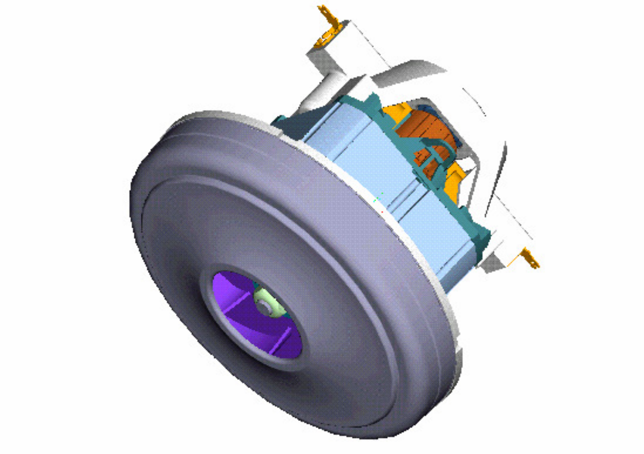
Integrated approach for noise reduction on vacuum motors



Tutorial

Dr. Jože Tavčar
DOMEL d.d.
Slovenia

Integrated approach for noise reduction on vacuum motors

Agenda

- Introduction
- Sound – physical background
- Sound pressure and power measurement
- Research methods
  - Vibration control
  - Aero-dynamic noise
  - CFD calculations
  - Noise camera
- Case study (noise control / peak removal)
  - Variation of impeller geometry
  - Helmholtz resonator
- Active noise control
- Conclusions

DOMEL®

DOMEL LOCATION

2005

- Domel d.d., Železniki, Slovenia
- Since 1946
- Global emotor producer
- http://www.domel.com

PRODUCT GROUPS

DOMEL

VACUUM CLEANER MOTORS - DRY ASPIRATION

VACUUM CLEANER MOTORS - WET & DRY ASPIRATION

DC MOTORS

UNIVERSAL COMMUTATOR MOTORS

BRUSHLESS EC DC BLOWERS/PUMPS

EC CENTRIFUGAL FANS

EC EXTERNAL ROTOR MOTORS

TOOLS

COMPONENTS

information: www.domel.com

2005

Sound – Physical background

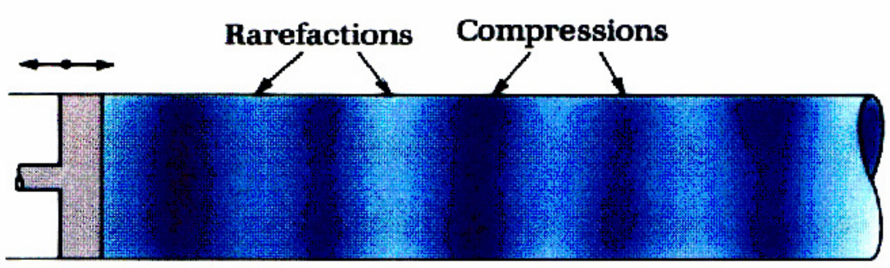
Physical background:

- Sound sources
- Human perception of the sound
- How to measure sound ?

Sound wave

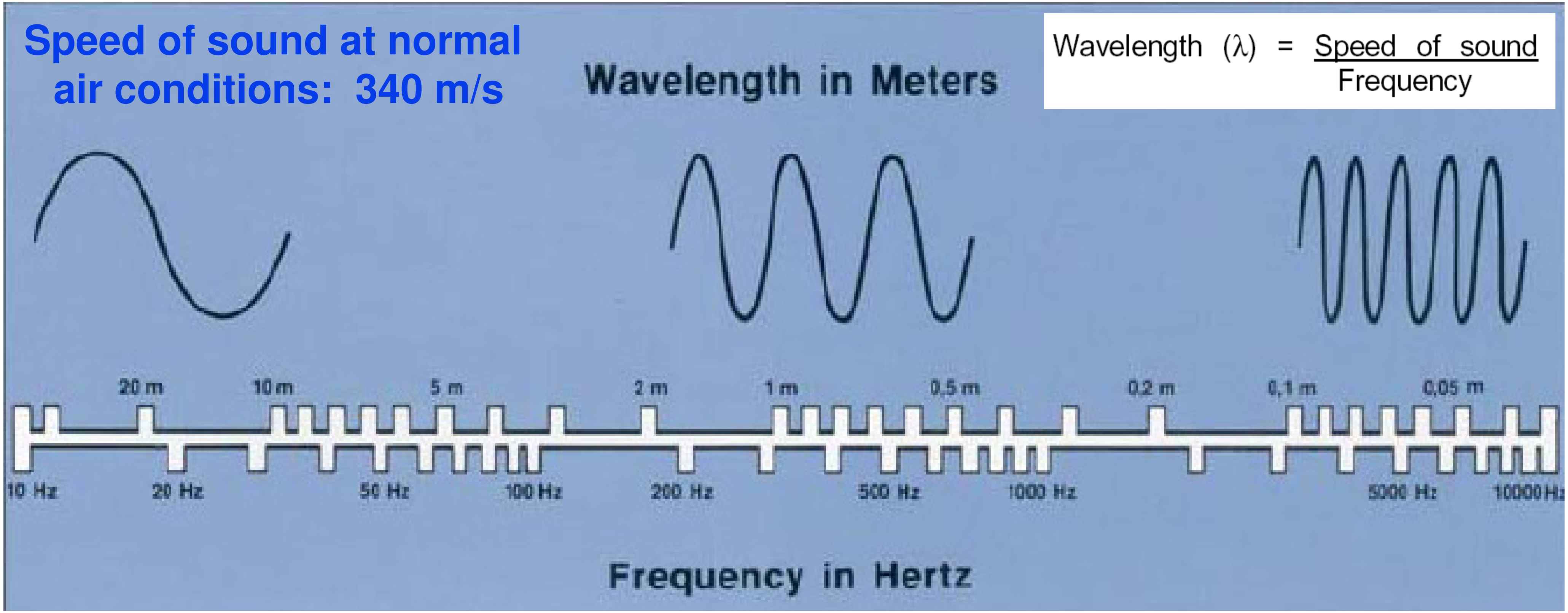
Bruel&Kjaer

- Sound Source:
  - Structural vibrations
  - Aero-dynamic - Fluid flow



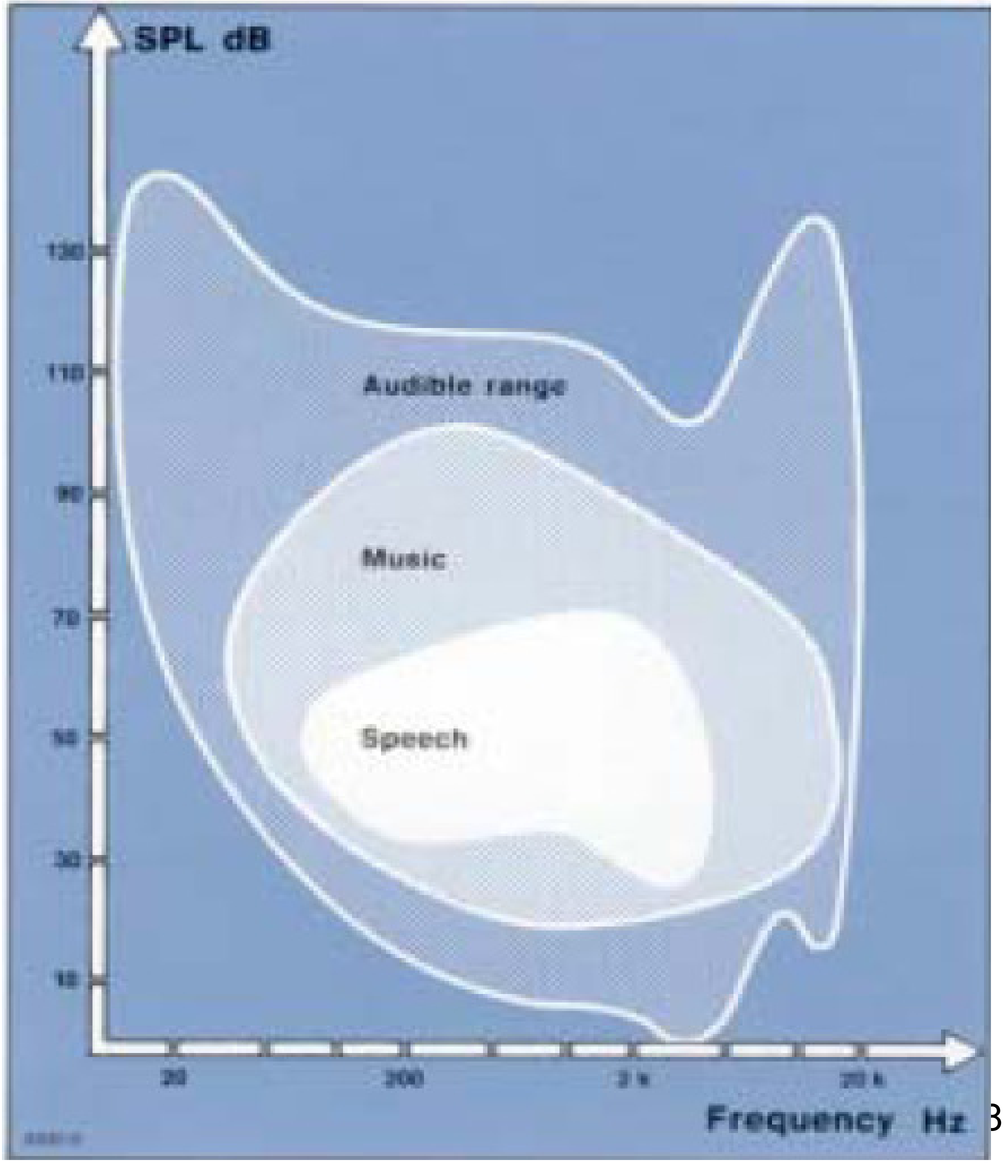
Speed of sound at normal air conditions: 340 m/s

$$\text{Wavelength } (\lambda) = \frac{\text{Speed of sound}}{\text{Frequency}}$$

