Reflections on the Shape of a Turbomachine

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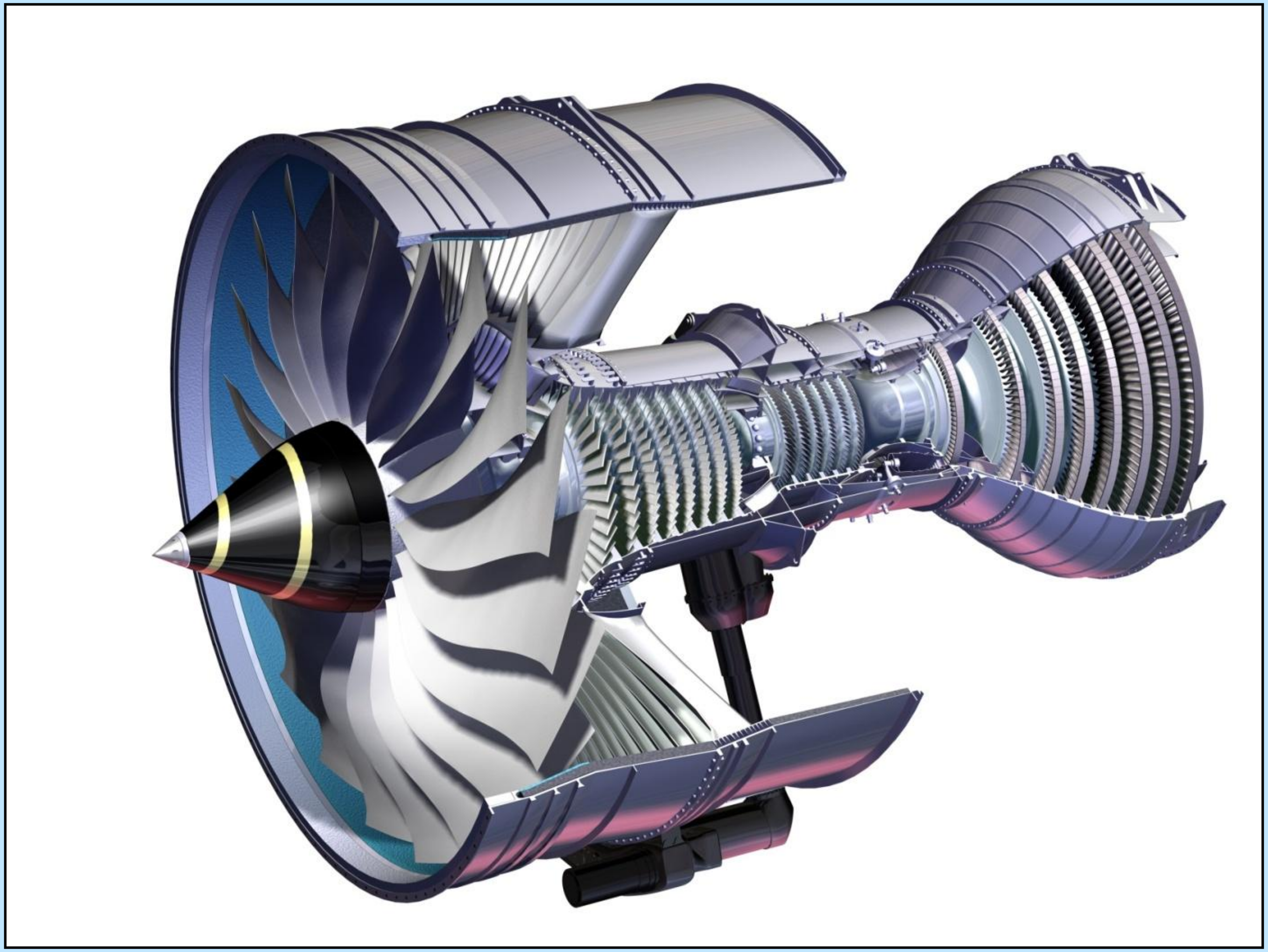
R-R Trent 1000 Engine

We are used to seeing and analyzing axial machines for aero engines. Their shapes may seem to have converged but exciting advances are being made in design techniques.

There is still strong progress to be made for economy and environment from these improvements. Today I would like to take a wider look at opportunities in newer applications where designs have not yet converged.



Hero's Turbine

This 2000 year old turbine is from Hero of Alexandria.

The young engineer, when confronted with an unusual turbomachine like this, should be able to classify it and understand how it operates. Should be able to repair it and maybe re-design it to work better.

turbo – turbinis (L) ___ I spin

I will firstly present a taxonomy of turbomachines. This should permit turbines of widely varying geometry and layout to be identified and classified. The process is illustrated with reference to different configurations of hydraulic and free flow turbines.

Taxonomy

Some Examples

Design Methodology

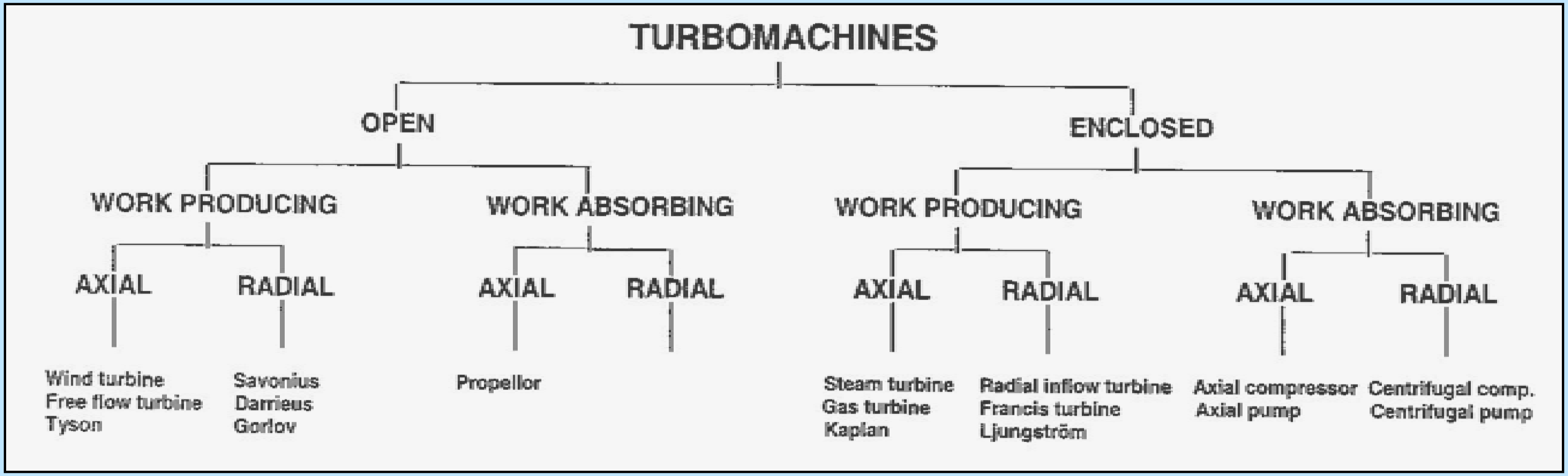
Low Pressure Turbines

Streamwise Vorticity

Blade Sweep

So how do we classify turbomachines?

Taxonomy of Turbomachinery



Does it look cluttered? It is, because we are dealing with a very wide range of machines. Although they operate according to the same fundamental laws the variety of purposes, constraints and geometries is enormous.

To reduce some of the confusion I will remove the work-absorbing machines, such as compressors and pumps, because today we are mainly discussing turbines.

Taxonomy of Turbines

TURBINES

- **OPEN**
  - **AXIAL FLOW**
    - Wind turbine
    - Free flow turbine
    - Tyson
  - **RADIAL / CROSSFLOW**
    - Savonius
    - Darrieus
    - Gorlov
- **ENCLOSED**
  - **AXIAL FLOW**
    - Steam turbine
    - Gas turbine
    - Kaplan turbine
  - **RADIAL / MIXED**
    - Radial inflow turbine
    - Francis turbine
    - Ljungstrom turbine

My experience is with enclosed flow machines so I will explore our learning from those. The question will be "are the techniques for enclosed flow machines applicable to open flow machines?" But the opportunities for open flow ones are exciting so I will set some of that context first. The question for turbines will be "are all the differences in configuration justified, or does it mean that we have not converged on the optimal solution yet?"

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An example from Hawaii

Ingenious Streetlamp Use of a Savonius Rotor

OPEN CROSSFLOW

Use of tidal power is not new.

An example of open crossflow from Suffolk that is over 800 years old

Woodbridge Tidal Mill

A tidal mill has operated on this site since 1170 AD - others since the Romans. Undershot / breast shot water wheel worked for four hours each day, at ebb tide.

OPEN CROSSFLOW

C

Conventional Overshot Water Wheels

Saugus Iron Works near Boston MA

Water wheel technology. Enthusastically adopted in the new world.

OPEN CROSSFLOW

Some Free Flow or ‘Run of the River’ Turbines

Norias on the Orontes River in Hama, Syria. Some date from C4th BC. Combined undershot water wheel and pump.

OPEN CROSSFLOW

River Rance, 240 MW

Brittany, France

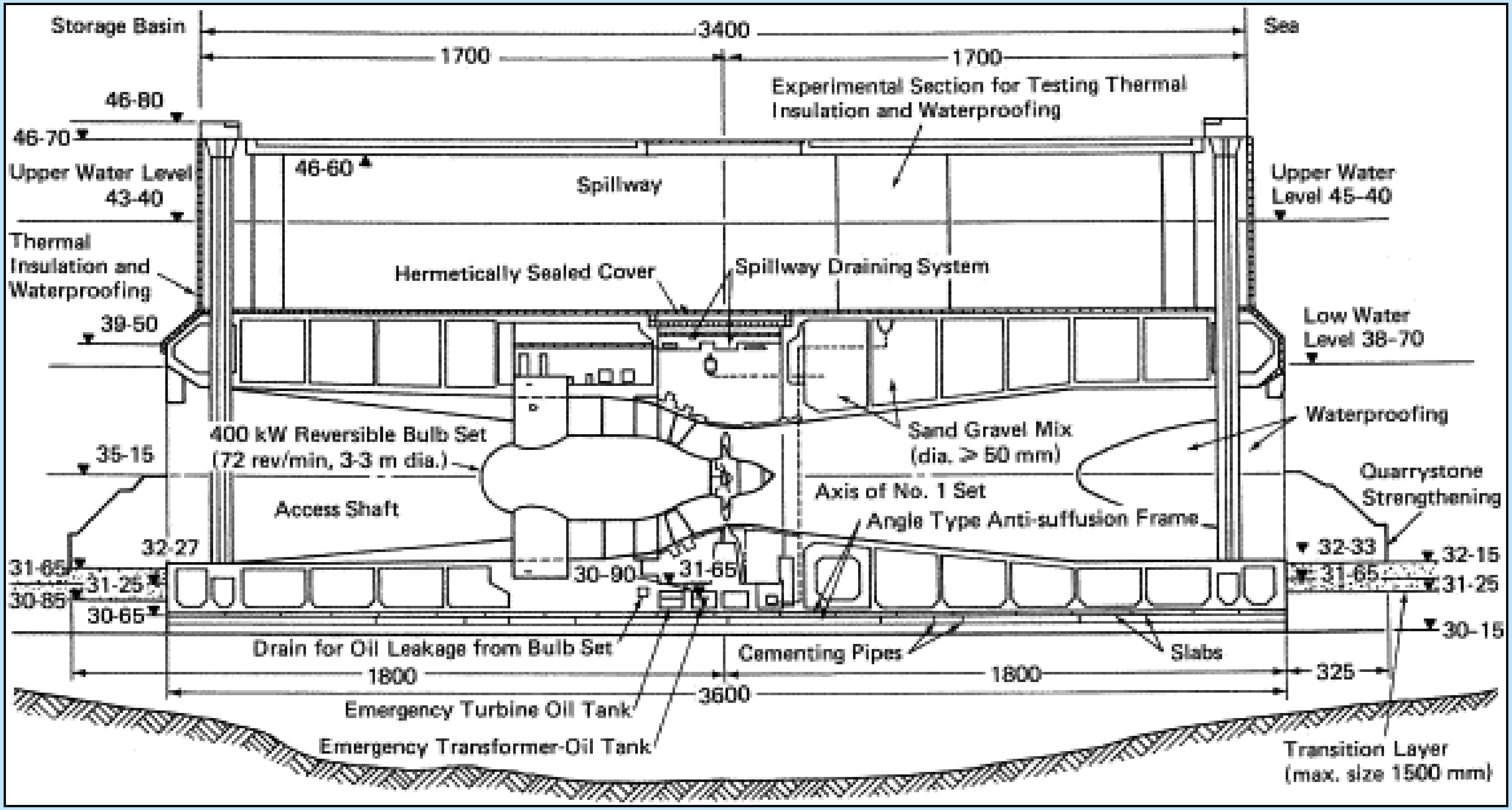
The biggest operating tidal scheme.

Opened in 1966.

ENCLOSED AXIAL

Bulb Turbines

Installed in France and Russia



ENCLOSED AXIAL

Annapolis Royal, 20 MW

Bay of Fundy, Nova Scotia, Canada

Generating station opened in 1984.

DUCTED / ENCLOSED AXIAL

OpenHydro 1 MW Tidal Turbine

Installed on seabed in Bay of Fundy, Nova Scotia. Bi-directional flow.

Canada has the biggest tides in the world; it should succeed with tidal power.

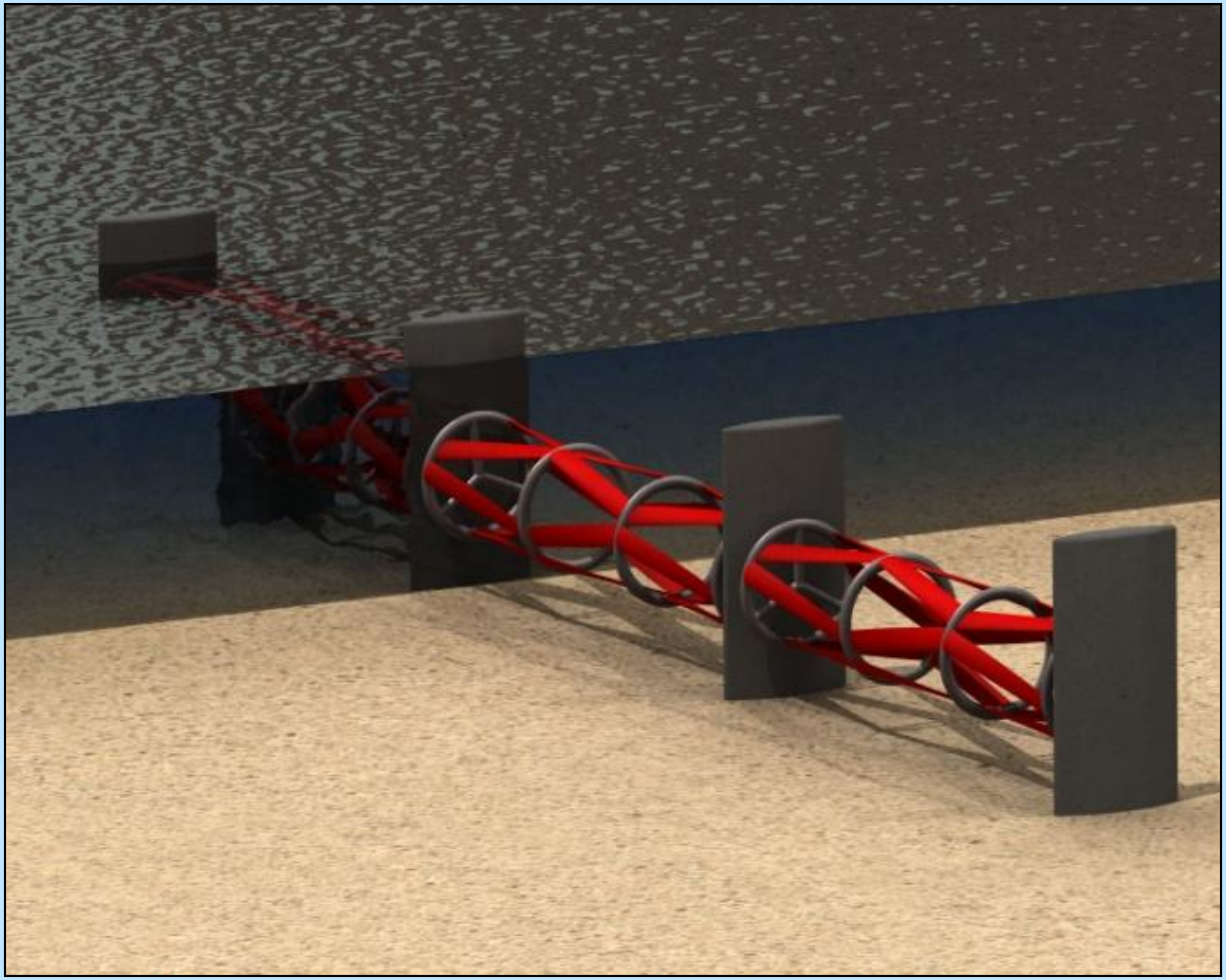
It is also well placed to exploit run of the river turbines.

DUCTED / OPEN AXIAL

Oxford Turbine

Specifically designed for hydro-electric applications in free flowing low head and tidal waters.

Strength comes from triangulated structure.

