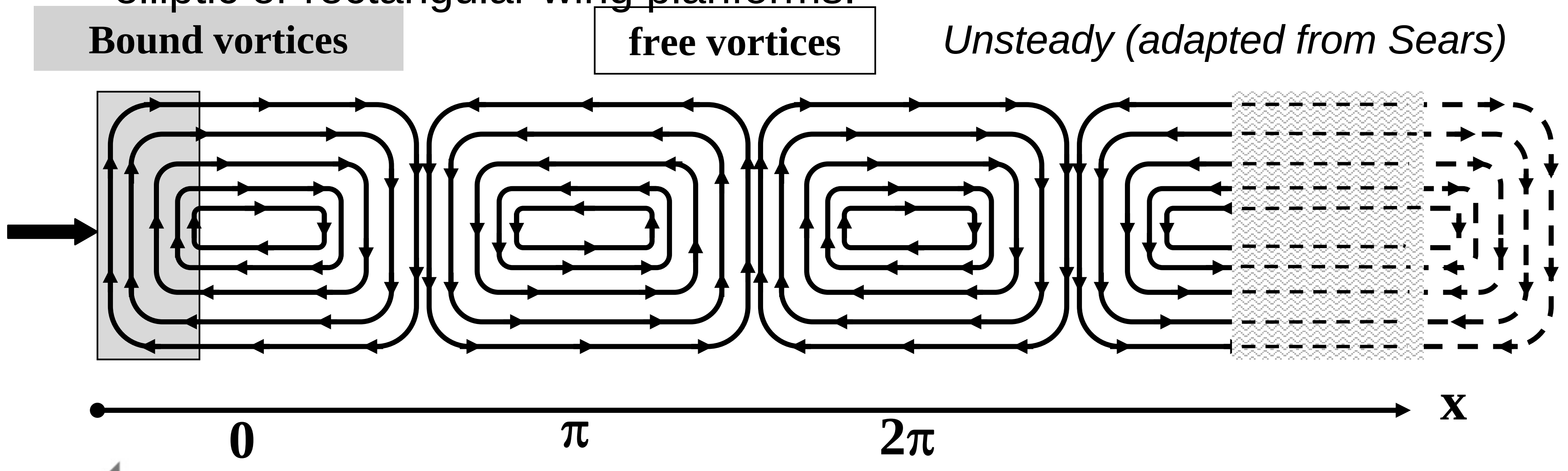
- Wings with aspect ratio (= area/chord) values < 5, esp. Tailplanes
- swept wings

Oscillating 3D Wings – a great Challenge

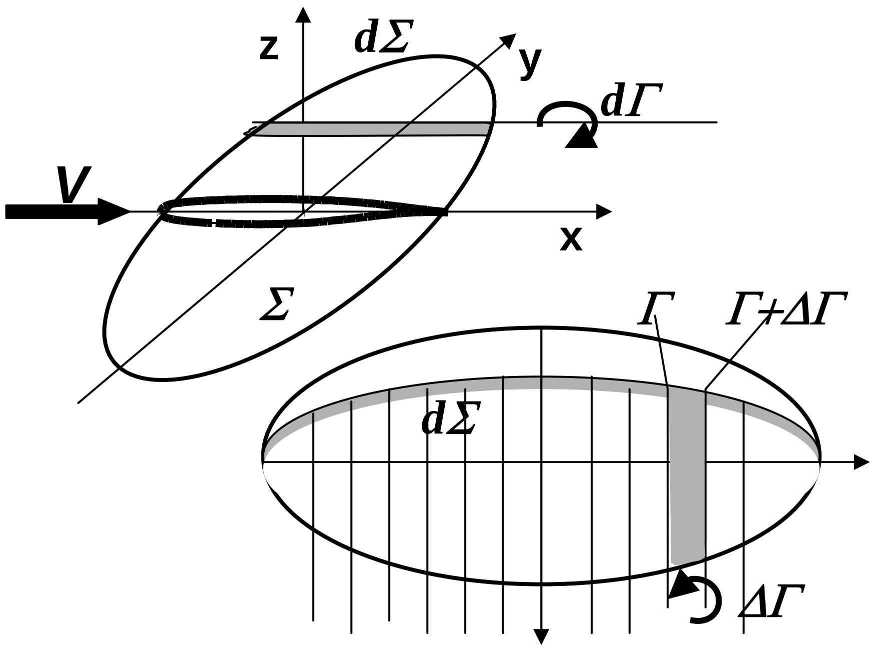
Mathematical modelling and computation of the system of interacting bound and free vortices with spanwise varying strength was a complicated task, and resulted in different approximate methods of Italian, German, British and American researchers :

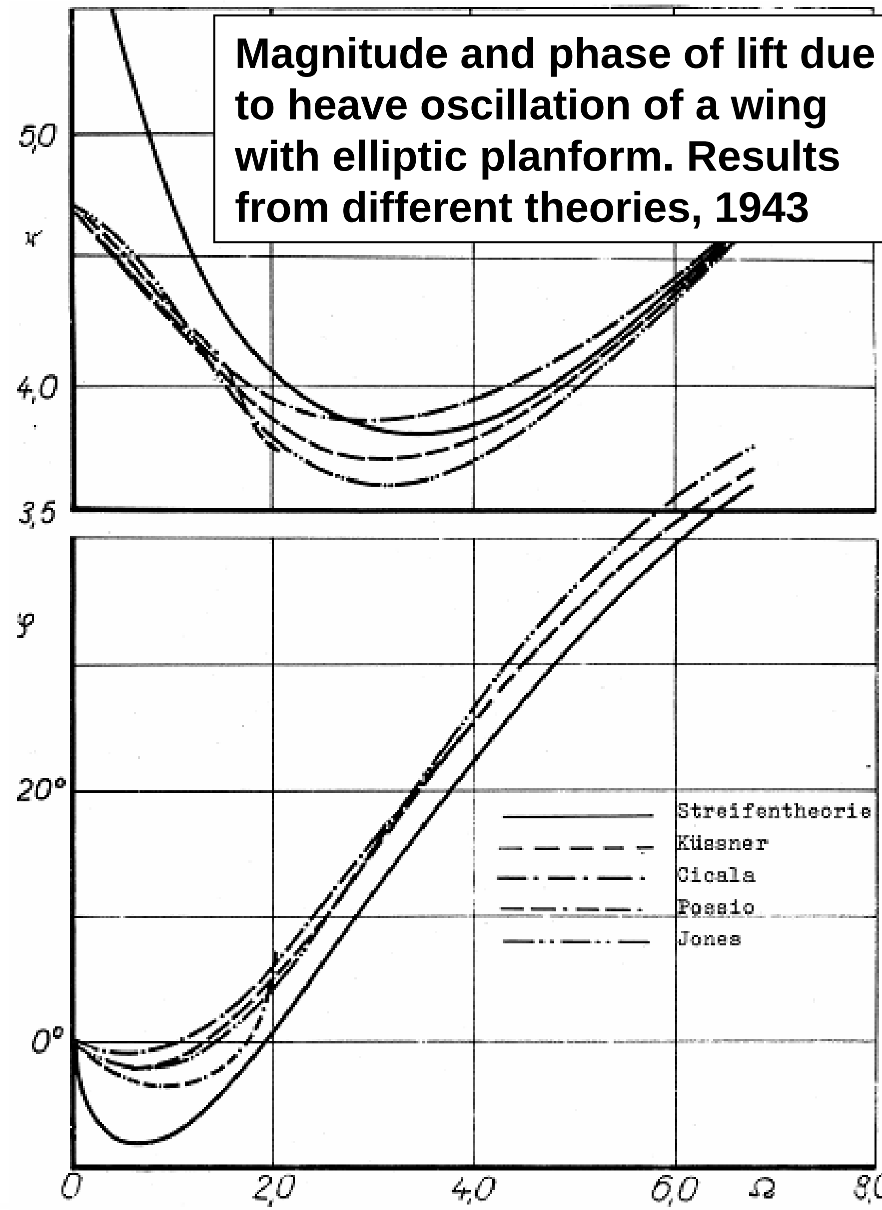
Cicala, **Possio**, Küssner, Sears, Jones (1935-1940).

Incompressible Flow (Laplace –equation, vortex singularities), elliptic or rectangular wing planforms.