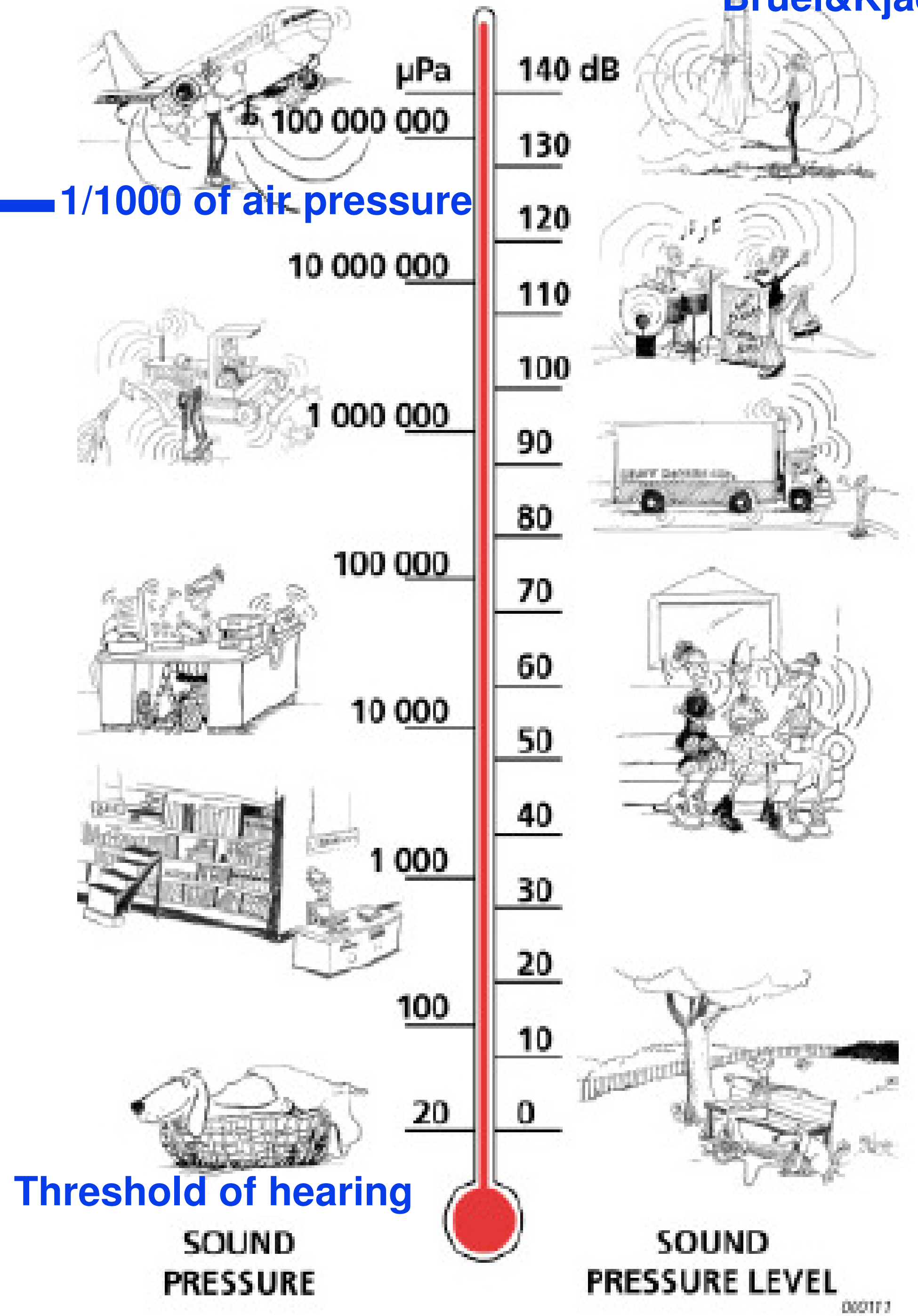


Sound pressure level

$L_{p} = 10 \log_{10} p^2/p_o^2$

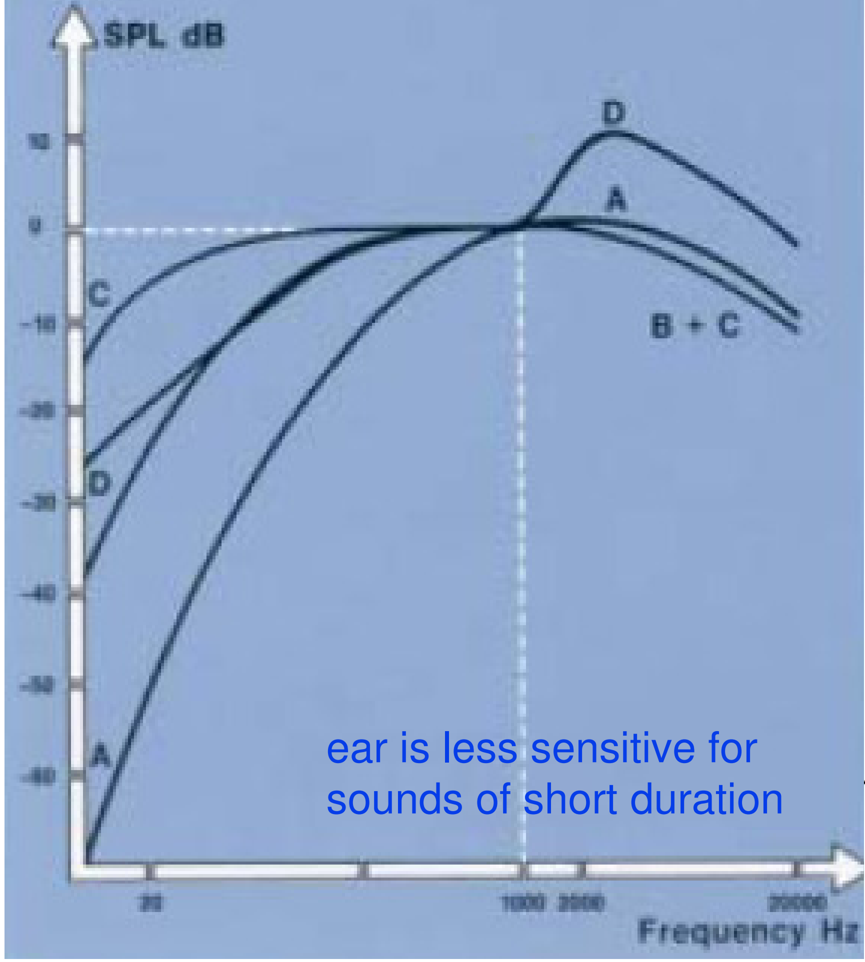


Bruel&Kjaer



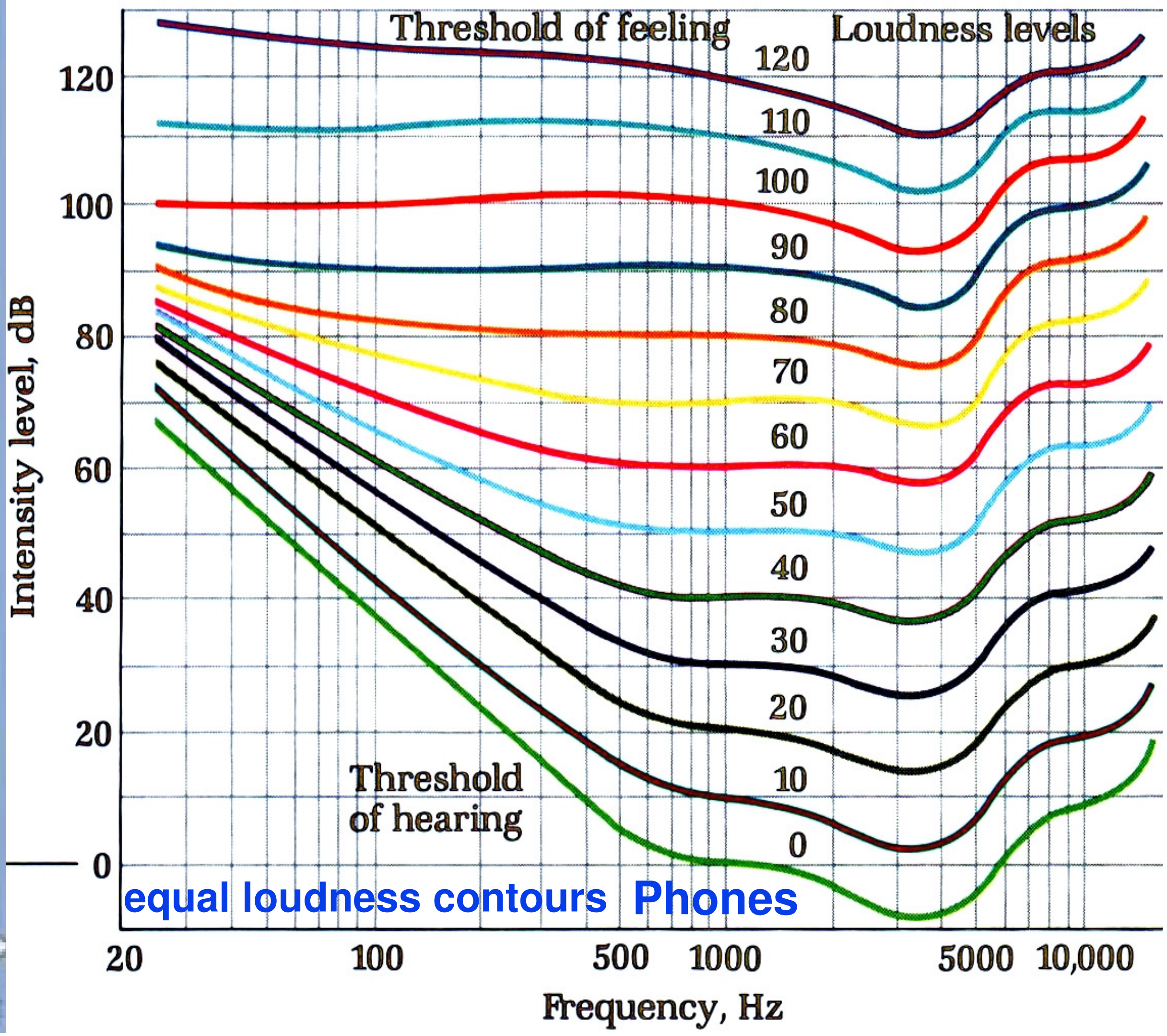
Human perception of sound

A - weighting network – at low sound pressure level – widely used
D – for aircraft noise measurements



ear is less sensitive for sounds of short duration

Curves of perceived equal laudness Bruel&Kjaer



equal loudness contours **Phones**

Analogy between sound pressure (L_p) and temperature (T) and sound power (L_w) and electric power

Sound Source :

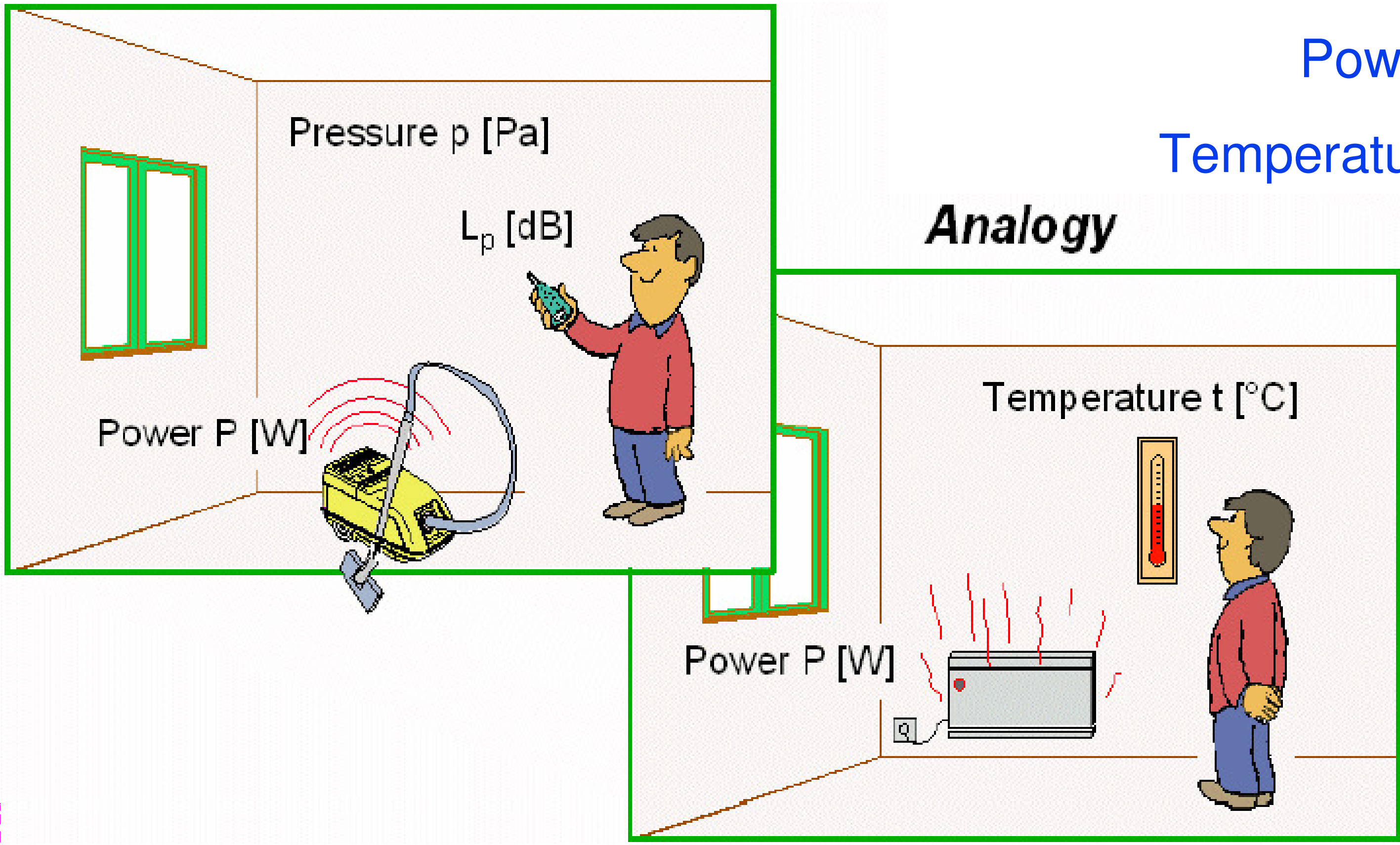
Sound Power P [W] Lw

Sound Pressure p [N/m2] Lp

Electrical Heater :

