12:th EUROPEAN TURBOMACHINERY CONFERENCE
3-7 April 2017, Stockholm

ROYAL INSTITUTE
OF TECHNOLOGY

Turbomachinery Aeroacoustics

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Content

- Aeroacoustics ?
- Sound from moving sources – FWH equation
- Aerodynamic source strength – scaling laws
- Sound from Turbomachines
- Acoustic installation effects
- Multi-port characterization of Turbomachines
- Experimental investigation of surge
- Numerical investigation of surge
- Summary and conclusions

AEROACOUSTICS ?

Cooling fans and turbo-chargers on cars and trucks

Gasturbines for aircrafts and powerplants

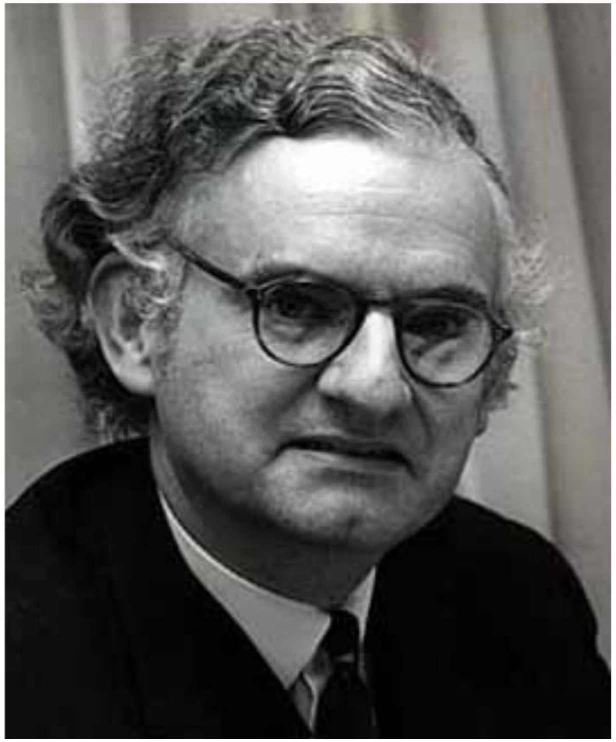
Ventilation fans for vehicles and buildings

Wind instruments – flutes, organs, …

Started around 1950´s related to noise issues with the then new jet powered civil aircrafts…

$$\boxed{\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = s}$$

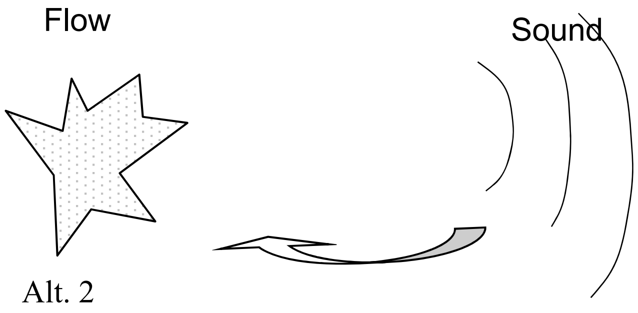
Lighthills acoustic analogy

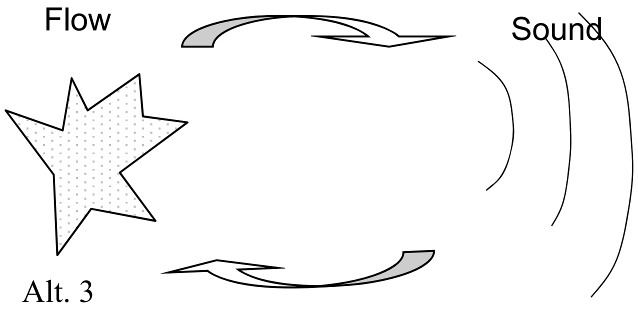


Sir Michael JAMES Lighthill FRS

(1924-1998)

Limitations in Lighthill´s theory





Lighthill or linear Aero-Acoustics is OK

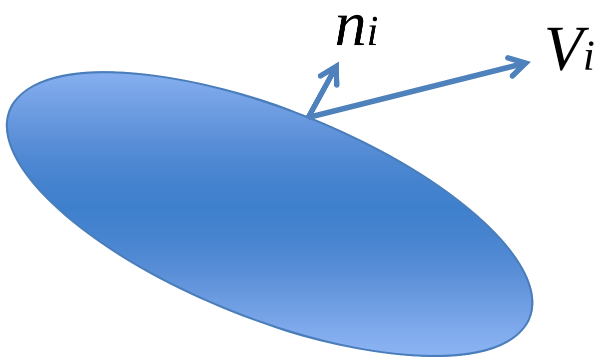
Alt. 1: Sound production by a flow.

Alt. 2: Sound-vortex interaction (dissipation/ amplification).

Alt. 3: Whistling (Non-linear Aero-Acoustics)

SOUND FROM MOVING SOURCES – FWH Equation

Ffowcs-Williams Hawkings equation is a reformulation of Lighthills acoustic analogy for moving bodies..



The motion (body surface) is described by a function f(**x**,t)=0 and it is further assumed that f < 0 inside the body and f > 0 outside.

Volume displacement
~ **Monopoles**

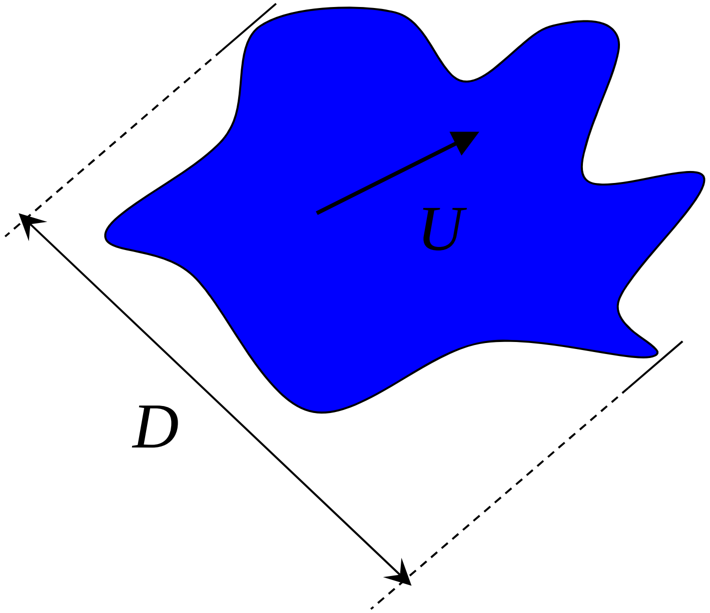
Fluctuating pressures
~ **Dipoles**

Unsteady Reynolds stresses or transport of momentum
~ **Quadrupoles**

$$\left(\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)(p'H) = \frac{\partial}{\partial t}\left(\rho_0 V_i n_i |\nabla f| \delta(f)\right) \underline{- \frac{\partial}{\partial x_i}\left(p' n_i |\nabla f| \delta(f)\right)} + \frac{\partial^2}{\partial x_i \partial x_j}\left(\rho u_i u_j H(f)\right)$$

AERODYNAMIC SOURCE STRENGTH – SCALING LAWS

For aerodynamically generated sound the time averaged sound power $\overline{W}$ will scale as:



$$\overline{W} \sim \rho U^3 D^2 M^{\alpha+n},$$

where *M* is Mach-number, *n* the space dimension (1,2,3) and:

$$\alpha = \begin{cases} -2, monopole \\ 0, dipole \\ 2, quadrupole \end{cases}$$

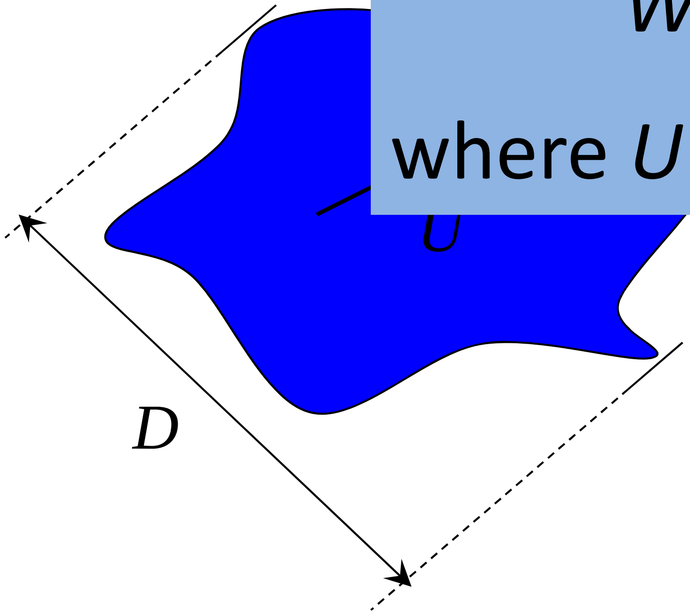
AERODYNAMIC SOURCE STRENGTH – SCALING LAWS

For aerodyn averaged
sound powe

For a dipole we will get

$$W \sim U^{4\text{-}6},$$

where *U* is the flow speed



where *M* is Mach-number, *n* the space dimension (1,2,3) and:

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Relative sound power W from aeroacoustic sources

$$\overline{W}_{monopole} : \overline{W}_{dipole} : \overline{W}_{quadrupole} \propto 1 : M^2 : M^4$$

- Combustion

-Piston machines (in/out flow openings)

- High Mach (>1) Turbomachines

-Fans

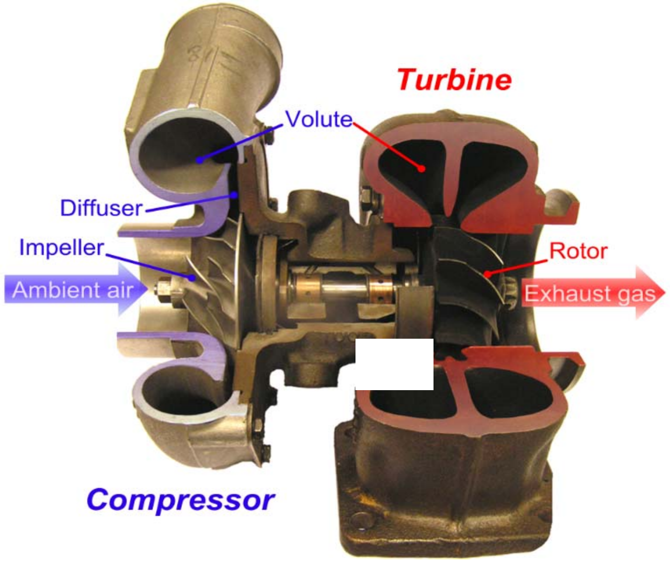
-Flow separation

- Free jets at high Mach (~1)

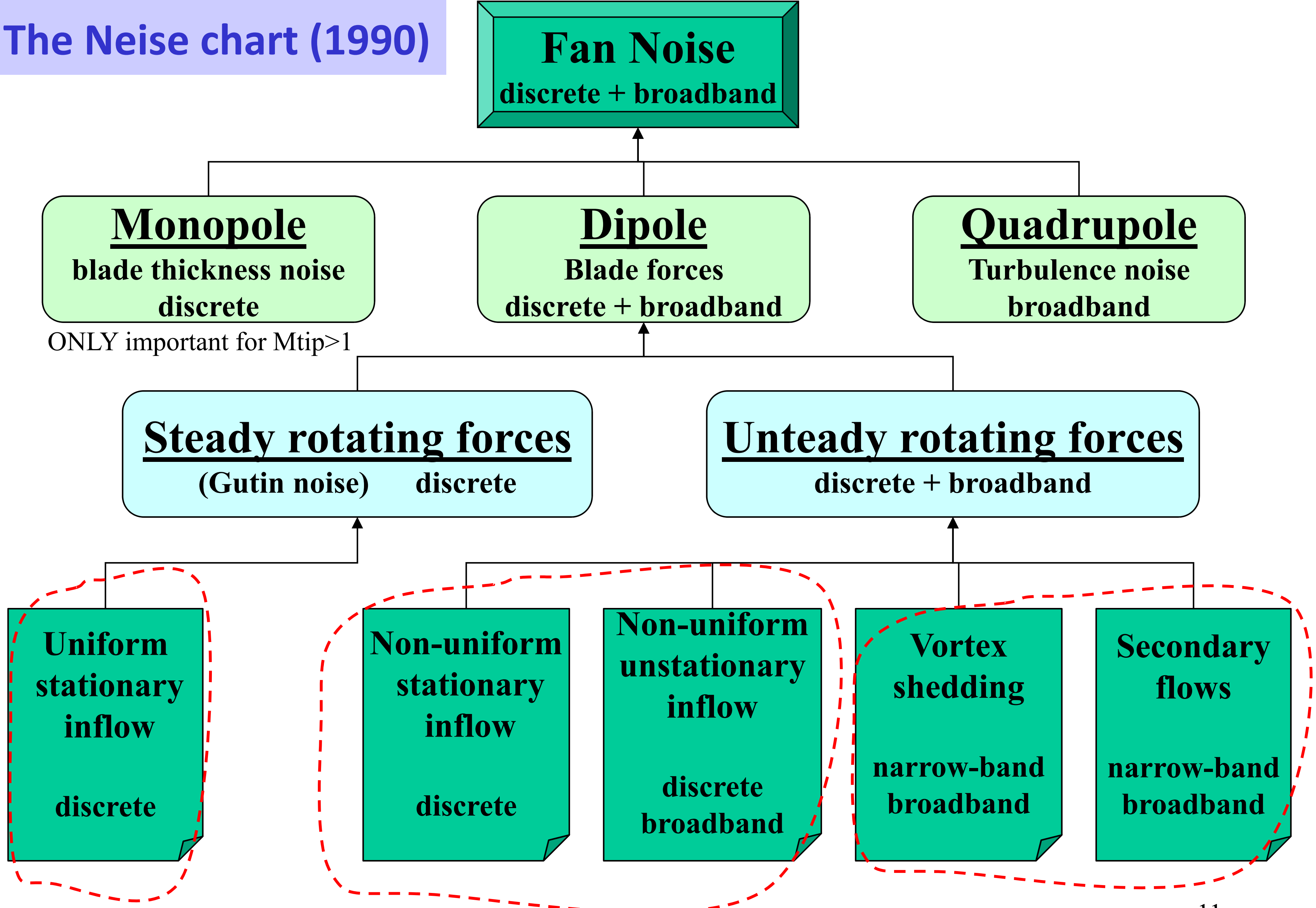
[M=Mach-number=U/c_0]