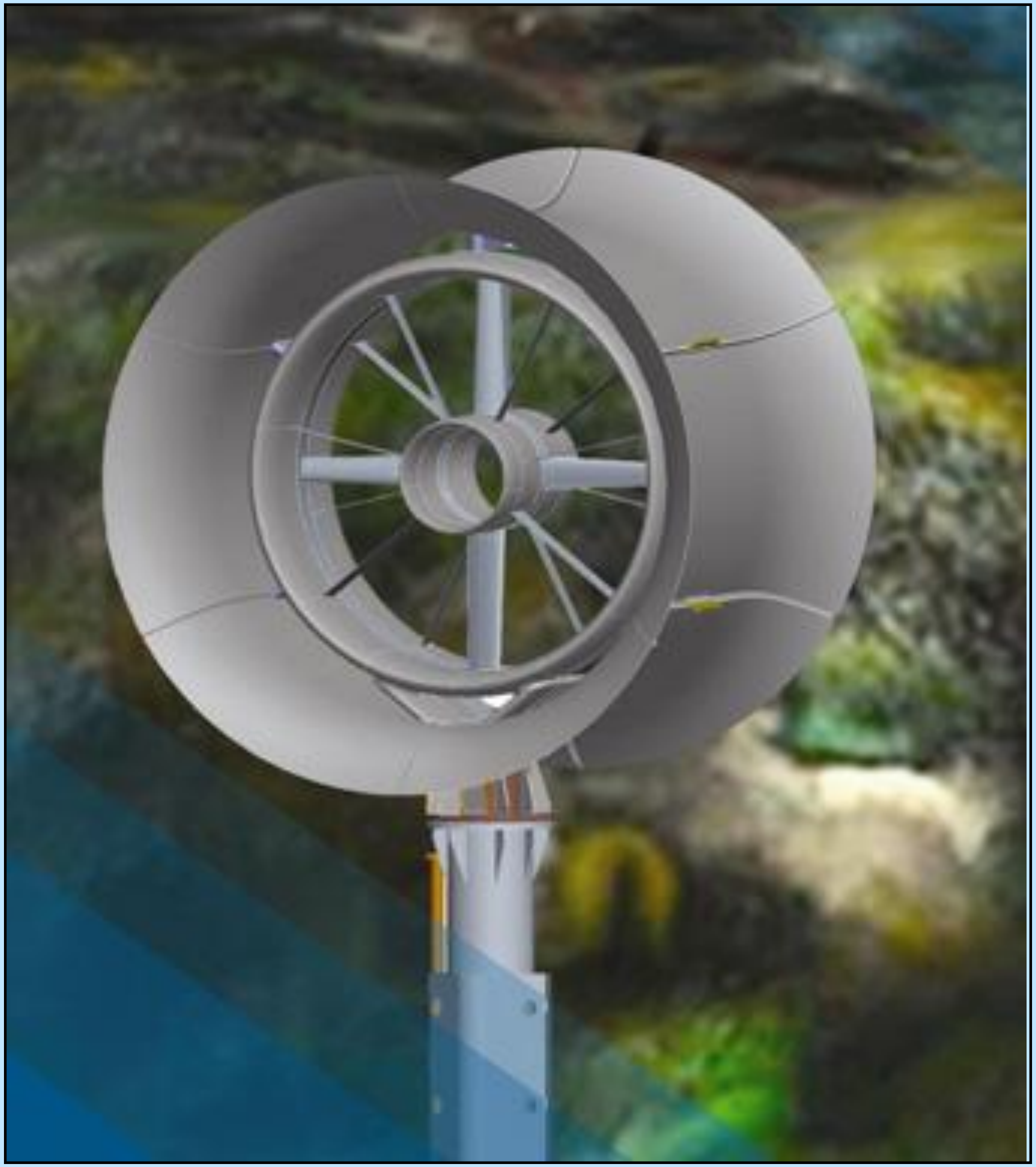


OPEN CROSSFLOW / TRIANGULATED

Clean Current Tidal Turbine

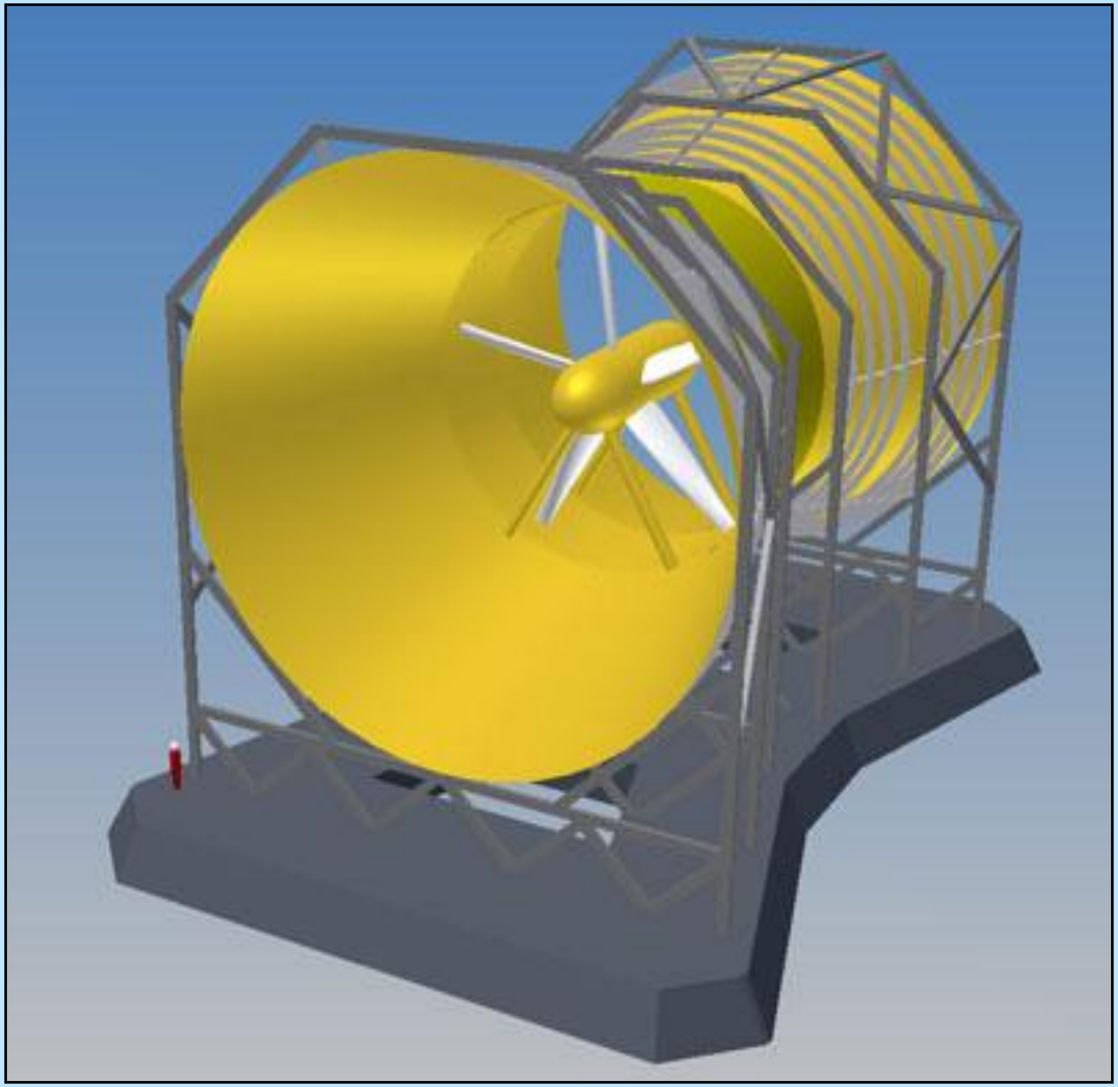
Clean Current's tidal turbine generator is a bi-directional ducted horizontal axis turbine with a direct drive variable speed permanent magnet generator. Over 50% overall efficiency claimed, Simple design that has one moving part - the rotor assembly containing the permanent magnets. No drive shaft or gearbox. Demonstration project at Race Rocks, BC. 1/4 scale, 65 KW turbine, installed 2006, powers lighthouse, weather station and infrastructure.

ENCLOSED (DUCTED)
AXIAL



Lunar Energy

UK-based tidal energy device developer. Bi-directional cone structure with turbine and power conversion components in a removable central cassette. The human figure gives a good sense of the size of tidal turbines. Lunar completed proof of concept testing in the laboratory and is currently building a full scale 1 MW device for installation on Orkney.



ENCLOSED AXIAL

EnCurrent Turbine

Mounted for testing at NRC Institute for Ocean Technology

Builds on VAHT work performed by NRC. Lift generated as water passes over vertical hydrofoils. Based on Darrieus design, turbine captures 40% to 45% of energy in moving water. Suitable for flow velocity of 1.5 to 3.5 m/s.

OPEN CROSSFLOW

Evopod Tidal Turbine

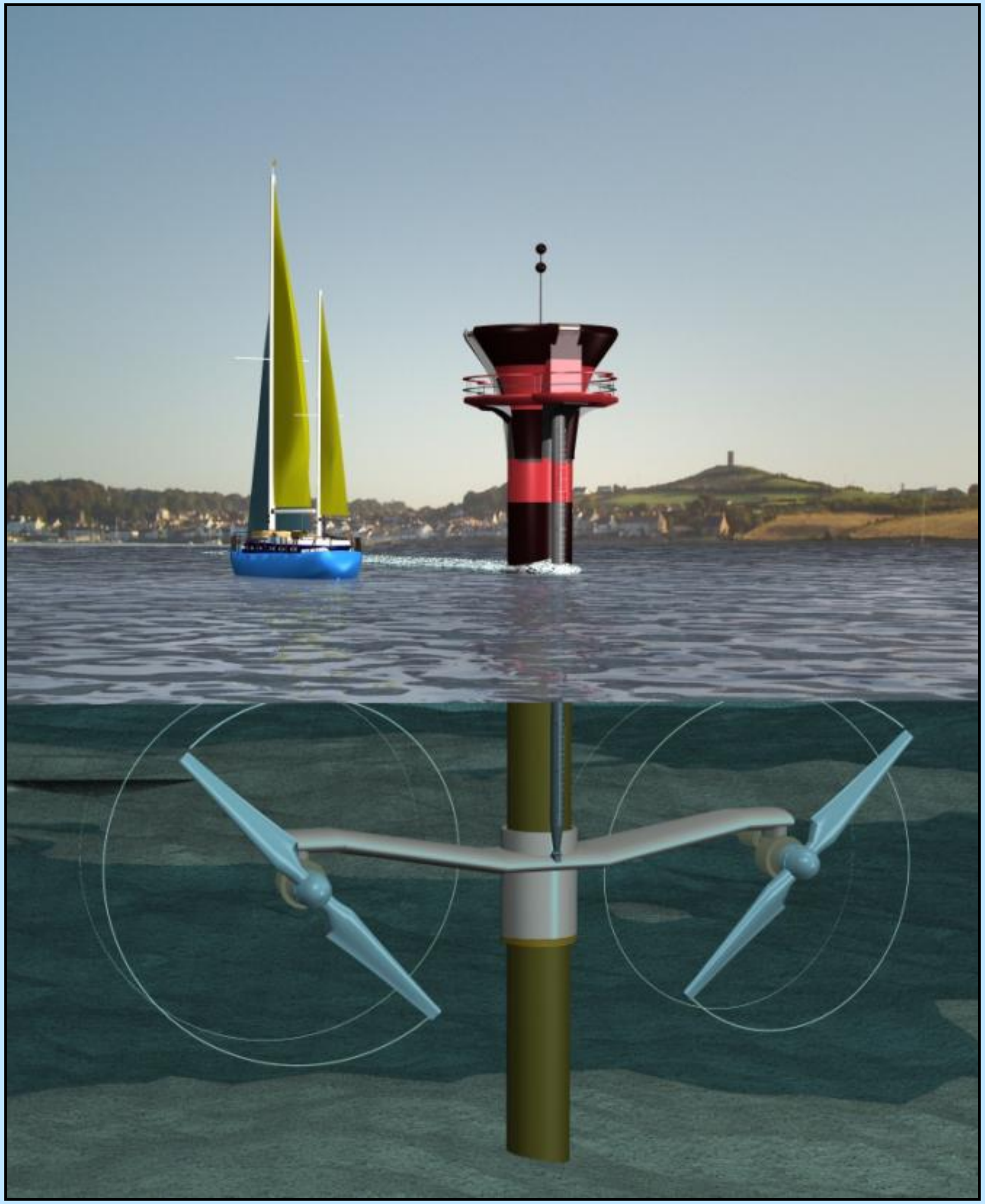
Operates in both ebb and flood tides.

1/40th scale model tested by Newcastle University.

1/10th scale model deployed in Strangford Loch, N. Ireland.

OPEN AXIAL

Marine Current Turbines

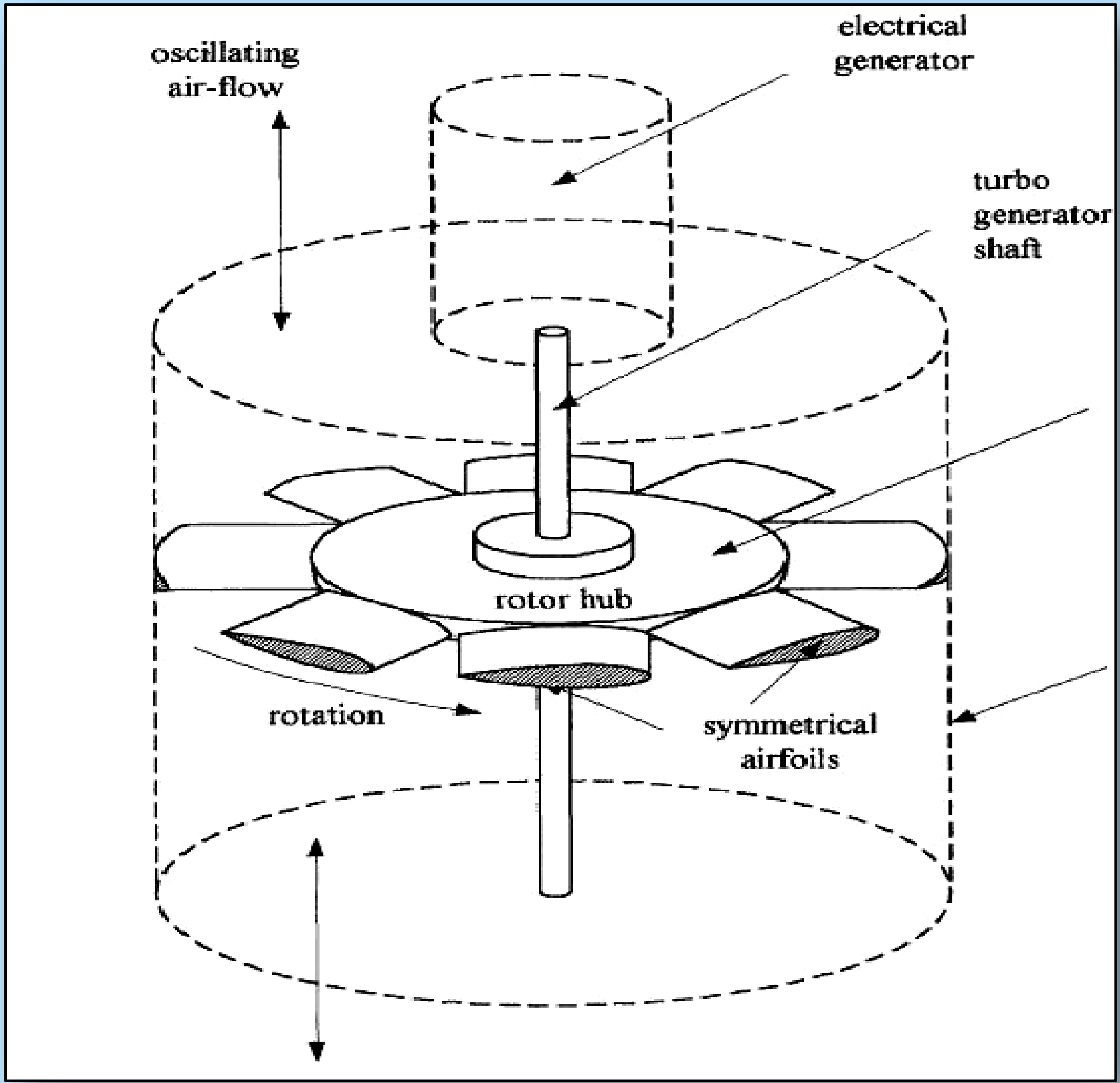


OPEN AXIAL

The Wells Turbine

Specifically designed to capture the oscillating flows of wave energy. Note the zero stagger blading.

CLOSED
AXIAL

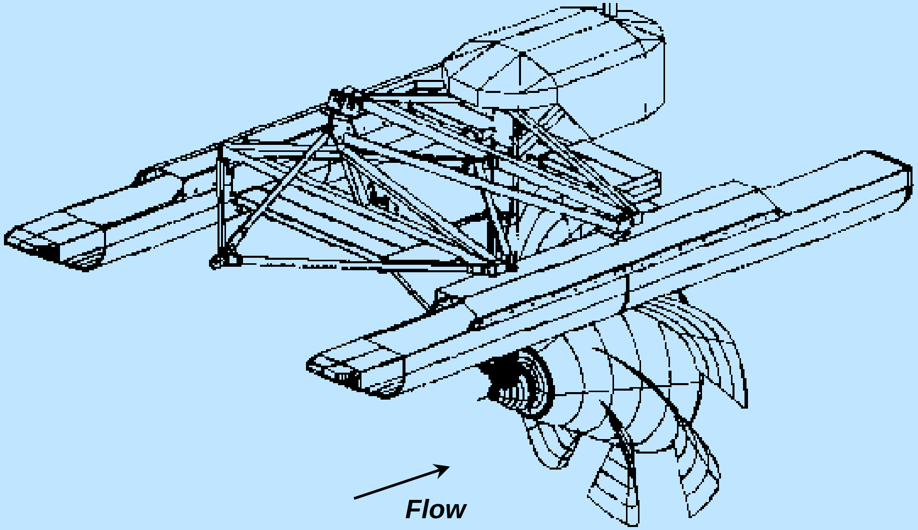


… more Free Flow or 'Run of the River' Turbines

This Garman turbine was designed by the Intermediate Technology Group and is produced by Thropton Energy Services. These systems have been operating for over 20 years and have an output of about 2kW. They are also packaged in a battery charging configuration by Marlec.

OPEN AXIAL

The Tyson Turbine - *from Wagga Wagga, Australia*



Mounted on a floating pontoon platform and usually moored in mid-stream of a flowing river. Both rotating and reciprocating outputs are available from the gearbox. Reciprocating operates a positive displacement pump for water; Rotating drives rotating machinery to provide DC power to charge batteries directly at the riverside or AC for longer distance transmission up to 5 km.

My friend and colleague Alex Revel did good work on this and other turbines. He had a great instinctive feel for the best shape of turbomachine for the job in hand. He died last year and I would like to dedicate this talk to his memory.

OPEN AXIAL

Gorlov Helical Turbine

Designed for hydro-electric applications in free-flowing low head water. Turbine rotates in same direction, independent of flow direction and can be assembled vertically, horizontally or in any other crossflow combination. Common shaft and generator used for an array of multiple turbines. The overlap of the blades twisted around the circumference ensures some of the blade is always at an optimum angle relative to the flow to generate lift. This enables the turbine to spin with minimal cavitation or vibration.

OPEN

CROSSFLOW / HELICAL

Quiet Revolution Helical Turbine

This was atop the Kettleby Cross pub., Melton Mowbray.

OPEN CROSSFLOW / HELICAL

What Shape?

With this great variety of shapes and sizes how does the designer go about selecting the most appropriate for the application? From dimensional analysis the concept of specific speed is useful. This works for pumps or turbines, air or water, and is particularly effective for cavitation avoidance.

The specific speed of a ***pump*** *is given by:* $Ns = N(Q^{1/2}H^{-3/4})$

For a ***turbine*** *the equivalent is:* $Ns = N(P^{1/2}H^{-5/4})$

N is rot. speed, Q is flow, H is head, P is power, p is pressure, v is velocity.

In this way the optimum shape of a turbine can be realised, based on the power output, P, and the head, H. Ranges of Ns are: Pelton 10 – 30, Crossflow 20 – 200, Francis 30 – 400, Propeller and Kaplan 200 – 1000.

Dimensional analysis also gives us the ***cavitation number****; this is a reliable indicator for cavitation avoidance:* $\sigma = (p_{at} - p_v + H)/ (\frac{1}{2} \rho v^2)$

What Specific Speed
do the power and head indicate?