Possio's unsteady 3D Theory

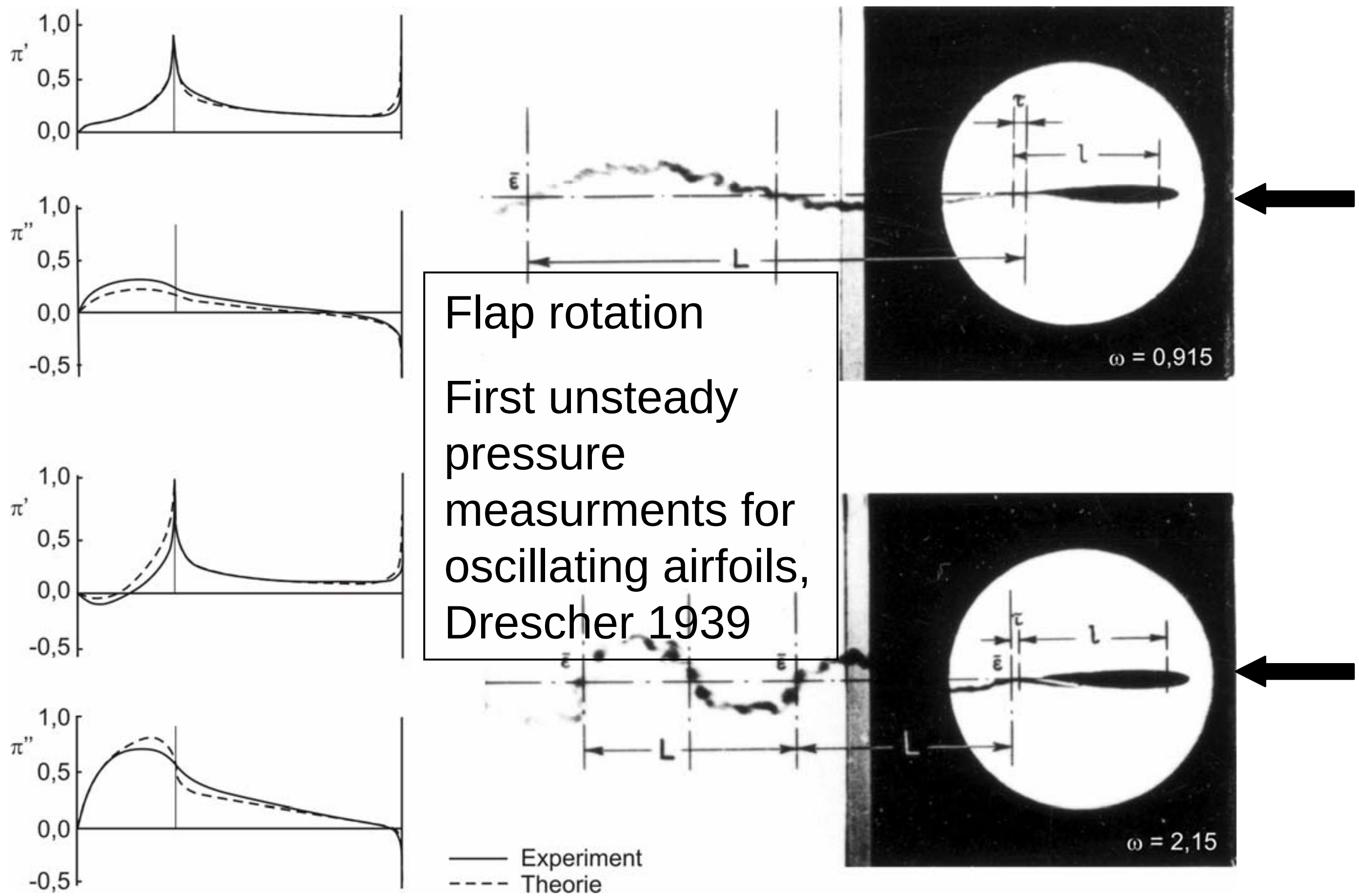




Magnitude and phase of lift due to heave oscillation of a wing with elliptic planform. Results from different theories, 1943

Possio modelled bound and free vortices separately by vortex distributions (<u>incompressible flow</u>) $\gamma(\xi,\eta)$, the strength of which is series expanded in trigonometric series in *x* and *y*, and the oscillation velocity w as well. Choice of an <u>elliptic planform</u> simplified numerical spanwise integration.

Validation of incompressible unsteady aerodynamic theories - Watertunnel measurements of unsteady pressures



Flap rotation

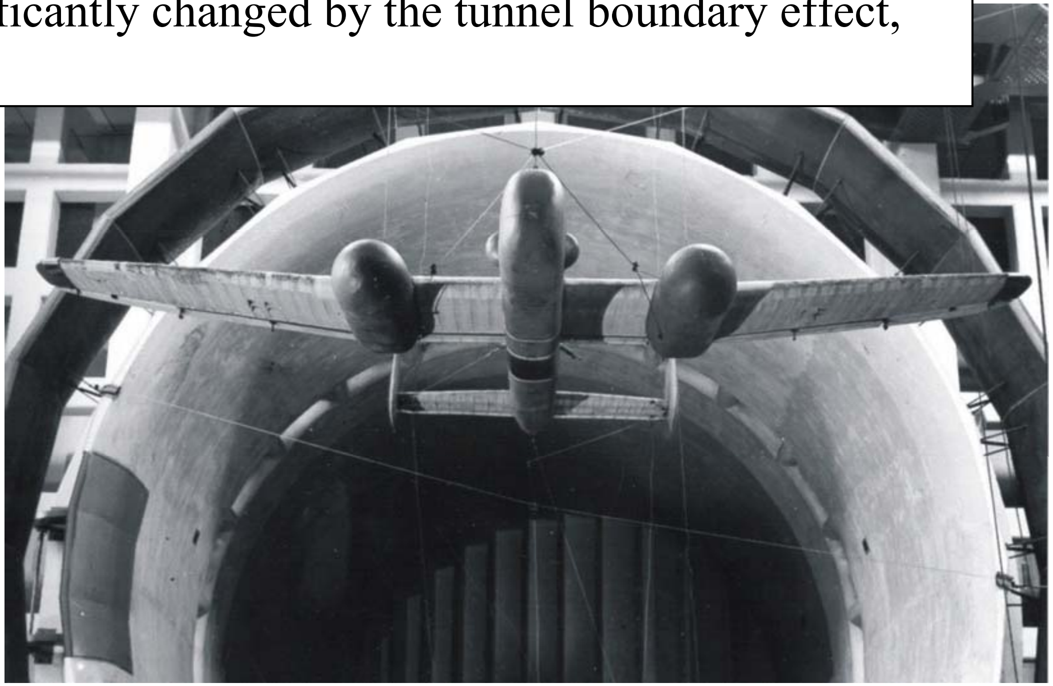
First unsteady pressure measurments for oscillating airfoils, Drescher 1939

C. Possio's work on Windtunnel Wall Interference

C. Possio demonstrated that for an oscillating wing model disturbances from windtunnel walls are decreasing with frequency like $1/\omega$.

For two types of wind tunnel boundaries (solid walls and free jet) he calculated the tunnel boundary effects. For the case of an finite wing of span 6 and elliptical planform, pitching oscillations of the wing model (full span $2b$ of the wing was 50% of the diameter D of the circular test section), $\omega^* = 2 \pi f b / (2 V) = 0.5$.

unsteady lift coefficient was significantly changed by the tunnel boundary effect, esp. imaginary part.



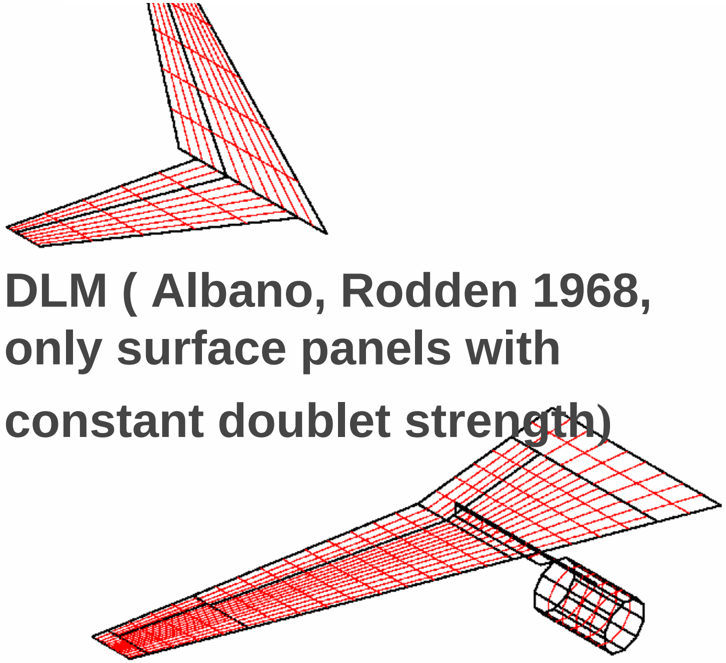
Flutter Model of Ju288 in Braunschweig LFA A3 Windtunnel (1940)

C. Possio's Impact on Küssner's „General Lifting Surface Theory" (1940) for 3D unsteady compressible Flow about oscillating surfaces of general planform

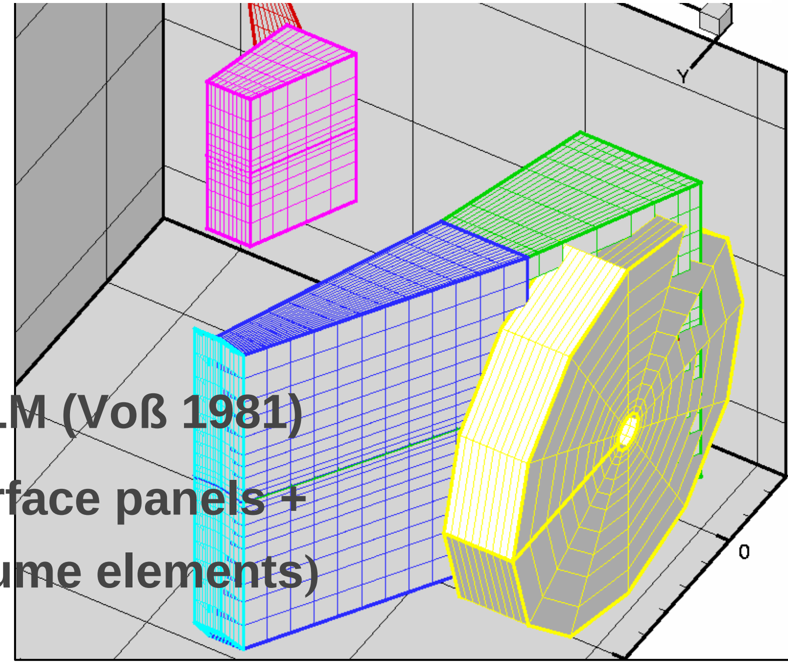
- H.G.Küssner (Göttingen) translated many Italian aeronautical papers, among them 10 of C. Possio, and thus was familiar with Possio's work.
- In 1940 Küssner's General Lifting Surface Theory. Using a Lorentz Transformation and acceleration potential corresponding to Possio's 2D theory, he derived an integral equation relating the unknown load $\Delta p(\xi,\eta)$ on a lifting thin surface and the normal velocity component *w* at any other point (x ,y) of the surface, by means of a new Kernel function *K.* He demonstrated that Possio's equation was the 2D limiting case.
- **This was the key to treat high speed flows, as well as swept and low aspect-ratio wings**.
- Numerical solutions of the general 3D compressible case only after world war II, the most mature and common industrial method appeared in 1969 (Doublet-Lattice Method DLM)

$$w(x,y,z,t)=\frac{1}{4\pi}\iint_S d\xi d\eta \frac{\Delta p(\xi,\eta)}{\rho V} e^{i\omega\frac{(\xi-x)}{V}} \frac{\partial^2}{\partial z^2}\int_{-\infty}^{x-\xi} \frac{e^{i\omega\left(\lambda - Ma\sqrt{\lambda^2+\beta^2(y-\eta)^2+\beta^2 z^2}\right)}}{\sqrt{\lambda^2+\beta^2(y-\eta)^2+\beta^2 z^2}} d\lambda,$$