SOUND FROM TURBOMACHINES [2-5,13]

There are two basic types axial and radial. For both types the sound generation can be classified using Lighthills analogy….



Fan source mechanisms - The Neise chart (1990)



Fan Noise
discrete + broadband

Monopole
blade thickness noise
discrete
ONLY important for Mtip>1

Dipole
Blade forces
discrete + broadband

Quadrupole
Turbulence noise
broadband

Steady rotating forces
(Gutin noise) discrete

Unteady rotating forces
discrete + broadband

Uniform stationary inflow
discrete

Non-uniform stationary inflow
discrete

Non-uniform unstationary inflow
discrete
broadband

Vortex shedding
narrow-band
broadband

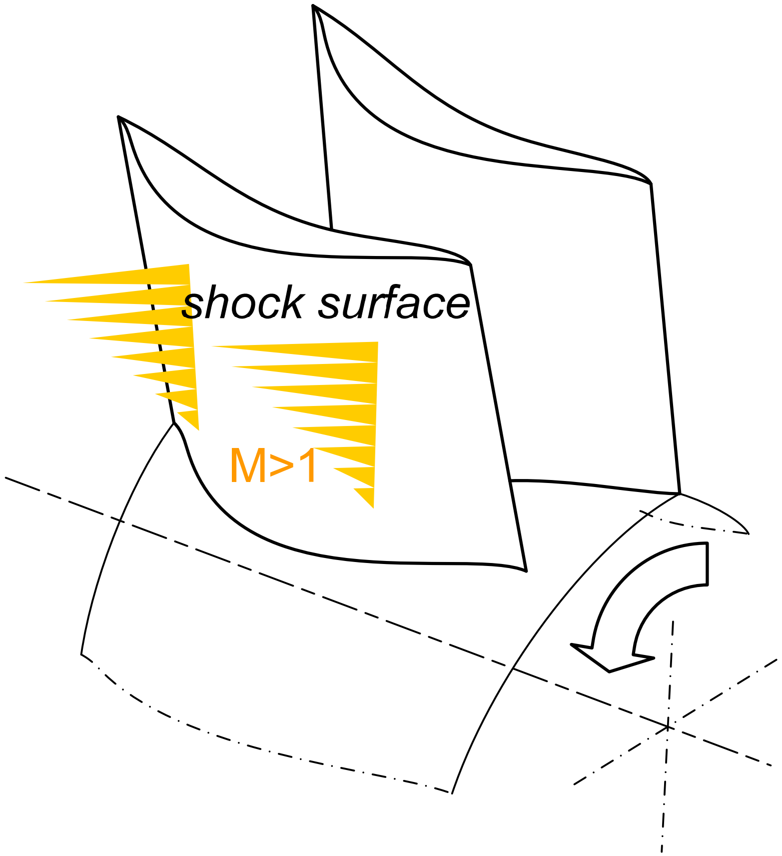
Secondary flows
narrow-band
broadband

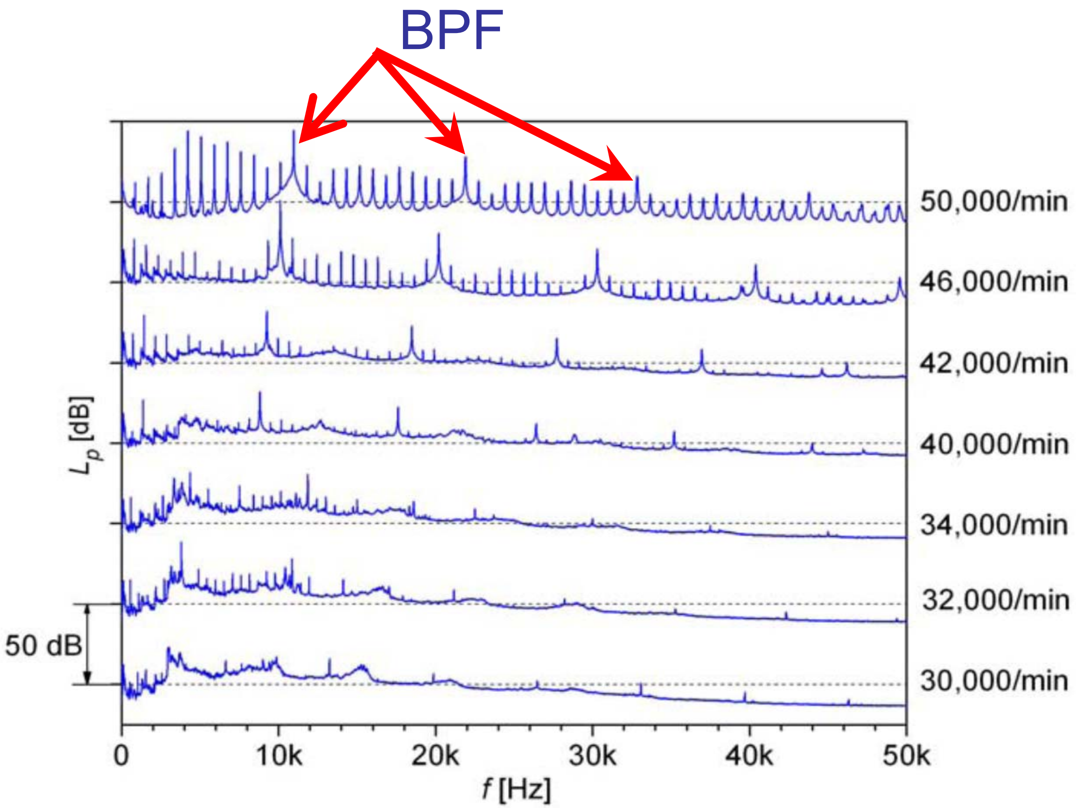
“Self Noise”

“**Aerodynamic installation effects**”

“Self Noise”

Example - sound pressure compressor inlet



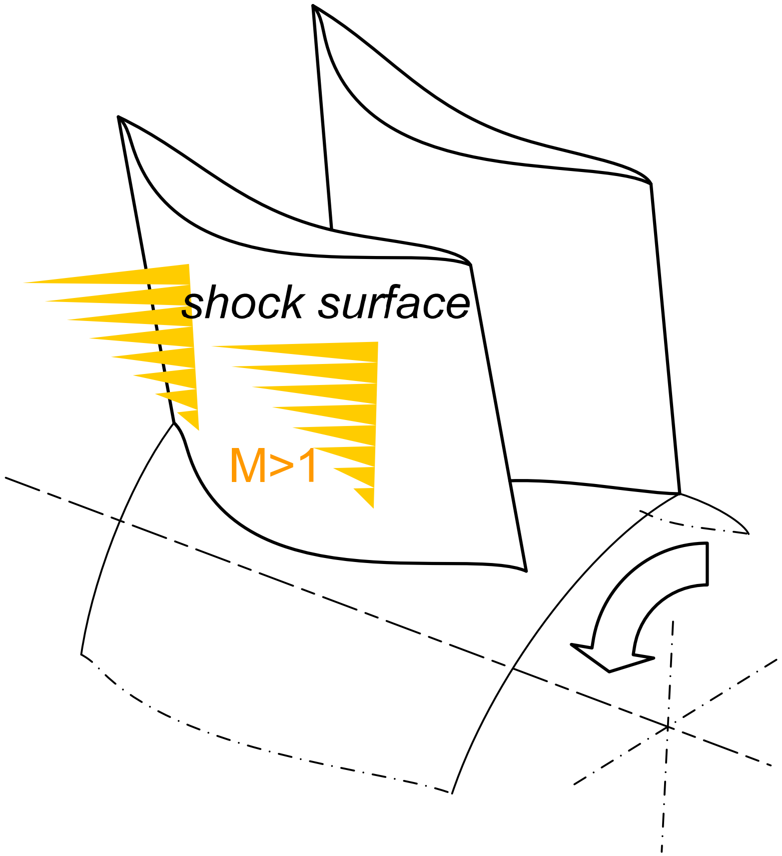


A compressor rotating with N RPM will generate harmonics of its Blade Passing Frequency (BPF):

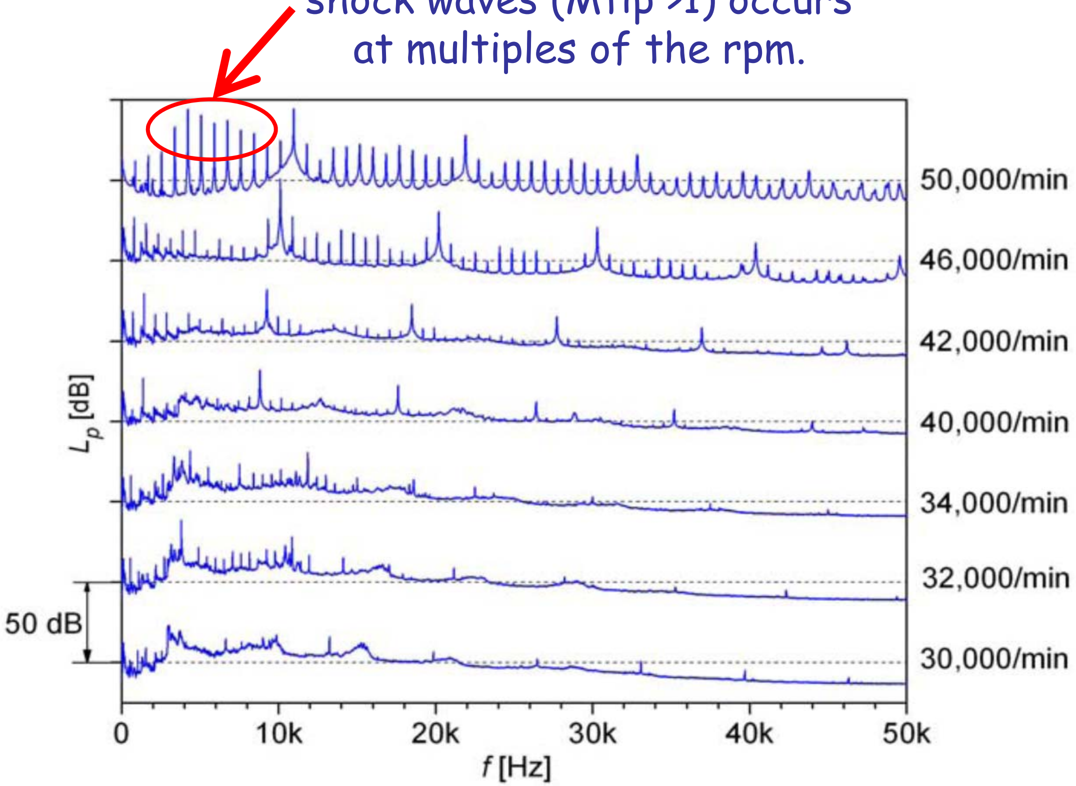
BPF = B · N/60, where B is the number of main rotor blades.