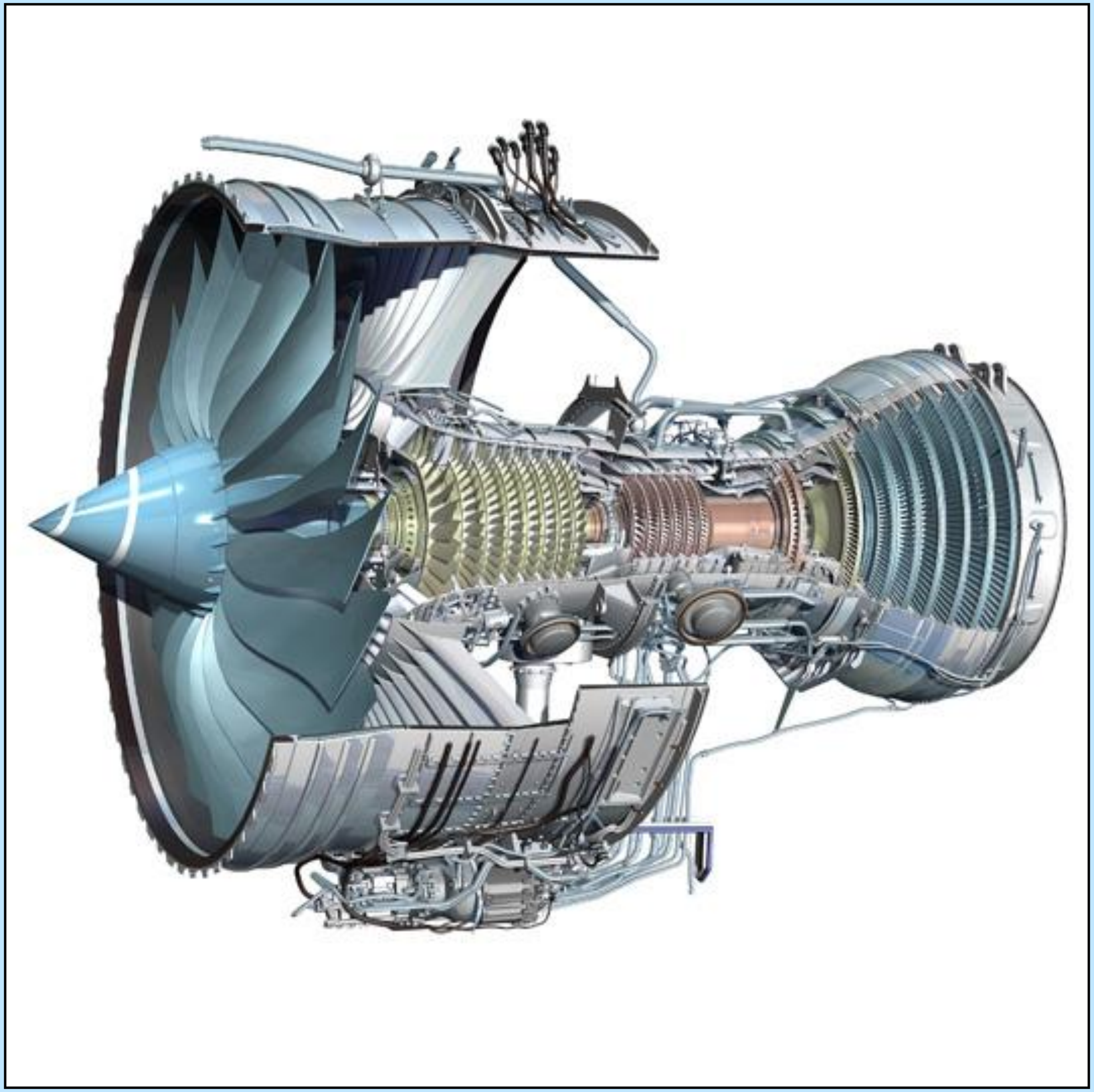
Low Ns, - Pelton Wheel, or high Ns, - Axial Flow Turbine?

Enclosed Axial Flow

Once the general shape of the turbine is established the designer looks for the mathematical design tools to do the job.

The most complete aero design tools have been developed for the enclosed turbines of aircraft engines. These turbines can give 93% efficiency and provide a benchmark.

The author's background is in research and design on enclosed flow turbines for aircraft propulsion. The design framework is introduced and could be useful for hydro turbine design.



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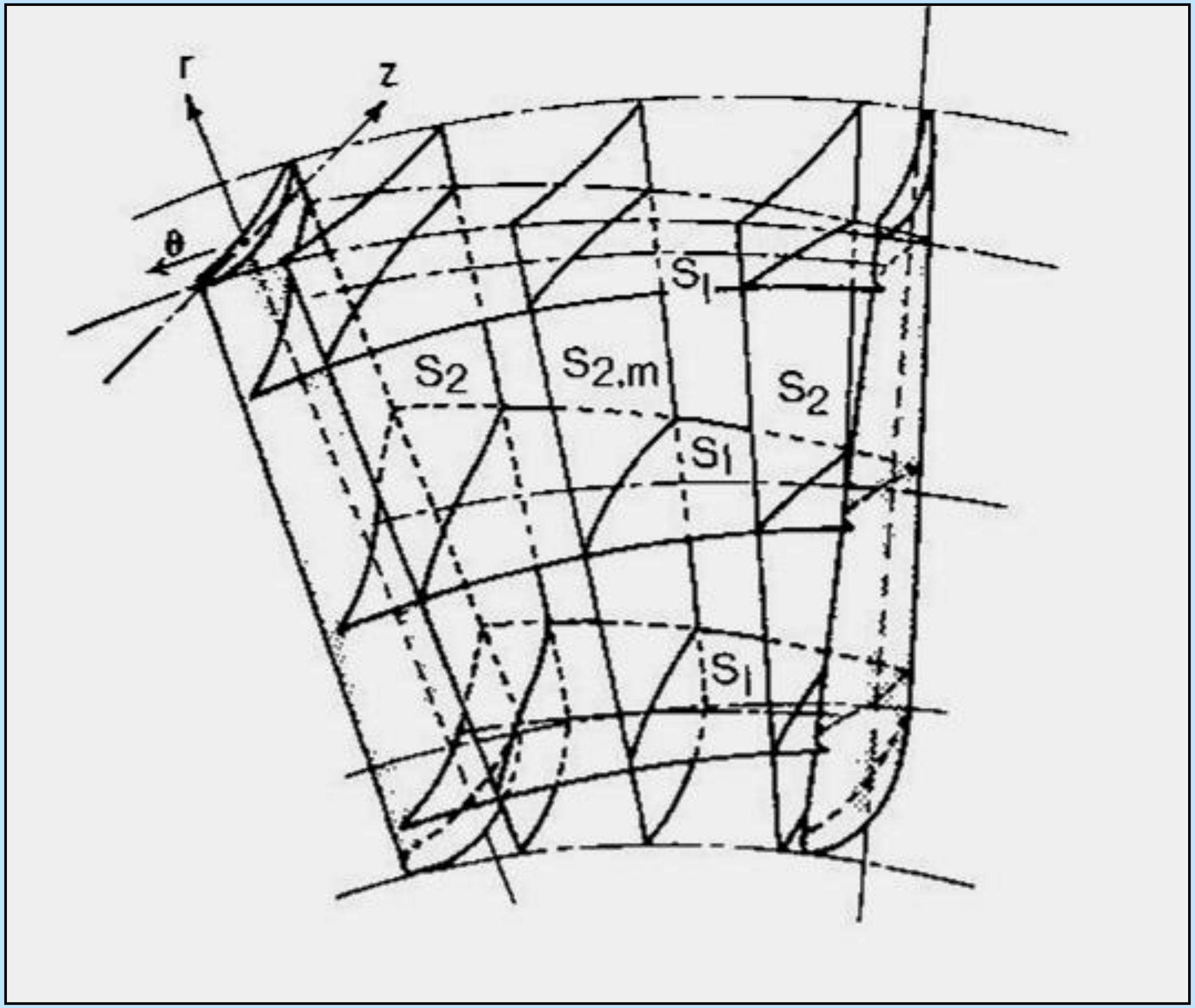
S1 and S2 Surfaces

Chung-Hua Wu, 1949

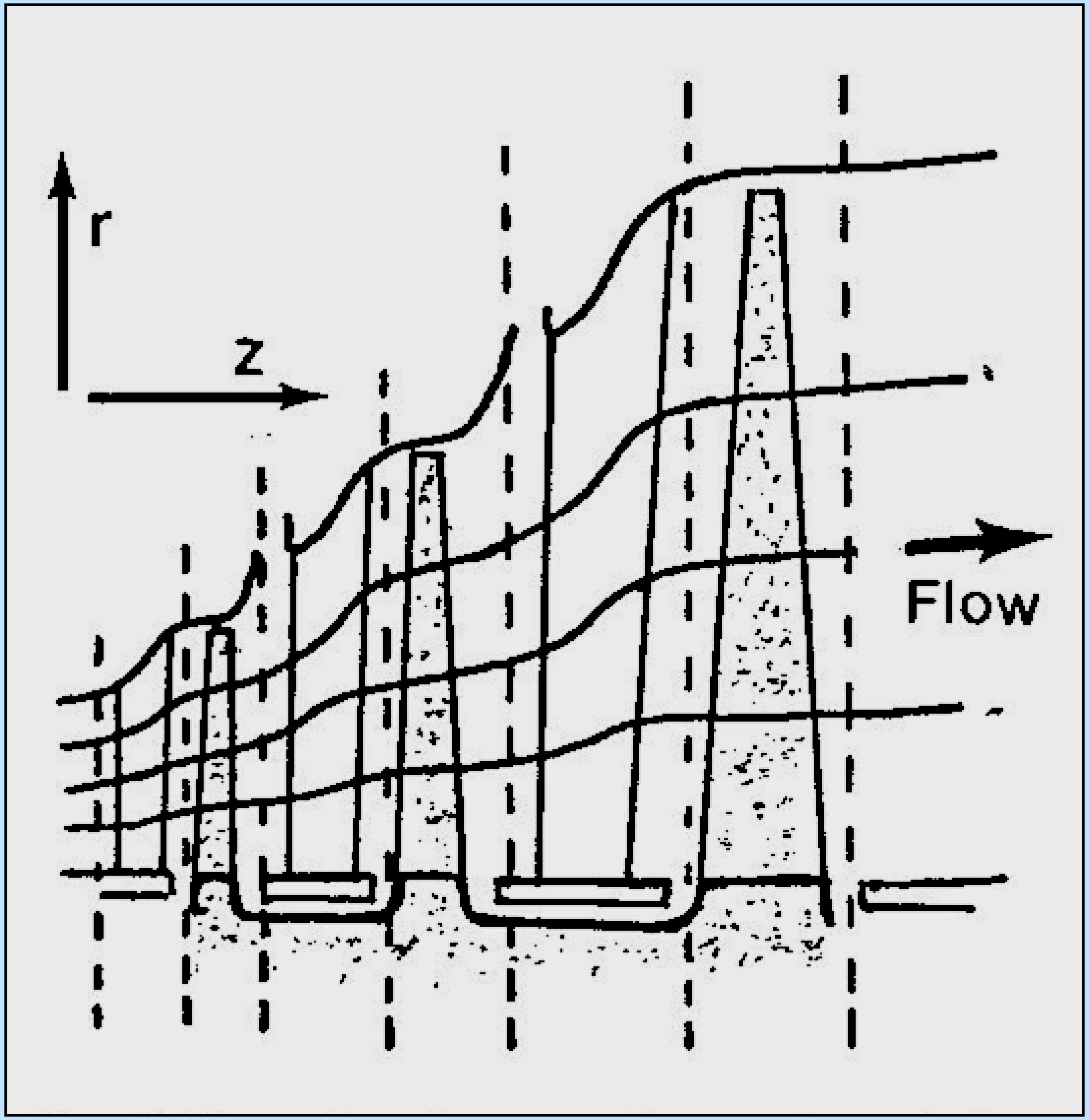
The first systematic approach was introduced by Prof. Chung Hua Wu sixty years ago. The turbine is divided into S2 (meridional) and S1 (cascade) planes and the flow is solved on each of these, iteratively relaxing between them.



The Meridional Plane (r,z)

The meridional plane forms the basic design and organisational unit. The flow is solved for these streamlines.

(Consider here whether we are dealing with swept blades.)



The Radial Equilibrium Equation of Turbomachinery

L. H. Smith Jr., 1954

The radial equilibrium equation was established and solved by Dr. L. H. Smith Jr. at GE in 1954. That original FORTRAN program, now known as CAFMIX, is still in use for preliminary design at GE.

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \left(\frac{1-M_z^2}{1-M_m^2}\right)\left(\frac{C_u^2}{r} + \sec\psi \frac{W_m^2}{r_m}\right) + \frac{A\,W_r}{1-M_m^2}$$

where

$$A = W_z\left[\frac{1}{r}\frac{\partial[r\tan\theta]}{\partial r} + \frac{\partial \tan\beta}{r\,\partial\theta}\right] - \frac{Q'}{c_p T} + \frac{W_u}{\rho a^2}\cdot\frac{\partial p}{r\,\partial\theta} + \frac{1}{\rho a^2}\cdot\frac{\partial p}{\partial t} - \frac{1}{W_z}\cdot\frac{\partial W_z}{\partial t}$$

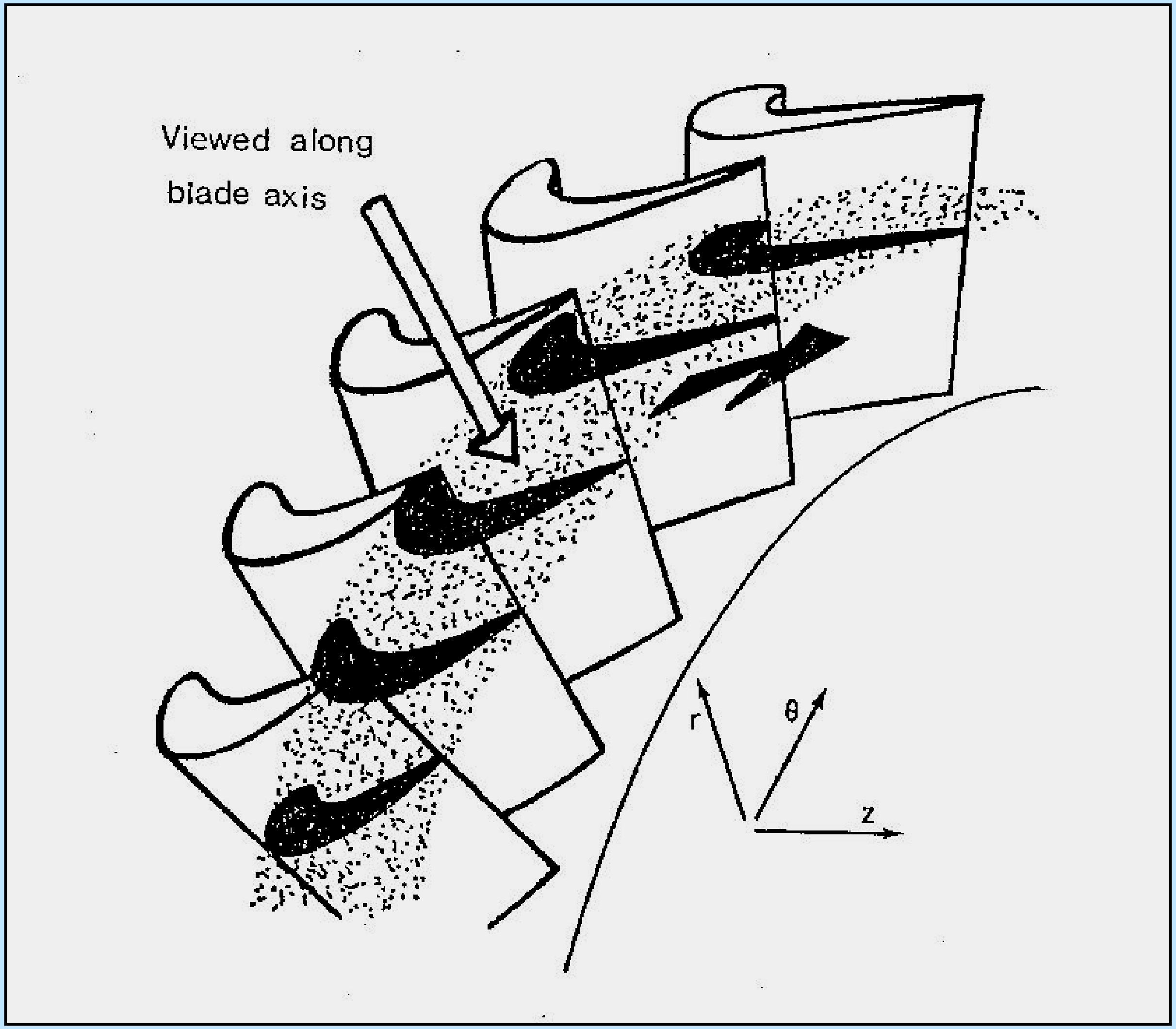
The Simple Radial Equilibrium Equation, SREE

If the stream surfaces are cylindrical, and the flow incompressible, this SREE may be used instead. It simply expresses in differential form the balance of pressure and centrifugal forces acting on a fluid element.

$$\partial p/\partial r \approx \rho . c_\theta^2/r$$

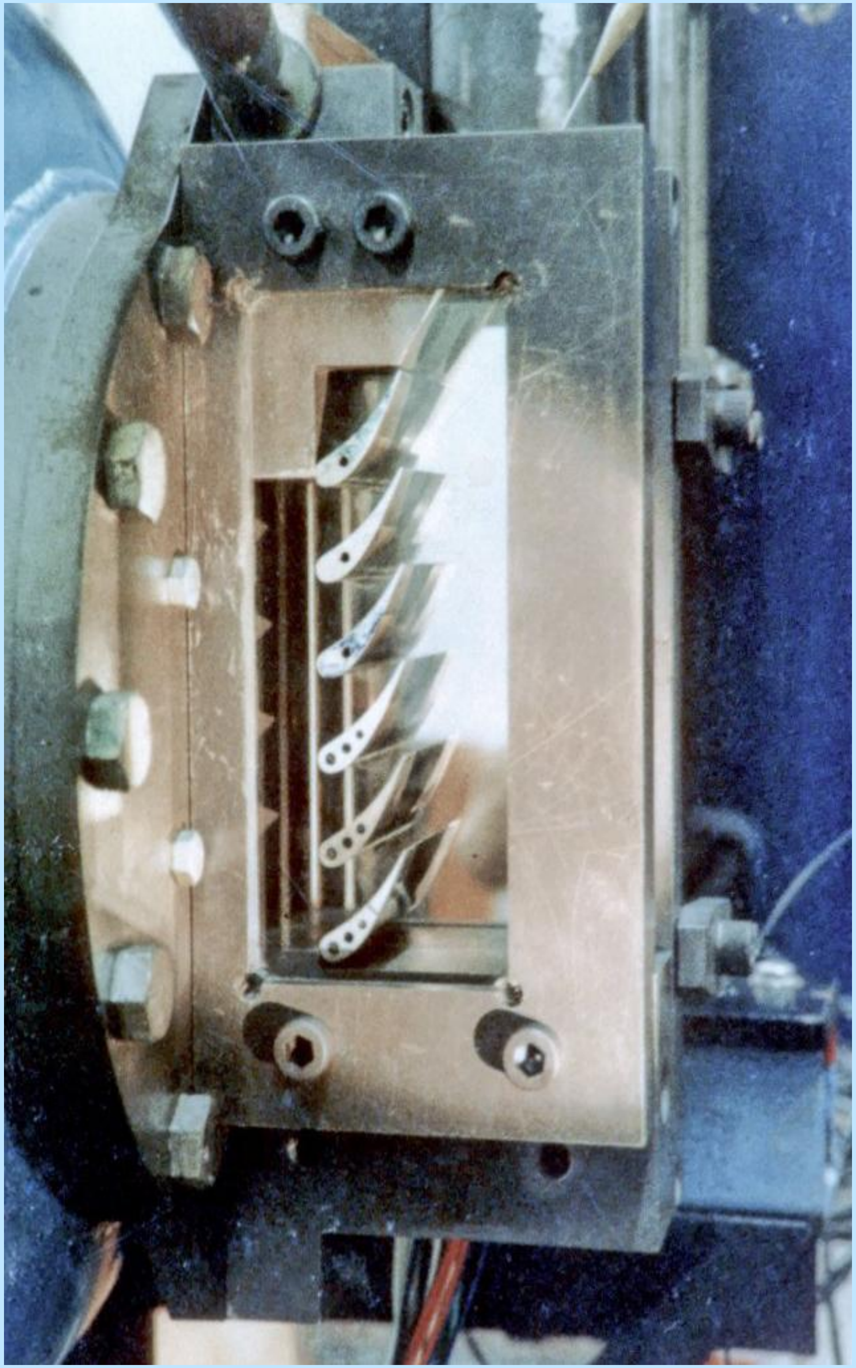
The Cascade Plane (θ,z)

Once the radial equilibrium equation is solved the overall shape is established. It is then necessary to consider the cascade plane in which the essential turning and losses are addressed. This is where the blade is shaped and where the efficiency is determined.