Extension of Possio's Theory to 3D Compressible and Transonic Flow – Use of Computers



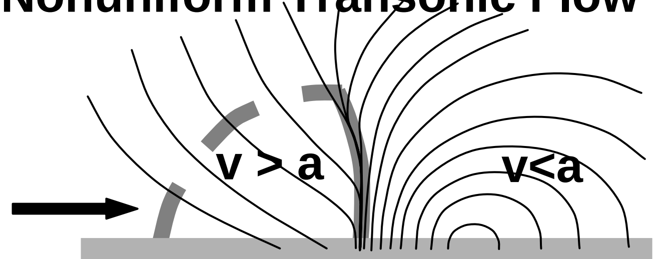
DLM (Albano, Rodden 1968, only surface panels with constant doublet strength)



TDLM (Voß 1981)

(surface panels + volume elements)

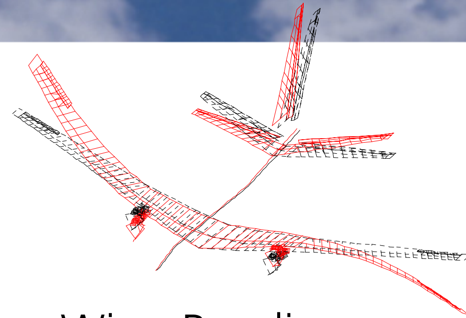
Nonuniform Transonic Flow



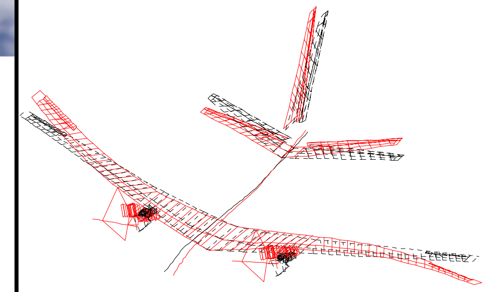
$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}+\lambda^2\psi=\left(\frac{\partial}{\partial x}+i\frac{\omega^*}{\beta^2}\right)\sigma\left[\frac{(\gamma+1)}{\beta^2}Ma^2\frac{\partial\Phi^0}{\partial x}\right]$$

$\Phi^0 = velocity..potential..of..steady..transonic..flow$

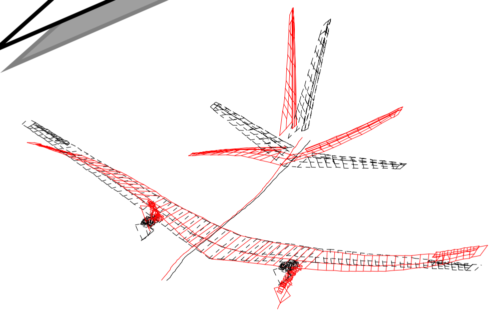
$\sigma = source..distribution..in..flowfield$



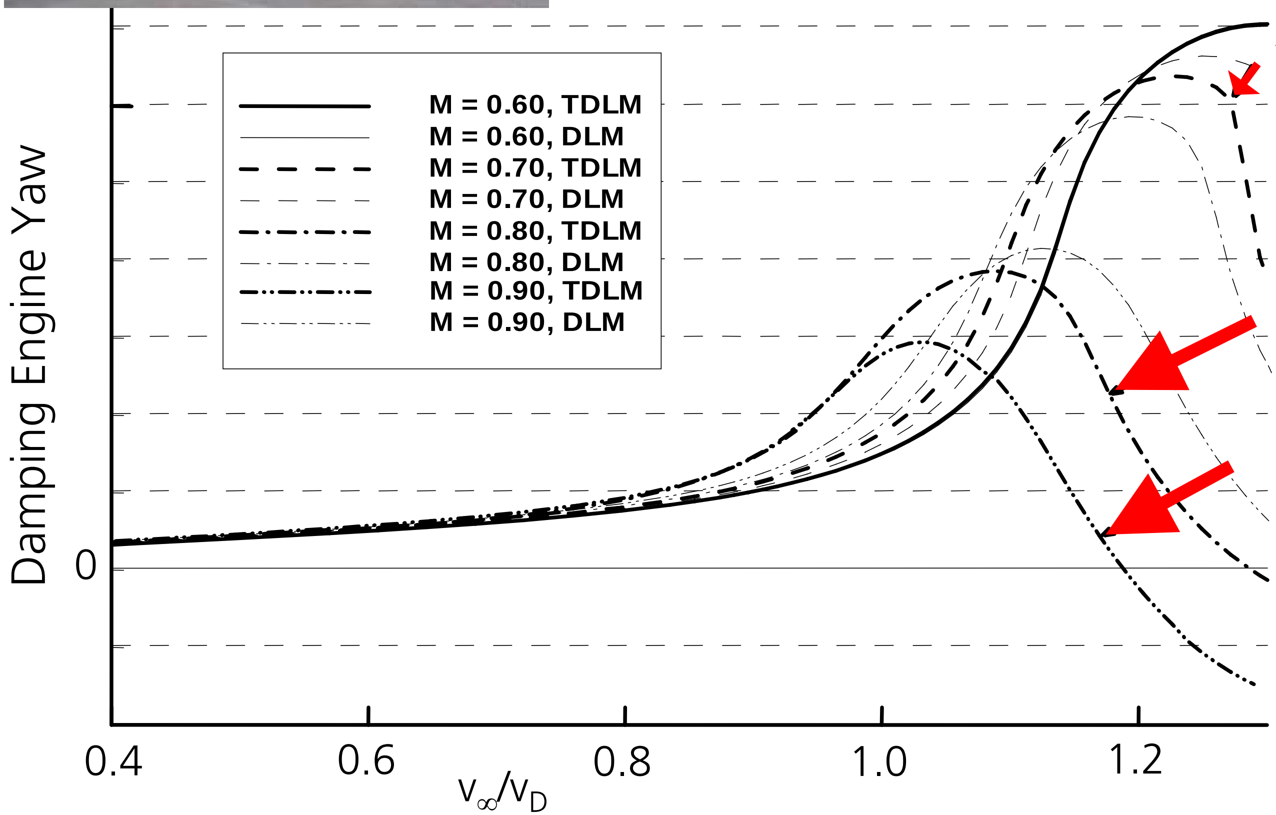
Wing Bending



Engine Yaw



Engine Pitch



TDLM versus DLM applied to DO 728

C. Possio's Work in Fields outside of Aerodynamics

Lateral firing from an airplane (1939) :

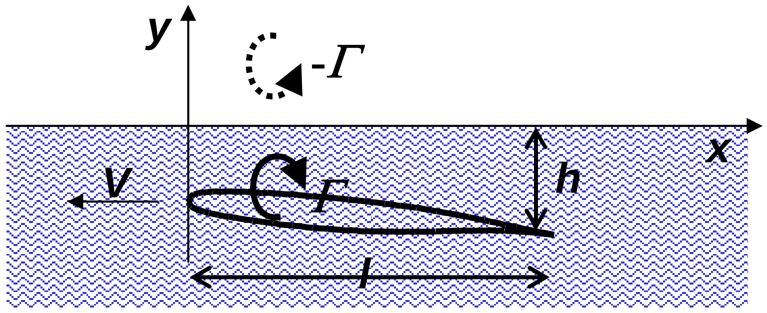
This ballistic problem was probably chosen wrt. Possio's military service. For a projectile fired from board of an aircraft, in a direction different from airplane flight direction, spinning axis and projectile path are not parallel, yielding an aerodynamic angle of attack and thus aerodynamic forces. With elementary mathematical tools C.Possio computes the airloads and the projectiles motion and shows that due to the spinning forces the projectile axis soon turns parallel to its path.

Hydrodynamic problems (1941) : free water surface effects.

