Turbomachinery & Turbulence.
Lecture 1: Introduction to turbomachinery.

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General introduction

- A turbomachine is a rotating machine which achieves a transfer of energy between its shaft and a moving fluid. The transfer can be done in two ways:
  - absorbing power ⇒ increase of the fluid pressure or head: *ducted and unducted fans, compressors and pumps;*
  - producing power ⇒ expansion of the fluid to a lower pressure or head: *wind, hydraulic, steam and gas turbines.*
- It consists of one or more
  - moving blade rows: *rotors, impellers, propellers*;
  - stationary parts: *stators, nozzles, volutes*.
- Changes of flow direction through moving surface ⇒ angular momentum and energy exchange ⇒ *Variation of stagnation enthalpy*.
- Several geometries according to flow direction: *Axial, Centrifugal (radial) and Mixed-flow*.
- 3D, unsteady, turbulent and rotating internal flows.
- Compressible and incompressible flows.

Functions and industrial domains

- Recovery of the energy of a fluid
  - liquid: Hydraulic potential energy recovery (dams)
  - gas: Production of mechanical energy (dental turbine, turbocharger, turbopumps)
- Gas compression
  - compressed air network
  - automotive internal combustion engine
- Fluid transportation
  - pumps to overcome gravity (elevation of a liquid)
  - to overcome head losses in a pipe
- Energy production from heat source (gas and steam turbines in a thermodynamic cycle)
- Production of thrust in aeronautics (turboreactors and turbofans)

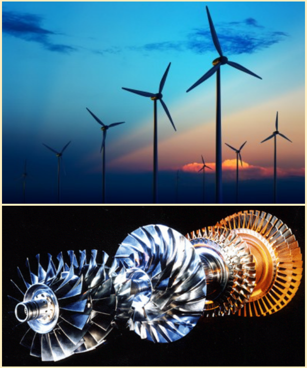
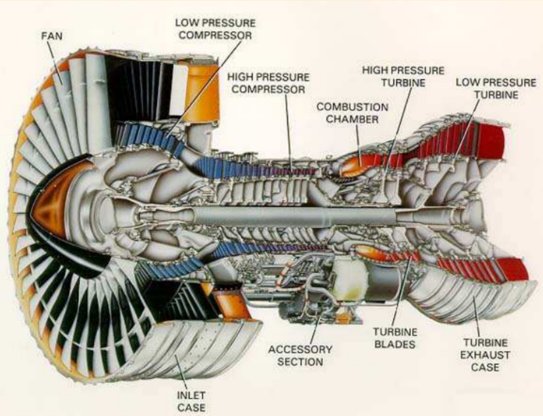
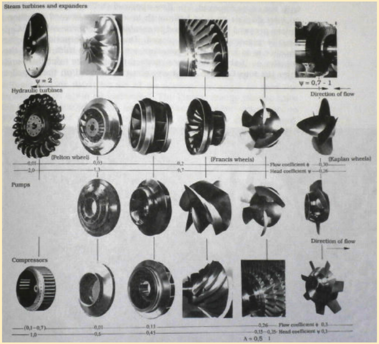


Figure : Windmills, turboreactor.

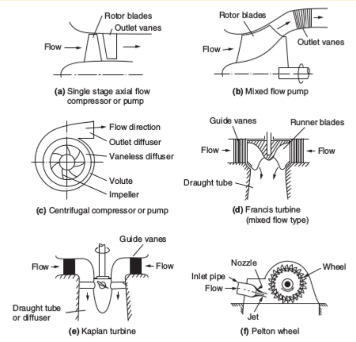
The turbofan: a complex set of various turbomachines