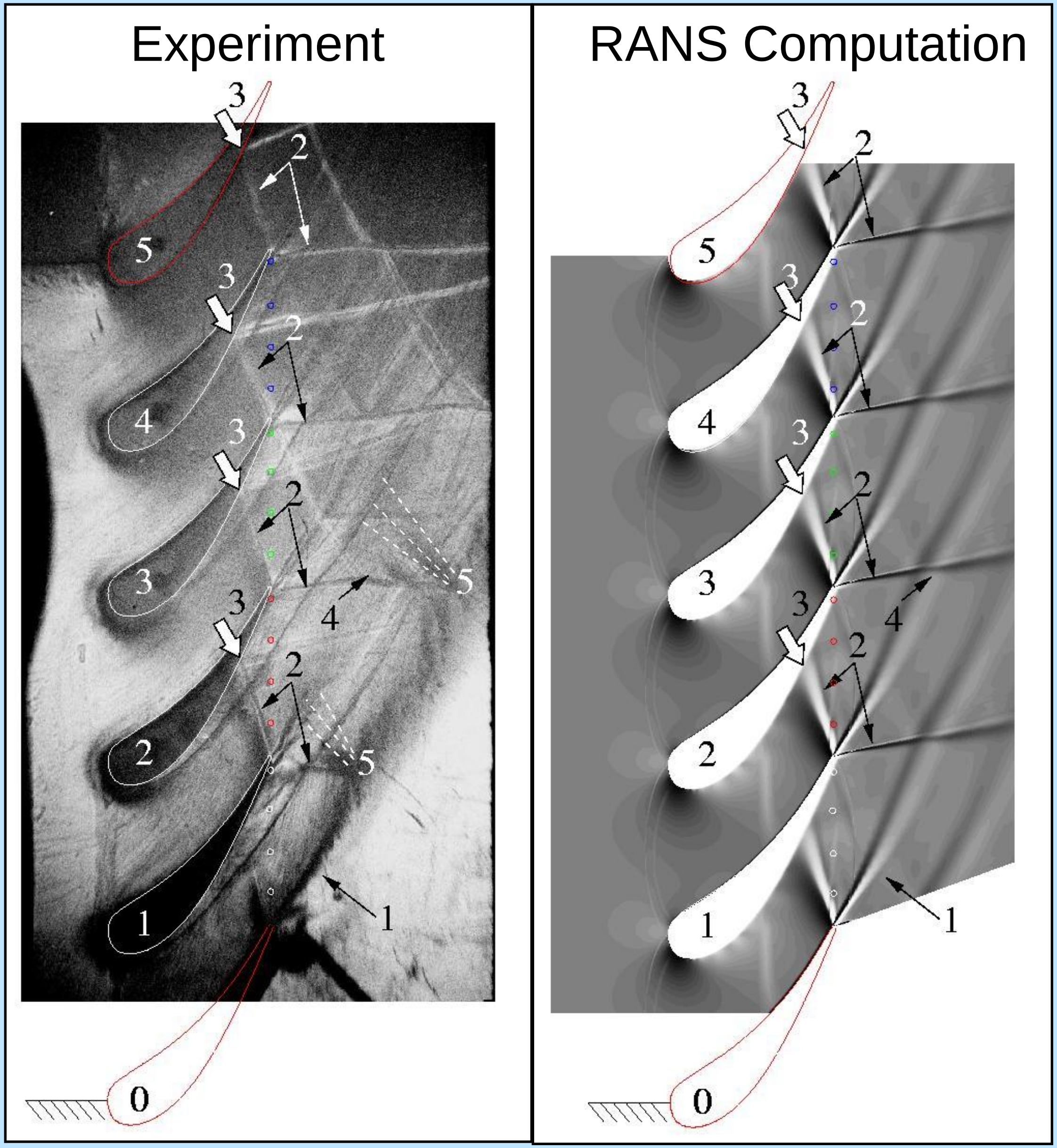


University of Leicester
Transonic Blowdown
Turbine Nozzle
Cascade Tunnel

The cascade plane is all about the flow physics. The most usual approach is to unroll the blades onto a linear cascade and to measure the turning and losses in a wind tunnel.



Mach 1.2 discharge from turbine blade

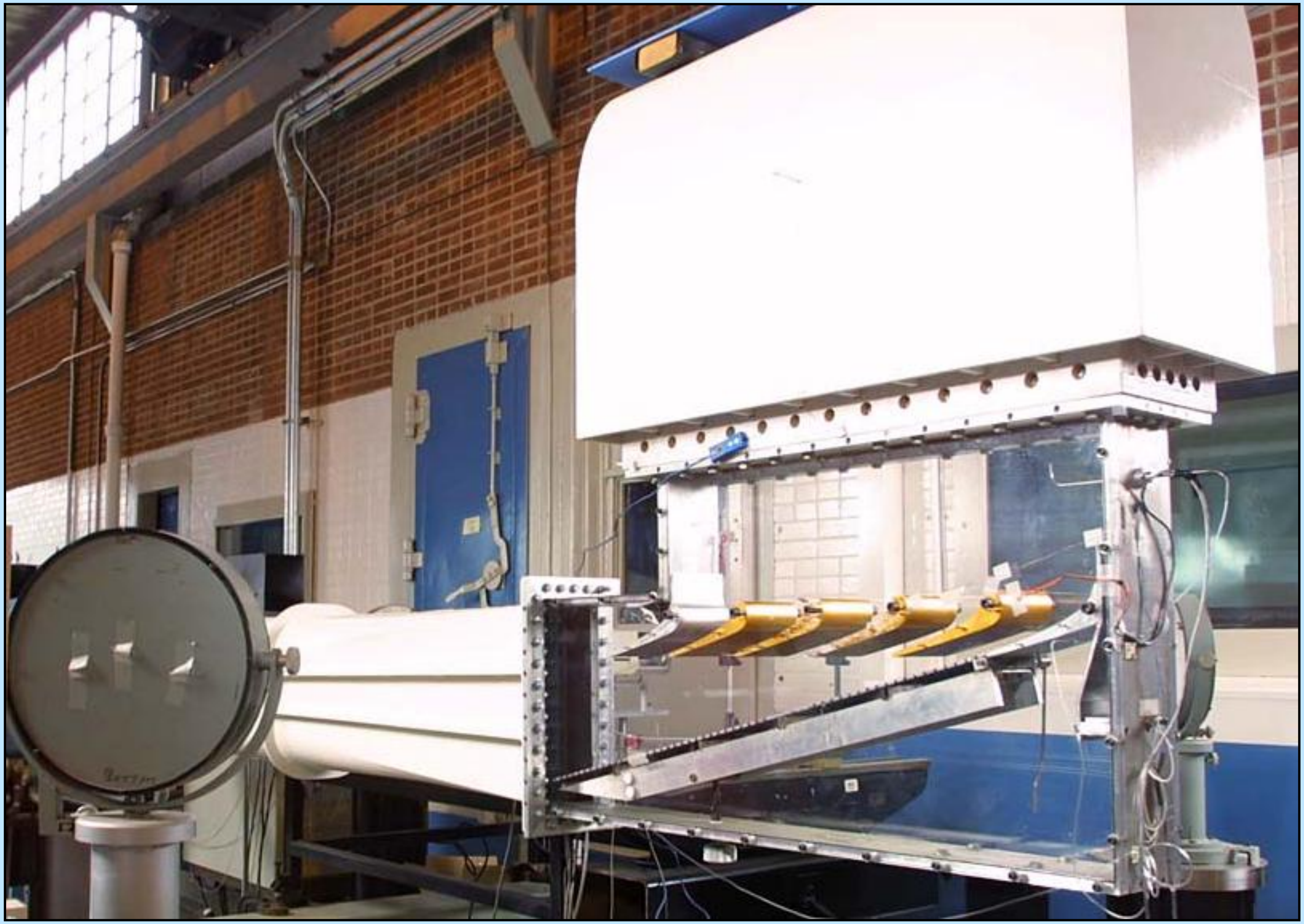


Spark schlieren photograph by Aldo Rona and computational schlieren prediction.

At the design condition we routinely get good agreement between experiment and CFD.

Off-design and with aggressive 3D shaping, such as blade sweep, is a different story.

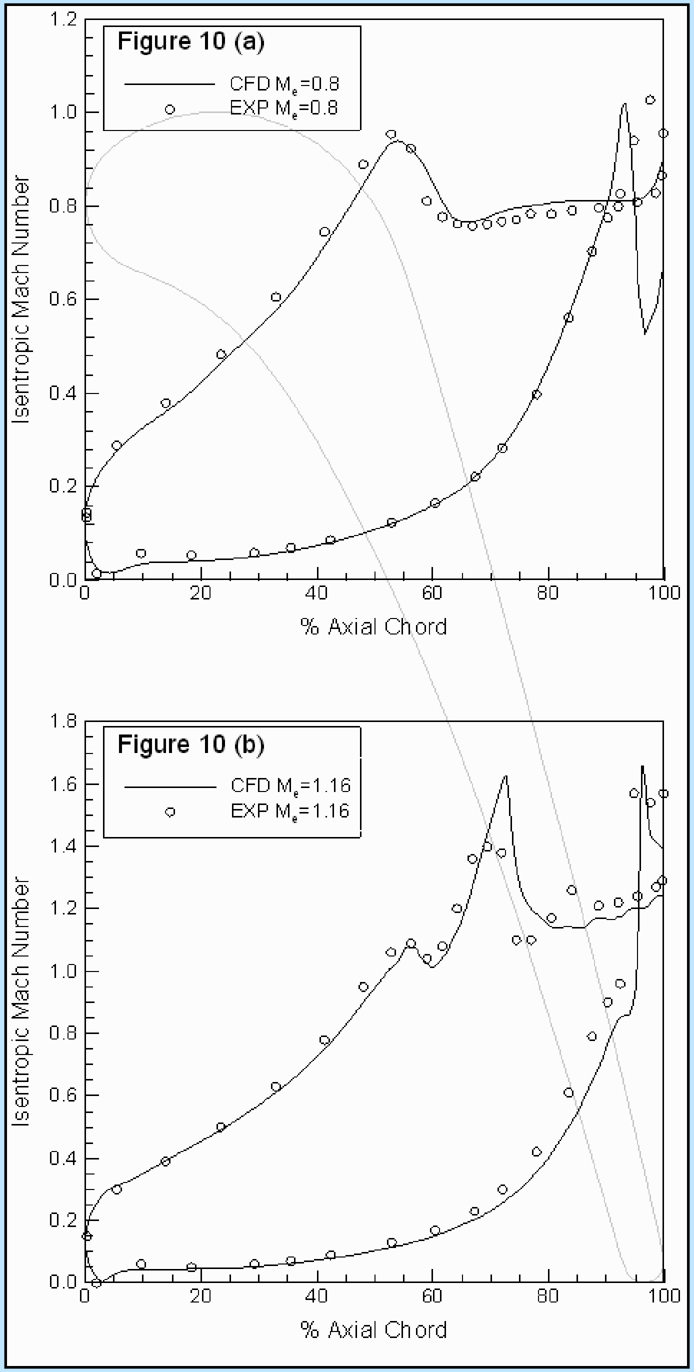
NRC Continuous Inflow
Planar Cascade Tunnel
for Transonic Turbine Blading



NRC Turbine Nozzle Experiments and Inviscid CFD →

Isentropic Mach Number Distribution Mach 0.8 and 1.16

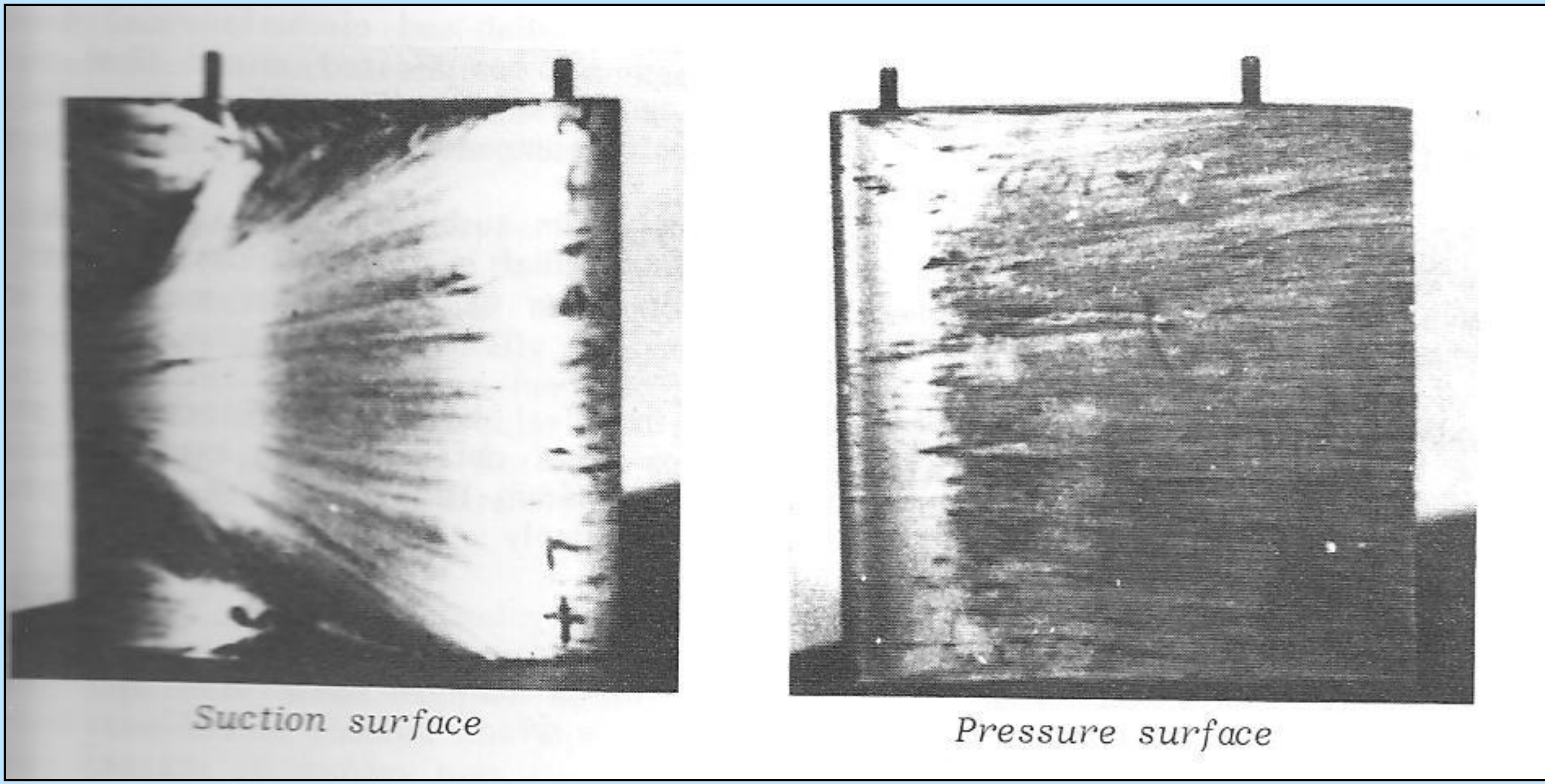
The use of advanced RANS and LES computational procedures is routine but end wall and off design effects are still not well-predicted, even for enclosed flow turbomachinery. This often results in serious efficiency penalties, directly impacting on fuel costs and with adverse environmental consequences.



Flow Visualization on a Compressor Blade

Although nominally 2D the flows can be quite 3D.