Power P [W]

Temperature t [℃]



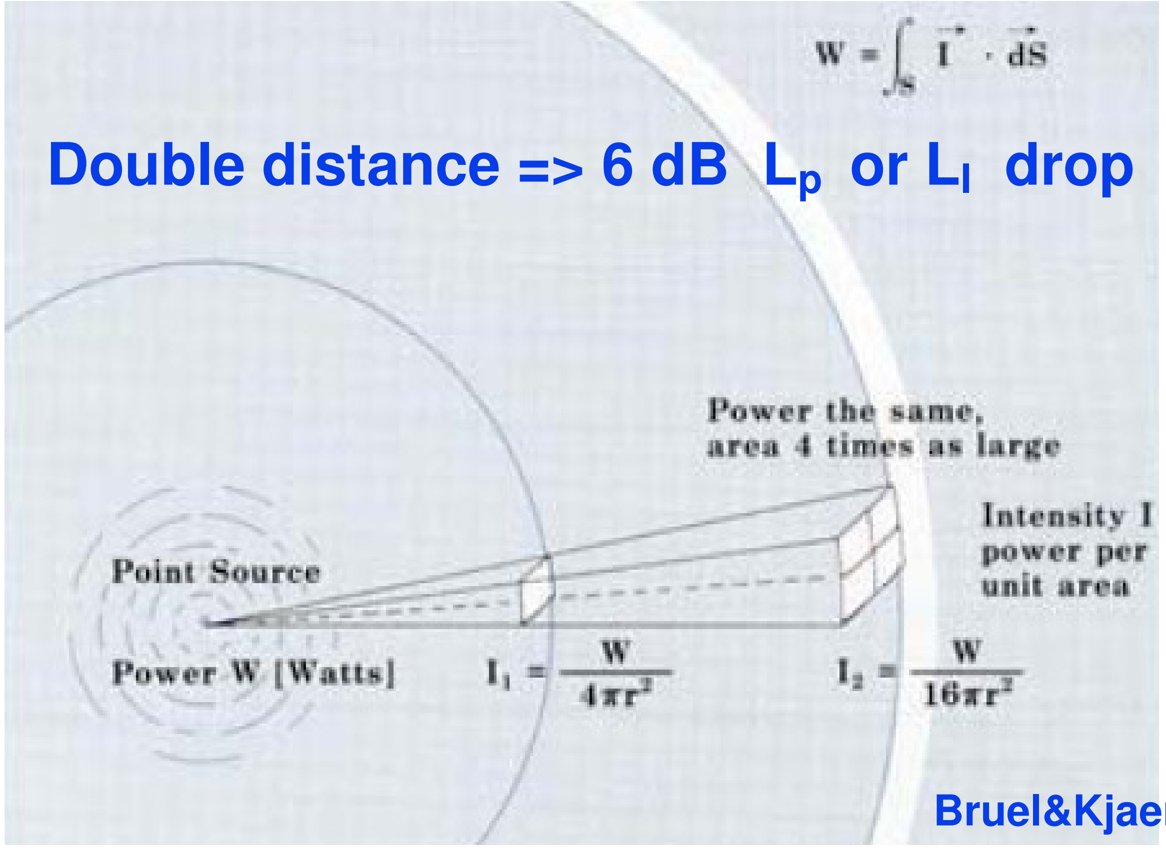
Quantifikacation of sound sources

- L_W … Sound power **94 dB(A) L_w**
- L_I … Sound intensity
- L_P … Sound pressure (1 m) **83 dB(A) L_p**

$$W = I \cdot S$$

$$I = \frac{(\Delta p_{max})^2}{2 \cdot v \cdot \rho}$$

Double distance => 6 dB L_p or L_I drop



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Ref. parameter	W_0	I_0	p_0
Unit	W	W/m²	Pa
Reference value	10^{-12}	10^{-12}	$2 \cdot 10^{-5}$

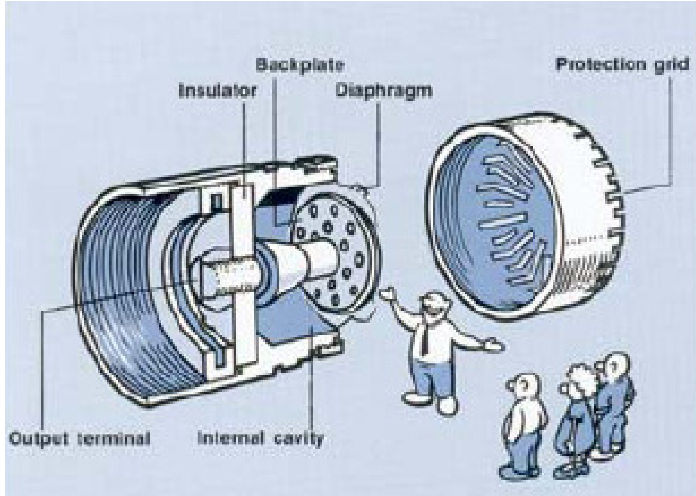
$$L_W = 10 \cdot \log_{10}\left(\frac{W}{W_0}\right) \quad [dB, dB_A]$$

$$L_I = 10 \cdot \log_{10}\left(\frac{I}{I_0}\right) \quad [dB, dB_A]$$

$$L_P = 10 \cdot \log_{10}\left(\frac{p^2}{p_o^2}\right) \quad [dB, dB_A]$$

Measurment equipment – sound pressure (L_p)

- Microphon
  (condenser, tensioned-metal diaphragm)
- Preamplifier
  (converts output signal into low impedance)
- signal analyser (FFT, CPB)
- **anechoic chamber (free field)**



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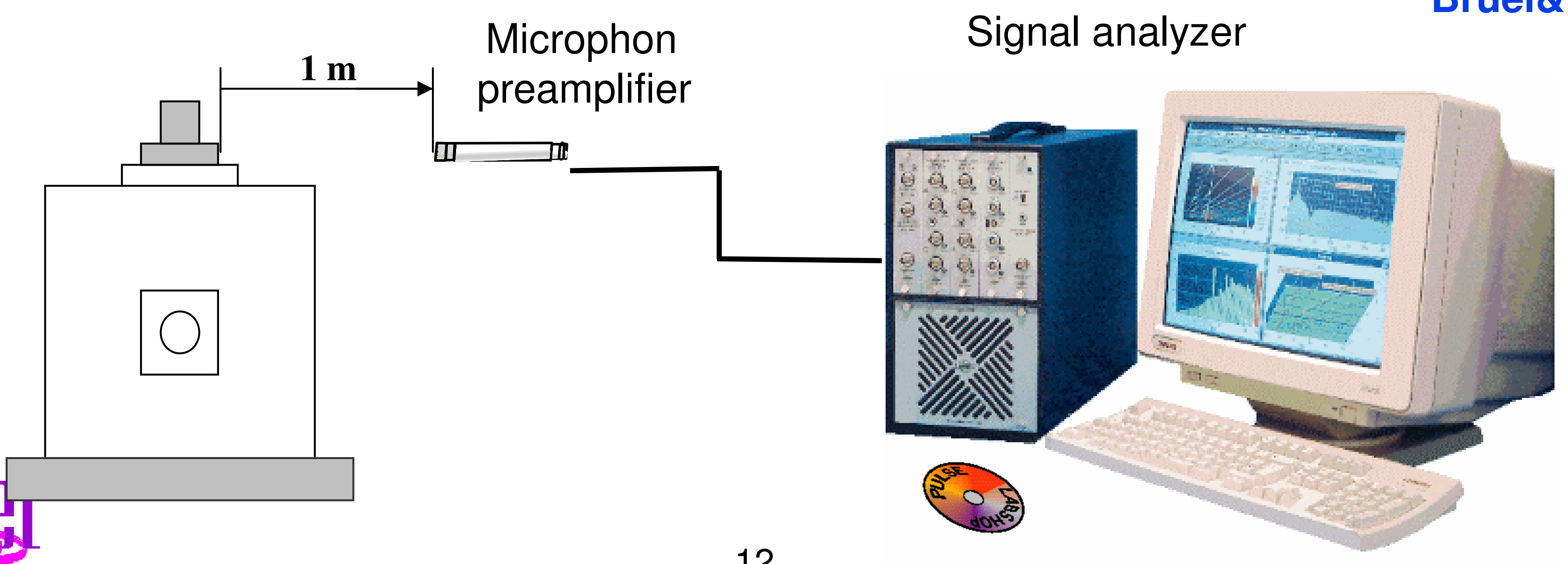

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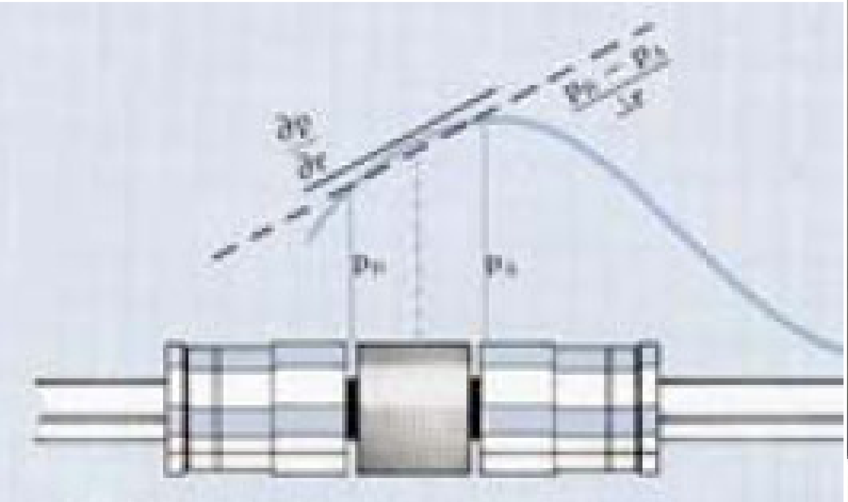
Sound intensity