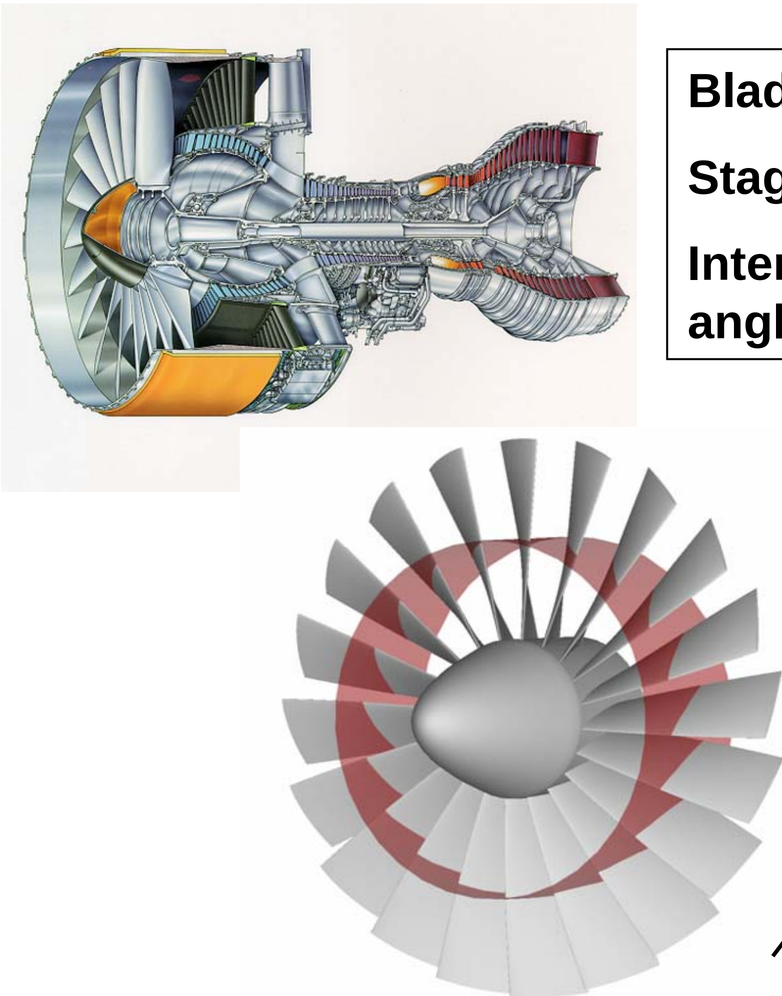
Lift and drag of a 2D hydrofoil. The inviscid incompressible irrotational flow is governed by the Laplace equation for the velocity potential. The effect of the free water surface is modelled as a linear perturbation, governed by Laplace equation too. He computes this perturbation using the constraints that the additional velocity has to vanish at infinite distance from the hydrofoil, and that pressure on the water surface has a constant value. The hydrofoil is modelled by a (chordwise) vortex (distribution), the disturbance potential by additional point vortices.

$$c_L = \frac{2\pi\alpha}{1+2/\lambda}, \ldots and \ldots c_D = \frac{c_L^2}{\pi\lambda},$$

$$\lambda = 2h\frac{\exp(2\beta)}{\beta\pi}, \ldots with \ldots \beta = \frac{gh}{V^2}$$



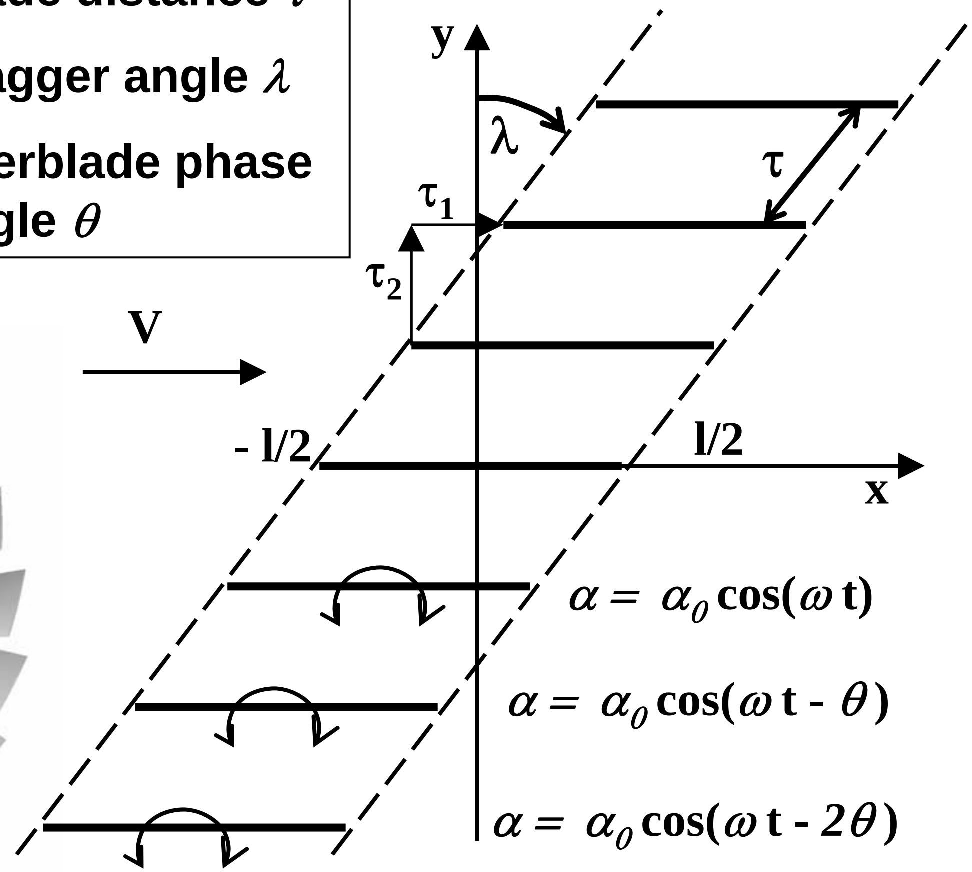
Extension of Possio's Equation to 2D turbomachine cascades – fan flutter



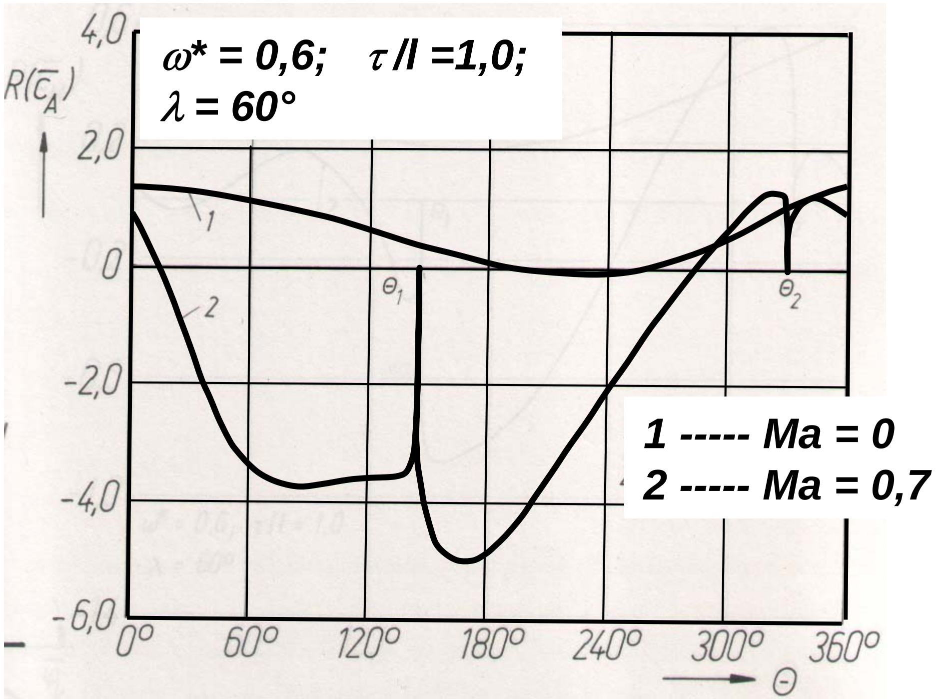
Blade distance τ

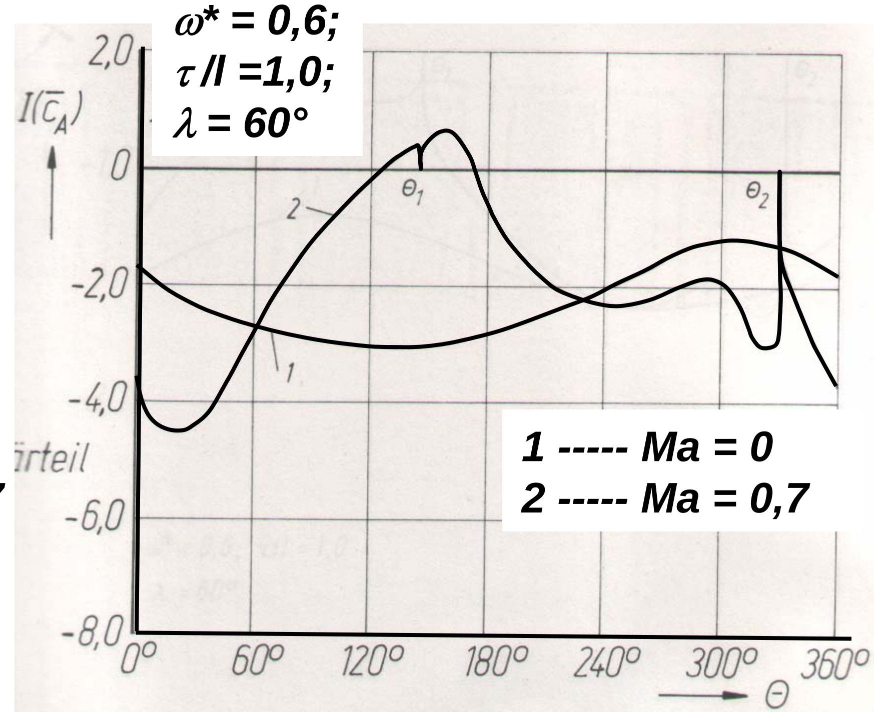
Stagger angle λ

Interblade phase angle θ



Possio‘s Equation for 2D plane cascade – influence of interblade phase angle θ on unsteady lift, Resonances