T.E. *L.E.* *L.E.* *T.E.*

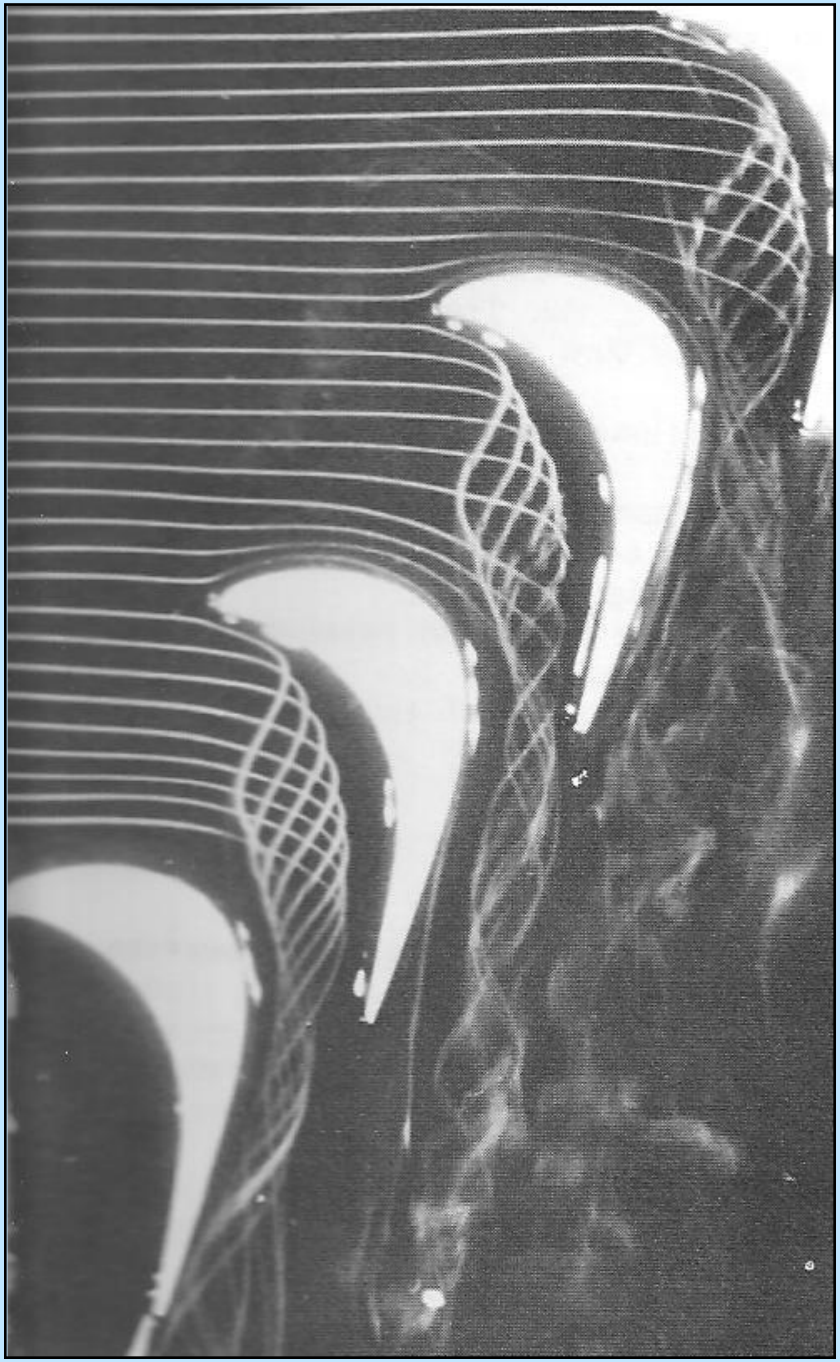


Suction surface Pressure surface

Visualization of Secondary Flows Near the End Wall in a Turbine Cascade

Courtesy, J. Fabri

$$\partial p/\partial n \approx \rho . c_\theta^{\,2}/R$$



- ***Taxonomy***
- ***Some Examples***
- ***Design Methodology***
- ***Low Pressure Turbines***
- ***Streamwise Vorticity***
- ***Blade Sweep***

Low Pressure Turbines

- and weight reduction

The Low Pressure Turbine (LPT) can contribute as much as 30% of the weight of an aircraft engine and contain as many as 1900 blades. This is the obesity problem that modern aero-engines share.

Weight reduction programs involving high-lift LPTs have been implemented for engines such as the Rolls-Royce BR715 for the Boeing 717 and the P&W/GE GP7000 for the Airbus A380. Current engines using high-lift turbine blading include the Rolls-Royce Trent 1000 and General Electric GEnx for the Boeing 787 Dreamliner.

Low Pressure Turbines

and Weight Reduction – GE's GEnx

New Revolutionary Turbine!

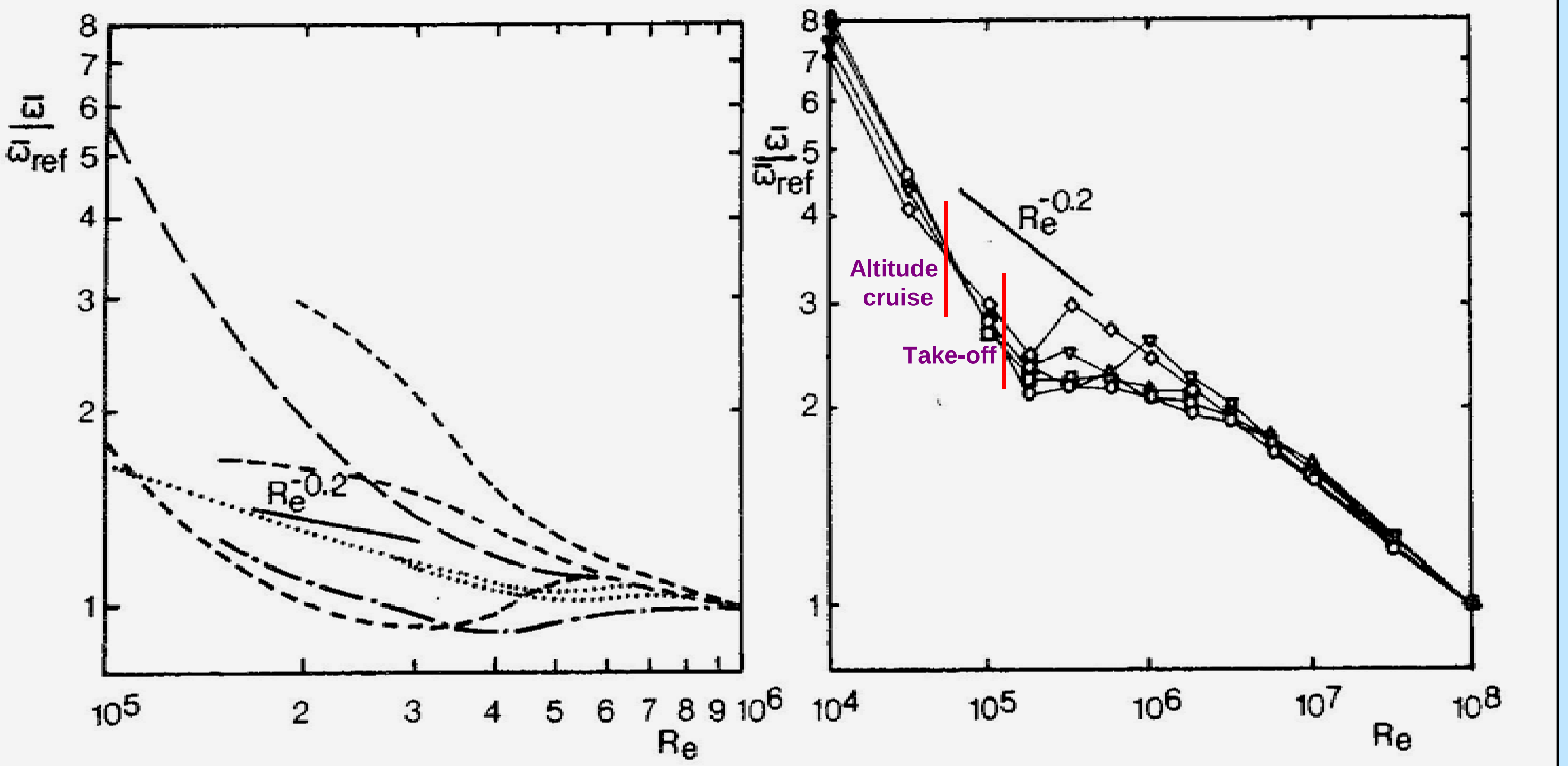
The job of the high and low pressure turbines is to extract work from core flow. This efficiency has never been better, thanks to recent improvements in design codes and turbine blade architecture. Fewer blades can now do the job more efficiently, while simultaneously reducing cost and weight. *(GE brochure)*

"In an effort to get a lightweight design, we took too many airfoils out of the turbine, and the engine told us it didn't like that."

(T. Brisken, GE project manager)

Reynolds Number Effects
- on turbine blade losses

LPT efficiency falls off between sea level take-off and altitude cruise conditions due to a halving of Reynolds number. This can result in a 40% increase in losses.



(a) Results of Dring and Heiser for $10^5 < Re < 10^6$.

(b) Results of Denton for $10^4 < Re < 10^8$.

Low Pressure Turbines

- the issues

Workshops were convened twenty years ago to address the weight reduction issue; highly-loaded low pressure turbine blading was conceived in the process. Extensive collaboration between universities and industry in attempts to understand boundary layer behavior on turbine airfoil surfaces dominated by unsteady transitional flows. These turbines were eventually deployed in commercial aircraft and major savings in engine weight and cost were achieved, but with a significant penalty in turbine efficiency. It is thought that design procedures have not adequately addressed issues such as secondary flows, purge flows and tip clearances, known to be principal contributors to loss. RANS codes are not performing well for transitional, separated and three dimensional flows. Research is now aimed at regaining the lost efficiency whilst retaining the hard-won weight and cost advantages.

Low Pressure Turbines

- impact of efficiency improvements

The LPT has a larger impact on the fuel consumption of commercial aircraft engines than other components. If the LPT efficiency is improved by 1%, then the fuel consumption for the engine is reduced by 0.7 to 0.95%. It is important to improve the performance of all components but incentives for the LPT are particularly high. To reduce CO2 signature, emissions and noise the best return on investment will be gained by improving the LPT efficiency. Raising this from 93% to 95% would yield a 1.8% fuel consumption reduction for aircraft engines.

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The Challenge of Vorticity

The difficulties presented by secondary flow vortices and three dimensional flows are discussed. A recent discovery is that of organized fine-scale streamwise vortical structures on turbine blading. This has aerodynamic and heat transfer implications and raises questions of leading edge bluntness, surface curvature and blade sweep.

Streamwise Vortices

The stability of contra-rotating vortex pairs is of airworthiness and commercial interest but is not well understood

Contra-rotating Streamwise Vortices

Previous investigators observed streamwise vortices and "streaky structures" on flat plates and on the suction surface of compressor blades. An organized system of contra-rotating streamwise vortex pairs on a circular cylinder, or a compressor or turbine blade suction surface, gives additional complications.

Experiments conducted on flow past transonic turbine blades and a circular cylinder in subsonic crossflow. Organized streamwise vortex systems were observed for both cases. This unfamiliar behavior, and the associated spanwise wavelength, had been predicted and observed in low speed flows. Turbine designers generally assume that streamwise vorticity is confined to the concave pressure surfaces. Examples will be given that should result in questioning this assumption.

Conditions at Leading Edge of Turbine Blade

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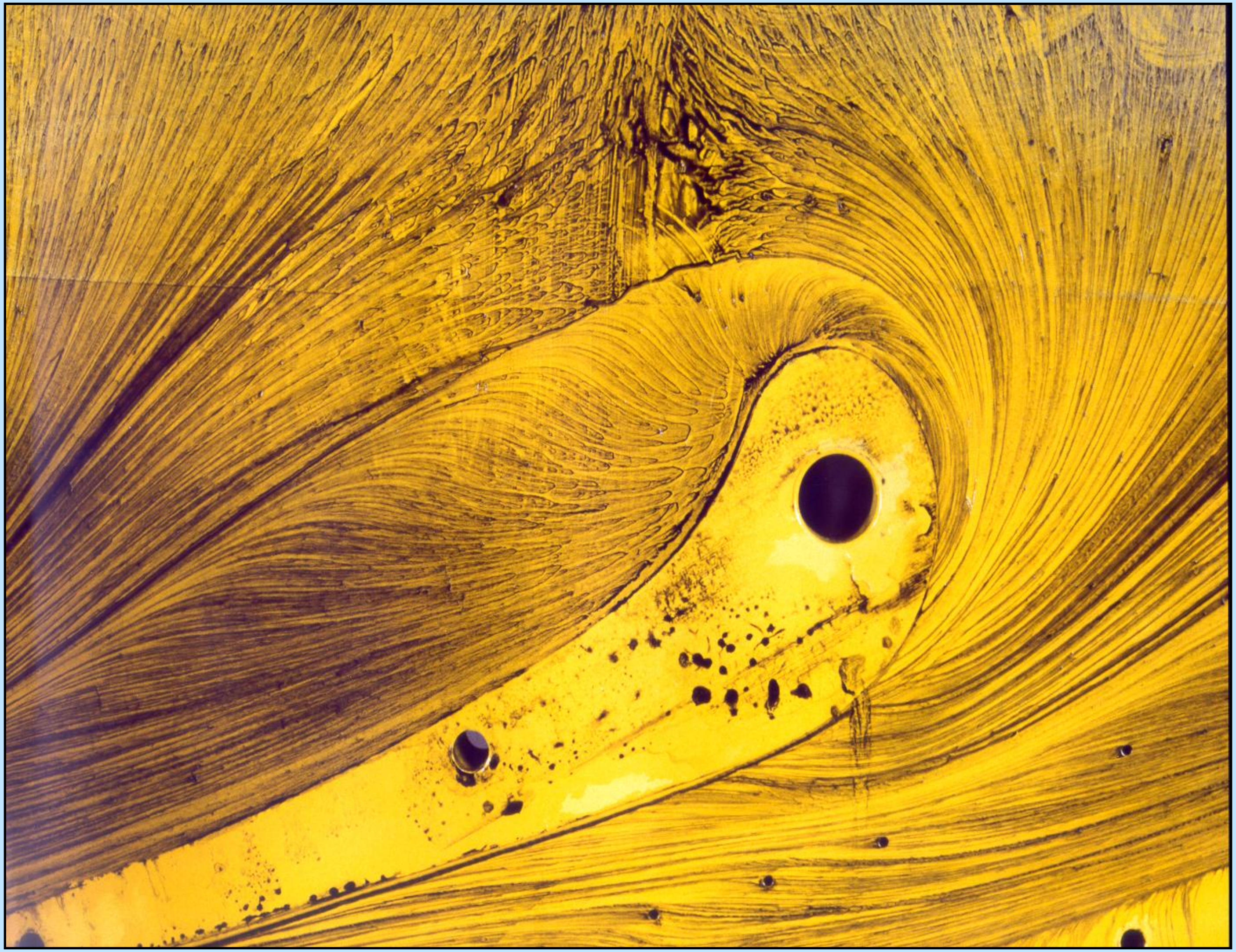


The L.E. inflow is initially disturbed; then undergoes rapid curvature changes before joining the convex suction surface. Vortex stretching is caused by both turbulence and curvature.

For a convex surface streamwise vorticity is consistent with the later predictions of Görtler (1955), who postulated instability on a convex surface from the concave streamlines ahead of the L.E. stagnation region.

A useful approach for a circular cylinder is that of Kestin and Wood (1970). Their stability analysis for approaching flow considered regularly distributed contra-rotating eddies strengthened by eddy-stretching in free stream turbulence. They predicted a spanwise wavelength between pairs, λ, for a cylinder of diameter, ***D****, given by:*

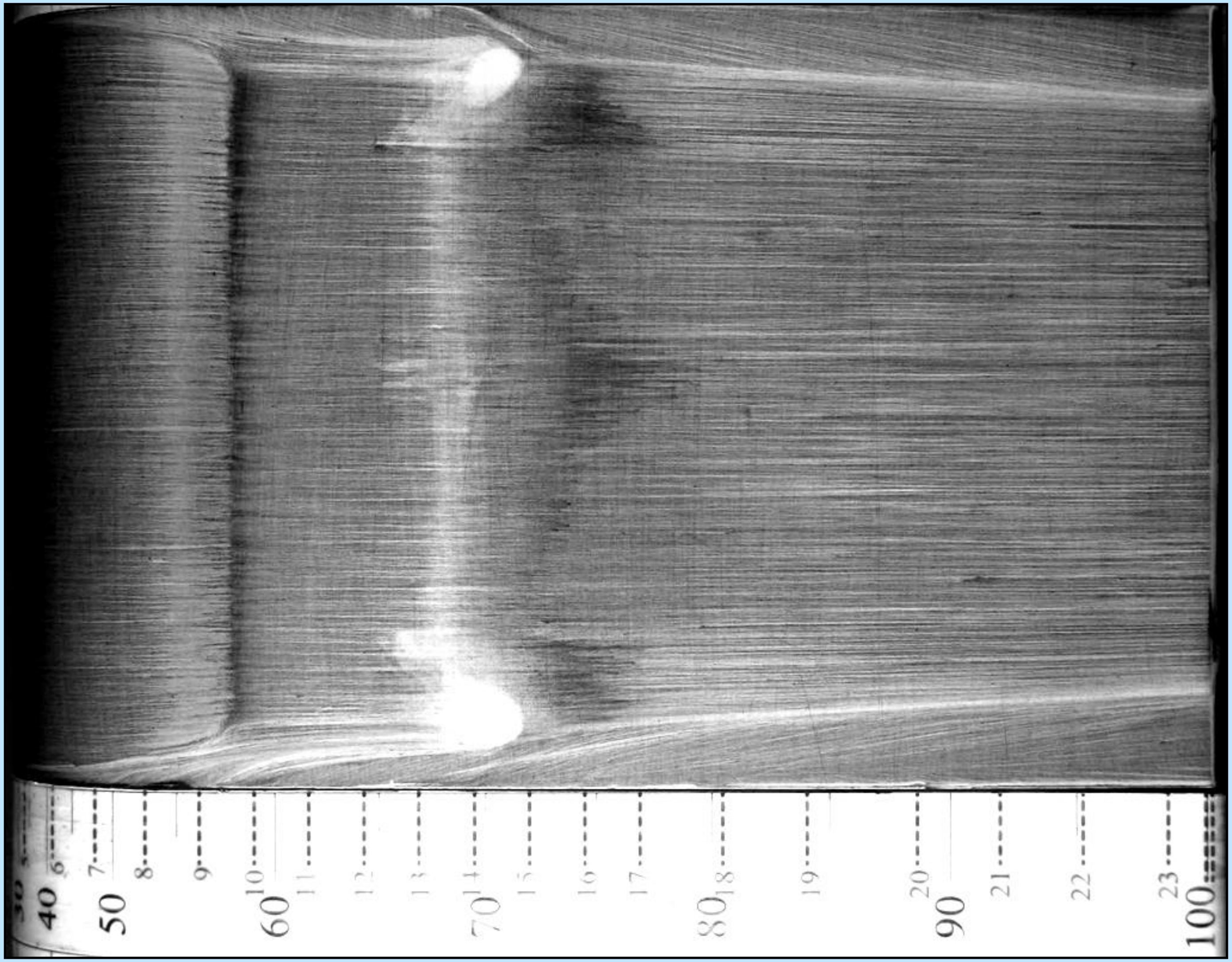
$$\boldsymbol{\lambda = 1.79\pi\, D\, Re^{-0.5}}.$$

Suction surface flow visualization

NRC Turbine Blade; M_e = 1.16

→

Under the influence of strong favorable pressure gradients on the blade's suction surface streamwise vortices were observed that persisted to the trailing edge.



NRC Turbine Blade

The suction surface leading edge is virtually circular; it then develops strong convex curvature becoming quite flat further downstream.

Suction surface flow visualization was performed at three speeds, displaying coherent streamwise vorticity extending to the trailing edge. The blade was covered with a sheet of self adhesive white vinyl; a mixture of linseed oil and powdered lampblack was applied in a very thin layer. After running for five minutes, the blade was removed and photographed.

Large numbers on the scale represent percentage axial chord and small numbers mark static tap locations. For $M_e = 1.16$ *the shock impingement and separation region is at an axial chord around 70%.*

Streamwise Vorticity

The streamwise vorticity can be caused by vortex stretching, streamline curvature or turbulence. Kestin and Wood predicted and measured streamwise vorticity on the forward quadrant of a cylinder. Can we expect similar fine scale streamwise vorticity on convex surfaces such as turbine blades? To what extent would they affect the flow and heat transfer and how should we go about modeling it?