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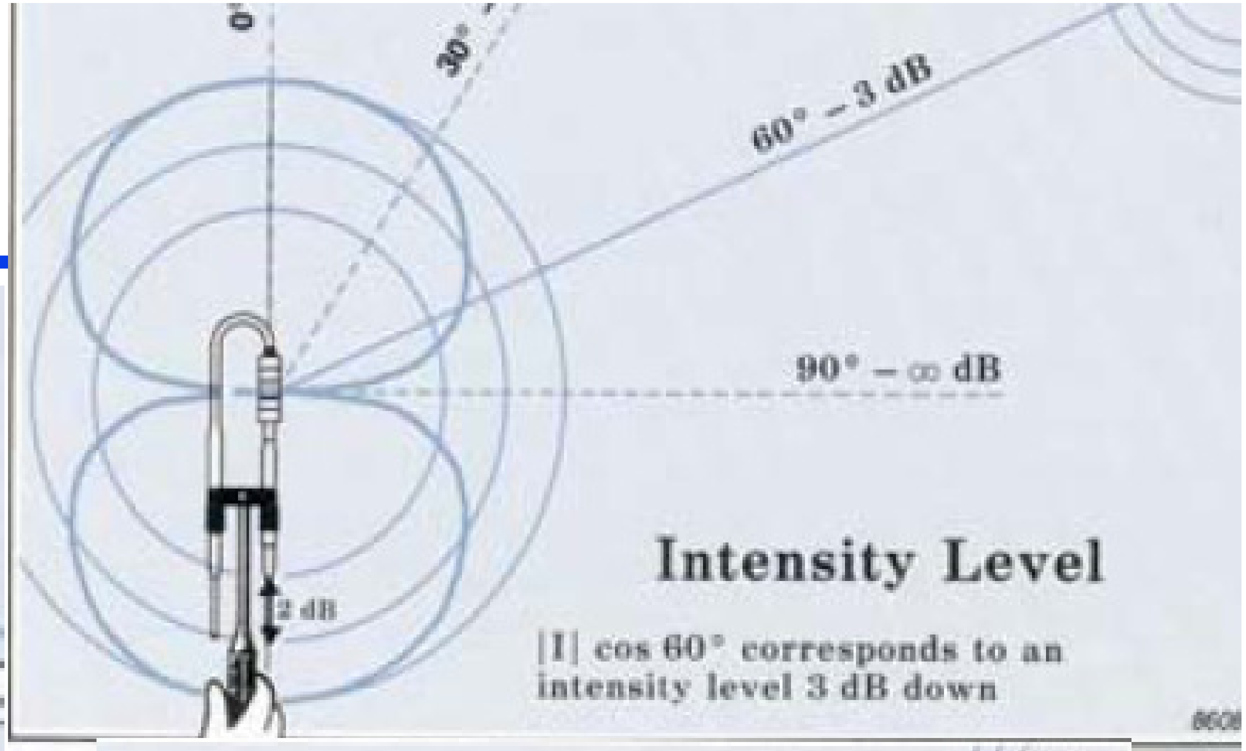

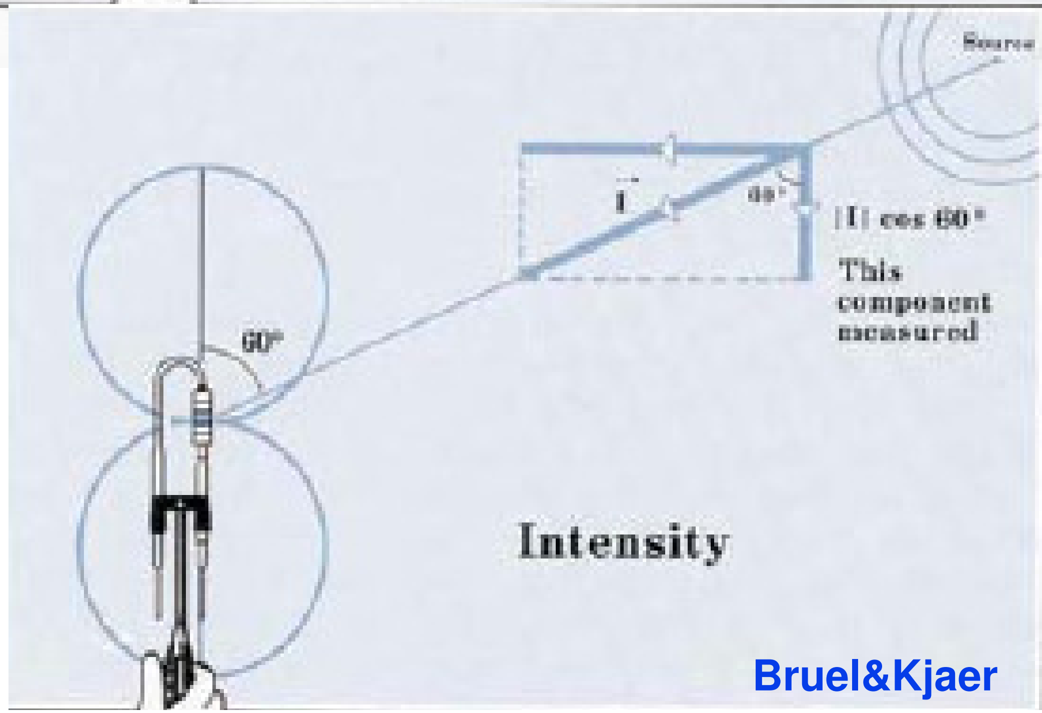

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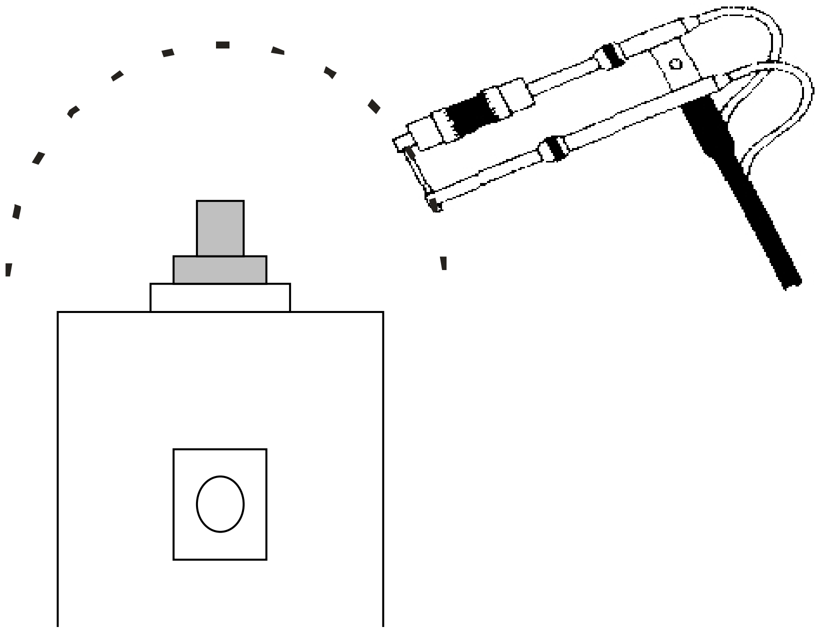
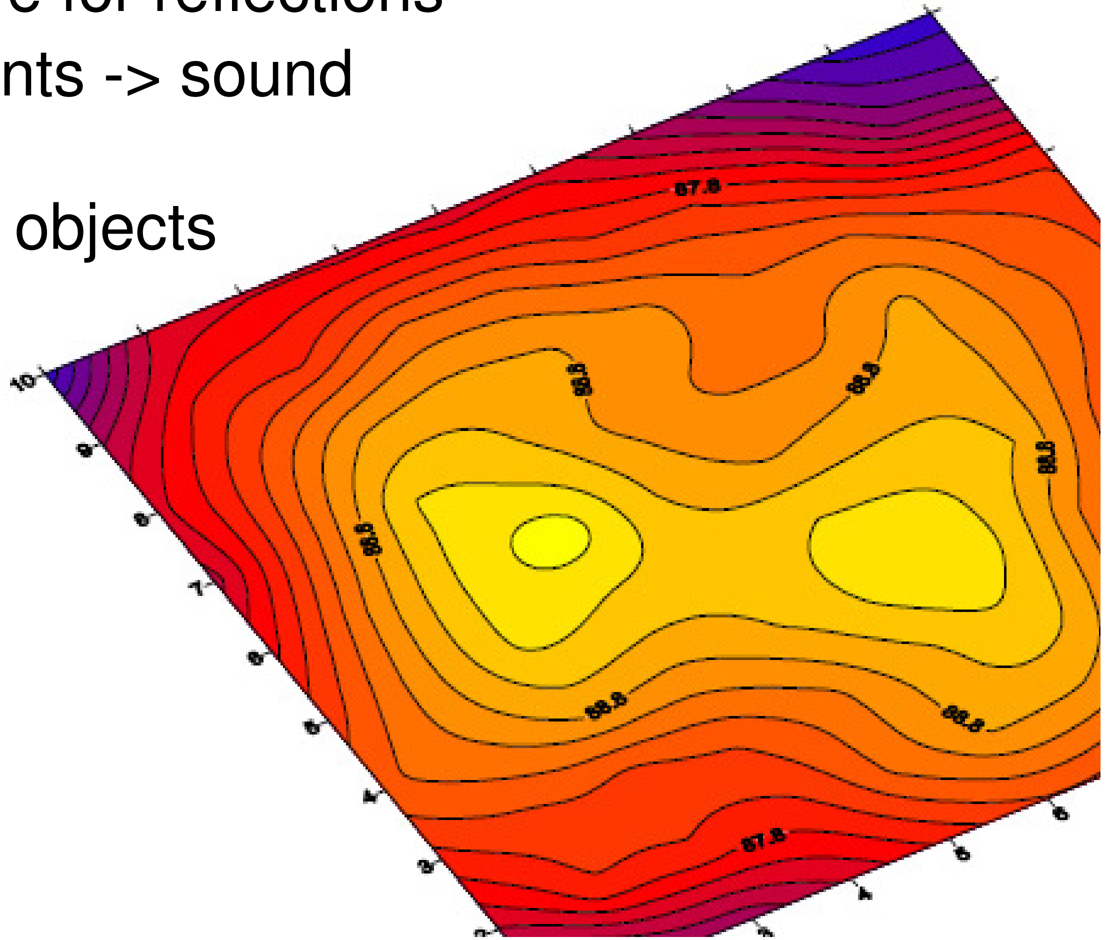
Sound intensity measure only the component perpendicular to the sound source.

Measurment equipment – sound intensity

- Equipment to measure sound intensity:
  - Sound sonde – 2 phase microphone
  - Measurement is not sensitive for reflections
  - Measurment at all mesh points -> sound intensity map
  - Sources of sound on bigger objects



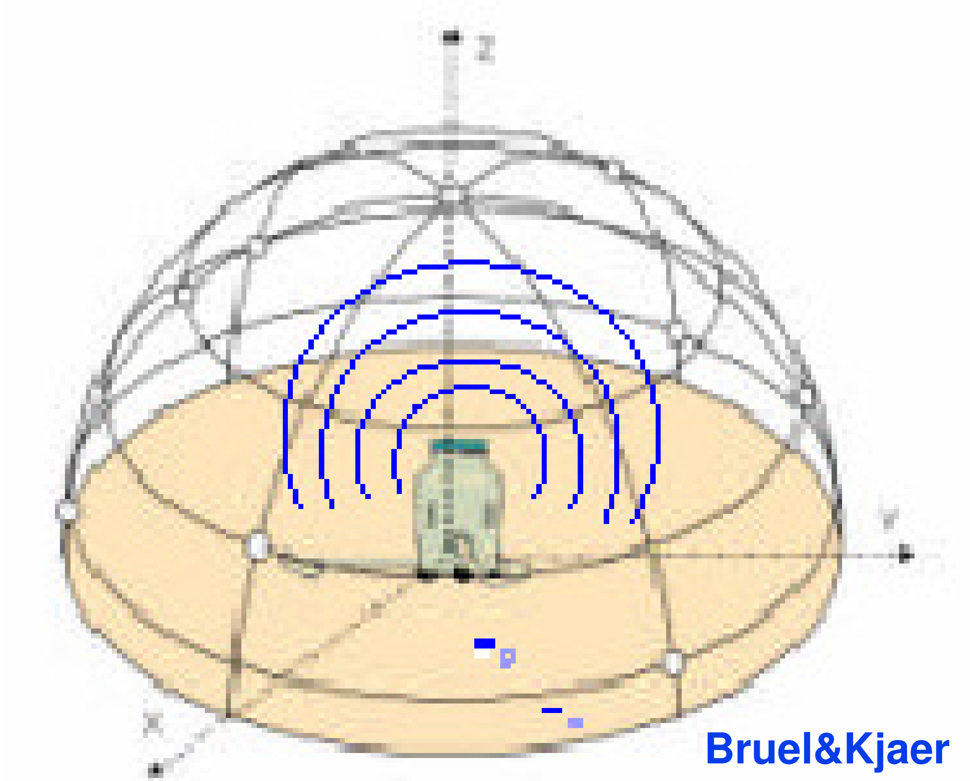


Measurements:
noise spectrum in anechoic chamber

- Noise pressure measurement L_p
- Noise power measurement L_w

Pressure-based, almost free-field,
ISO 3744 (soft padding on the walls)