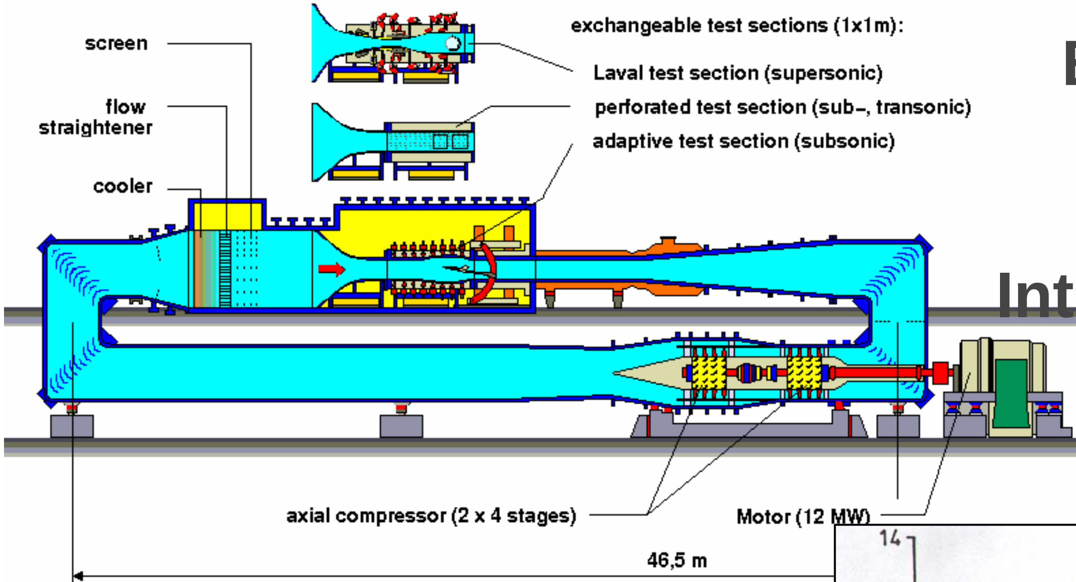
Adapted from

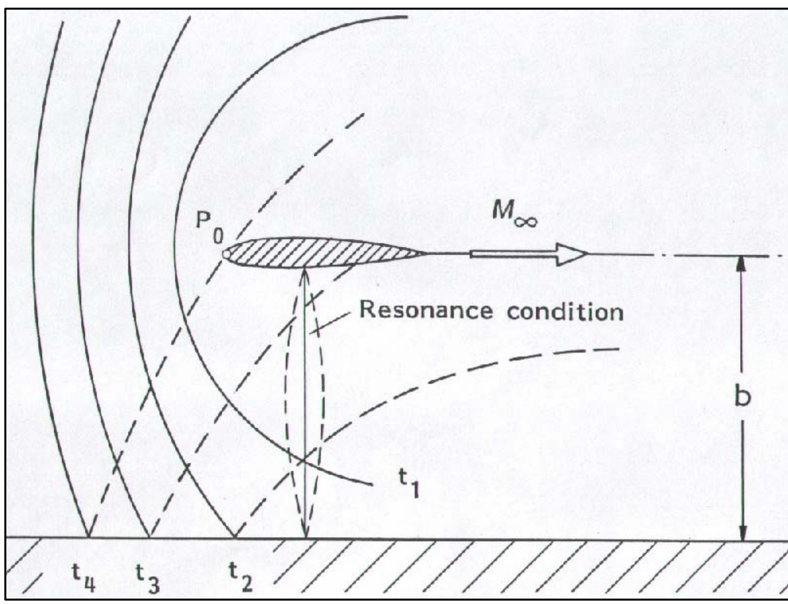
V. Carstens 1973

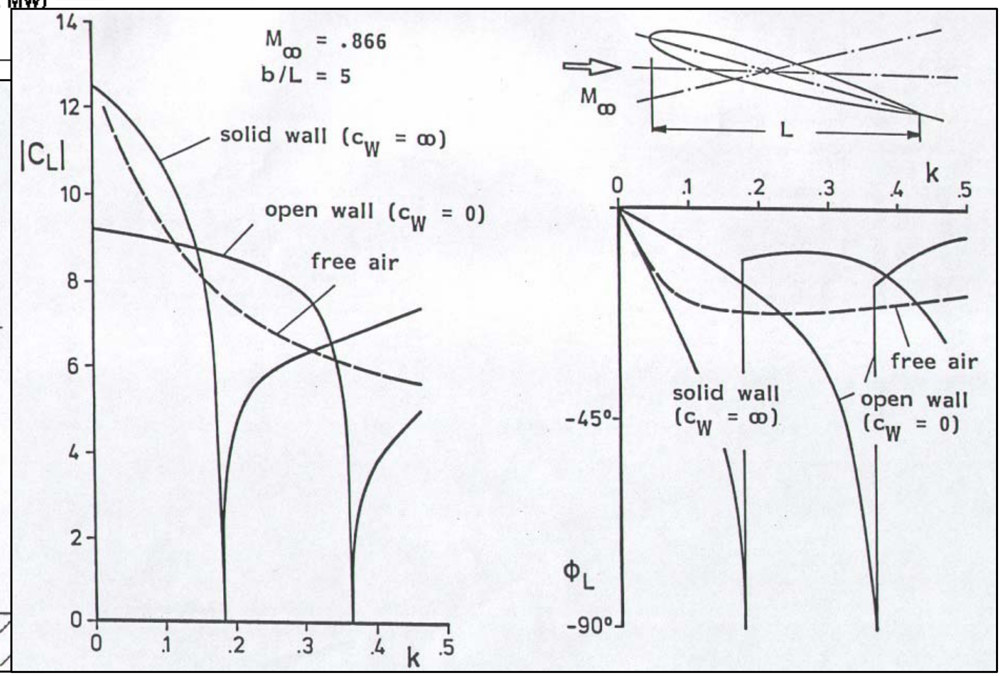
$$w(x) = \frac{\omega}{\rho V^2} \int_{-b}^{b} \Delta p(\xi) K\left(Ma, n, \lambda, \tau, \theta, \frac{\omega^*(x-\xi)}{b} \right) d\xi,$$

Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

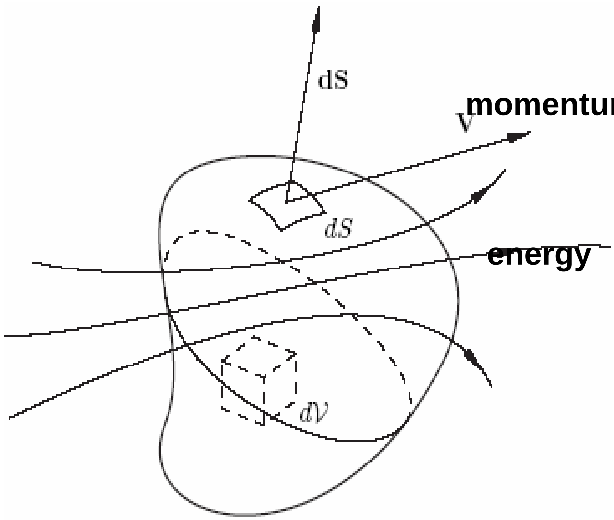
Extension of Possio's Theory for 2D Windtunnelwall Interference on oscillating airfoils







Current Status



mass

$$\frac{\partial}{\partial t}\iiint_{\mathcal{V}} \rho \, d\mathcal{V} + \iint_{S} \rho \mathbf{V} \cdot \mathbf{dS} = 0$$

momentum

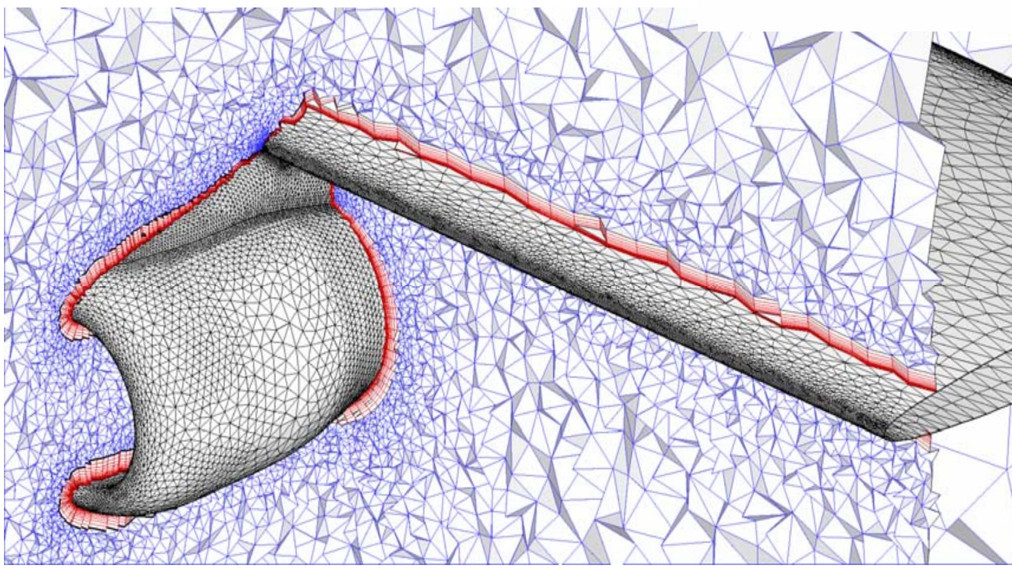
$$\frac{\partial}{\partial t}\iiint_{\mathcal{V}} \rho \mathbf{V} \, d\mathcal{V} + \iint_{S} (\rho \mathbf{V} \cdot \mathbf{dS})\mathbf{V} = -\iint_{S} p \, \mathbf{dS} + \iint_{S} \underline{\underline{\tau}}\mathbf{dS} + \iiint_{\mathcal{V}} \rho \mathbf{f} \, d\mathcal{V}$$

