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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...

Lighthills acoustic analogy

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

Sir Michael JAMES Lighthill FRS
(1924-1998)
Limitations in Lighthill’s theory

Alt. 1: Sound production by a flow.

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

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

Lighthill or linear Aero-Acoustics is OK
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.

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

- Volume displacement: Monopoles
- Fluctuating pressures: Dipoles
- Unsteady Reynolds stresses or transport of momentum: Quadrupoles
AERODYNAMIC SOURCE STRENGTH – SCALING LAWS

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

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

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

$$\alpha = \begin{cases} 
-2, & \text{monopole} \\
0, & \text{dipole} \\
2, & \text{quadrupole}
\end{cases}$$
AERODYNAMIC SOURCE STRENGTH – SCALING LAWS

For a dipole we will get

\[ W \sim U^{4-6}, \]

where \( U \) is the flow speed

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

\[ \alpha = \begin{cases} 
-2, & \text{monopole} \\
0, & \text{dipole} \\
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\end{cases} \]
Relative sound power $W$ from aeroacoustic sources

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

- Combustion
- Piston machines (in/out flow openings)
- High Mach ($>1$) Turbomachines
- Fans
- Flow separation
- Free jets at high Mach ($\sim 1$)

$[M = \text{Mach-number} = U/c_0]$
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
    - **Steady rotating forces** (Gutin noise), discrete
  - **Dipole**: Blade forces, discrete + broadband
    - **Unteady rotating forces**, discrete + broadband
    - **Quadrupole**: Turbulence noise, broadband
      - **Non-uniform unstationary inflow**, discrete + broadband
      - **Vortex shedding**, narrow-band broadband
      - **Secondary flows**, narrow-band broadband

**“Self Noise”**

**“Aerodynamic installation effects”**
A compressor rotating with N RPM will generate harmonics of its Blade Passing Frequency (BPF):

\[ \text{BPF} = B \cdot \frac{N}{60}, \text{ where } B \text{ is the number of main rotor blades.} \]

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”.
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Buzz-saw noise or rotating shock waves \((M_{\text{tip}} > 1)\) occurs at multiples of the rpm.
ACOUSTIC INSTALLATION EFFECTS ("No free-field")

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

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

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

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

In practice the limit is around 10 propagating modes or:

\[ He = kd < 3\pi, \]
MULTIPOINT 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

\[
p(x, y, z) = \sum_n \left( \hat{p}_n \Psi_n(x, y) \exp(-ik_{+z,n}z) + \hat{p}_n \Psi_n(x, y) \exp(ik_{-z,n}z) \right)
\]
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

$$p_+(f) = S \ p_-(f) + p_+^s(f)$$

$S$ Scattering Matrix ("passive part")
$p_+^s$ Source vector ("active part")

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 content
- 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

- 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.
- Complex systems can be broken down into sub-elements each described by a multi-port.

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

\[ p_s^+ = (E - SR)(E + R)^{-1}p \]

\[ G^s = p_s(p'_s)^\dagger = \begin{bmatrix} G_{p^s_a p^s_a} & G_{p^s_b p^s_a} \\ G_{p^s_a p^s_b} & G_{p^s_b p^s_b} \end{bmatrix} \]
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 ~0.5 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.
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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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

<table>
<thead>
<tr>
<th>Turbo compatibility</th>
<th>Heavy truck engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power range</td>
<td>400 to 850 kW</td>
</tr>
<tr>
<td>Number of blades</td>
<td>10 full blades</td>
</tr>
<tr>
<td>Exducer diameter</td>
<td>88 mm</td>
</tr>
<tr>
<td>TRIM</td>
<td>56</td>
</tr>
<tr>
<td>Diffuser area ratio</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Ported shroud compressor supported by four unequally spaced ribs
• 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

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)

RO (spinning mode)
Frequency Surface Pressure Spectra / surge (case A)

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 “reflection-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]
Reference list