$L_p = 10 \log_{10} p^2/p_o^2$ $L_w = 10 \log_{10} W/W_o$



Bruel&Kjaer

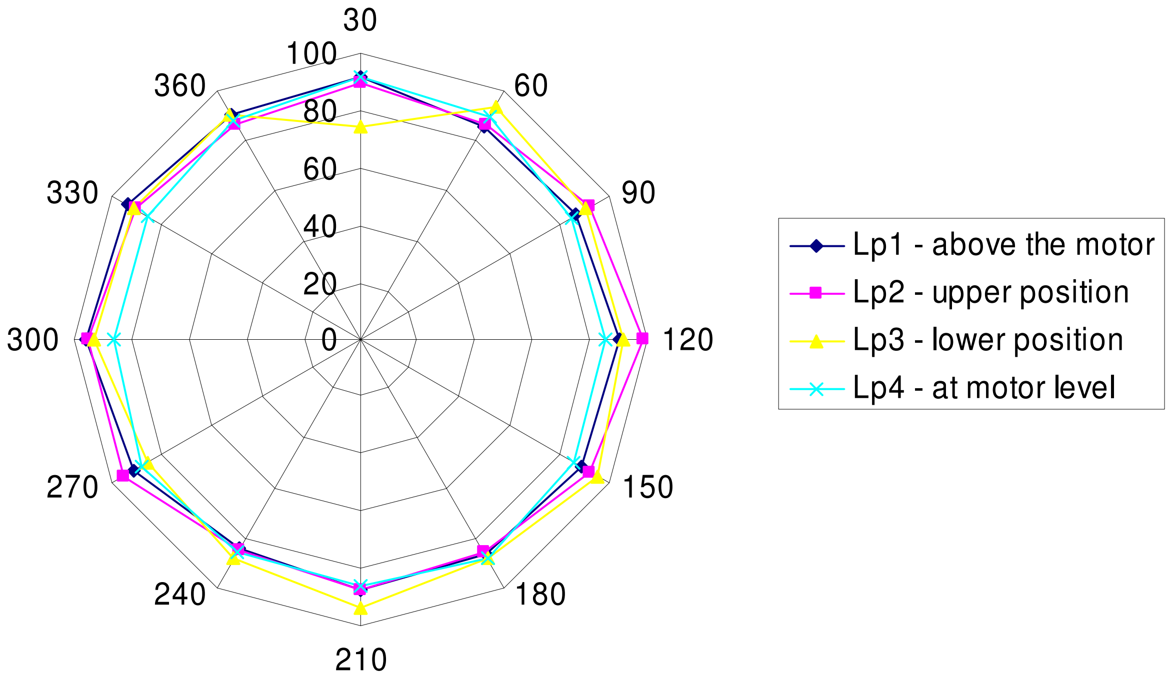
Req. No. 11830905
Working ord. No. 98914
date: 21th September, 2005
measured by: Dragica Bačič

BR / J.Tavčar
463.3.201 standard
226V / 50Hz

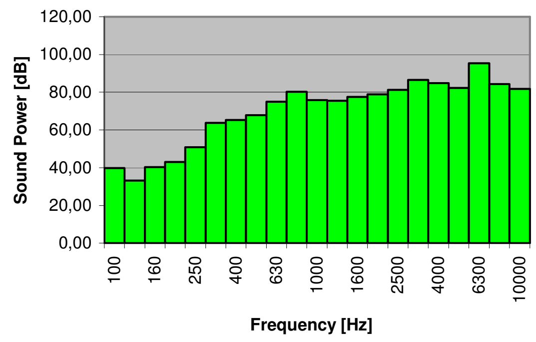
Noise power level (Lw) report

Sound pressure level Lp [dB]

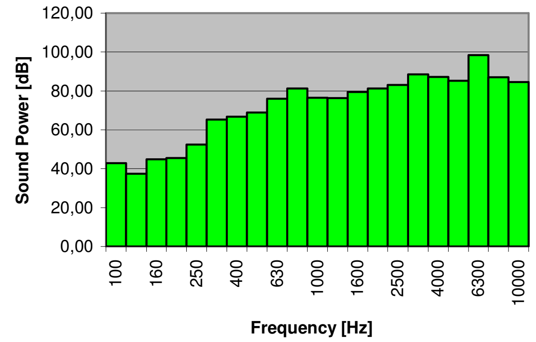
(around object at 1 m distance)



Sound power spectrum Lw

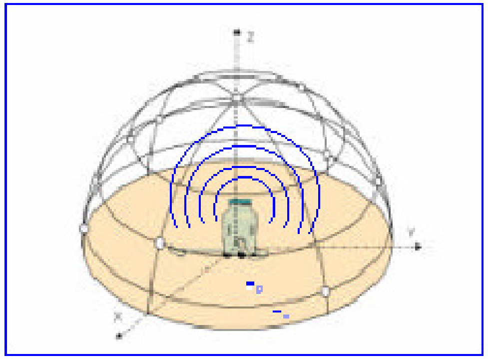


Sound power spectrum Lw corrected K2



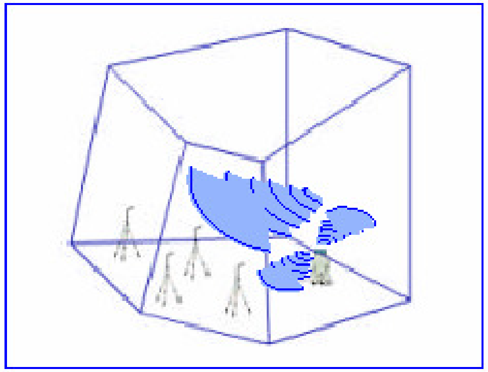
Methods of measuring Sound power (P_w) level

- Pressure-Based, Free Field
  - – Almost free-field, ISO 3744
  - – Anechoic or Semi-anechoic chamber, ISO 3745

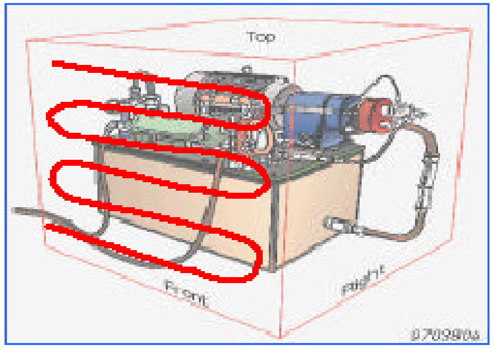


- Pressure-based, Diffuse Field
  - – Reverberation room, ISO 3741
  - – Special reverberation room, ISO 3743

  sound energy is uniformly distributed



- Intensity
  - – Scanned Measurements, ISO 9614 - 2
  - – Point measurements, ISO 9614 - 1



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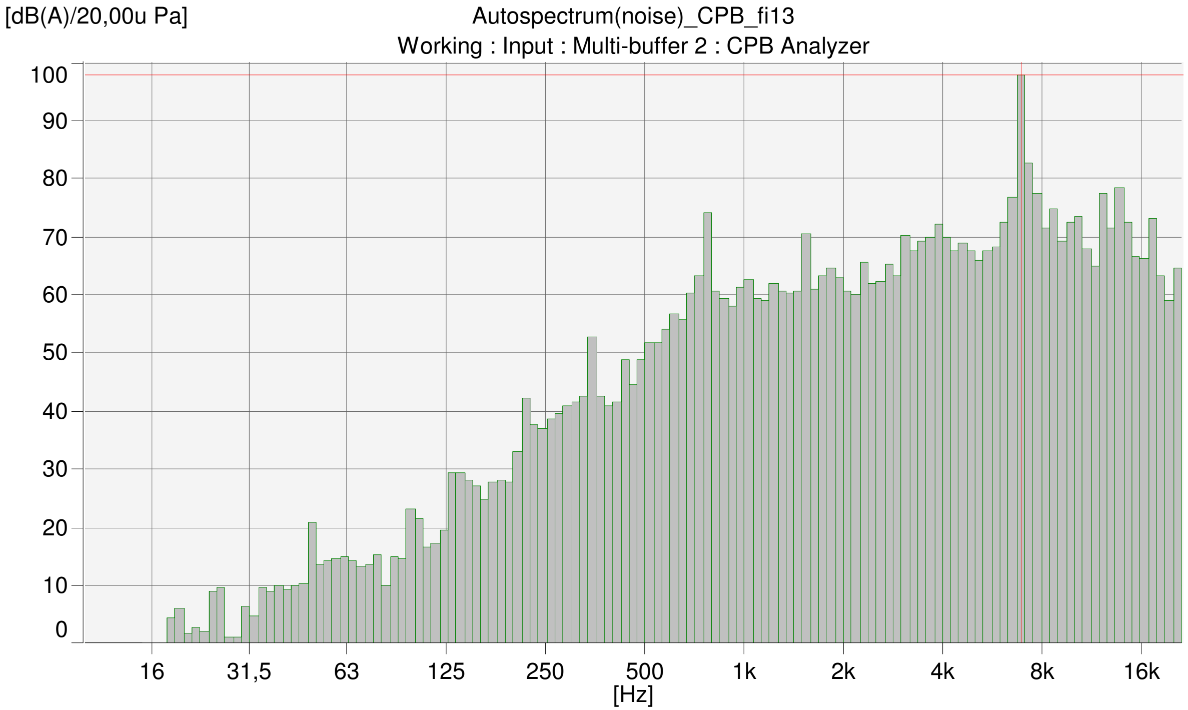
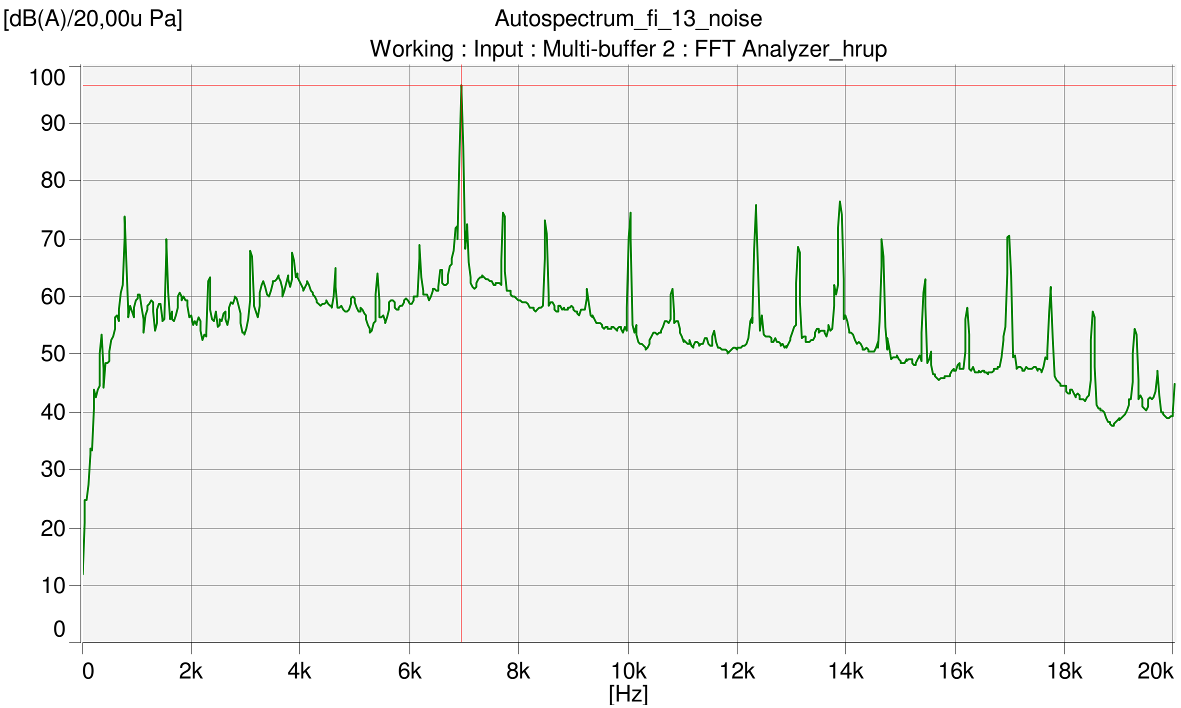




FFT and CPB spectrum

CPB – Constant Percentage Bandwidth
1/12 octave / 1/3 octave

250 Hz – 500 Hz 1 Octave
higher frequency = 2 x lower freq.
1 Octave = **8 tones** in music

A third octave:
higher freq. = 1,26 times lower freq.