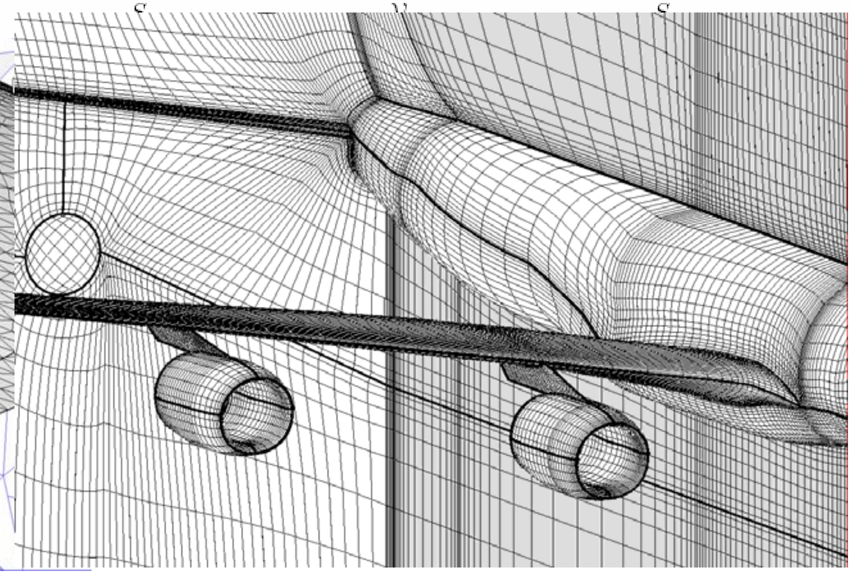
energy

$$\frac{\partial}{\partial t}\iiint_{\mathcal{V}} E\rho \, d\mathcal{V} + \iint_{S} E(\rho \mathbf{V} \cdot \mathbf{dS}) =$$

$$\iiint_{\mathcal{V}} \dot{q}\rho \, d\mathcal{V} + \iint_{S} \kappa \nabla T \cdot \mathbf{dS}$$

$$-\iint_{S} \mathbf{V} \cdot (p \, \mathbf{dS}) + \iiint_{\mathcal{V}} \mathbf{V} \cdot (\rho \mathbf{f} d\mathcal{V}) + \iint_{S} \mathbf{V} \cdot (\underline{\underline{\tau}} \, \mathbf{dS})$$





Current Flutter Simulation : Staggered Coupling Schemes

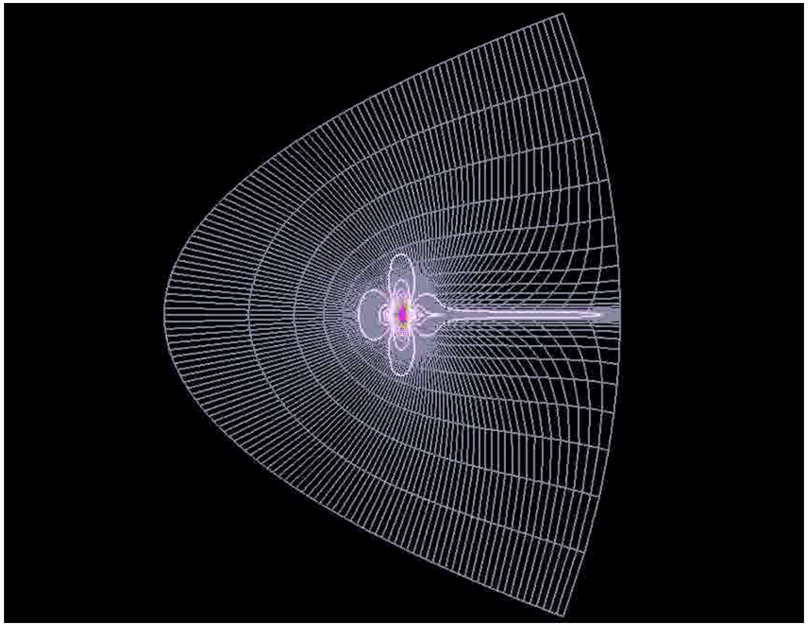
$$\underbrace{\begin{bmatrix} m & S_\alpha \\ S_\alpha & I_\alpha \end{bmatrix}}_{\mathbf{M}} \ddot{\mathbf{u}} + \underbrace{\begin{bmatrix} D_h & 0 \\ 0 & D_\alpha \end{bmatrix}}_{\mathbf{D}} \dot{\mathbf{u}} + \underbrace{\begin{bmatrix} k_h & 0 \\ 0 & k_\alpha \end{bmatrix}}_{\mathbf{K}} \mathbf{u} = \mathbf{f}$$

Newmark procedure

$$\mathbf{u}_{i+1} = \mathbf{u}_i + \dot{\mathbf{u}}_i \Delta t + \frac{\Delta t^2}{2} \ddot{\mathbf{u}}_i$$

$$\ddot{\mathbf{u}}_{i+1} = \left(\mathbf{M} + \frac{\Delta t}{2}\mathbf{D}\right)^{-1} \left[\mathbf{f}_{i+1} - \mathbf{K}\mathbf{u}_{i+1} - \mathbf{D}\left(\dot{\mathbf{u}}_i + \frac{\Delta t}{2}\ddot{\mathbf{u}}_i\right)\right]$$

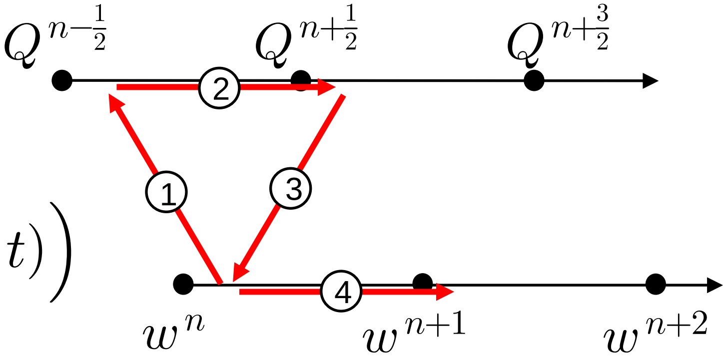
$$\dot{\mathbf{u}}_{i+1} = \dot{\mathbf{u}}_i + \frac{\Delta t}{2}(\ddot{\mathbf{u}}_i + \ddot{\mathbf{u}}_{i+1})$$



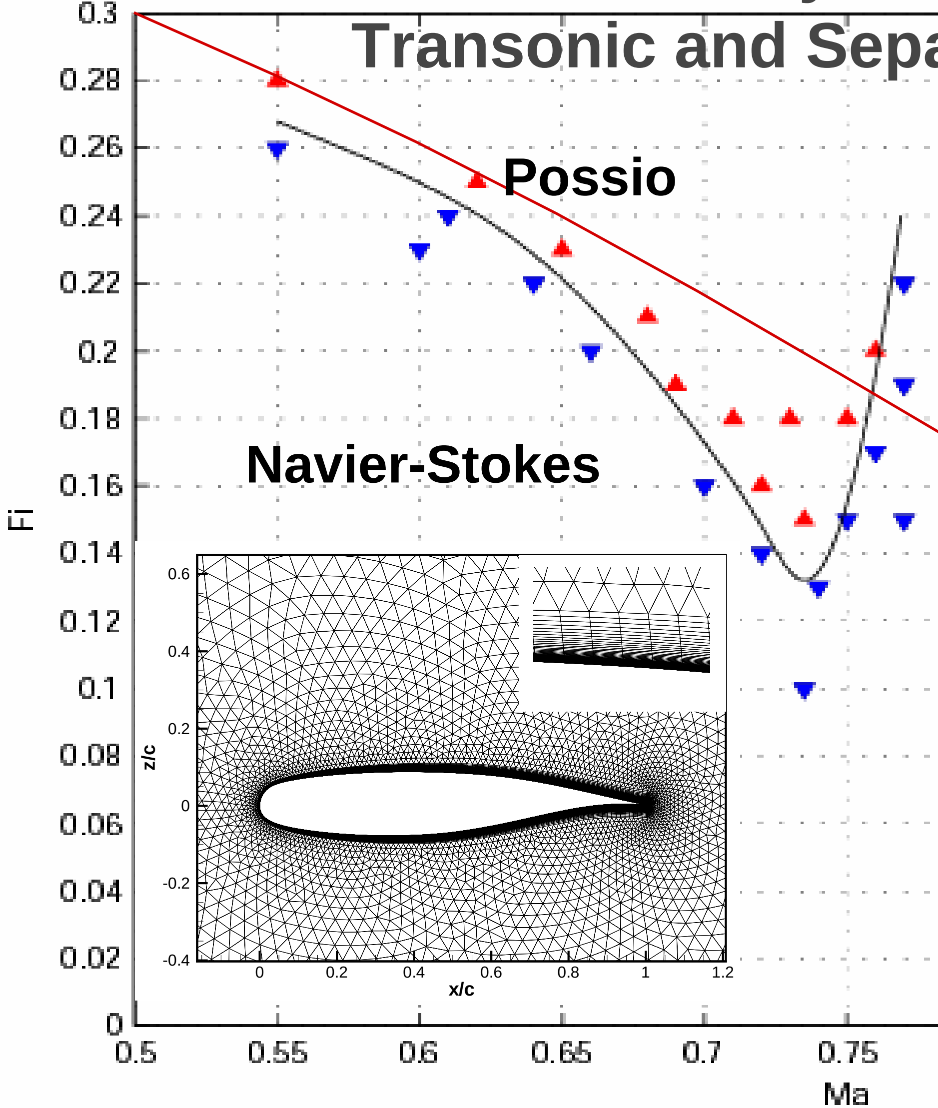
Fluid : $$\frac{d\vec{Q}}{dt} = \vec{R}\left(\vec{Q}(\vec{w}, \dot{\vec{w}}, \ddot{\vec{w}}, t)\right)$$