Averaged sound pressure level in the compressor inlet duct after “T.Raitor and W.Neise (2006), Sound Generation in Centrifugal Compressors, 12th AIAA/CEAS Aeroacoustics Conference”.

Example - sound pressure compressor inlet



Buzz-saw noise or rotating shock waves (Mtip >1) occurs at multiples of the rpm.



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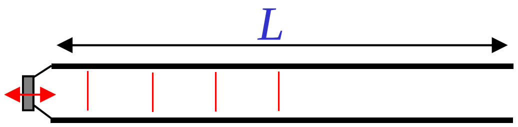
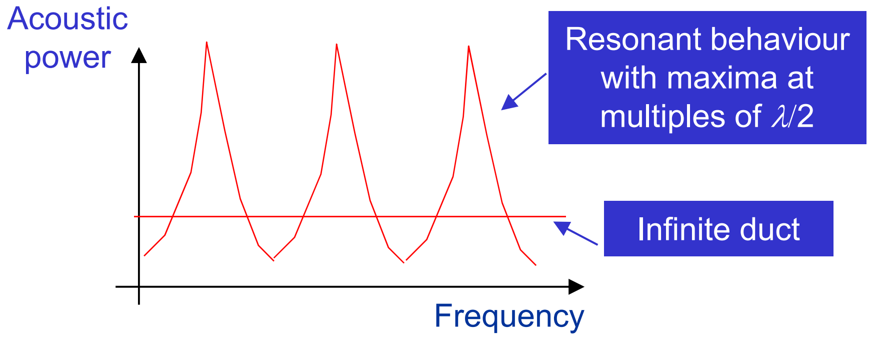
ACOUSTIC INSTALLATION EFFECTS (”No free-field”)

- In the low frequency (plane wave) range ($f < f_{cut\text{-}on}$) a source is strongly coupled to a system and the acoustic output (power) can vary strongly.



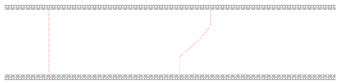
Duct excited by a loudspeaker

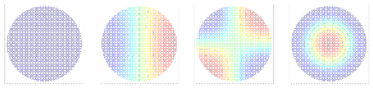


Resonant behaviour with maxima at multiples of $\lambda/2$

Infinite duct

- In the mid frequency range up to (2-3)x $f_{cut\text{-}on}$, *plane + non-plane waves* exist. Also in this range strong coupling between source and system is possible.





- In the high frequency range $f > 3xf_{cut\text{-}on}$, sound propagates as rays, there is no coupling between a source and a system and the acoustic power equals the free field value.

ACOUSTIC INSTALLATION EFFECTS
(”No free-field”)

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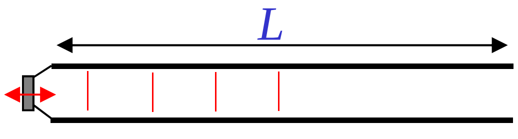
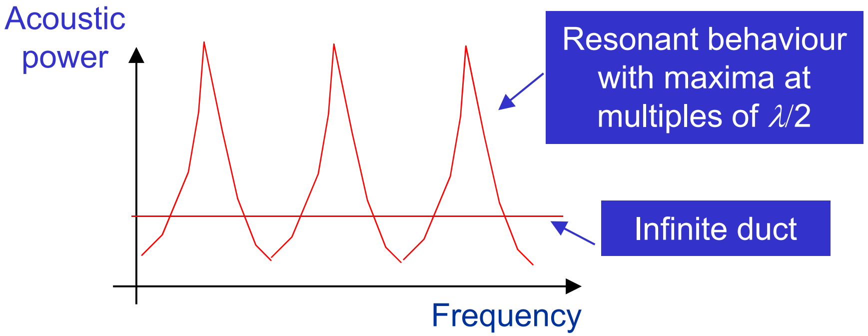


Duct excited by a loudspeaker



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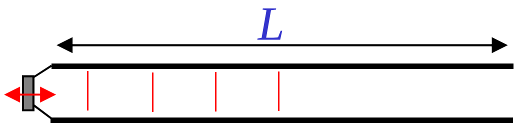
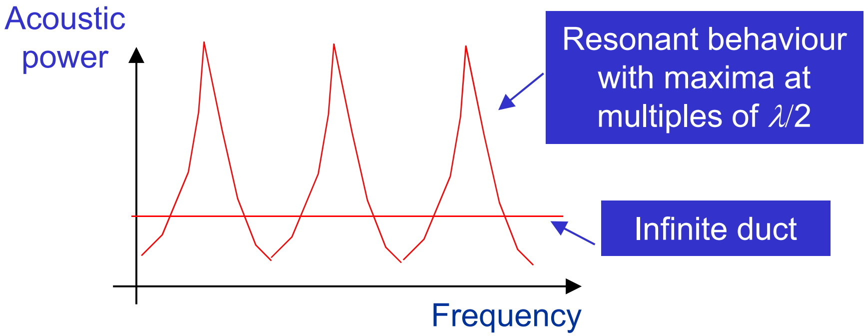
ACOUSTIC INSTALLATION EFFECTS (”No free-field”)

Coupled models required

- In the low frequency (plane wave) range ($f < f_{cut\text{-}on}$) a source is strongly coupled to a system and the acoustic output (power) can vary strongly.



Duct excited by a loudspeaker



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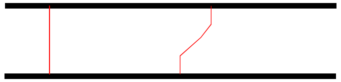

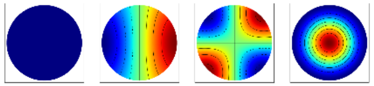

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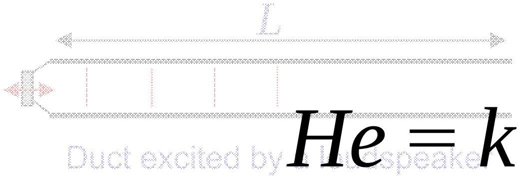
ACOUSTIC INSTALLATION EFFECTS (”No free-field”)

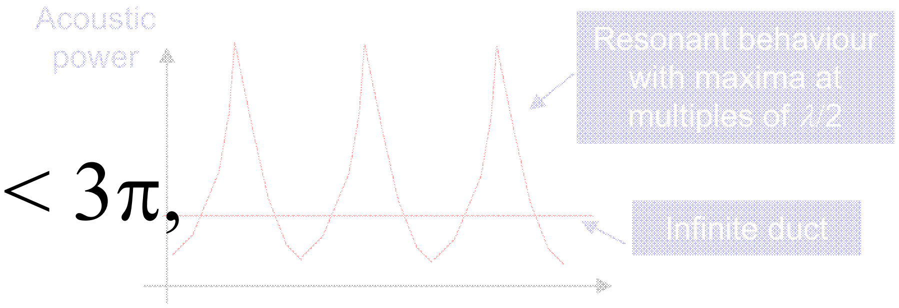
Coupled models required

- In the low frequency (plane wave) range ($f < f_{cut\text{-}on}$) a source is strongly coupled to a system and the acoustic output (power) can vary strongly.

In practice the limit is around 10 propagating modes or:



$$He = kd < 3\pi,$$



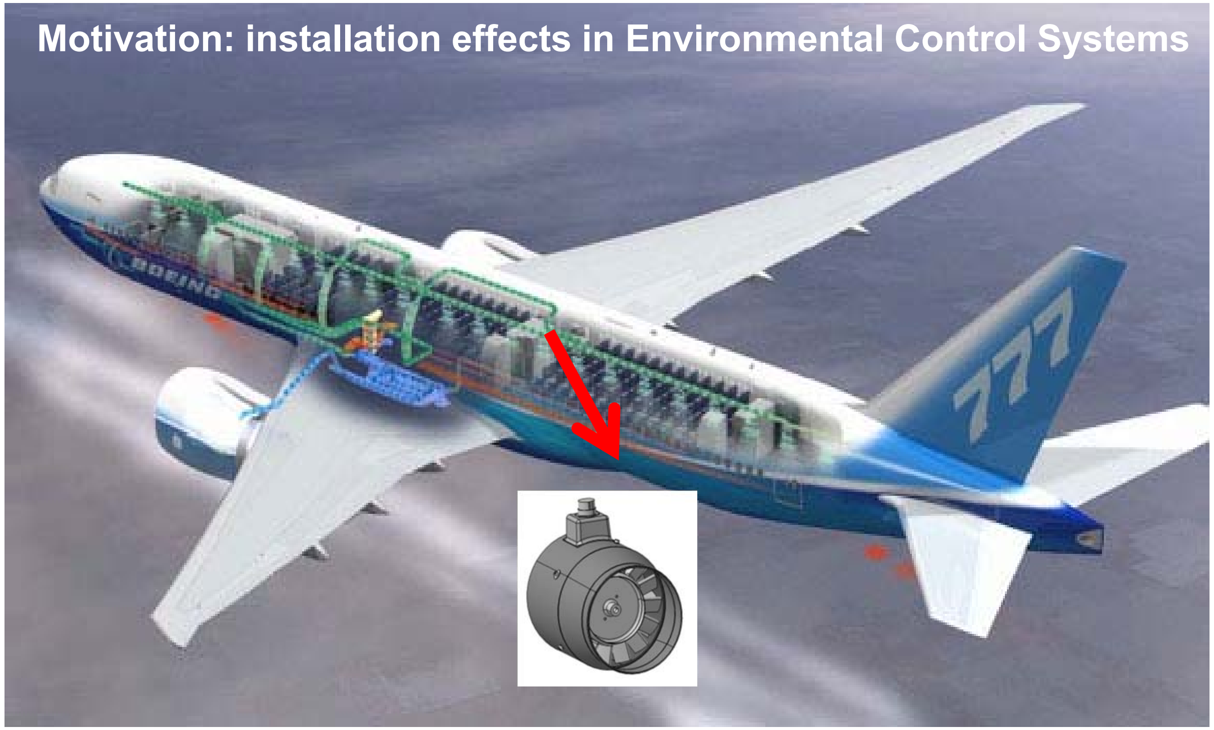
where k is the wave-number and d the duct diameter.

- In the mid frequency range up to (2-3)x $f_{cut\text{-}on}$, *plane + non-plane waves* exist. Also in this range strong coupling between source and system is possible.

- In the high frequency range $f > 3xf_{cut\text{-}on}$, sound propagates as rays, there is no coupling between a source and a system and the acoustic power equals the free field value.

MULTIPORT CHARACTERIZATION OF TURBOMACHINES [1,12-13]

Stefan Sack and Mats Åbom
KTH - The Royal Institute of Technology, Stockholm, Sweden

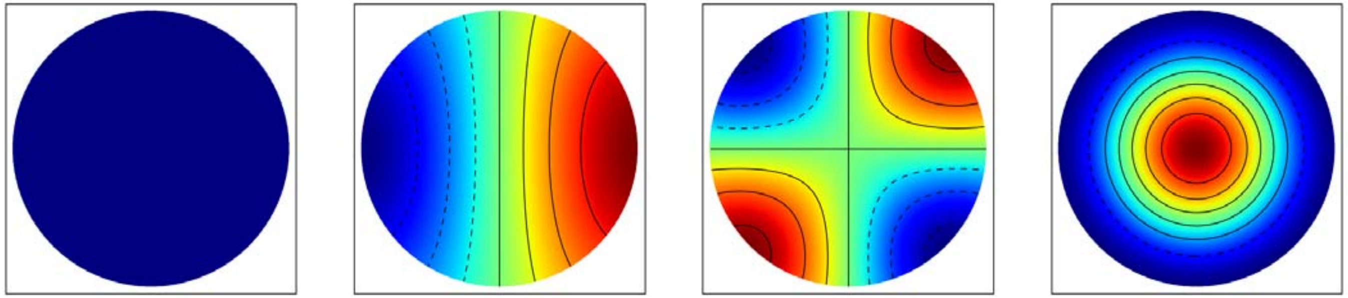

Motivation: installation effects in Environmental Control Systems

Multi-Port approach

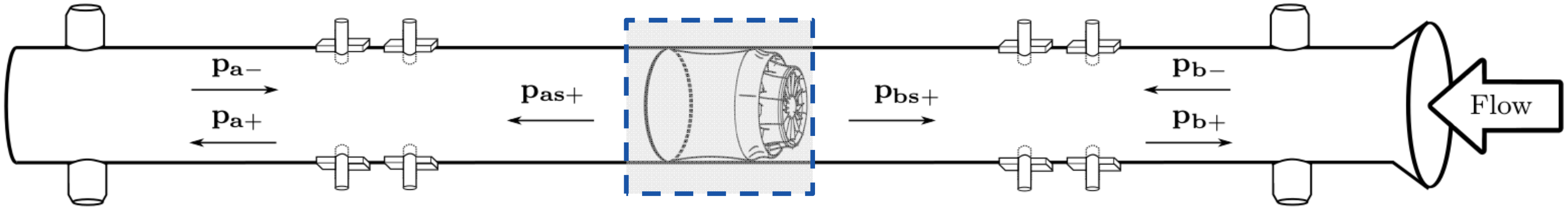
The sound field pressure (p) inside the duct is a **superposition** of acoustic **eigen-modes**

$$p(x,y,z)=\sum_{n}\left(\hat{p}_{+n}\Psi_{n}(x,y)\exp(-ik_{+z,n}z)+\hat{p}_{-n}\Psi_{n}(x,y)\exp(ik_{-z,n}z)\right)$$