FFT – Fast Fourie Transformation
linear frequency scale (x-axis)

Octave

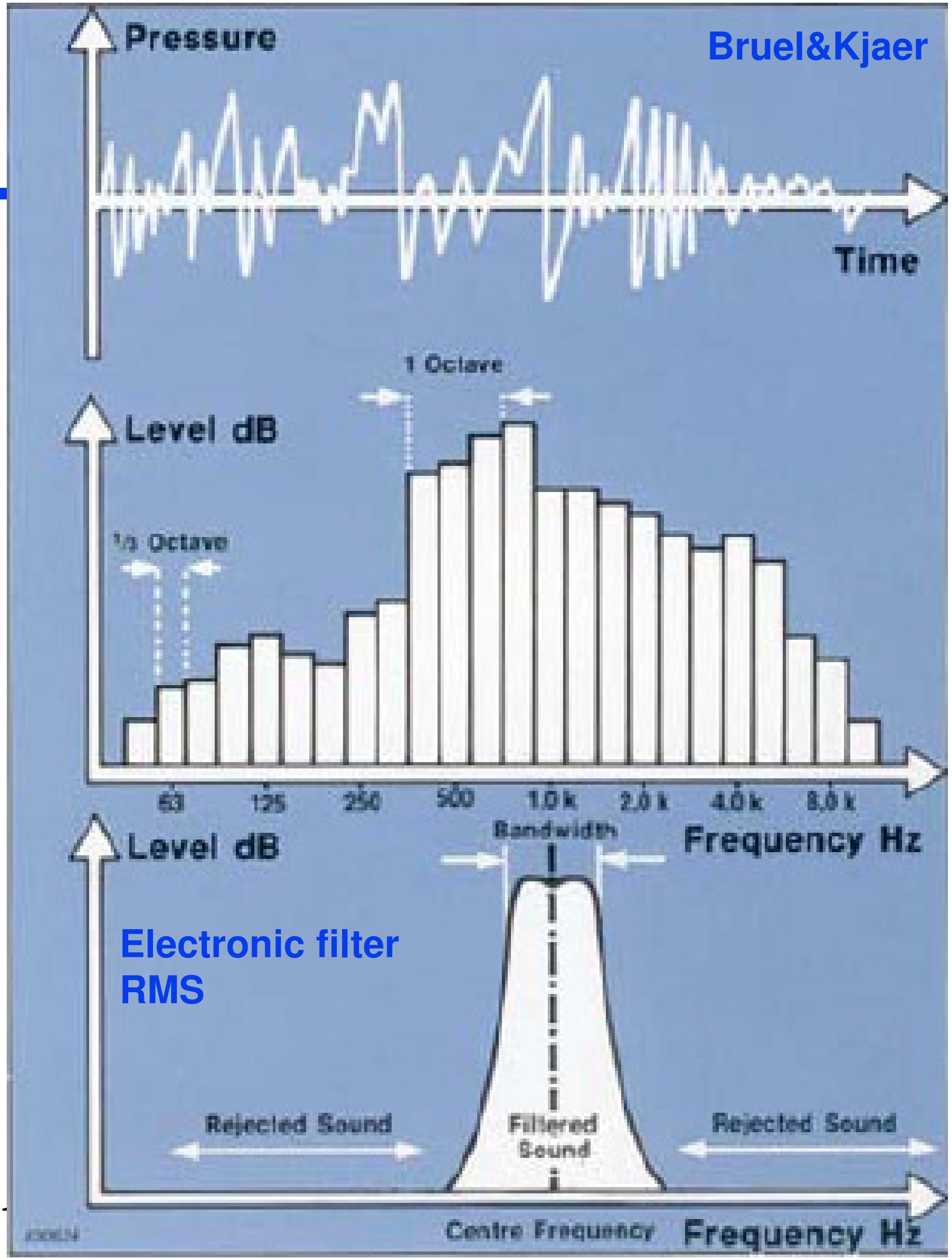
A tonal difference of two pairs of tones is perceived equally if the ration (and not absolut difference) of the two frequency pairs is equal.

$$\frac{f_{a1}}{f_{a2}} = \frac{f_{b1}}{f_{b2}}$$

+ 50
2550 Hz

500 Hz
x 1.1
550 Hz

2500 Hz
X 1.1
2750 Hz



Multiple sound sources

$$L_{p\,sum} = 10 \log_{10} \sum_{i=1}^{n} \left(10^{L_{pi}/10}\right)$$

Example:

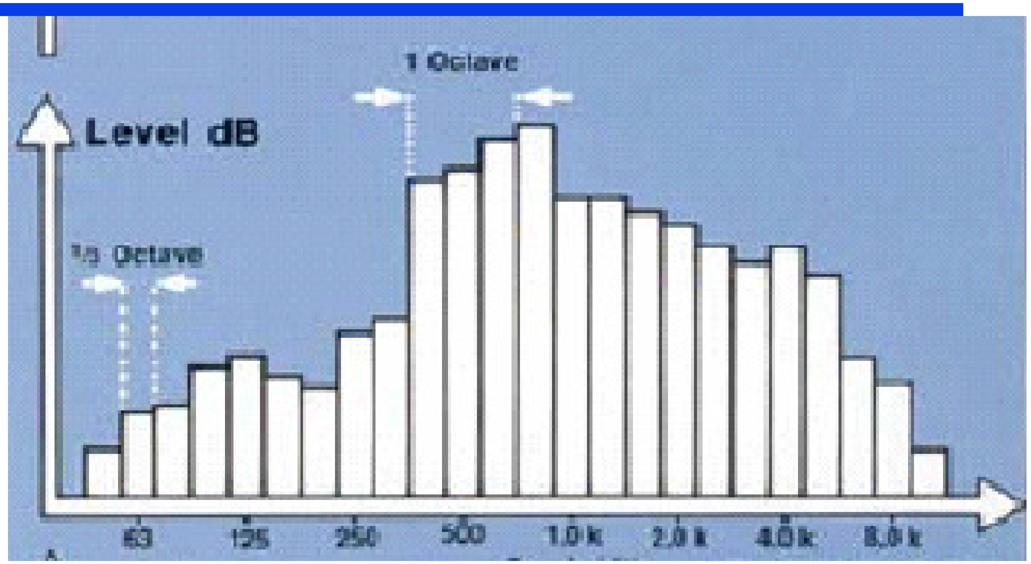
65 dB + 65 dB = 65 + 3 dB = 68 dB

10 x 65 dB = 65 + 10 dB = 75 dB

90 dB + 80 dB = 90.4 dB

82 dB + 77 dB = 83.2 dB

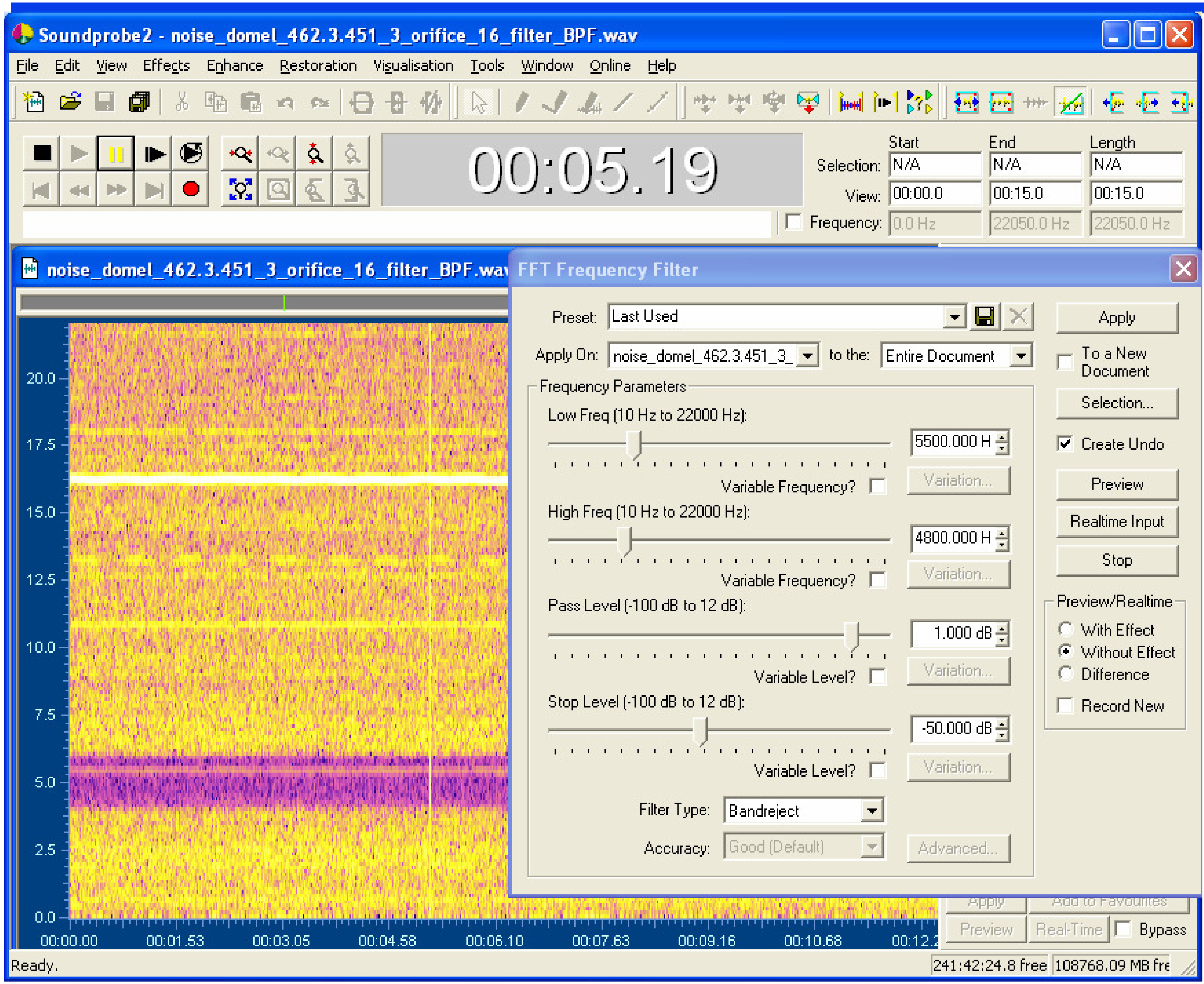
Influence of the peaks or wider broadband noise is important



Example:

Noise level	Pressure increase	
20 dB	1000 %	
10 dB	316 %	twice as loud
6 dB	100 %	
3.5 dB	50 %	smallest change we can hear