Structure : $$[M]\ddot{\vec{w}} + [K]\vec{w} = \vec{f}\left(\vec{Q}(\vec{w}, \dot{\vec{w}}, \ddot{\vec{w}}, t)\right)$$

Energy error : $\Delta E \sim (\Delta t)^2$



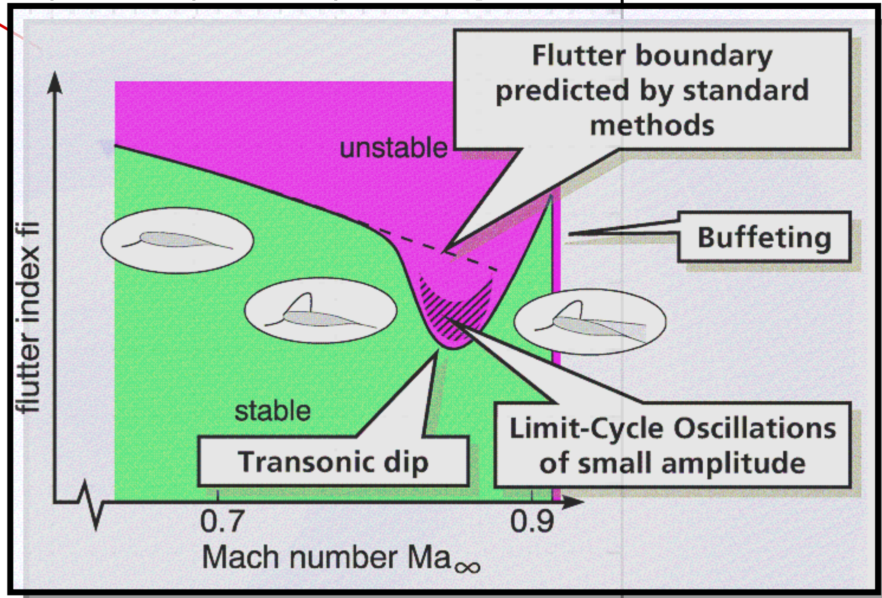
Current Status of Unsteady Aerodynamics : Flutter in Transonic and Separated Flow



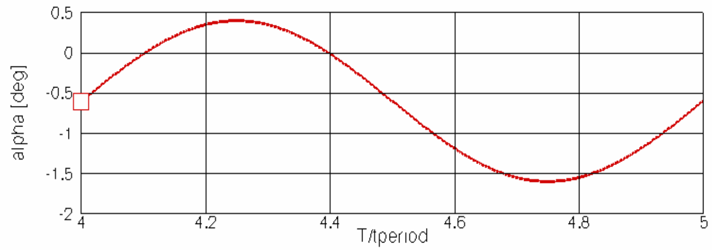
The non-dimensional flutter index

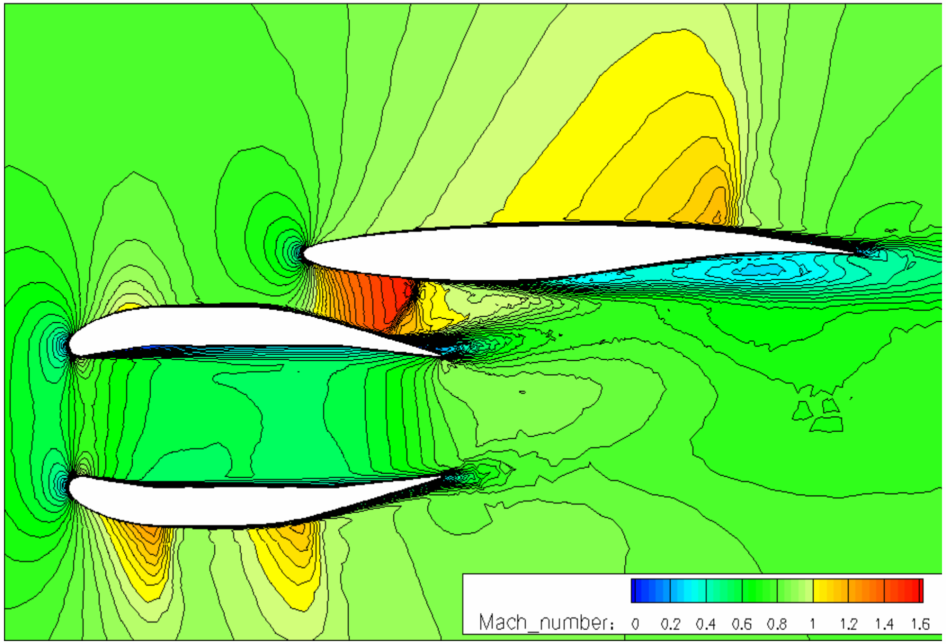
$$Fi = \frac{2V_\infty}{\sqrt{\mu} c \omega_\alpha}$$

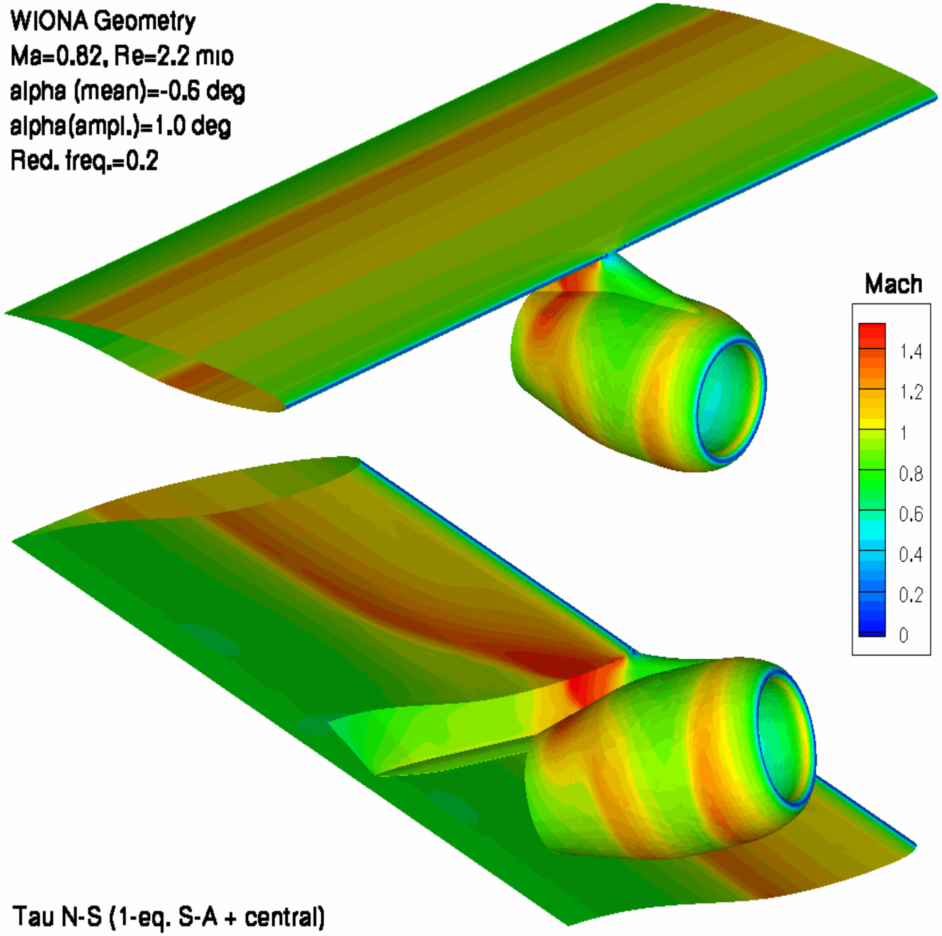
represented versus Mach number



Current Status of Unsteady Aerodynamics : Unsteady Transonic Separated Flow for 3D Configuration