Ψ_n:



Multi-Port approach (Frequency domain)



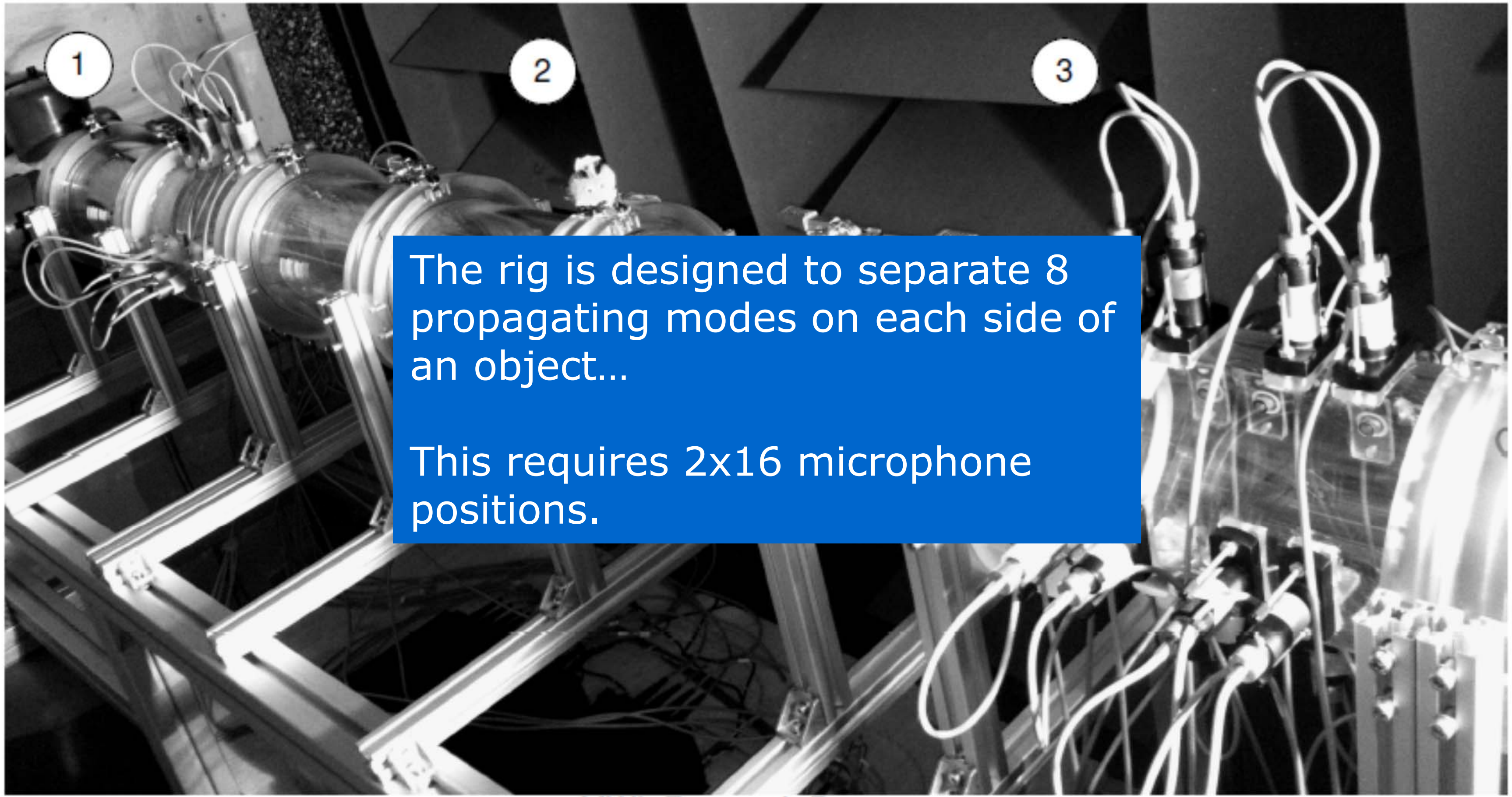
We define a network ("black box") model assuming a linear and time-invariant system relating the mode amplitudes in +/- direction

$$\boxed{\mathbf{p}_{+}(f) = \mathbf{S}\,\mathbf{p}_{-}(f) + \mathbf{p}_{+}^{s}(f)}$$

$\mathbf{S}$	Scattering Matrix ("passive part")
$\mathbf{p}_{+}^{s}$	Source vector ("active part")

<u>See: </u>**S. Sack, M. Åbom and G. Efraimsson (2016)**. On Acoustic Multi-Port Characterisation Including Higher Order Modes. Acta Acustica united with Acustica vol. 102, 834-860.

Test rig built by VKI & KTH



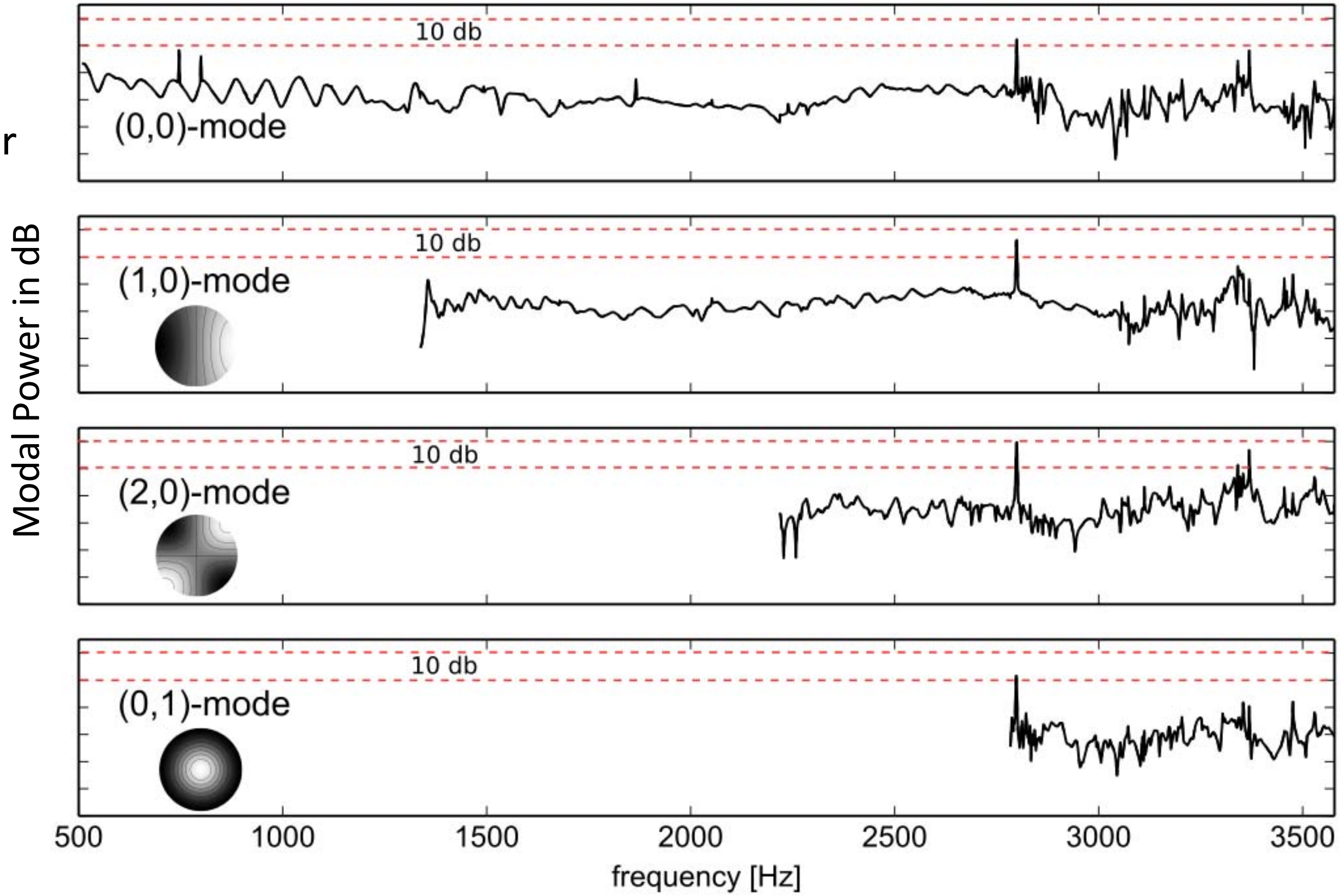
The rig is designed to separate 8 propagating modes on each side of an object…

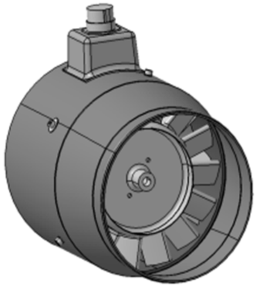
This requires 2x16 microphone positions.

Axial compressor spectrum

- Axial compressor with strong BPF (2700 Hz) and higher order mode conten

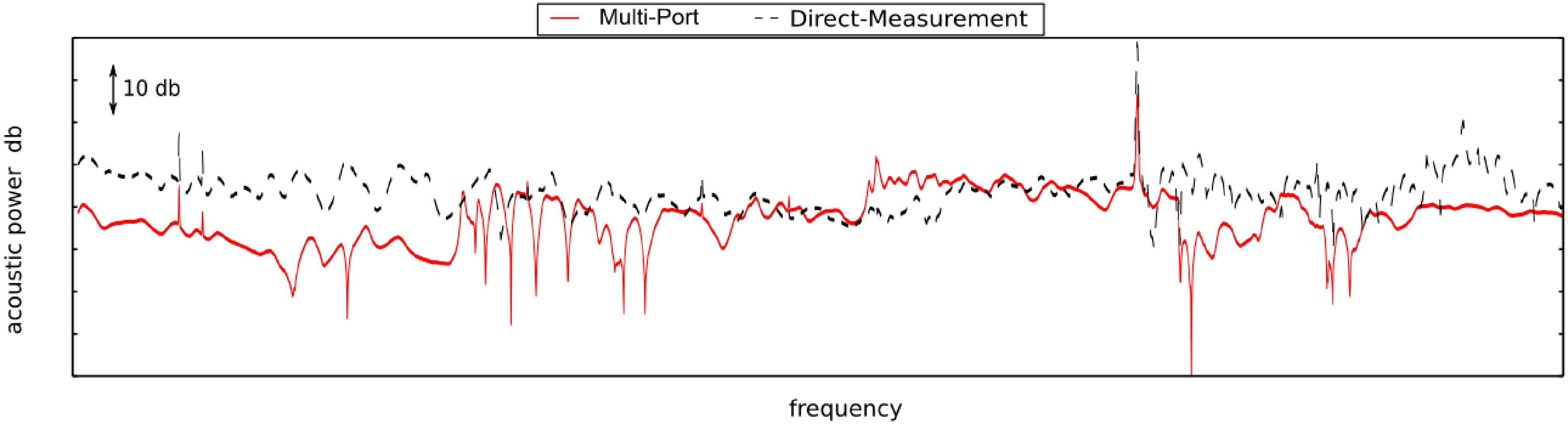
- The (0,0) & (2,0)
- modes are
- particularly strong





Advantages (Experimental/Numerical) of the Multi-Port Method

- **The effects of boundary conditions are eliminated** i.e. reflection free source data can be determined
- Projecting the pressure field on the acoustic modes will also **suppress Hydrodynamic pressure fluctuations**