Sound quality; editing frequency band filters, special effects



5000 Hz Like BPF tone

550 Hz

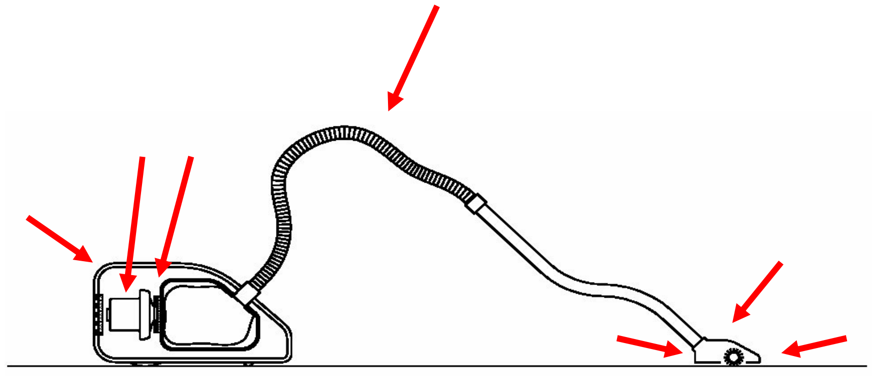
Motor sound

Motor sound + BPF filter

Vacuum cleaner (broadband sound)

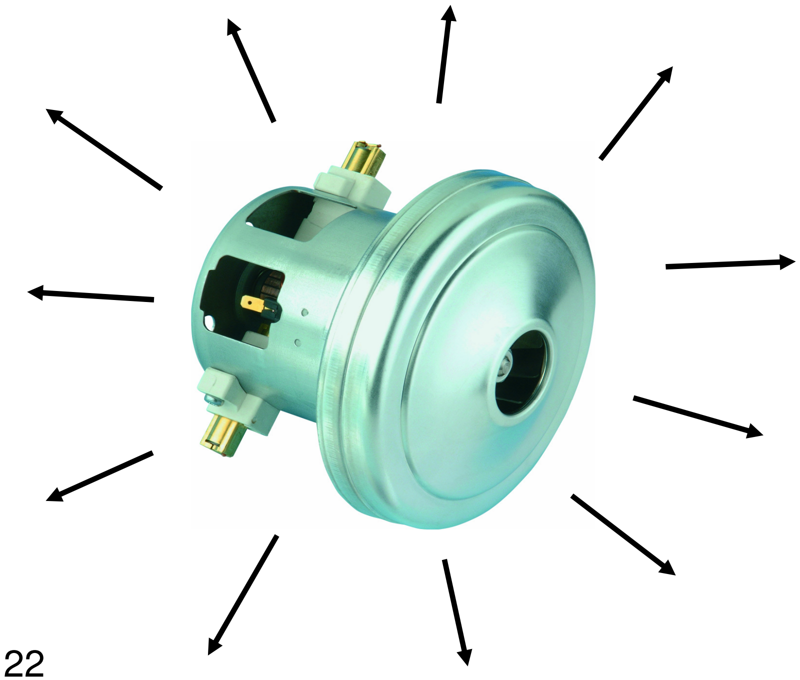
Noise sources on Vacuum Cleaner

•vacuum cleaner motor
•vibrations of the vacuum cleaner housing
•not optimized flow channels, flow distortion
•motorized power nozzle
•high velocities of air at the intake



VC Motor noise sources:

- *Aero-acoustic reasons,*
- *vibrations of the VCM structure,*
- *mechanical reasons (sliding contact between brush and commutator, bearings…)*
- *electromagnetic reasons,…*



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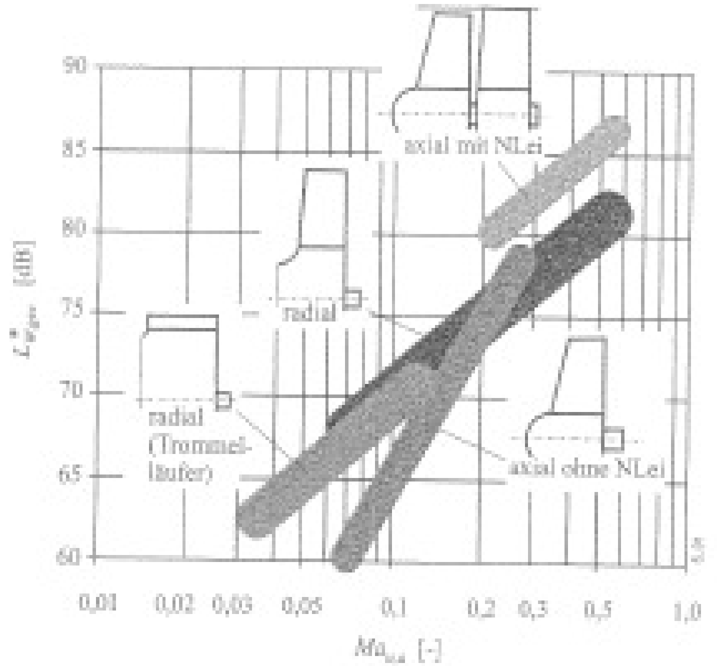
L_w – Noise power level

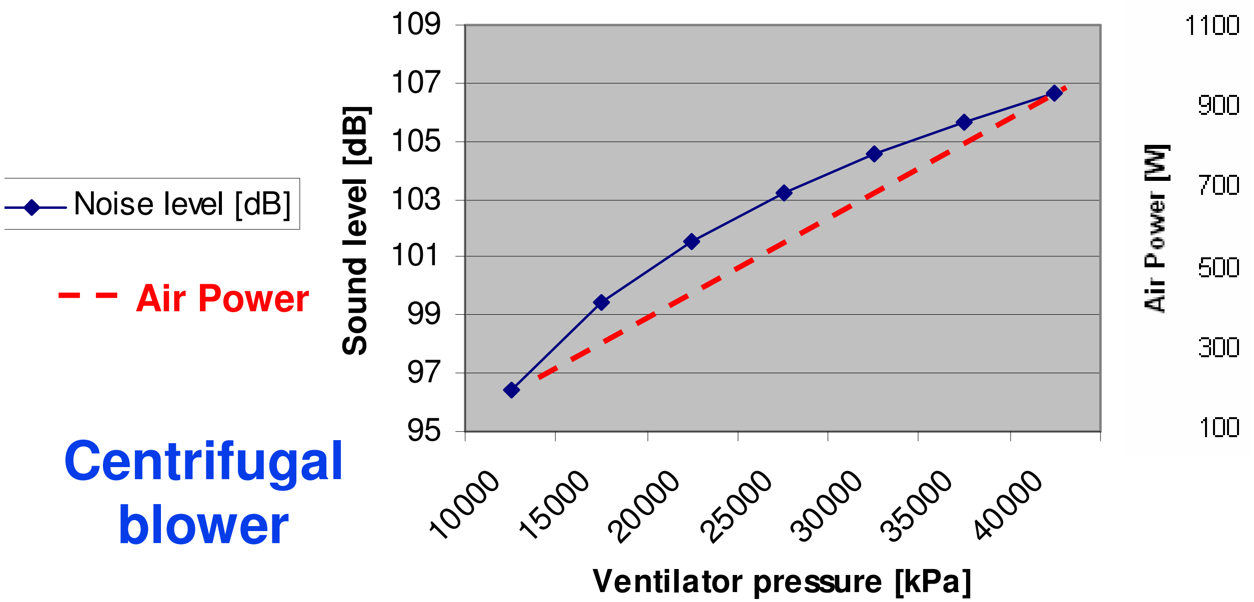
$$L_w = f\left(V/t * dp * M^m\,(Pi*D*n/c_o)\right)\ [dB]$$

$$P = V/t * dp \qquad \text{airflow power} \quad [W]$$

V/t - Airflow,
dp - Pressure difference
M – Mach number (speed)
m - Fan type

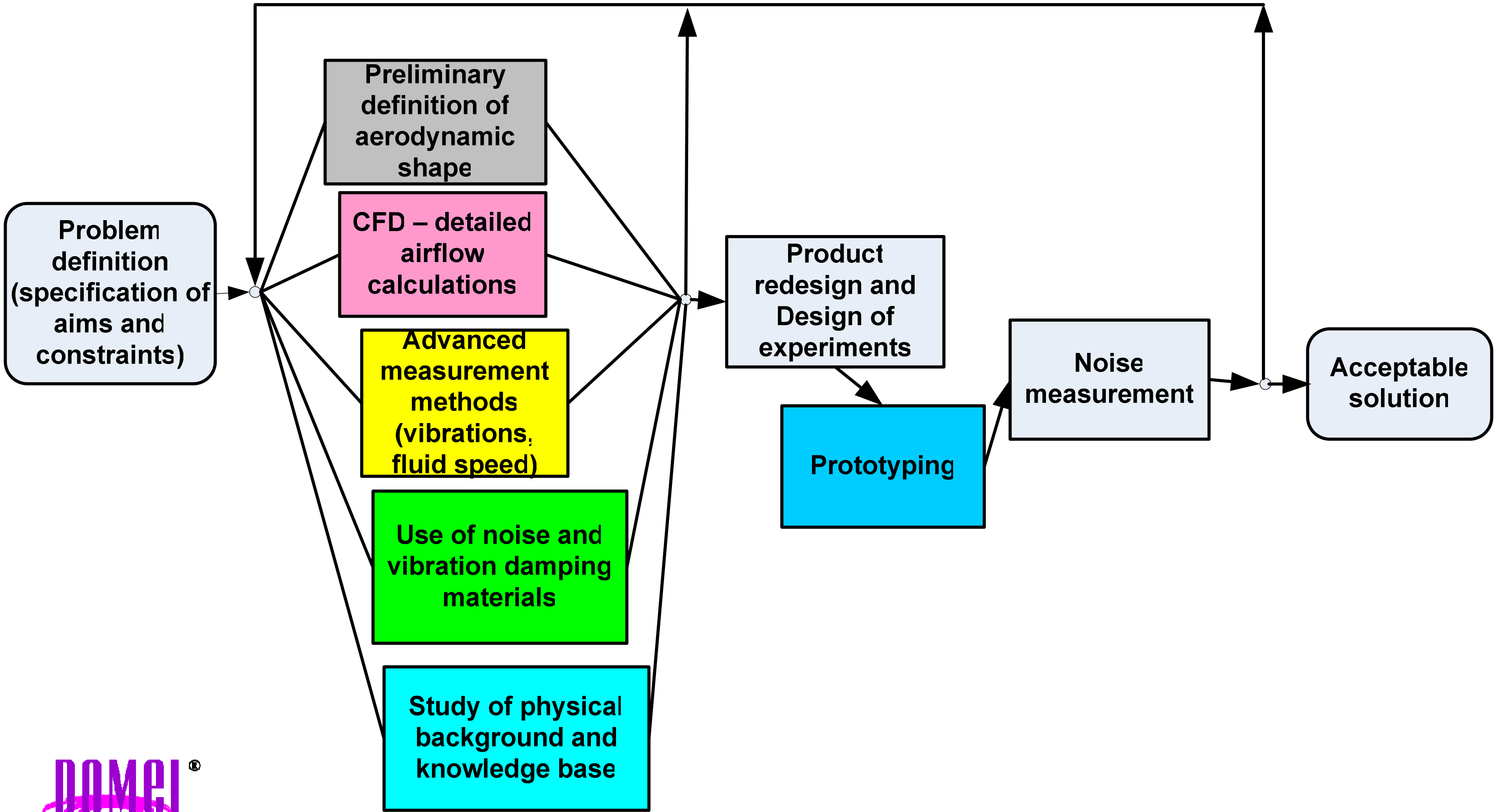


How sound depend on ventilator pressure at q=25 l/s and n=40000 RPM



Centrifugal blower

Integrated approach to noise reduction



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Noise sources

Structural born noise:

- Case study: vibrations of the vacuum cleaner cover
- Run up analyses
- Modal analyses
- Vibrations damping