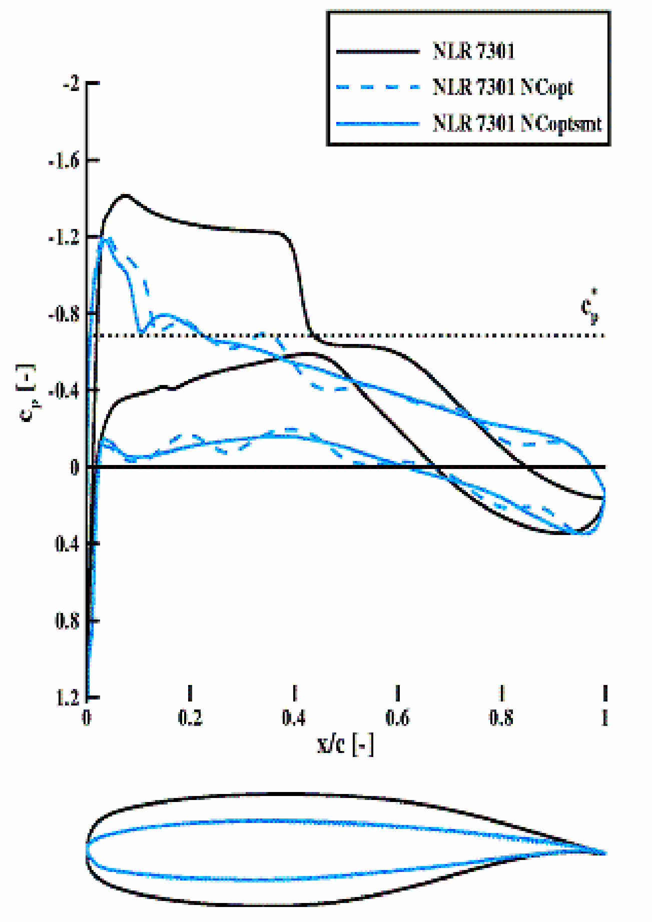




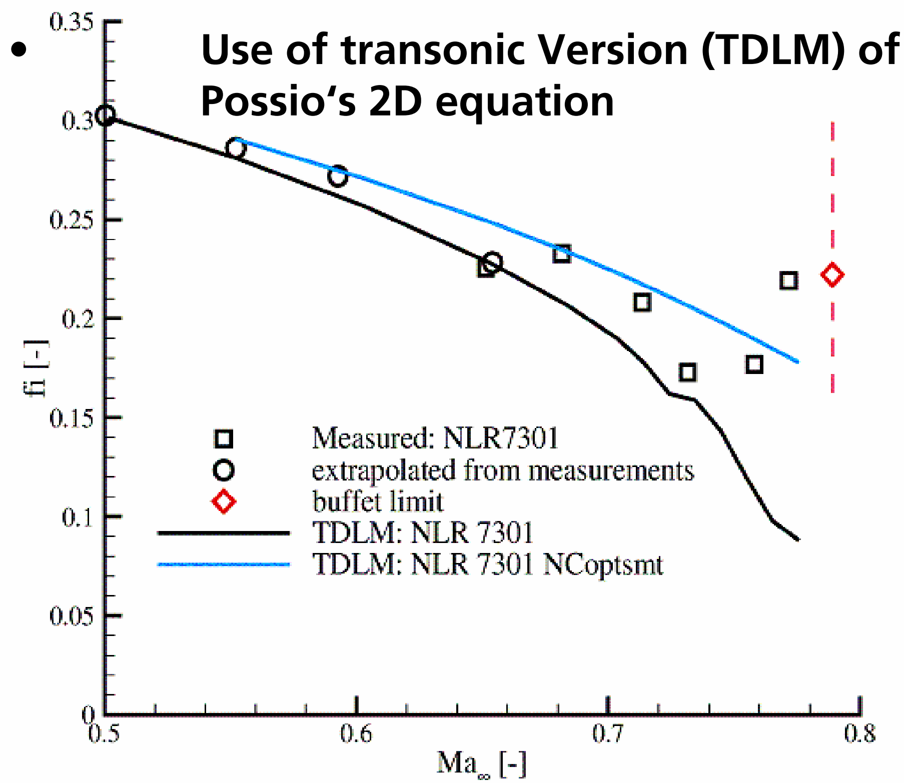


NTPER = 500, NINNER = 40, 16 CPUs, 68 hrs / period !

Current Use of Possio-type methods : **Shape Optimisation with aeroelastic objectives**



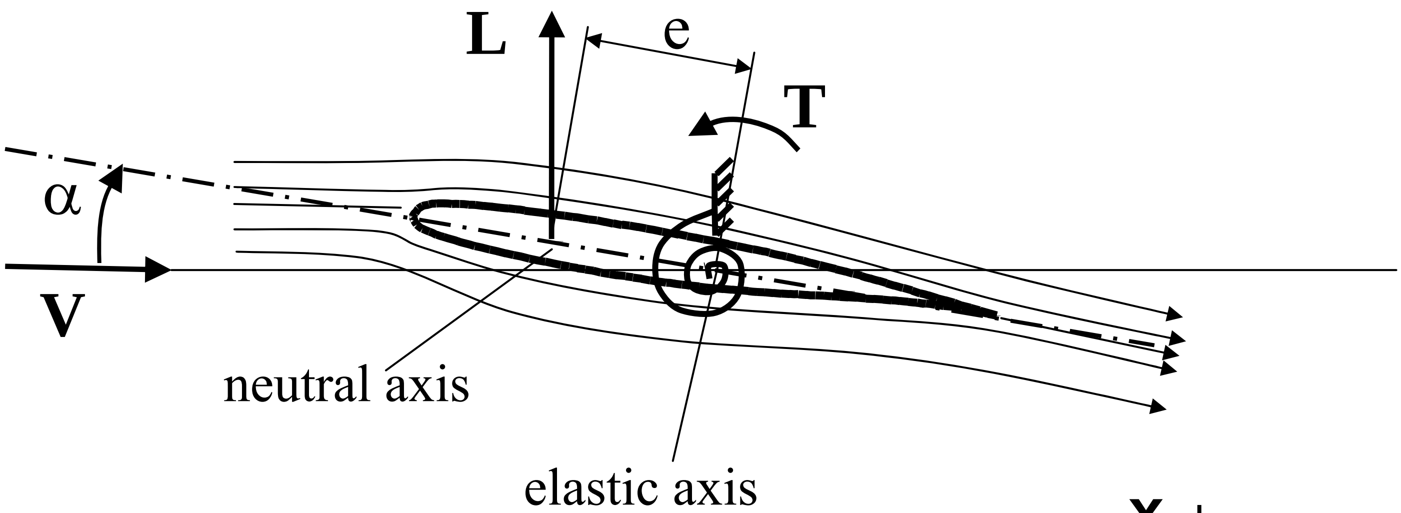
- **Objective : minimised drag and relaxed flutter boundary**
- **Constraint : lift for a given Mach-Reynolds number combination**
- **Use of transonic Version (TDLM) of Possio's 2D equation**

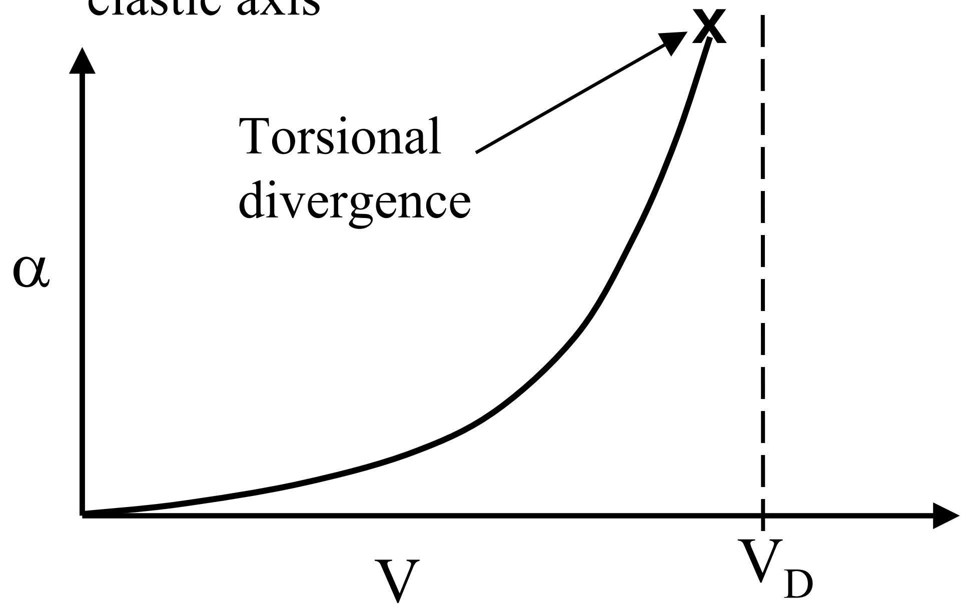


Conclusion

- Camillo Possio‘s work is today still relevant, solutions of „Possio‘s Equation“ are still in use,
- His work in unsteady aerodynamics is worldwide referenced,
- He prepared the path for the development of unsteady aerodynamic standard methods after the war, in high speed up to transonic and supersonic flow,
- He gave sifnificant contributions to other fields than unsteady aerodynamics,
- He was a brilliant mathematician and engineer, because he combined physical understanding, mathematical modelling of essential phenomena and complex numerical analysis,
- He had only 7 years time for research, but had a high impact on aeronautic research and technology. He probably would have become one of the greatest aerodynamicists.

Static aeroelastic problems :Torsional Divergence





Camillo Possio's scientific papers

- 1937 Sul moto razionale dei gas, *Atti Accad. Naz. Lincei,*
- 1937 Sul problema della regolazione indiretta, *Ric Ingen*
- 1937 L'azione aerodinamica sul profile oscillante alle velocita ultrasonore, *Pontifcia Accademia Scientiarium Acta*
- 1938 L'azione aerodinamica sul profilo oscillante in un fludio compressible a velocita iposonara. *L'Aerotechnica*
- 1938 L'azione aeodinamica su una superficie portante in moto oscillatorio. *Atti Accad. Naz. Lincei,*
- 1938 Determinazione dell'azione aerodinamica corrispondente alle piccolo oscillazioni del velivolo. *L'Aerotechnica*
- 1939 Sul moto non stazionario di una superficie portante. *L'Aerotechnica*
- 1939 Sul moto non stazionario di un fludio compressible. *Atti Accad. Naz. Lincei,*

Camillo Possio's scientific papers continued

- 1939 L'azione aeodinamica su di una superficie portante in moto vario. *Atti Accad. Scienze Torino*
- 1939 Sulla determinazione dei coefficienti aerdinamici che interessano la stabilita del velivolo.
- 1939 Sullo sparo di fianco da bordo di un aereo. *L'Aerotechnica*
- 1940 Sul problema del moto discuntino di un'ala. Nota 1, *L'Aerotechnica*
- 1940 Sul problema del moto discuntino di un'ala. Nota 2, *L'Aerotechnica*
- 1940 L' interference della galleria aerodinamica nel caso di moto non stazionario, *L'Aerotechnica*
- 1940 Campo di velocita creato da un vortice in un fluido pesante a superficie libera , *L'Aerotechnica*
- 1941 Sulle teoria del moto stazionario di un fluido pesante con superficie libera, *L'Aerotechnica*
- 1943 The influence of the viscosity and thermal conductibility on sound propagation. *Atti Accad. Scienze Torino*