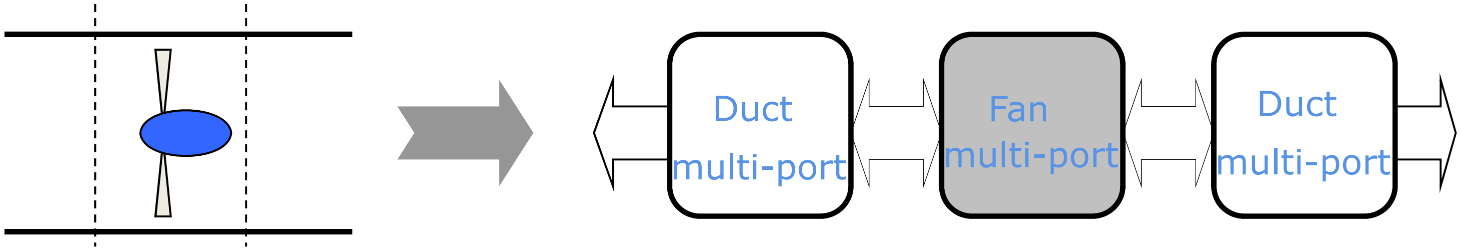


Fan measurements as part of the IdealVent project

Advantages (Experimental/Numerical) of the Multi-Port Method

In practice the full multi-port approach is restricted to the low- and mid-frequency range or (say) 10 modes

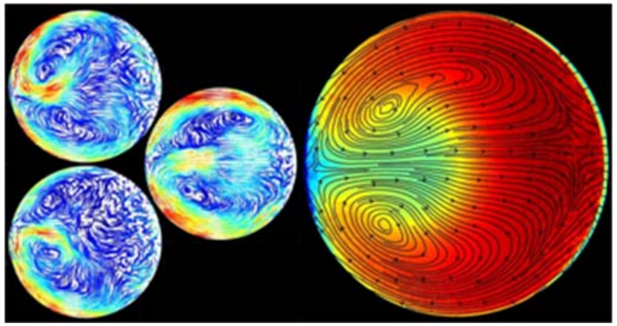
- **The ef** **minated** i.e. reflecti
- Projec nodes will also **su** **ctuations**
- Complex systems can be broken down into sub-elements each described by a multi-port



CCGEx

Competence **C**enter for **G**as **Ex**change (CCGEx) www.ccgex.kth.se

- Research focus on the gas management of IC engines.
- Combined effort between KTH, the Swedish Energy Agency and some leading OEMs.
- Main research fields are fluid mechanics and acoustics.



Energimyndigheten SCANIA VOLVO VOLVO BorgWarner

CCGEx

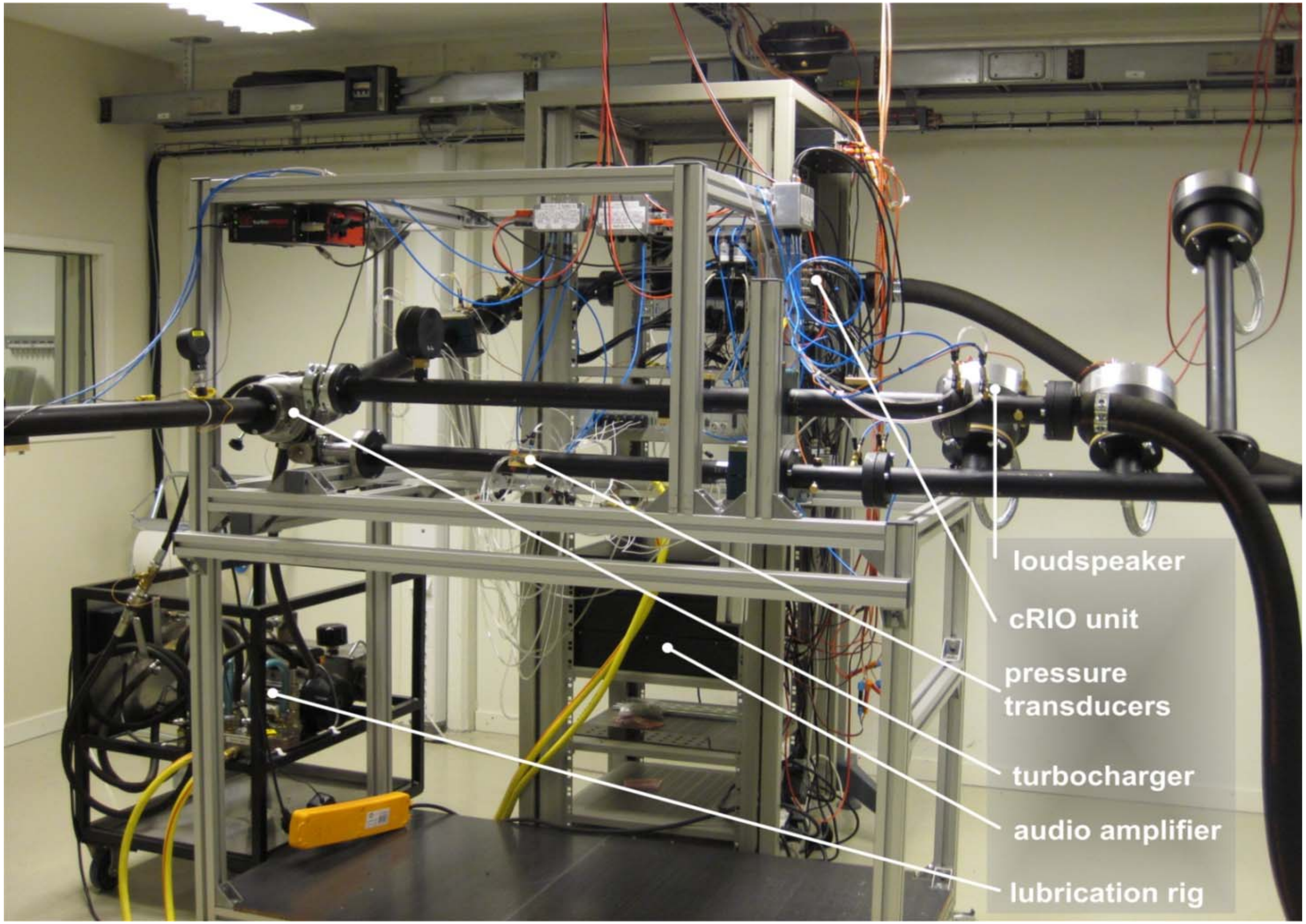
Competence Center Gas Exchange
CCGEx
”Charging for the future”

EXPERIMENTAL INVESTIGATION OF SURGE [9]

Raimo Kabral

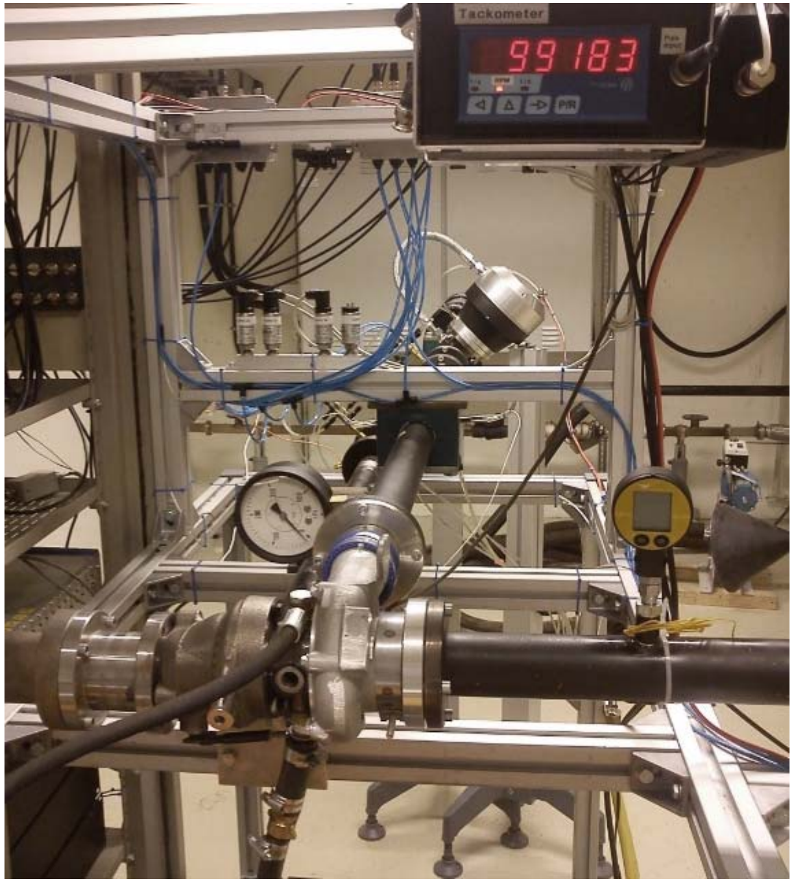
Mats Åbom, Hans Bodén and Magnus Knutsson (Volvo CC)

KTH-CCGEx Acoustic Testrig [6]



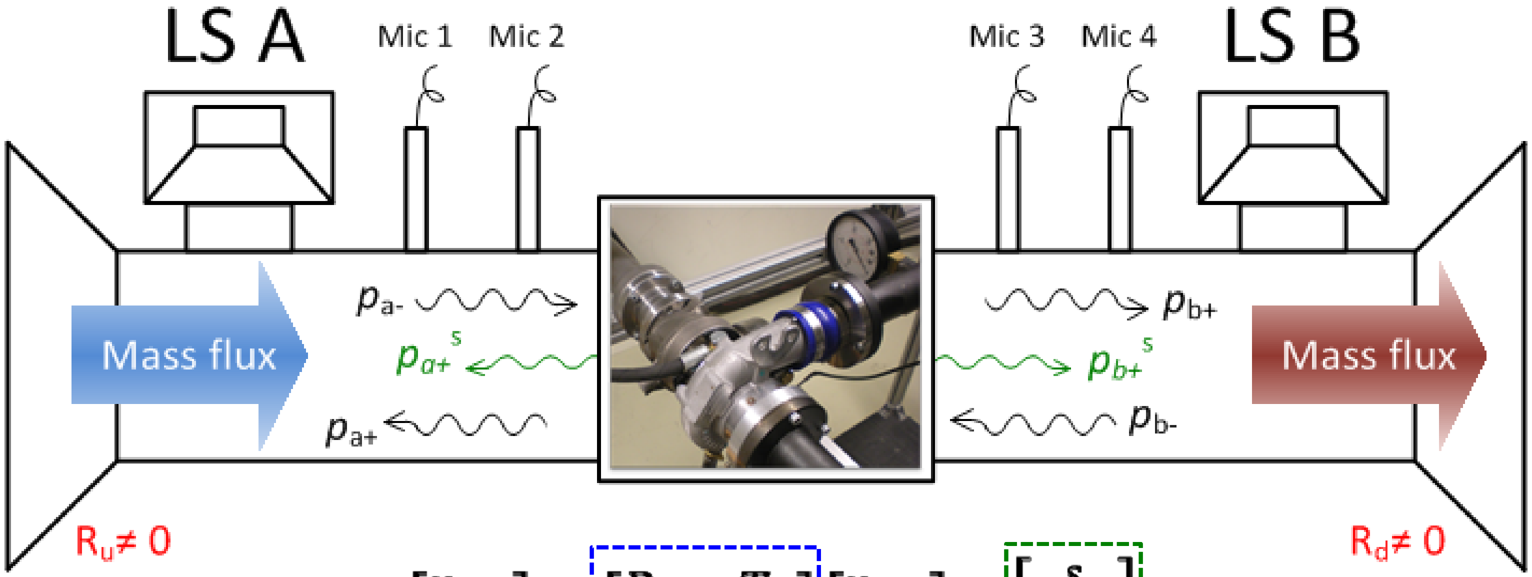
Compressor used in experiments

- Passenger car turbocharger Garrett GT1752 driven by the compressed air feed to the turbine.
- Inlet diam. is 44mm.
- Outlet diam. is 42mm.
- The rotor has 6 (+6 splitter) blades.
- Shaft frequency ~80…180kRPM – blade pass frequency 8…18kHz.