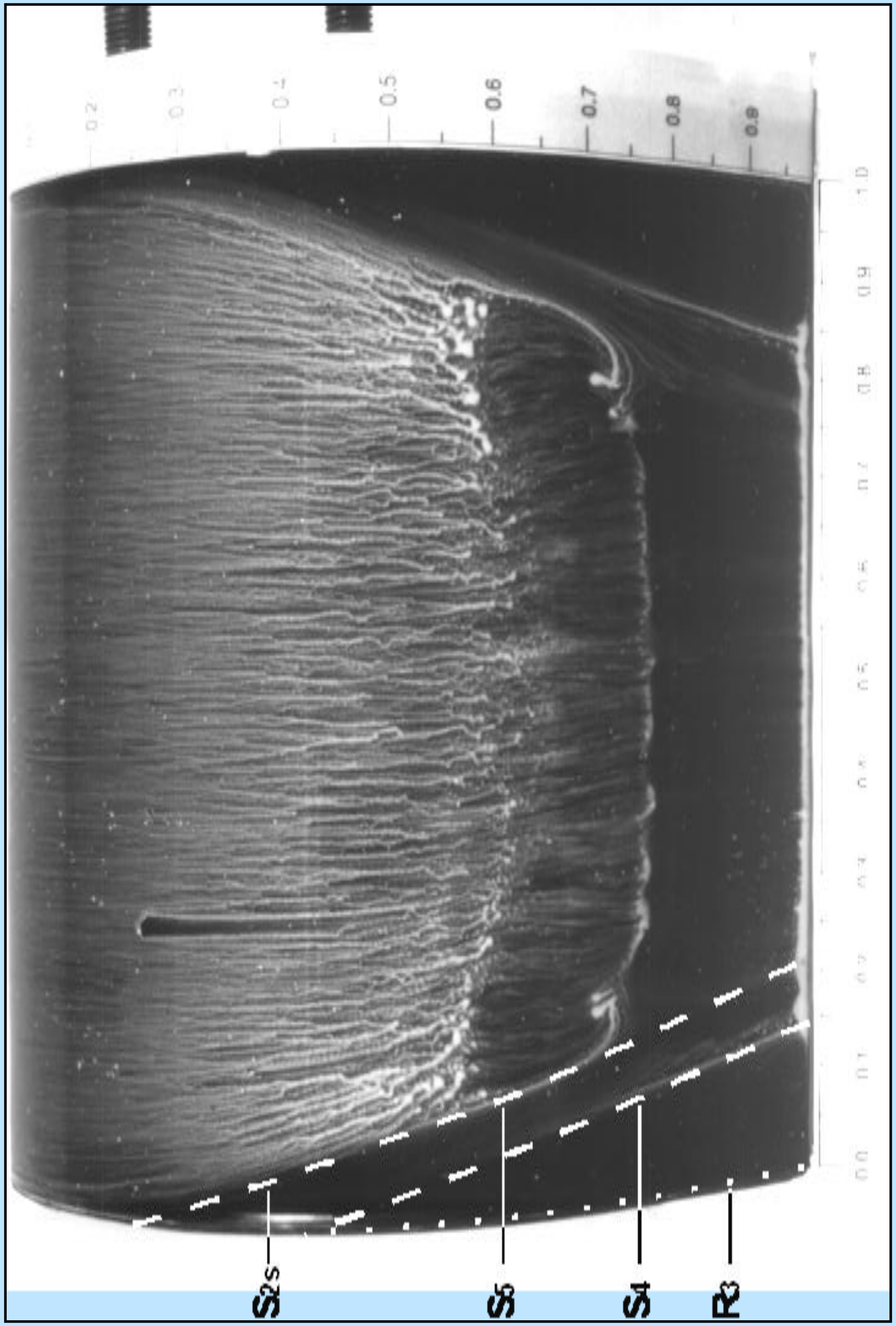
Published examples of visualization from compressor and turbine blade suction surfaces were examined to see if a consistent wavelength existed between streaks. In all cases repeatability of measurements from photographs was high.

Streamwise Vortices on Turbine Blade Suction Surface

Benner

Turb. Level 0.3%

→

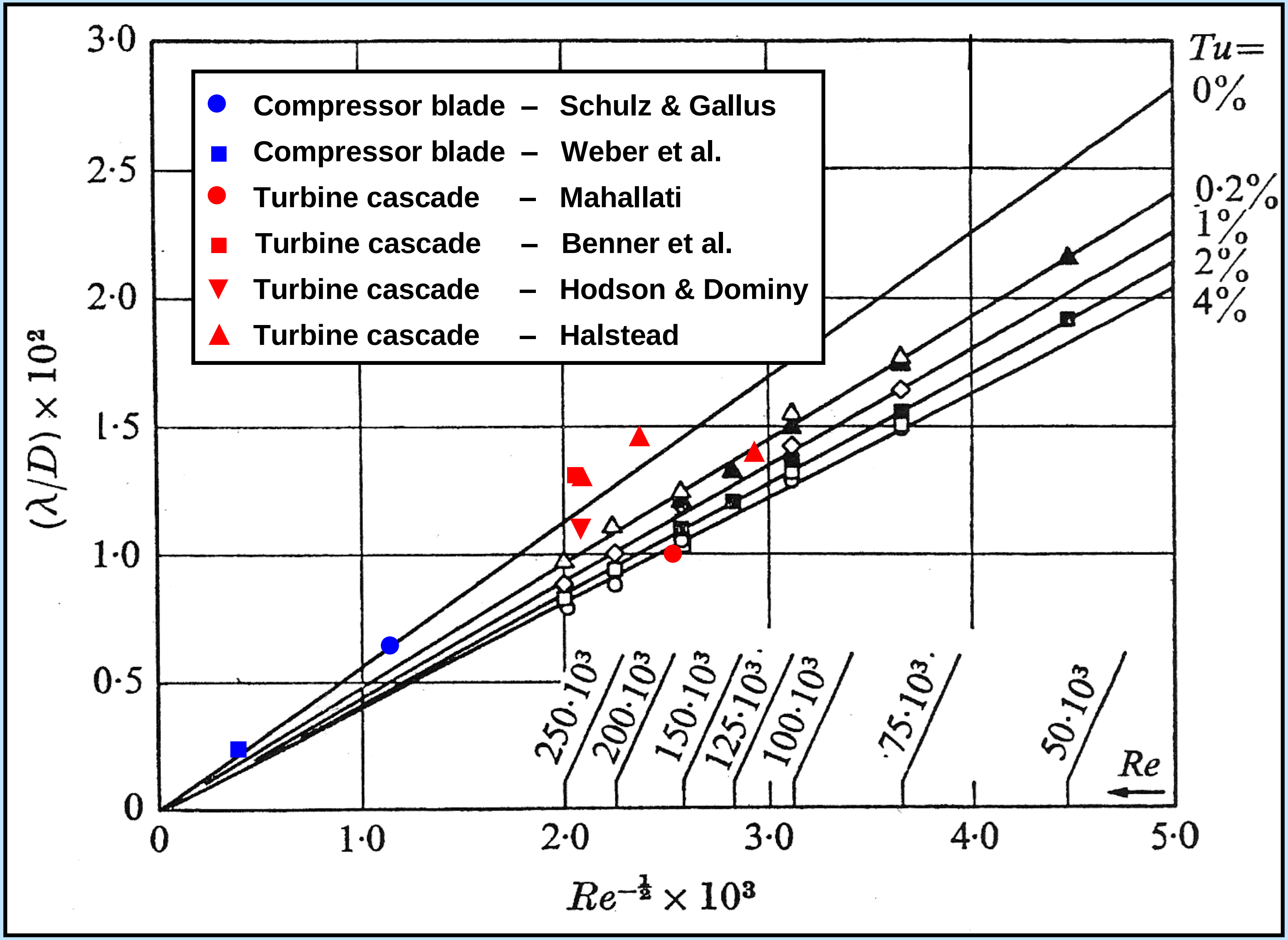


Evaluation of Turbine and Compressor Blading

The turbine blade leading edge is blunt but has high curvature; subsequently the suction surface initially retains strong convex curvature but is flat further downstream; what effective diameter should be used for comparing with theory?

According to the theory the measured wavelength, of 0.55mm, is compatible with the surface curvature on the suction surface at around 10% true chord. The diameter of the osculating circle on the suction surface, at 10% true chord, was therefore taken as the value of D.

Wavelength Measurements and comparison with Kestin and Wood predictions

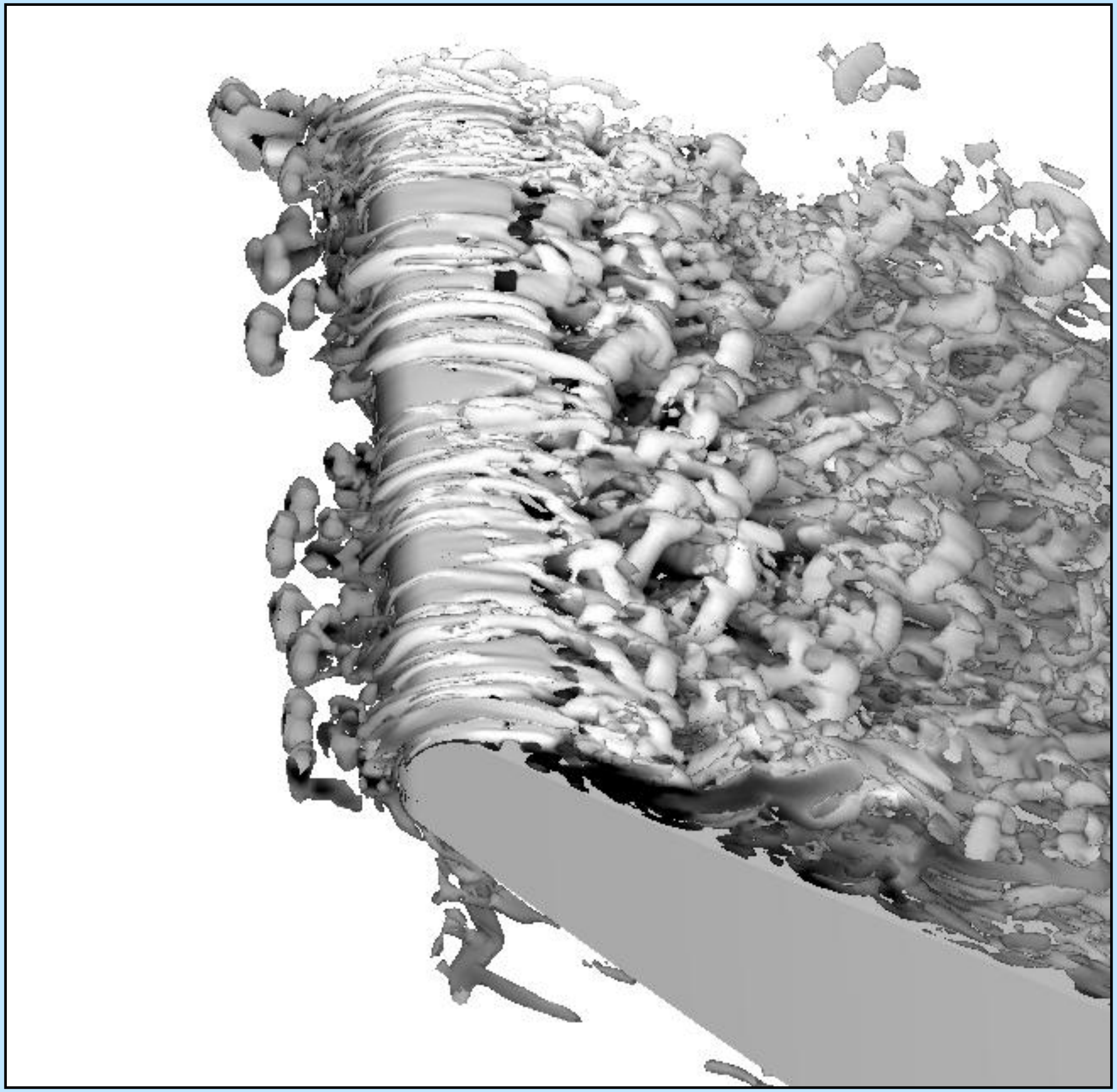


Compressor Blade
pressure surface

McMullan LES on Monterey compressor blade

Low angle of attack

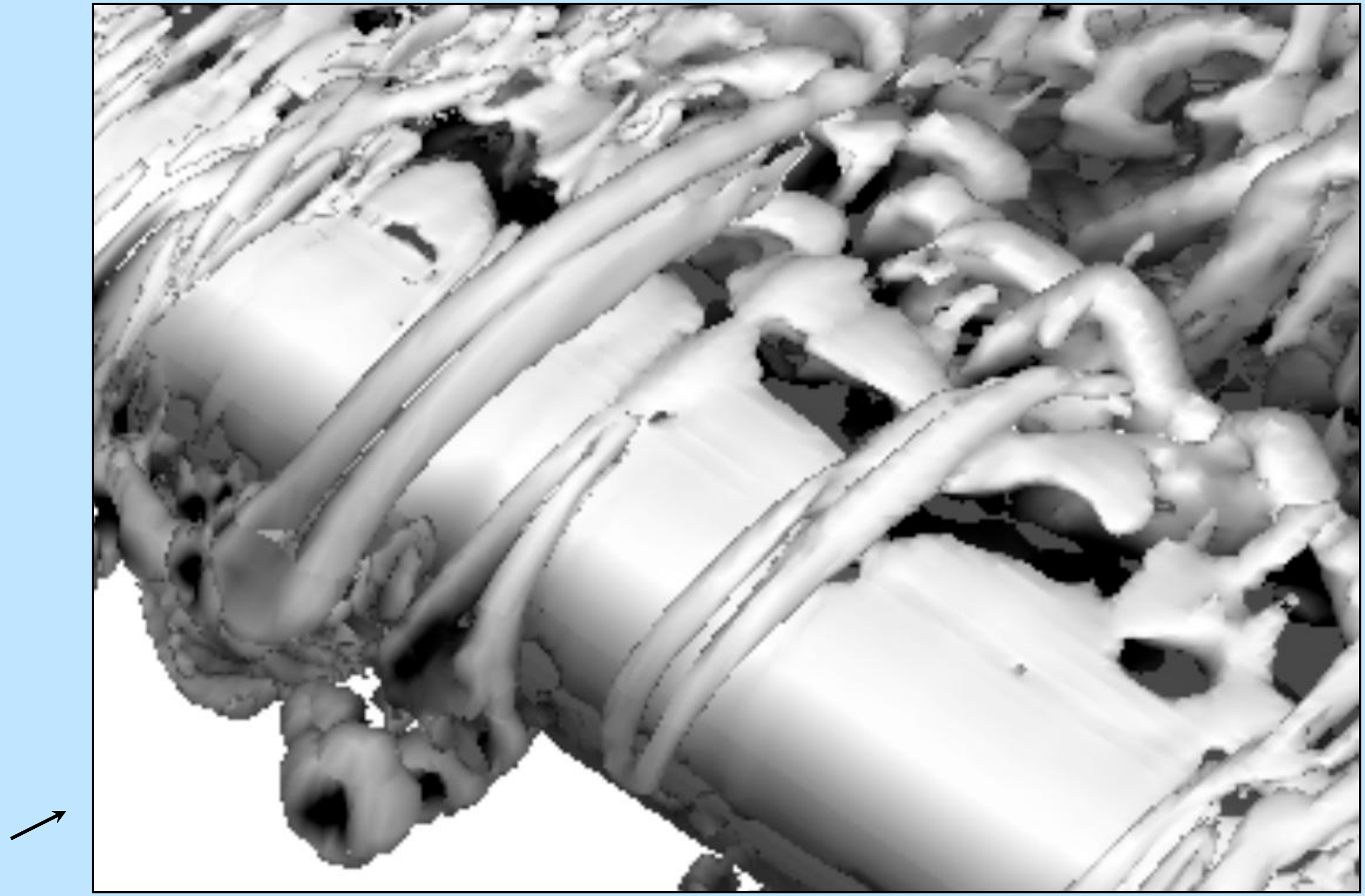
Flow behavior at leading edge; streamwise vorticity and separation on pressure surface.



Close up of Leading Edge

pressure surface

The toroidal vortex structures appear to produce streamwise vortices. But where did they originate, suction surface or upstream?