Classification/ elements of turbomachines

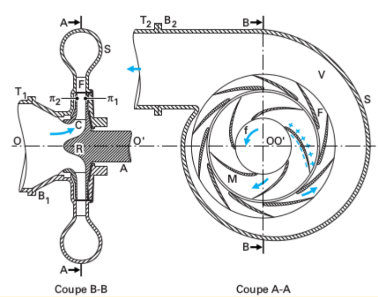


Rotors of various turbomachines

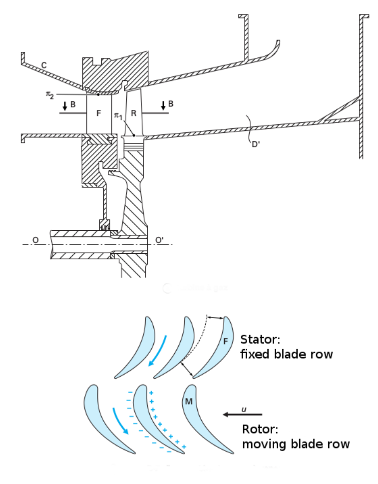


Various arrangements of rotors and stators

Description of two typical single-stage turbomachines

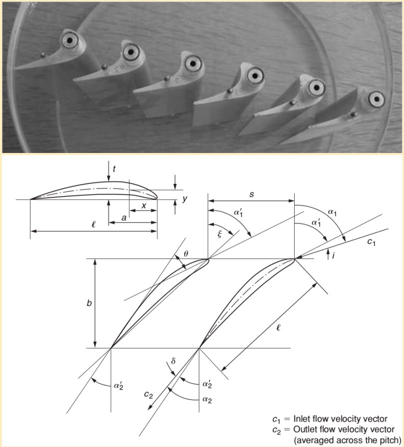


Centrifugal compressor



Axial-flow turbine

Blade Cascade



- Natural coordinate system: cylindrical r, θ, x.
- Absolute velocity is $\vec{C}$. Meridional velocity:

$$C_m = \sqrt{C_r^2 + C_x^2}$$

- Swirl angle:

$$\alpha = \arctan\left(\frac{C_\theta}{C_m}\right)$$

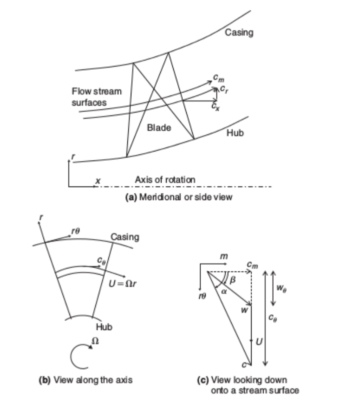
- Relative frame of reference rotating with $U = r\omega$. If the relative velocity is $\vec{W}$:

$$\vec{C} = \vec{U} + \vec{W}$$

- Relative flow angle:

$$\beta = \arctan\left(\frac{W_\theta}{W_m}\right) = \arctan\left(\frac{W_\theta}{C_m}\right)$$

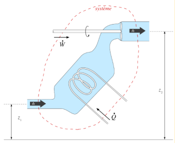
$$\tan\beta = \tan\alpha - \frac{U}{C_m}$$

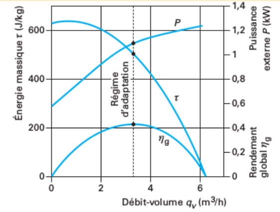


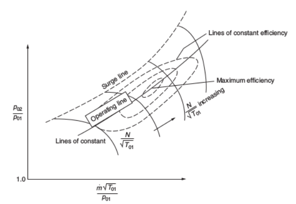
Characteristics of incompressible and compressible flow turbomachines

First law of thermodynamics for open systems:

$$\dot{m}\Delta h_0 = \dot{Q} + \dot{W}$$







Incompressible flow:

- Mechanical energy rise τ *vs.* volumetric flow-rate q_v
- Shaft power P
- Efficiency $\eta = \frac{\rho q_v \tau}{P}$ (pump)

Compressible flow:

- Mechanical energy rise *vs.* mass flow-rate $\dot{m}$
- Speed of sound a_{01} (Mach number) $\Rightarrow$
- Total pressure ratio π_t *vs.* flow capacity for a given Mach number
- Surge limit and choked flow limit.

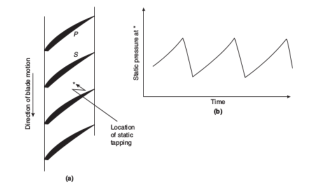
Unsteadiness and non-axisymmetry: a key to work transfer

Work transfer in turbomachinery: the underlying mechanism is fundamentally unsteady:

$$\frac{dh_0}{dt} = \frac{1}{\rho}\frac{\partial p}{\partial t}$$

A pressure field moves with the blades ($\approx$ steady in the relative frame of reference). At a fixed position in space:

$$\frac{\partial p}{\partial t} = \omega \frac{\partial p}{\partial \theta}$$



Different time scales

Unsteady phenomena of two kinds:

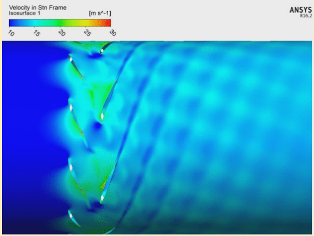
- Not periodic phenomena: transient start, turbulent fluctuations, ...
- Periodic phenomena:
  - correlated with the blade row rotation rate ω: rotor/stator and rotor/rotor interactions
  - uncorrelated to the blade row rotation rate: system instabilities, trailing edge vortex releases, ...

Rotor/stator interaction

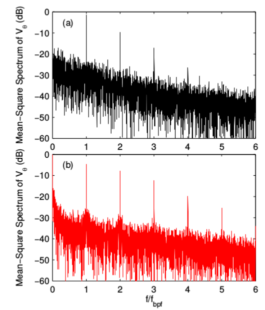
-In a stage, one blade row is downstream of the other (!)