Acoustic 2-port formulation

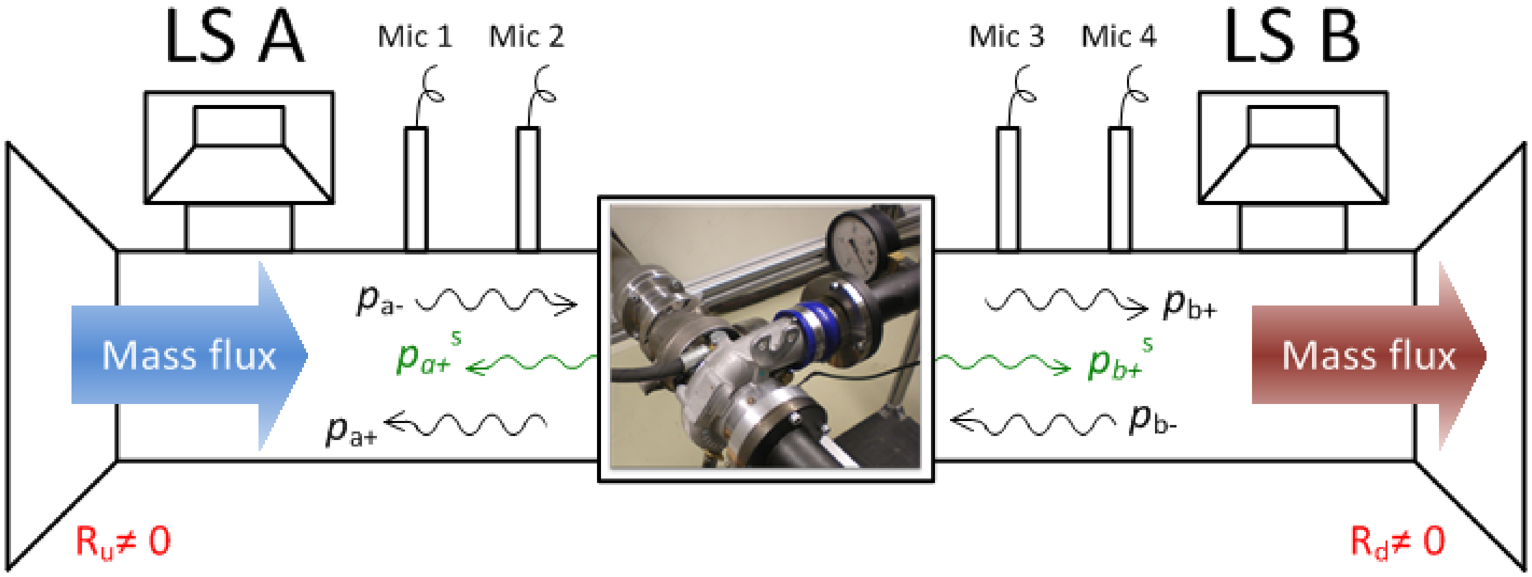
$$\boxed{f_c = \frac{1.814 \cdot c}{\pi d}}$$



$$\begin{bmatrix} p_{a+} \\ p_{b+} \end{bmatrix} = \underbrace{\begin{bmatrix} R_a & T_b \\ T_a & R_b \end{bmatrix}}_{\text{S-matrix}} \begin{bmatrix} p_{a-} \\ p_{b-} \end{bmatrix} + \begin{bmatrix} p_{a+}^{s} \\ p_{b+}^{s} \end{bmatrix}$$

- The acoustical performance of a flow duct element is determined by the full 2-port model which consists both the passive and the active parts.

Reflection-free sound generation

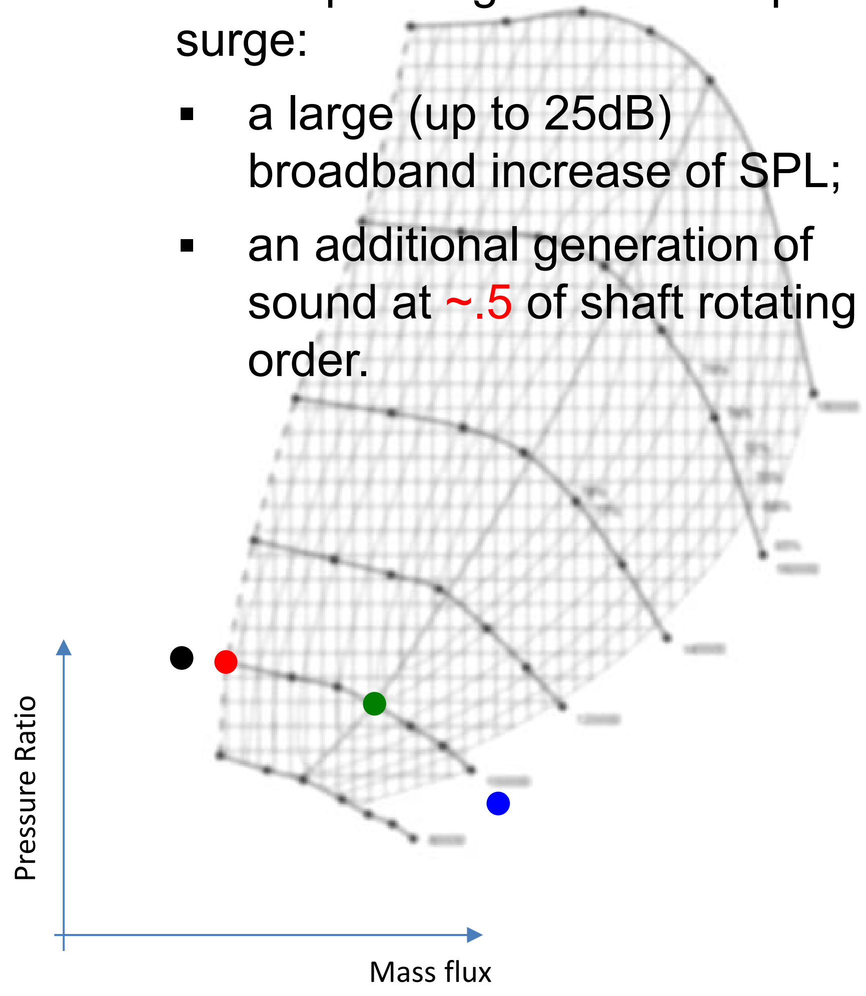


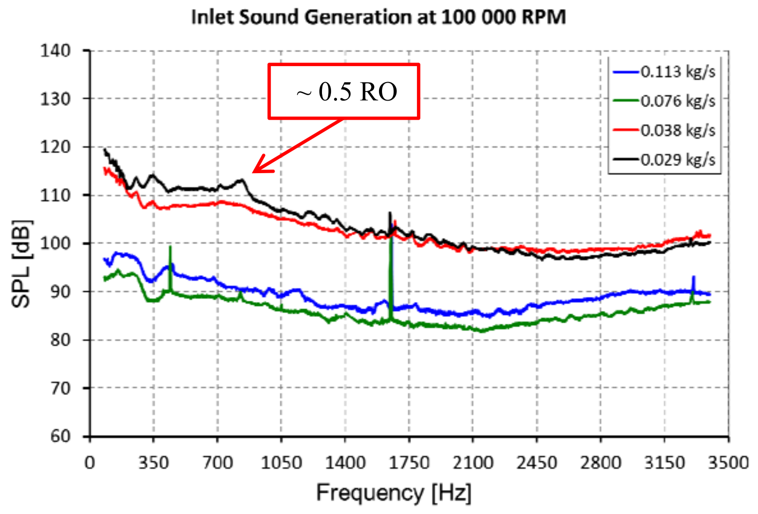
$$\boldsymbol{p}_{+}^{s} = (\boldsymbol{E} - \boldsymbol{S}\boldsymbol{R})(\boldsymbol{E} + \boldsymbol{R})^{-1}\boldsymbol{p}$$

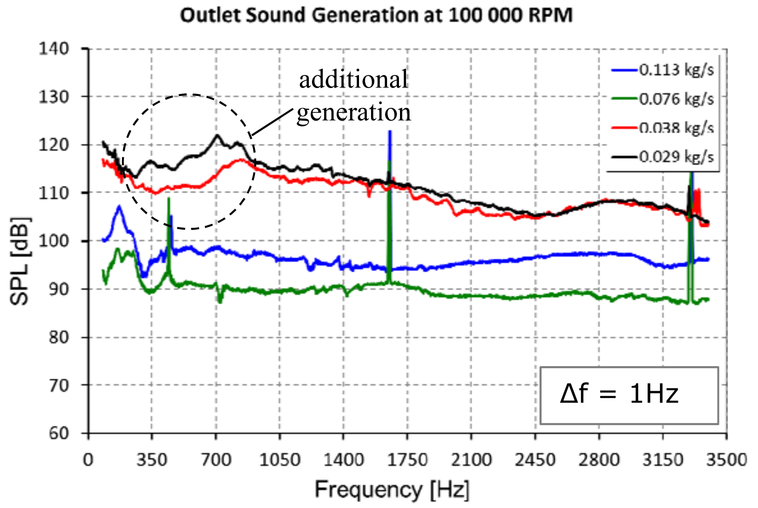
$$\boldsymbol{G}^{s} = \boldsymbol{p}_{s}(\boldsymbol{p}_{s}')^{\dagger} = \begin{bmatrix} G_{p_a^s p_a^s} & G_{p_b^s p_a^s} \\ G_{p_a^s p_b^s} & G_{p_b^s p_b^s} \end{bmatrix}$$

Sound generation of the compressor

- The following can be observed while operating close to deep surge:
  - a large (up to 25dB) broadband increase of SPL;
  - an additional generation of sound at ~.5 of shaft rotating order.