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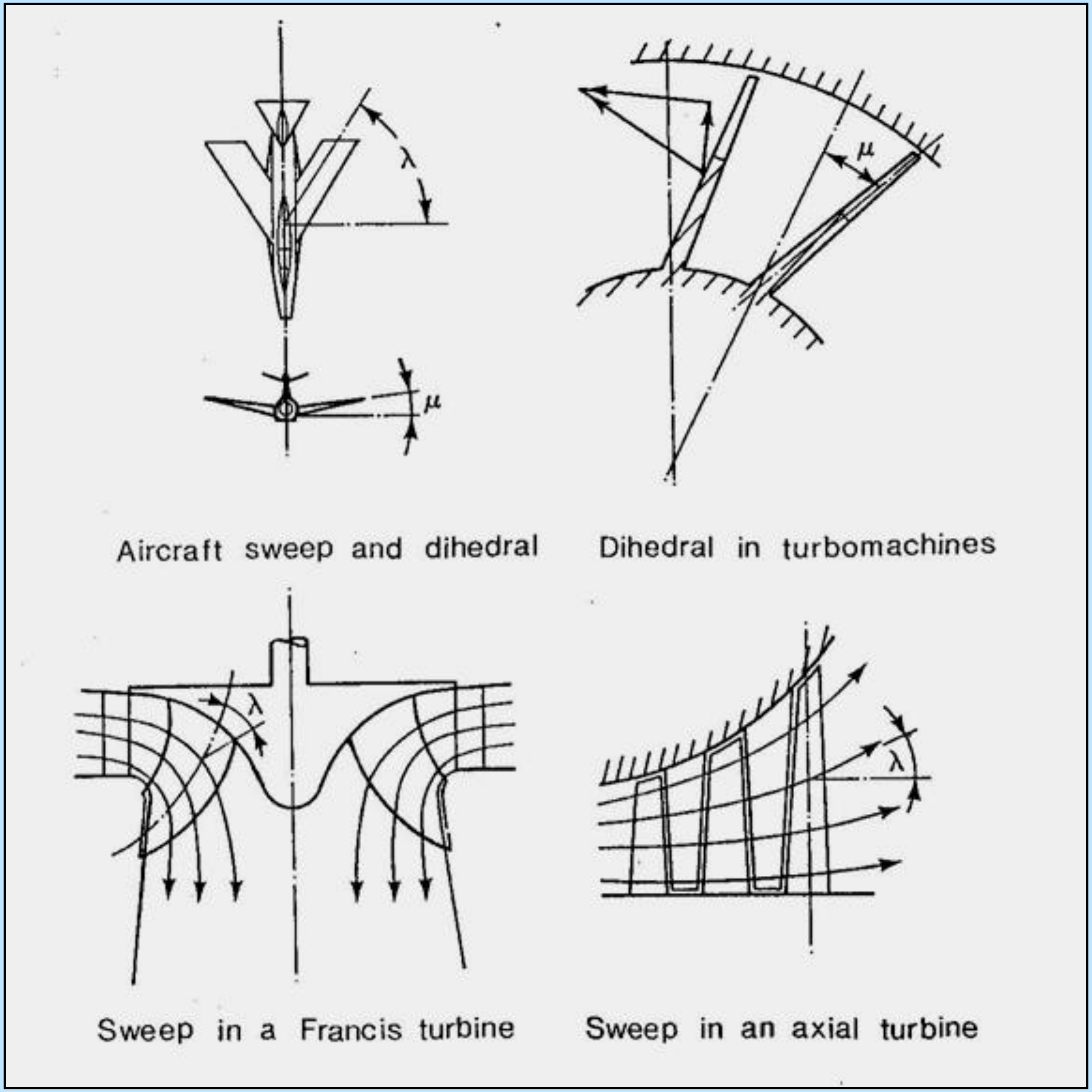
Sweep and Dihedral of Lifting Surfaces

R.I. Lewis,
J. Mech. Eng. Sci., 1971

Blade sweep is also very relevant for free flow turbines

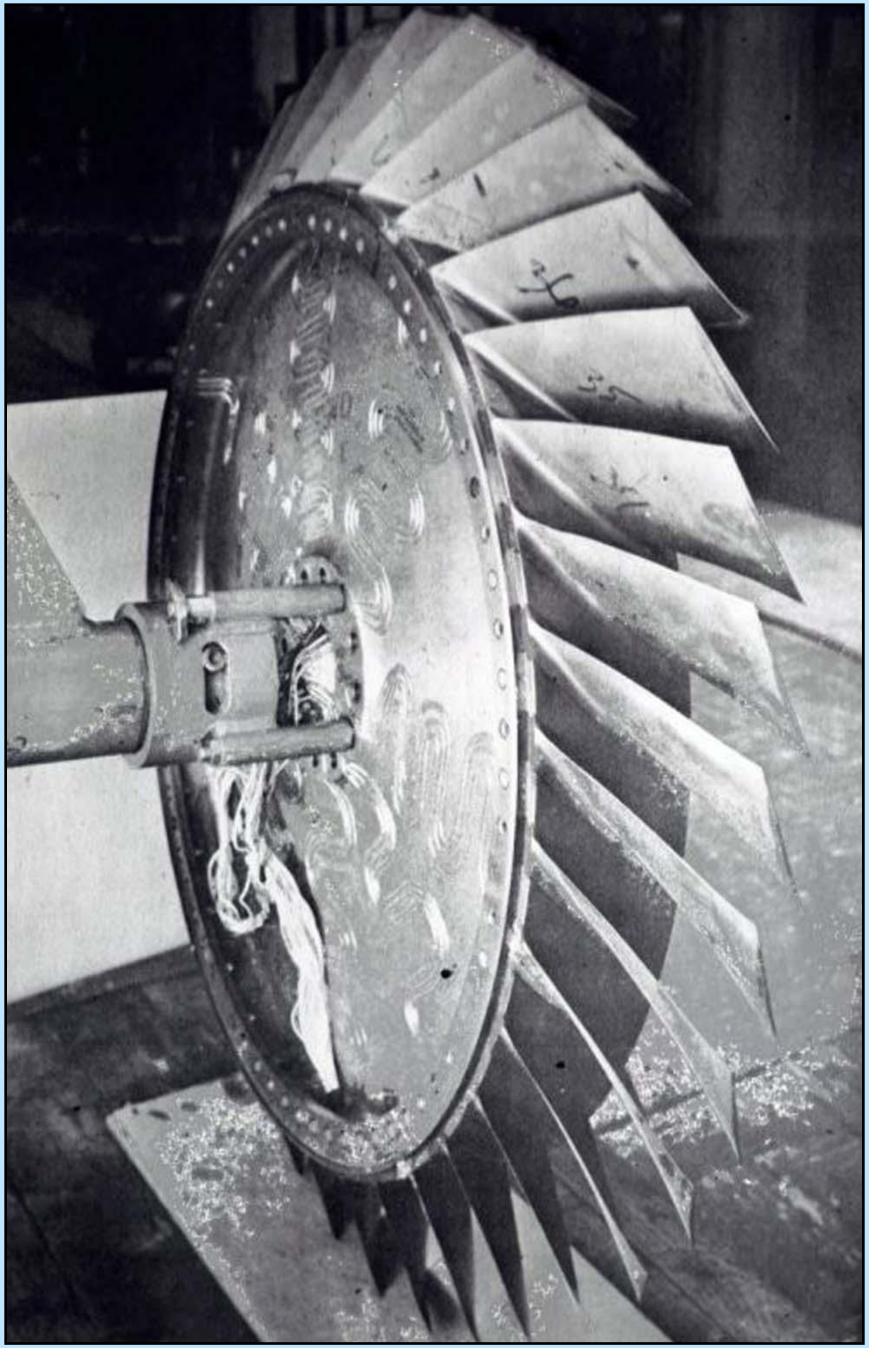


Quiet Revolution

helical VAWT design

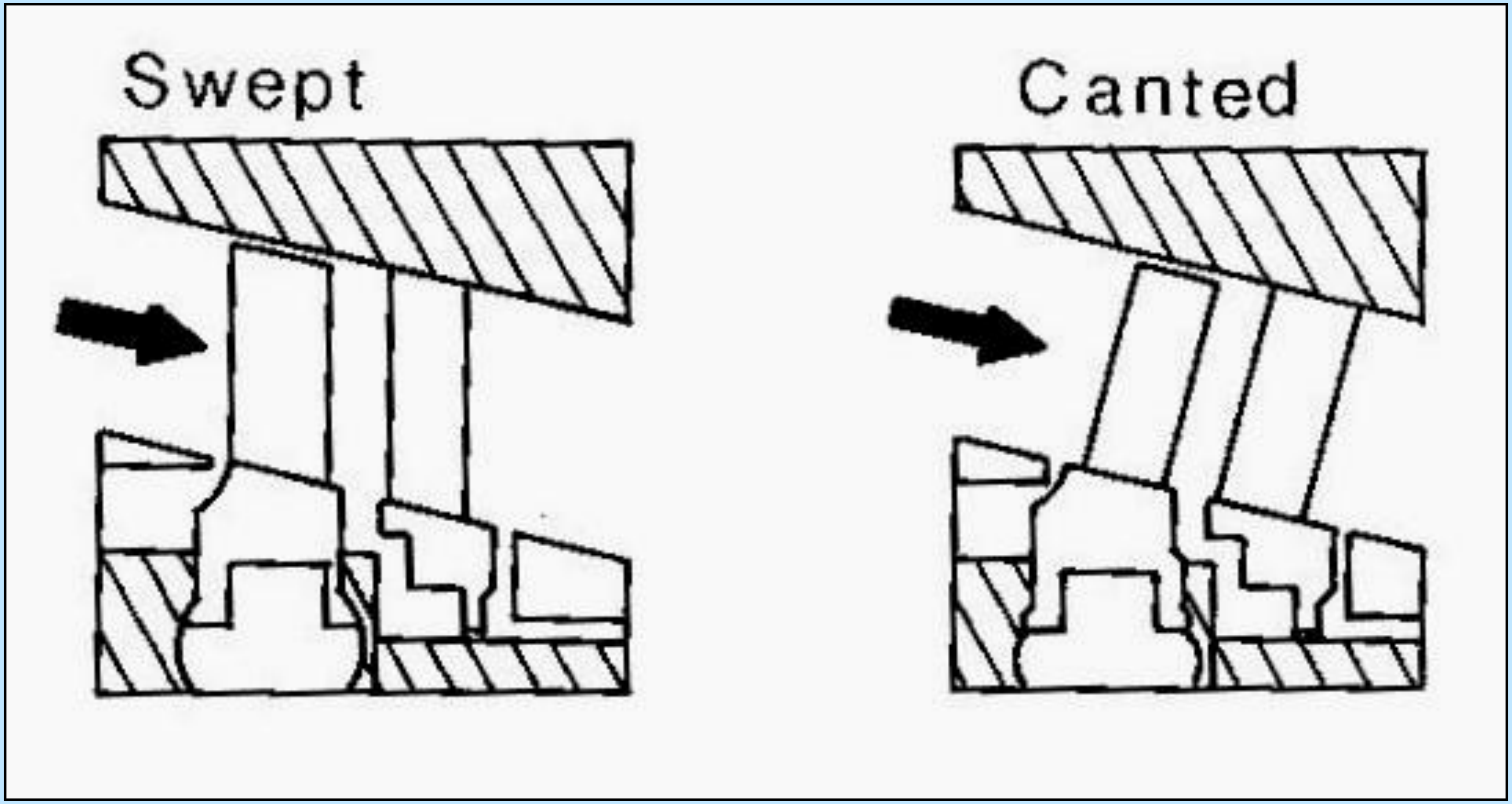
OPEN
CROSSFLOW / HELICAL

Swept back transonic fan rotor: 45 years ago!



The theory for blade sweep and dihedral was developed by Smith and Yeh and published in 1963 in Trans. ASME, J. Basic Eng.

Swept and Canted Blades

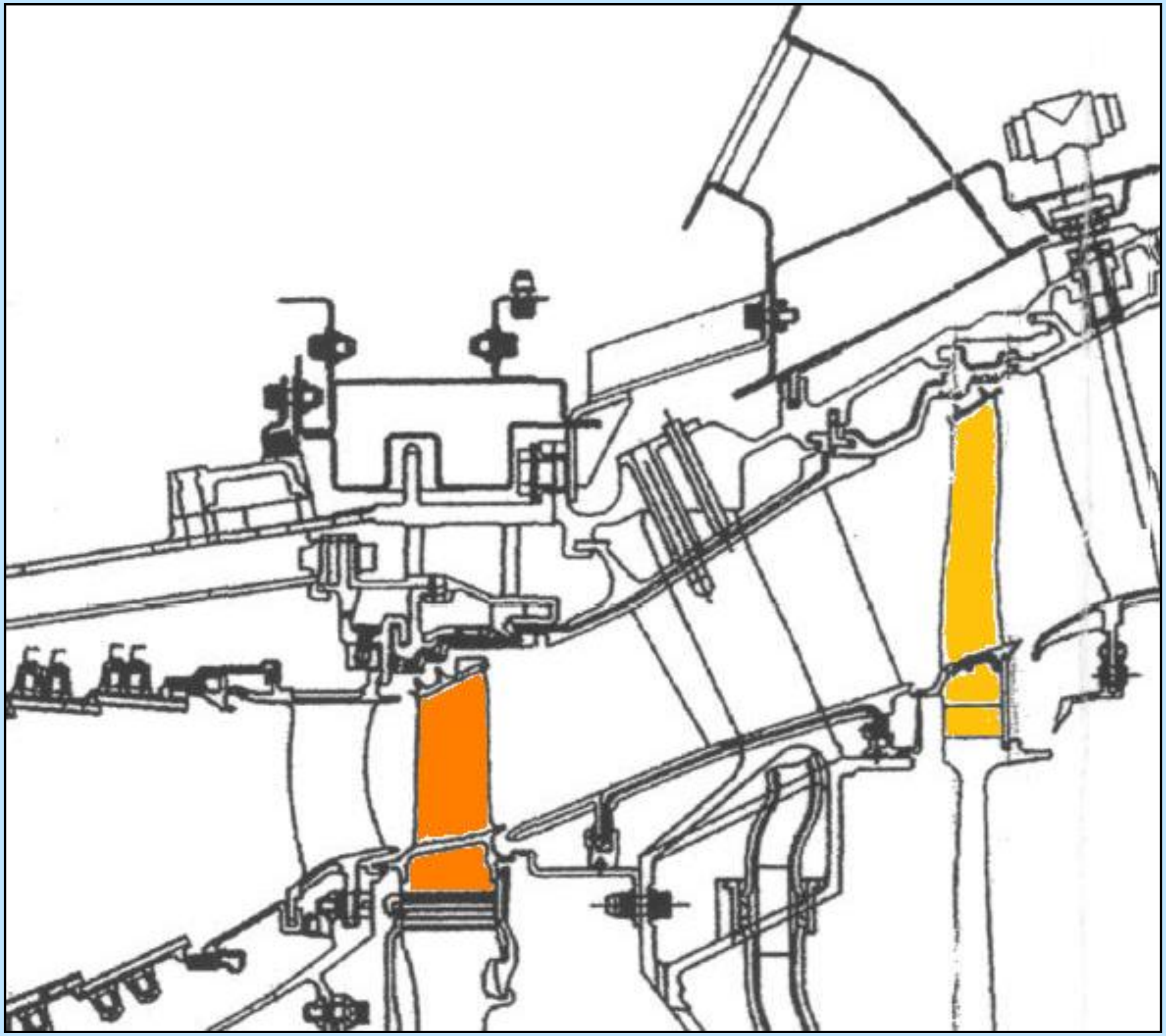


Rolls-Royce Turbine Blades

Shrouded blades and honeycomb

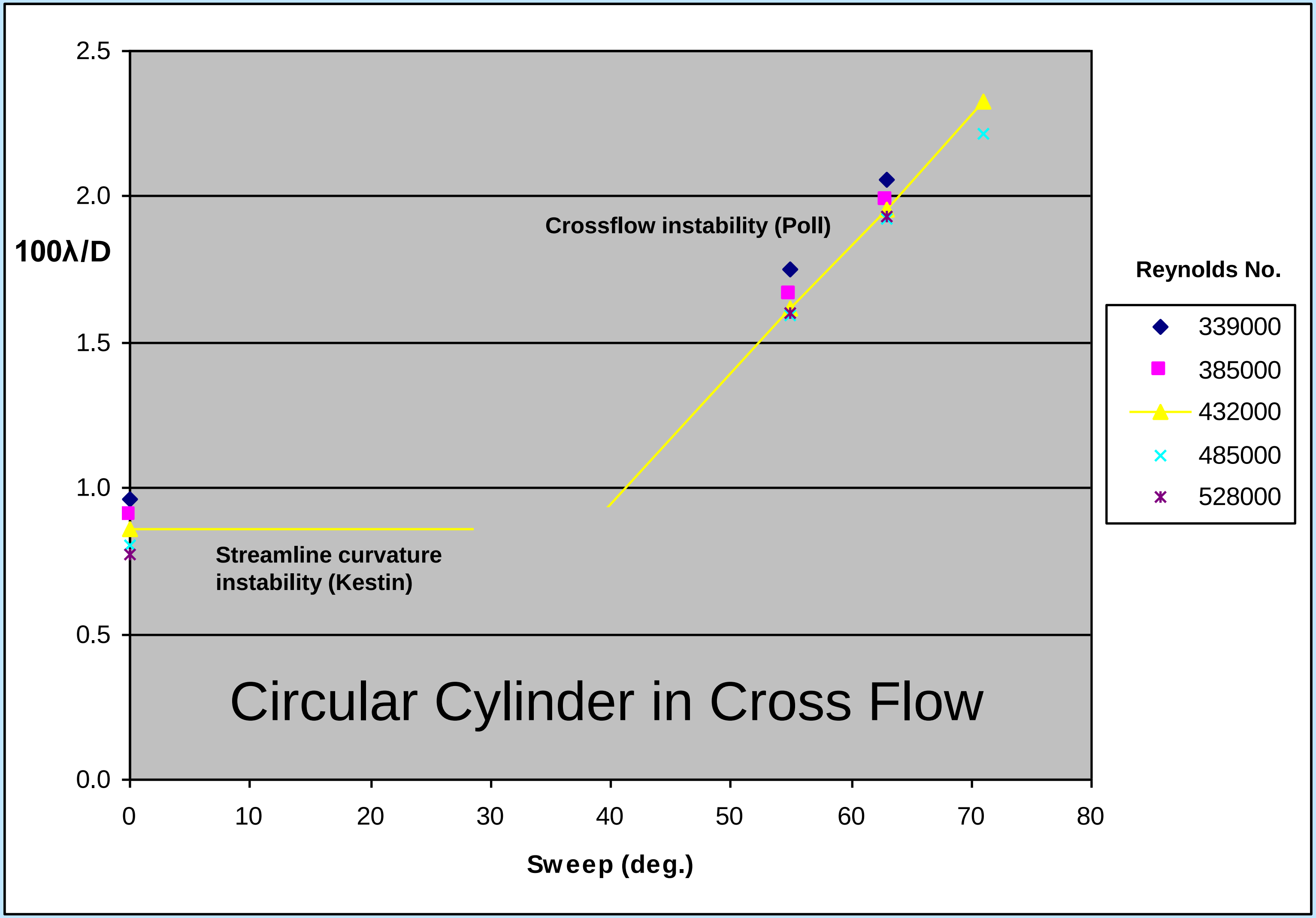
Notice use of sweep – which are swept, the rotor blades or the stator blades?

Which are canted?



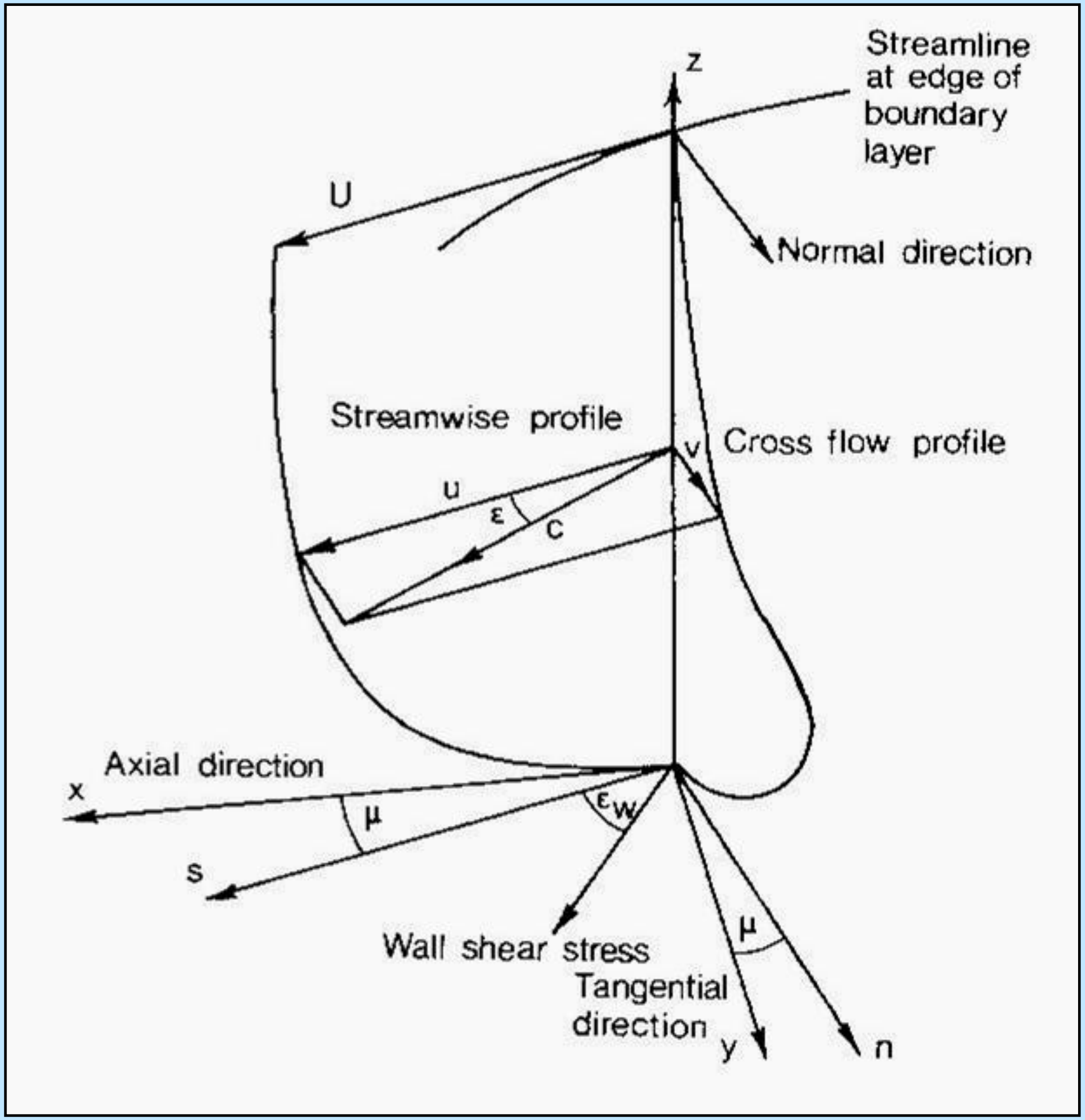
Poll and Kestin Results

Does crossflow instability cut in at about 38^o?
What is missing is reliable experimental data with sweep between zero and 55^o.