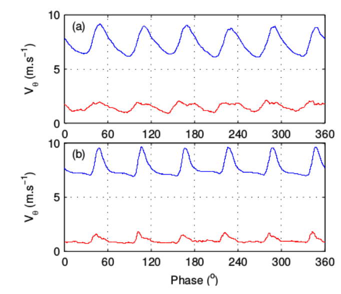
-For a blade row rotation rate ω, with Z the number of blades, l the chord length and C_m the meridional velocity:

- Blade passing time scale: $t_{bpf} = \frac{2\pi}{Z\omega}$
- Convective time scale: $t_c = \frac{l}{C_m}$
- Reduced frequency: $f = \frac{t_c}{t_{bpf}} = \frac{Z\omega l}{2\pi C_m}$
  - $f \ll 1$: convective phenomena are dominant $\Rightarrow$ quasi-steady flow.
  - $f \gg 1$: periodical perturbations are dominant $\Rightarrow$ unsteady flow.



Time features of the flow downstream of a single row

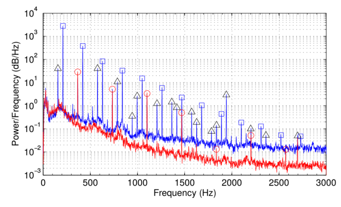


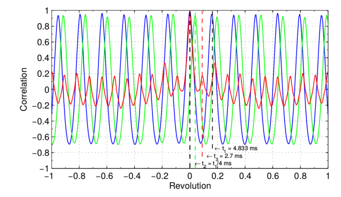


LDA measurement of the velocity downstream of axial-flow fans (single rotor).

- On the left: power spectrum.
- On the right: phase-averaged velocity (blue) and phase-averaged rms of the velocity (red).
- (a) and (b) are two different fans.

Time features of the flow between two rotors



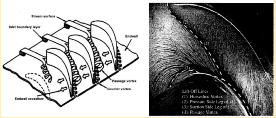


Casing pressure fluctuations between two counter-rotating axial-flow fans.

- On the left: power spectrum.
- On the right: Autocorrelation function and cross-correlation function (green) between two microphones separated by 90^o.
- red and blue are two different distances between the rotors.

Small-scale turbulence is a second-order effect, confined into casing/blades boundary layers and wakes.

Viscous effects



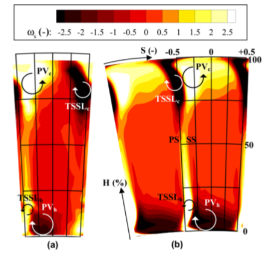


Fig. 5 Measured (5hp) (*a*) and predicted (*b*) streamwise vorticity ω_s at rotor inlet in the absolute frame of reference

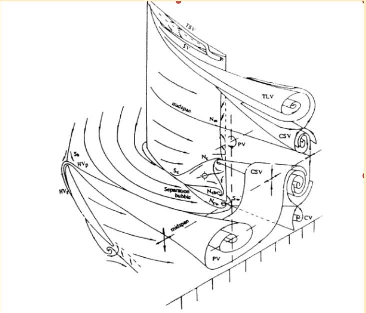
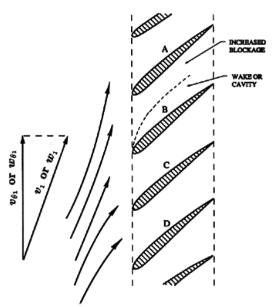


Figure 1. Schematic of secondary flow structure in a compressor cascade with tip clearance, Kang [6]: PV – Passage vortex; HV – Horseshoe vortex; TLV – Tip leakage vortex; TSV – Tip secondary vortex; SV – Secondary vortex; CSV – Concentrated shed vortex; CV – Corner vortex

Cross-stream pressure gradients + boundary layers ⇒ Secondary flows (recirculations).
Streamwise adverse pressure gradient ⇒ Diffusion ⇒ Stall, flow separation and backflow, leading to large scale instabilities.

Stall, Stage stall and surge



Rotating stall: frequency of the order of the rotating frequency.
Surge: system instability, slow time scales.

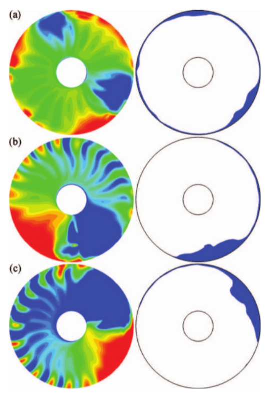


Fig. 7 Static pressure distribution (left) and reverse flow region (right) upstream of the fan in the rotating frame after 20 rev: (a) 70% fan speed, (b) 80% fan speed, and (c) 90% fan speed