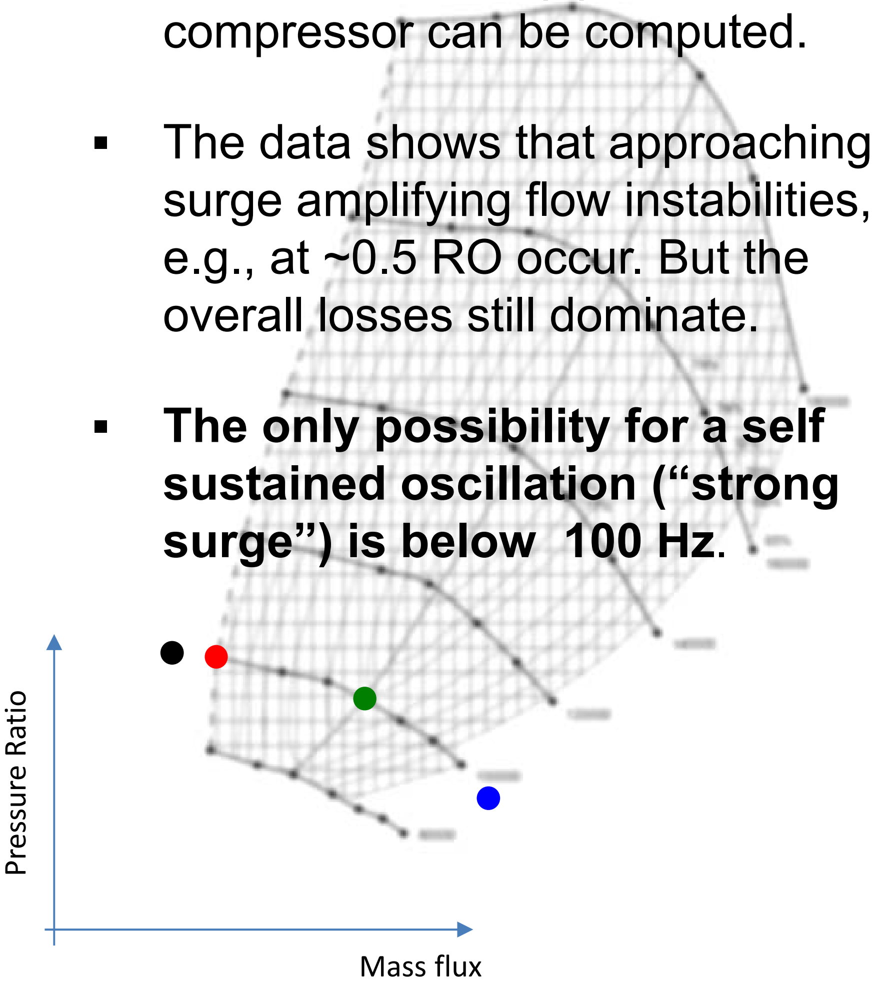


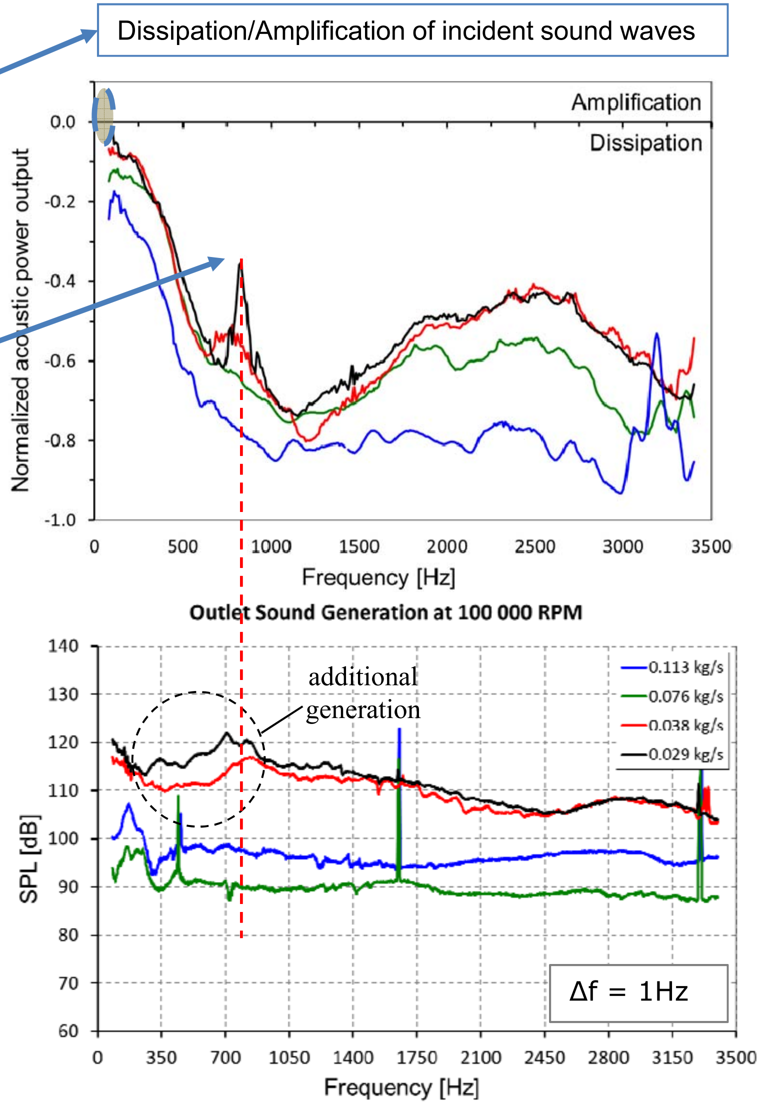




Aero-acoustic coupling

- From the S-matrix **dissipation (-) or amplification (+)** of the compressor can be computed.
- The data shows that approaching surge amplifying flow instabilities, e.g., at ~0.5 RO occur. But the overall losses still dominate.
- **The only possibility for a self sustained oscillation ("strong surge") is below 100 Hz**.




Dissipation/Amplification of incident sound waves

NUMERICAL ("LES") INVESTIGATION OF SURGE [10]

Elias Sundström and Mihai Mihaescu

Royal Institute of Technology (KTH)
School of Engineering Sciences, Dept. of Mechanics

Competence Center for Gas Exchange (CCGEx)

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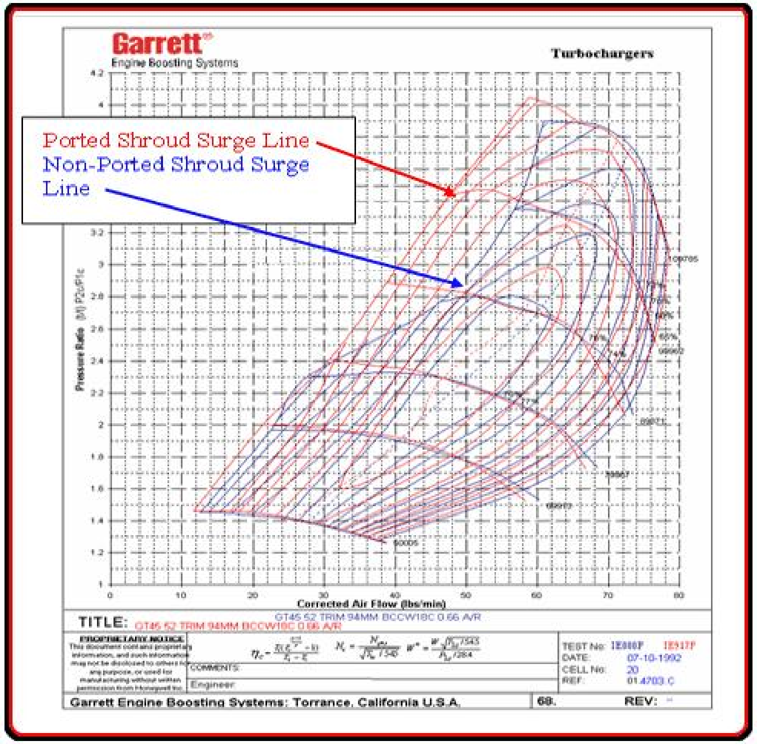
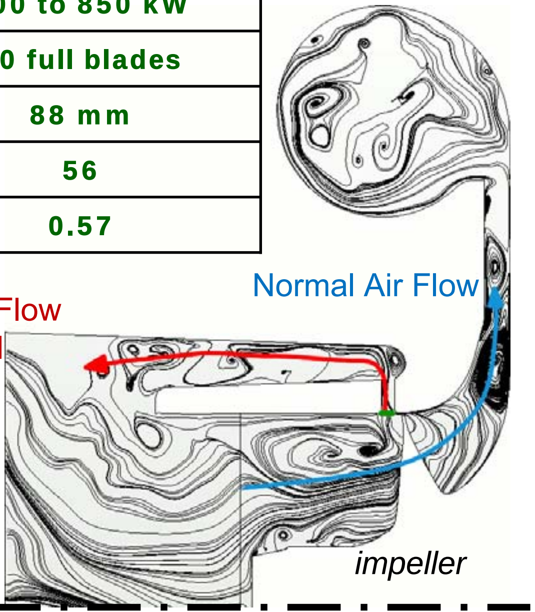
Web: https://www.kth.se/profile/mihaescu/

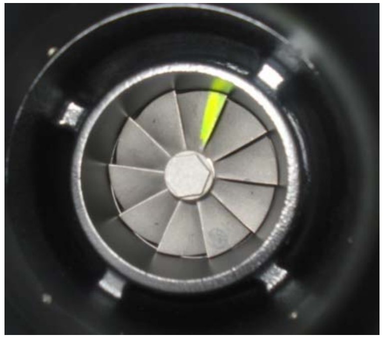
Investigated Compressor: GT40 Turbo

- Problem: Instabilities at low mass flow rates which limit the compressor range of operation
- Ported Shroud solution used to extend this range

Turbo compatibility	Heavy truck engine
Power range	400 to 850 kW
Number of blades	10 full blades
Exducer diameter	88 mm
TRIM	56
Diffuser area ratio	0.57





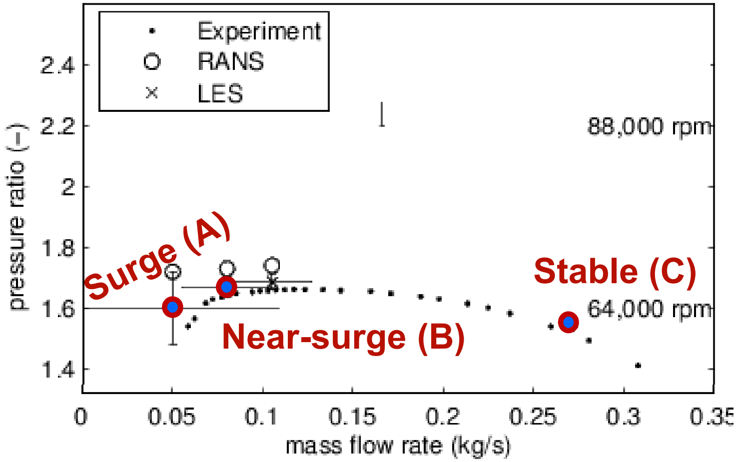


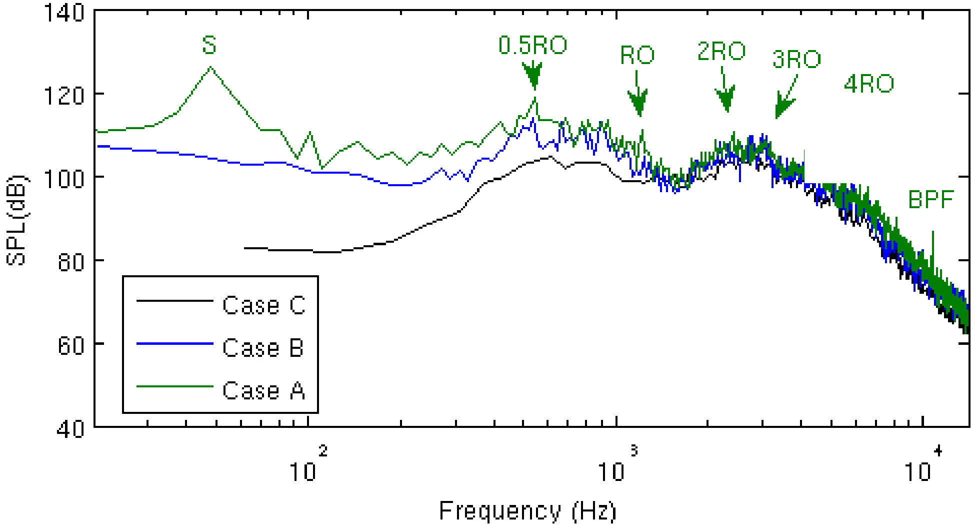
Ported shroud compressor supported by four unequally spaced ribs

CCGEx

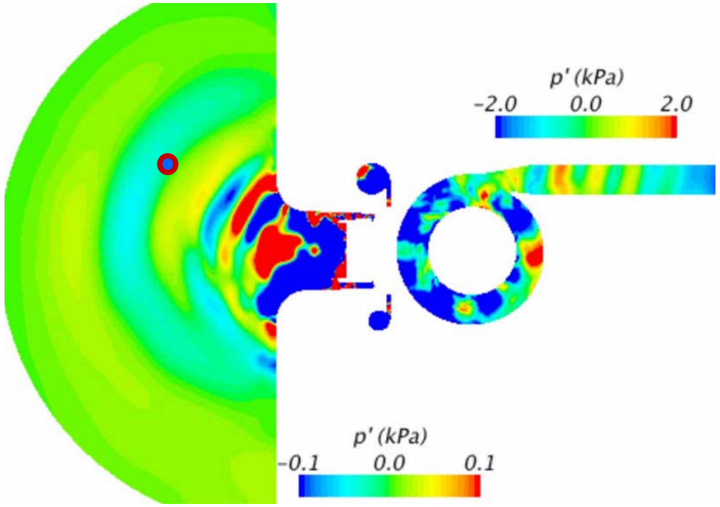
Acoustic pressure spectra

- SPL amplitude amplifies towards surge
- Broadbanded features around 0.5RO and 3RO, in agreement with other observations, e.g. Evans D. and Ward A., SAE2005-01-2485; Teng C. and Homco S., SAE2009-01-2053





Sundström, Semlitsch & Mihaescu, AIAA Paper, AIAA 2015-2674, 2015.

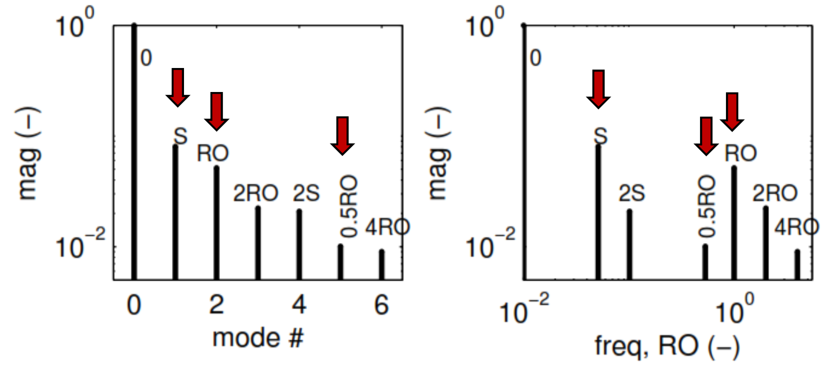


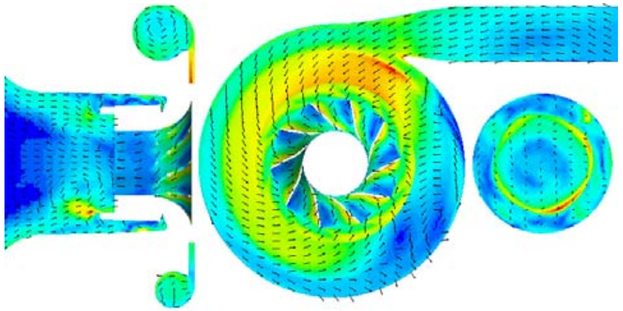
Near-surge (B): 0.070kg/s

CCGEx

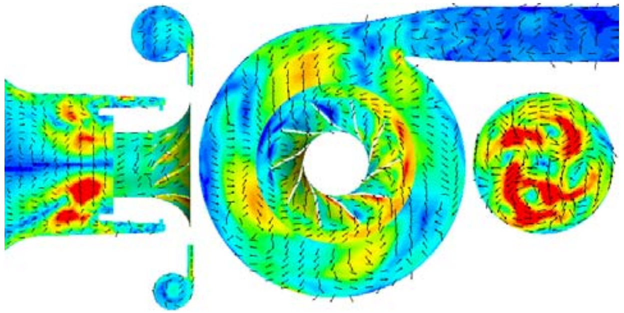
DMD / surge (case A) - Velocity

- Quantification of flow instabilities observed
- Dynamic Mode Decomposition at surge (case A)