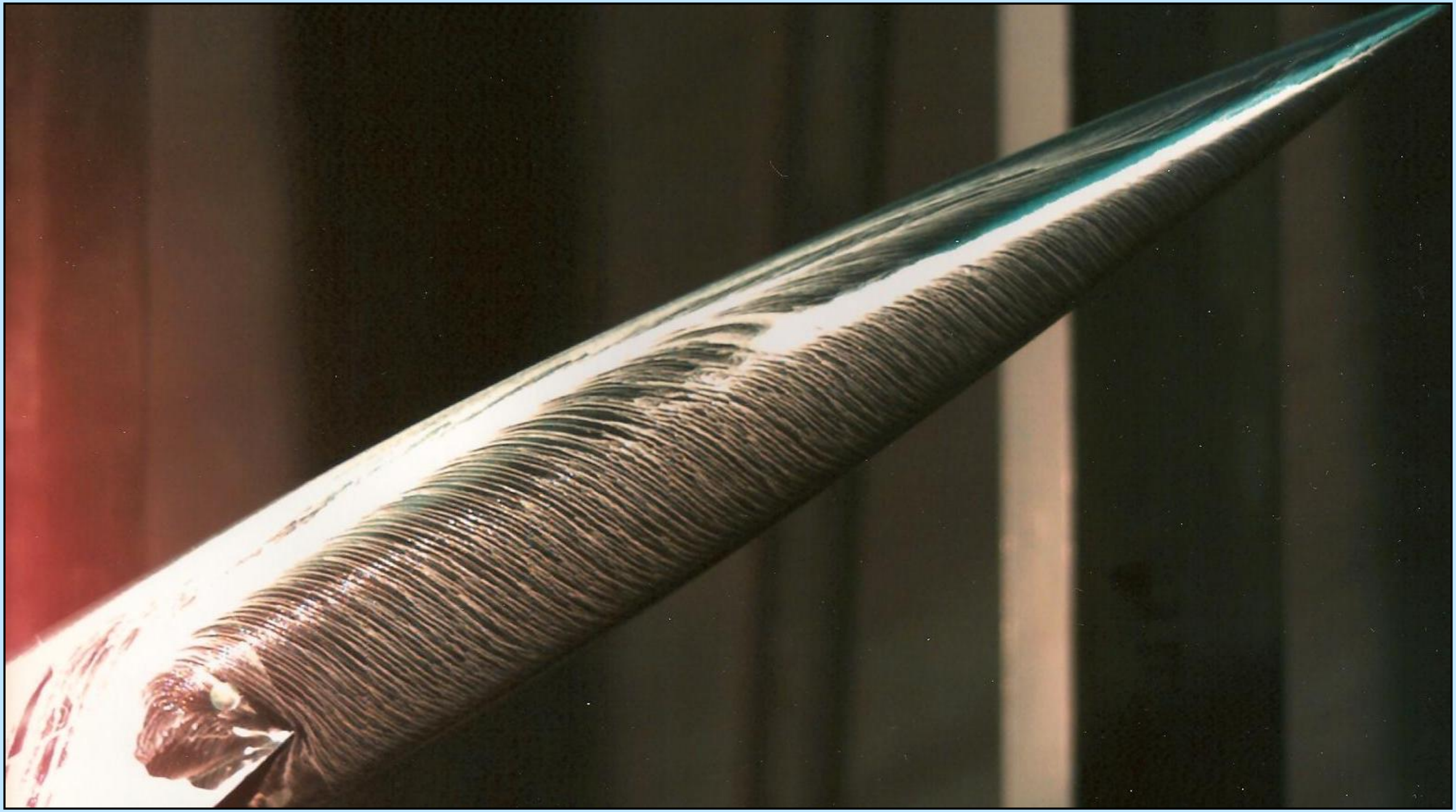
Streamwise and Crossflow Velocity Profiles

The cross flow profile develops an obvious and aggressive instability as the sweep increases, resulting in severe cross flow vorticity. The next slide, of the flow over a fuselage (effectively a circular cylinder with 60º sweep) shows this quite clearly.



Streaks on Fuselage Indicate Crossflow Vortices

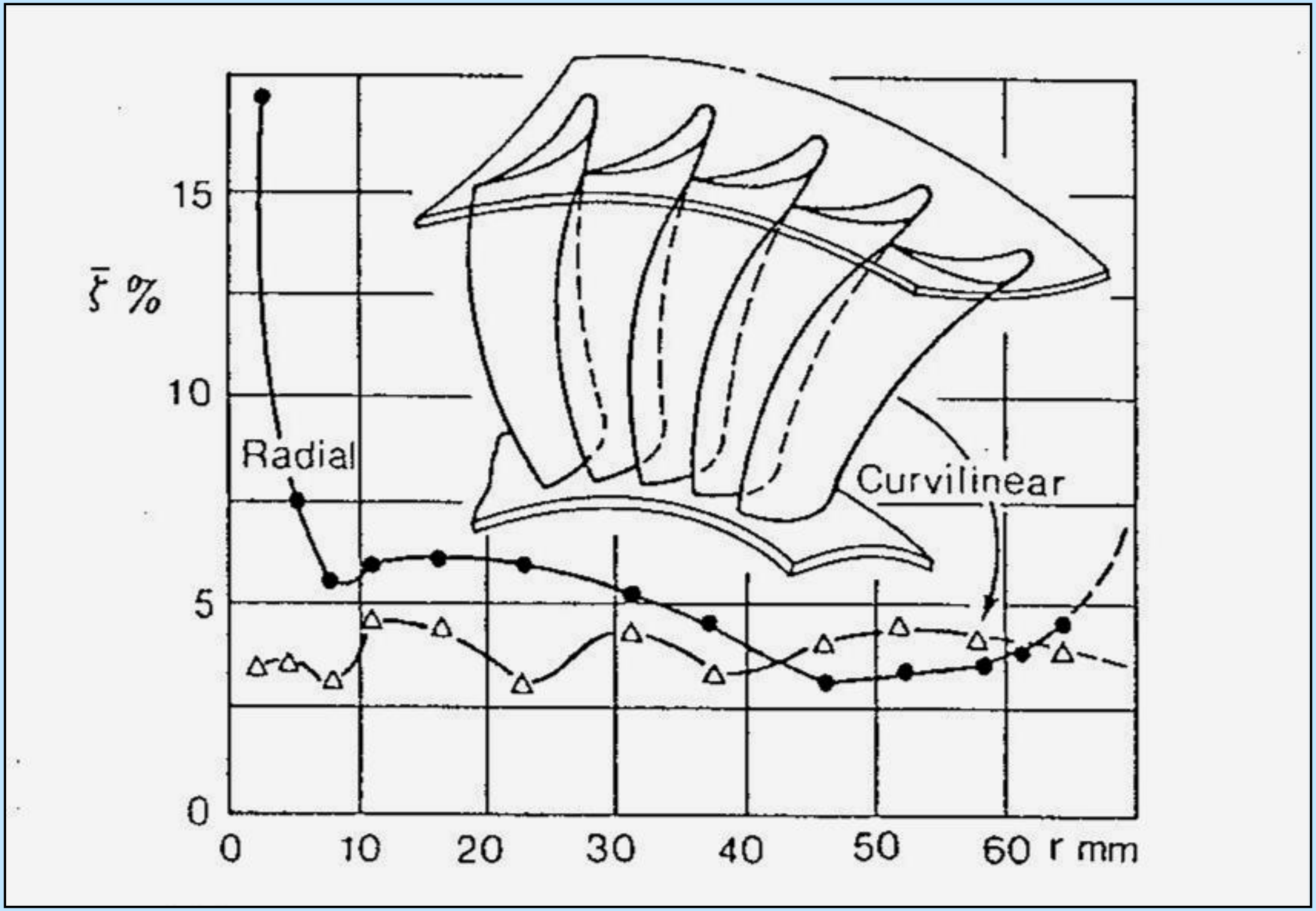
Surface Visualization by Hanff



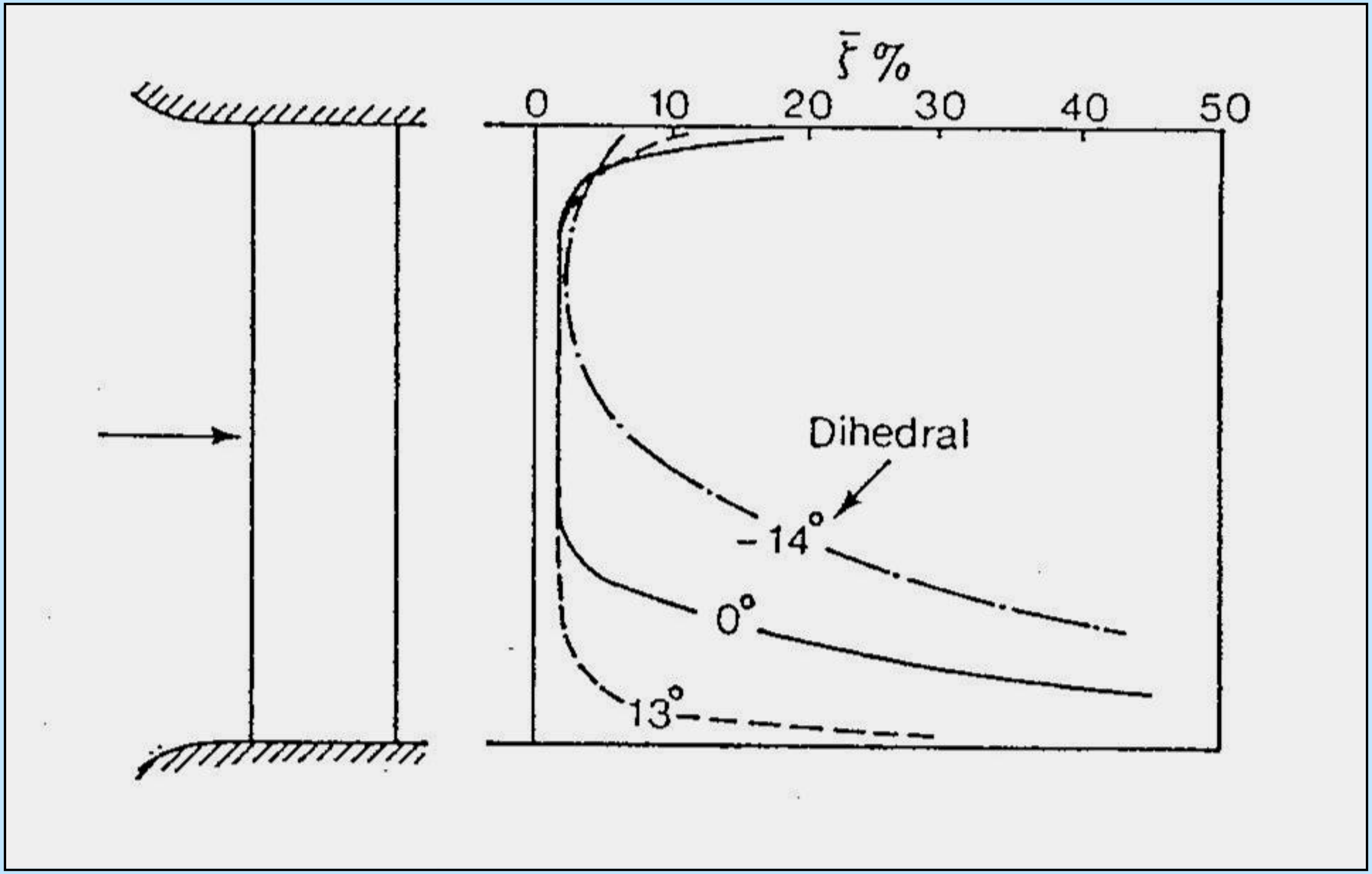
Curvilinear Nozzle Blades

and associated loss improvement

Filippov and Wang, 1964



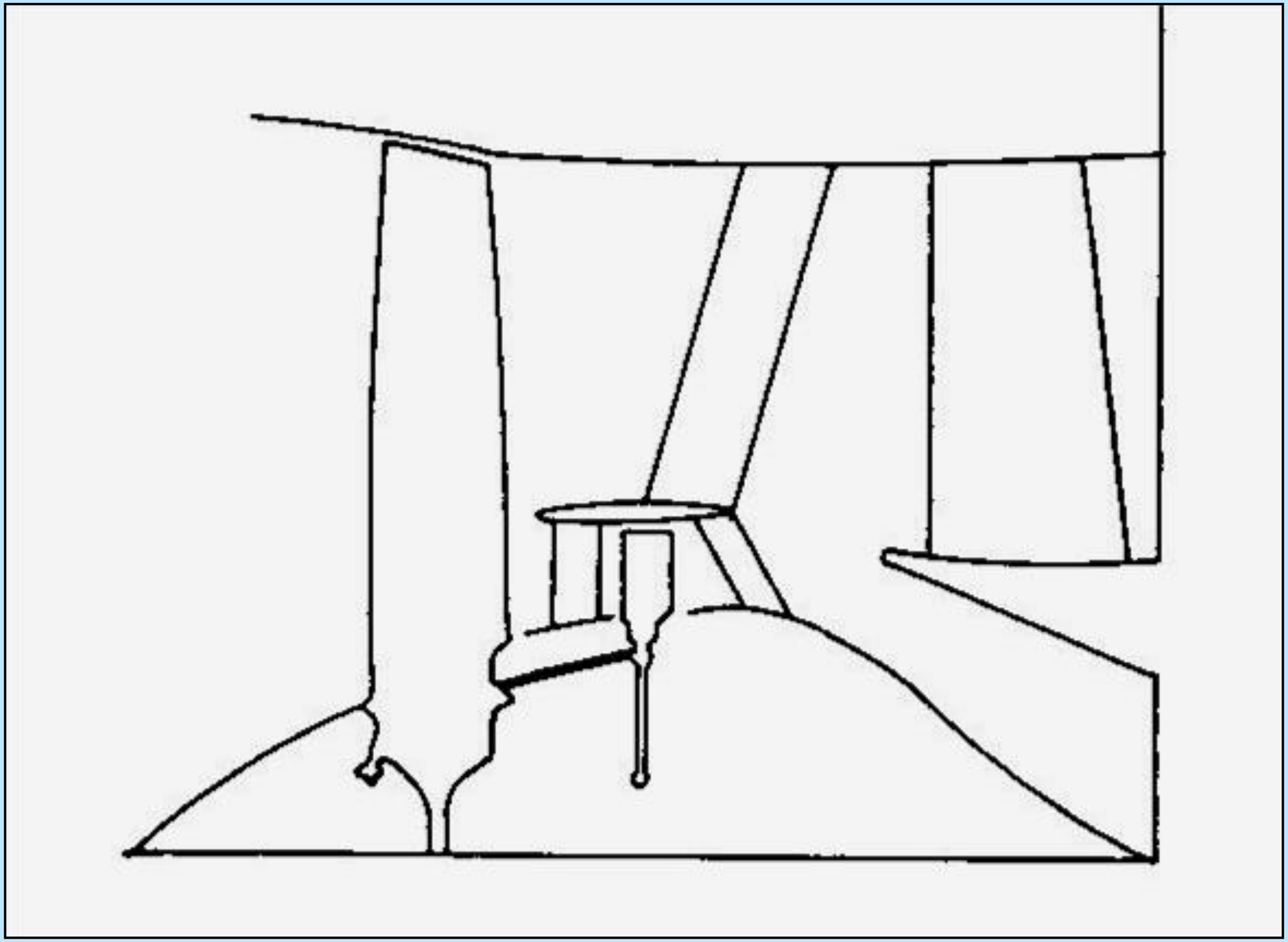
Effect of Inclination on Losses



Use of Sweep and Dihedral

in CF6 Engine to Impart Downward Body Forces

L.H. Smith Jr., 1968



Conclusions - 1

- ***A taxonomy of turbomachines is presented, permitting turbines of widely varying geometry and layout to be identified and classified. The process is illustrated with reference to different configurations of hydraulic and free flow turbines.***

- ***The framework employed for analysis and design of enclosed axial turbomachines is introduced. Although the traditional approach to the design of enclosed turbines uses intersecting two dimensional planes it is recognized that all turbomachinery flows are three dimensional and unsteady. The use of advanced RANS and LES computational procedures is routine but these effects are still not well-predicted.***

- ***Universities and industry have collaborated in the last two decades to produce highly-loaded low pressure turbines. Deployed in commercial aircraft and major savings in engine weight and cost achieved, but with a penalty in turbine efficiency. Research now aimed at regaining lost efficiency but retaining weight and cost gains.***

Conclusions - 2

- ***Streamwise streaks are present in the laminar portion of the flow over the convex surfaces of circular cylinders and turbomachinery blades. Consistent spanwise wavelengths indicate organized behavior. Confirmation needed.***

- ***Measured spanwise wavelengths of the periodic vortex arrays on blading are predicted quite well by the Kestin and Wood theory. If this behavior is common it will have implications for blade aerodynamic and cooling design.***

- ***The sweep question seems particularly relevant for most approaches to the design of free flow turbines. This is an important part of the analysis for most blades.***

Conclusions - 3

- ***The <u>shape</u> of a turbomachine is vitally important. It responds to and affects its environment and its operation in that environment. It should never become the object of a graphic designer's whim.***

- ***The fact that open flow machines have so many different shapes and configurations tells us that they are responding to a very wide range of environments and functions but also that their design technology is far from mature. And that is why good turbomachinery designers have a job that is always interesting and varied – a job for life.***

- ***For progress to be maintained it is essential for analytical, computational and experimental work to proceed in a balanced, collaborative and interactive manner. Best achieved by the relaxation of traditional disciplinary barriers in universities and industry.***