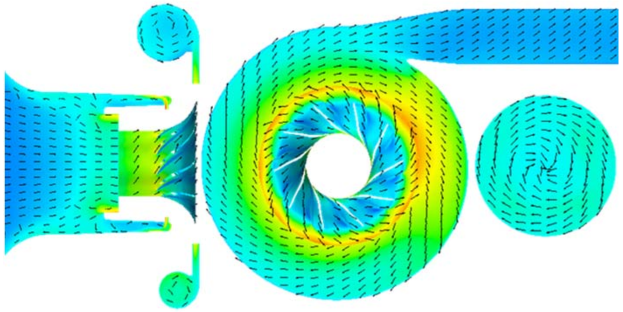




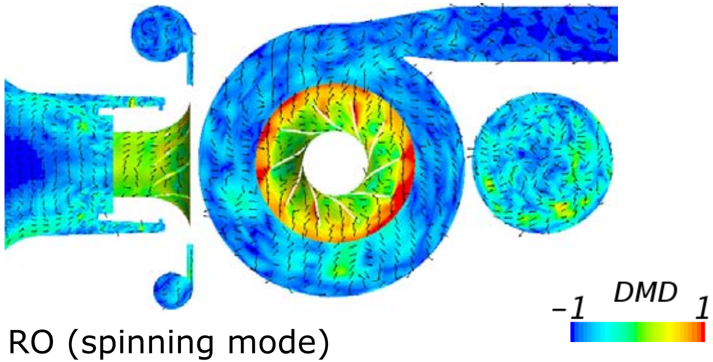
Surge (43 Hz, pulsating)



0.5RO (rotating stall in the diffuser)



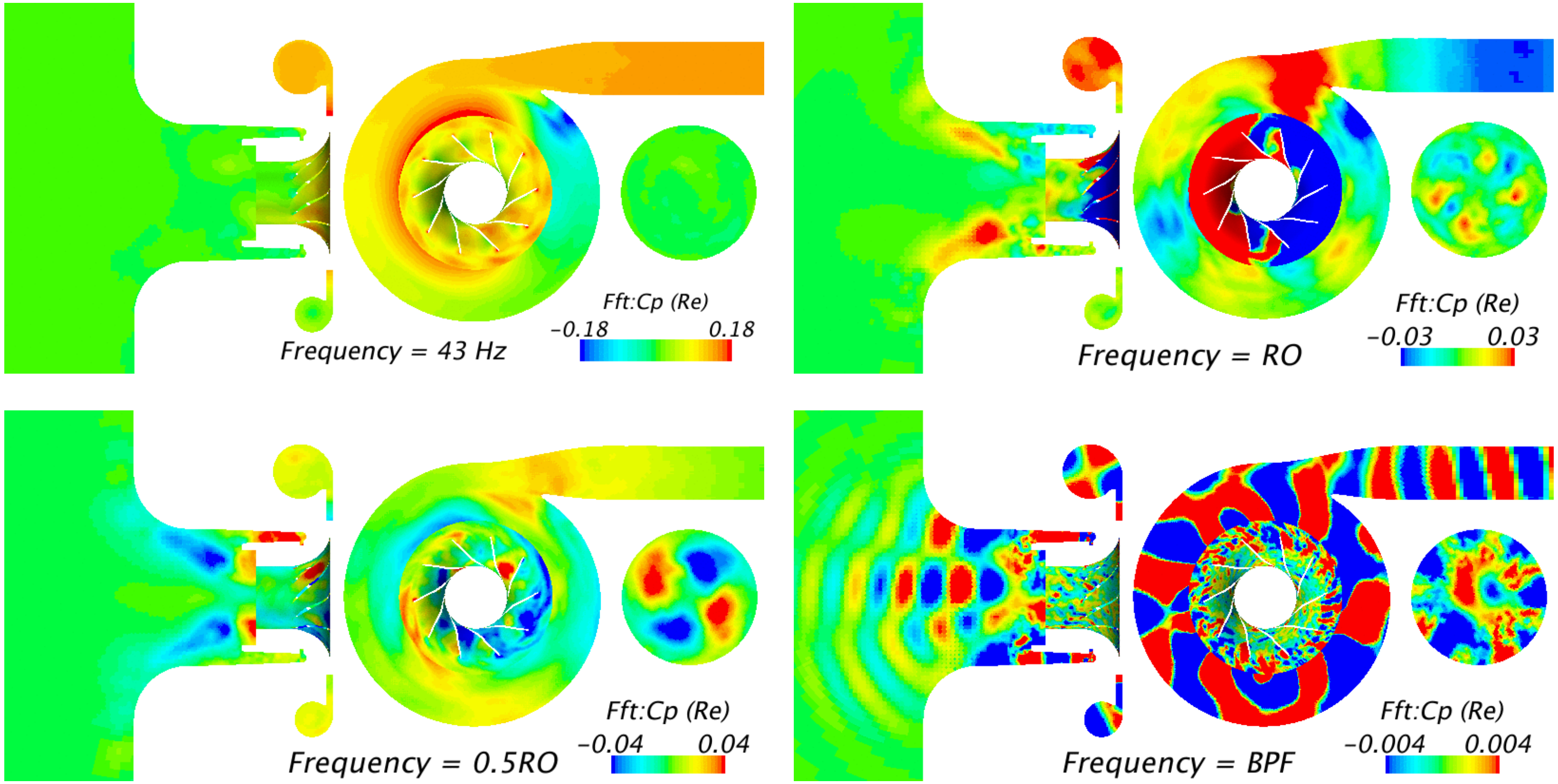
M0 Mean



RO (spinning mode)

CCGEx

Frequency Surface Pressure Spectra / surge (case A)

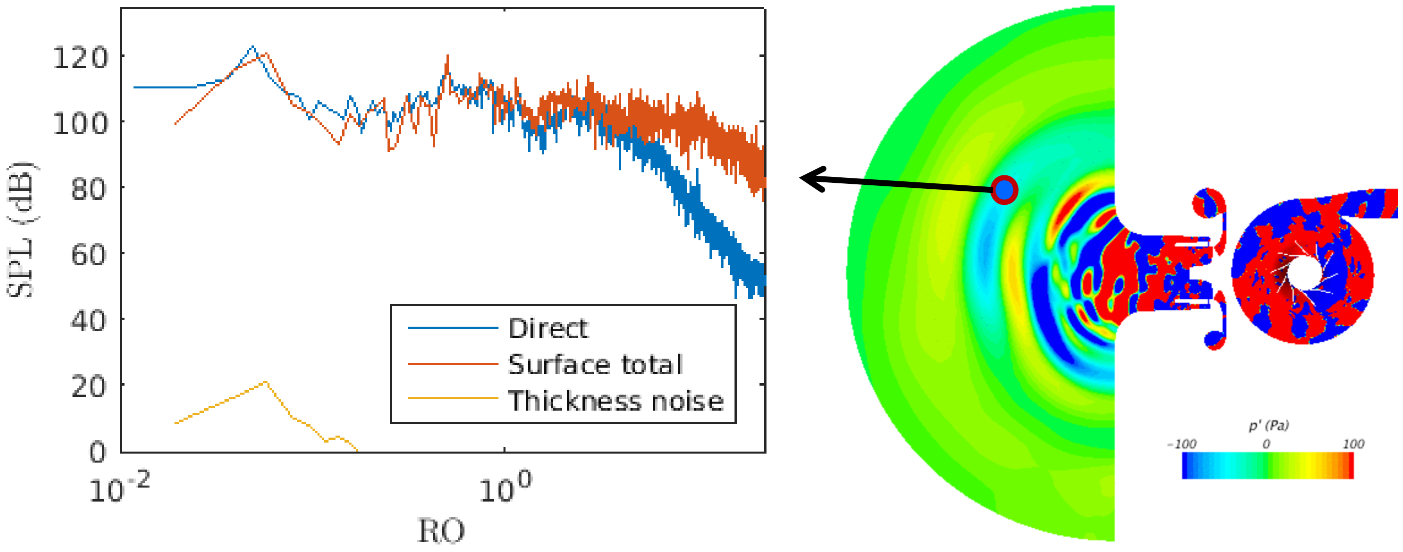


Sundström, Semlitsch & Mihaescu, AIAA Paper, AIAA 2015-2674, 2015.

CCGEx

Connection between flow and acoustics (case A)

- FWH integrated assuming free space flow between source and receiver
- Surface integrals Thickness (monopole) and Loading noise (dipole)



SUMMARY

- The dominating aeroacoustic source from turbomachines is fluctuating forces (-dipoles) **ONLY** for supersonic tip speeds will volume flow sources (-monopoles) become important.

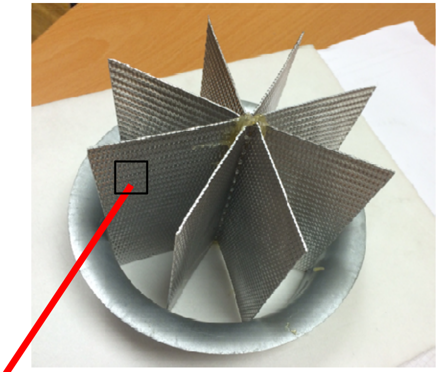
- The dipole source strength is strongly dependent of inflow disturbances (”**Aerodynamic installation effects**”).

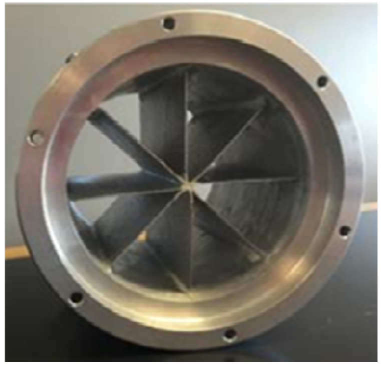
- The sound power at low to intermediate frequencies depends also on **Acoustic installation effects** (”Modal/Resonant response”).

Summary-Work at KTH

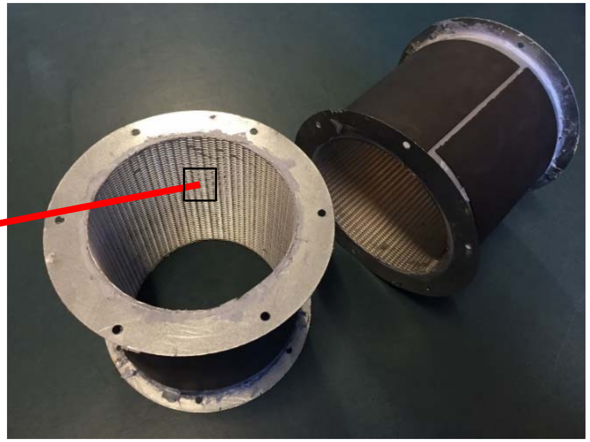
- Recent work on **multi-port methods** have demonstrated their potential (exp/num) to deliver ”**refection-free**” turbo-machinery **source data**.
- **A unique acoustic turbo testrig** for measuring complete 2-port data has been developed.
- **High fidelity CFD (”compressible LES”)** is applied in particular towards quantification of **acoustic noise sources at off-design** operating conditions
- Both the experimental and numerical work have created interesting **new insights to surge inception**.

New efficient type of Micro-Perforated Plate (MPP) Silencers for Turbomachines [8,11]

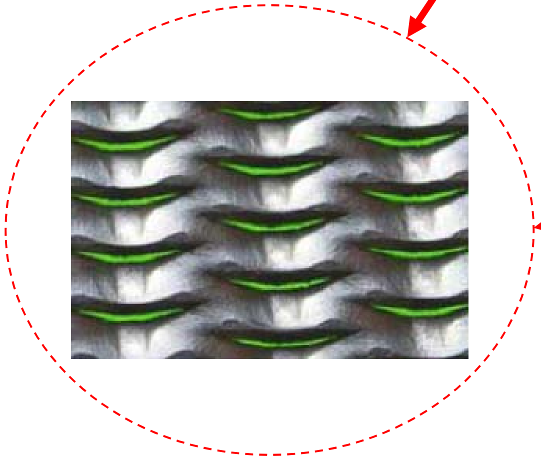




Modal-
Filter



Cremer
silencer



Micro-perforated plate (MPP)
with sub-millimeter slits

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