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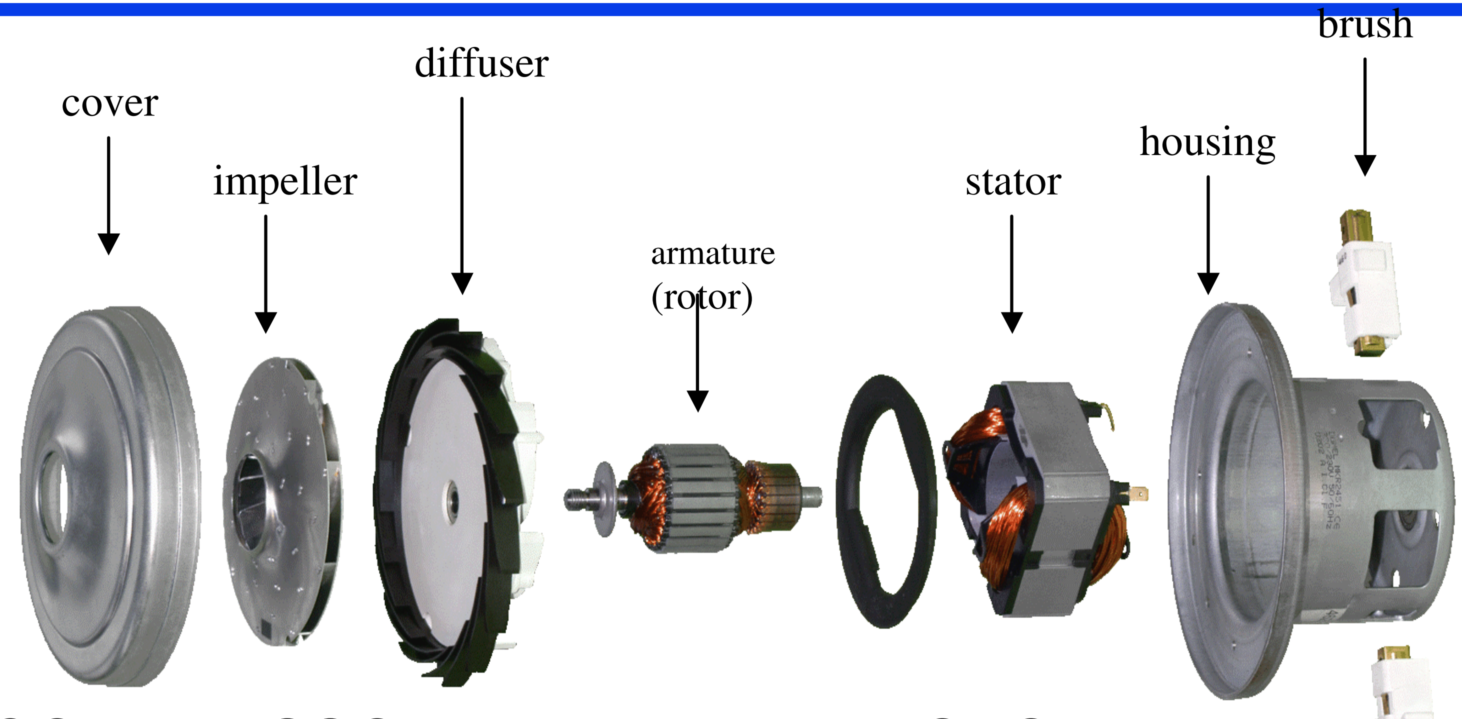
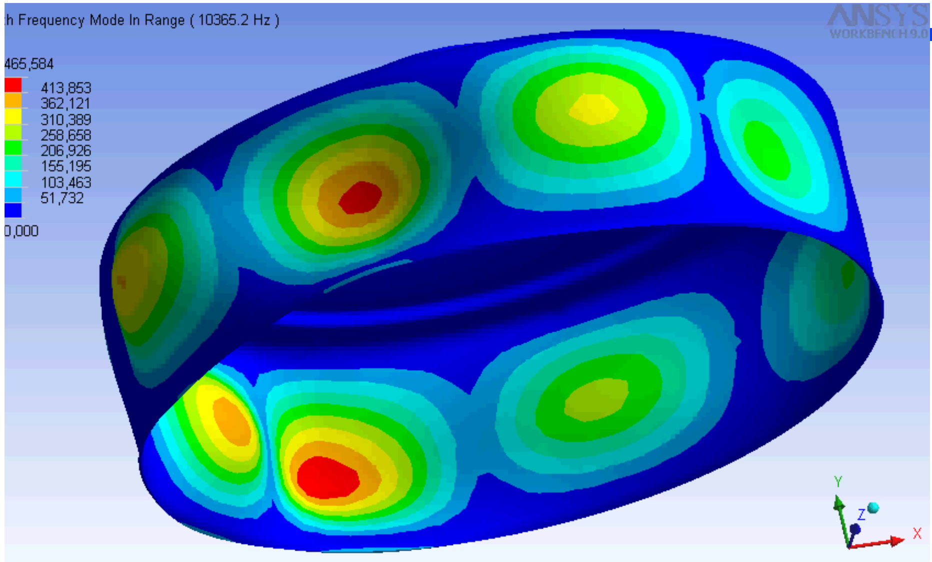
Parts of Vacuum Motor

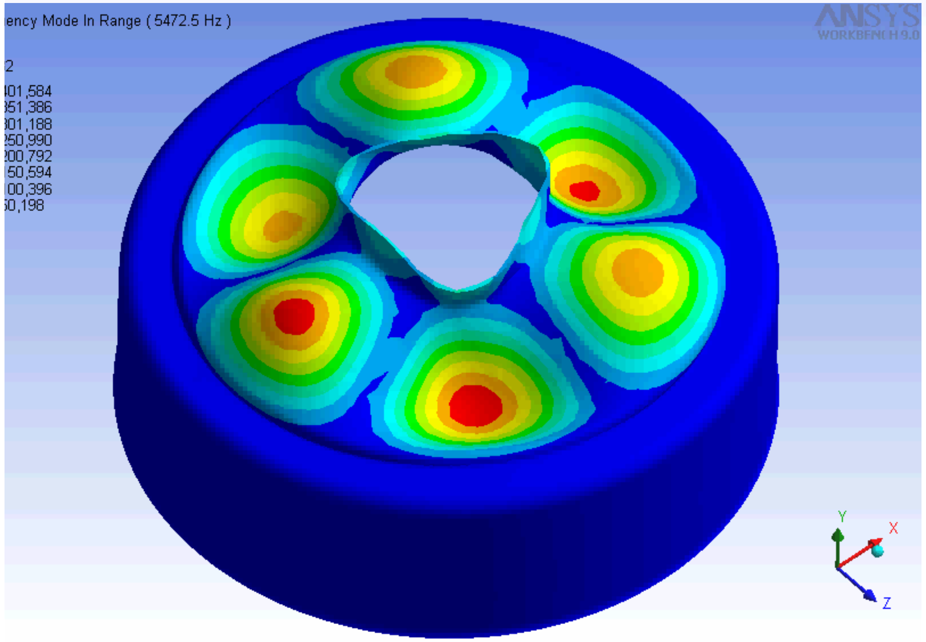


- **COMPRESSOR:**
  - **Diameter of impeller**
  - **number of stages**
  - **impeller outlet width**
  - **with/without diffuser**
- **MOTOR:**
  - **lamination size**
  - **hight of the stack**
  - **winding**

50.000 RPM – concentrated power

Sound power calculation of structural borne noise from vibration level and surface size (ISO 7849)





$$W(f) = \rho c \overline{v^2(f)} S \sigma(f)$$

$$L_W = 10 \log \frac{W}{W_0}$$

$$\sigma = 1/((1 + 0.1 \frac{c^2}{(fd)^2}))$$

$$d = \sqrt{\frac{S}{\pi}}$$

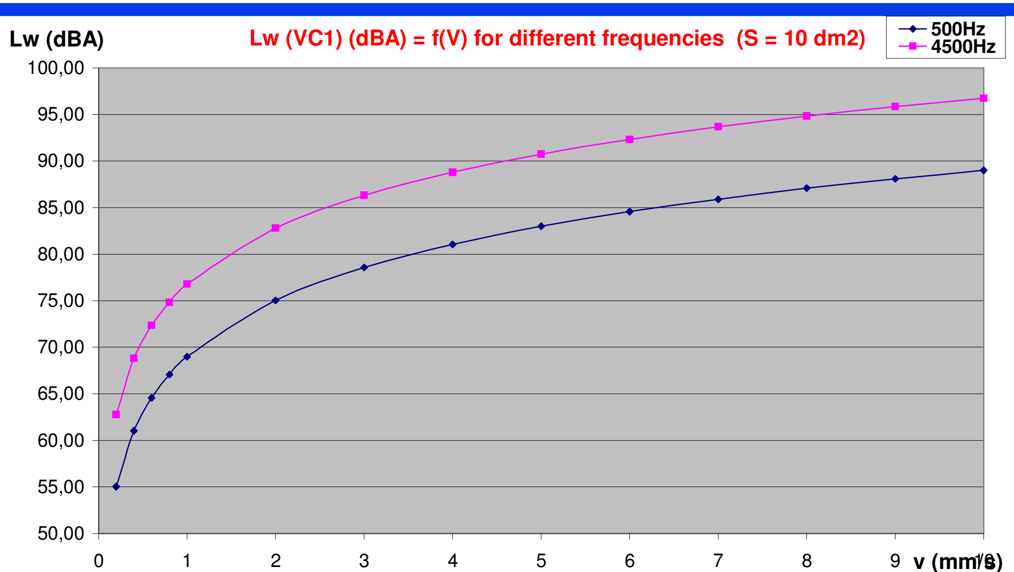
W(f)	-	sound power at specific frequency (W)
ρ	-	air density (1,2 kg/m3)
c	-	speed of the sound (340 m/s)
$v^2(f)$	-	vibration level at particular frequency (m/s)
S	-	surface size (m^2)
f	-	frequency (Hz)
σ	-	surface dissemination factor
Lw	-	sound power level in dB
Wo	-	reference sound power (1 pW)

- **Resonance on the motors cover at BPF**
- **FEM calculation (Boundaryconditions)**

Sound power Lw calculation
Influence of the surface size - S

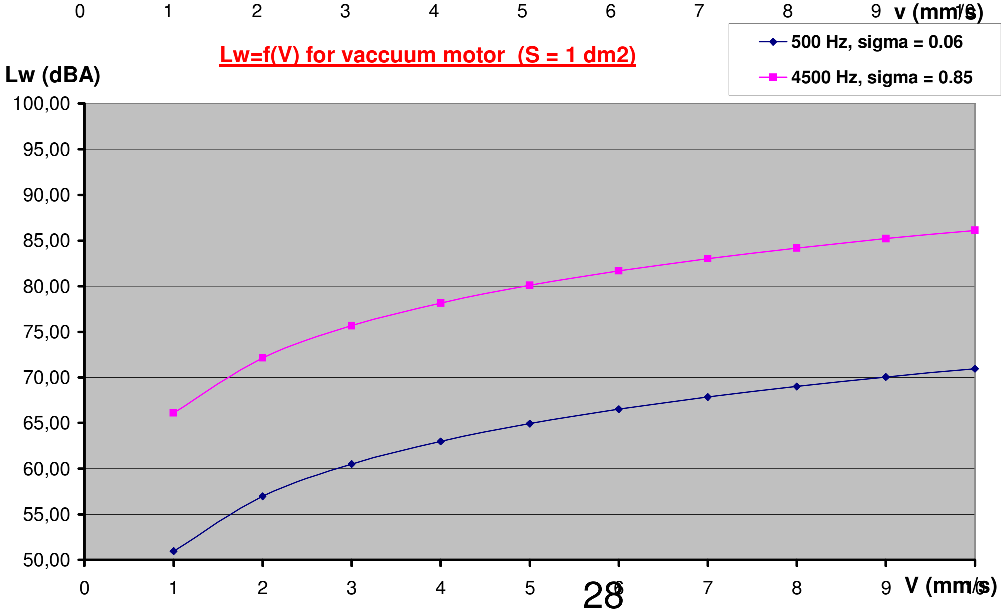
BPF
4500 Hz

Rotation speed
500 Hz



S = 10 dm²

Vacuum cleaner



S = 1 dm²

motor

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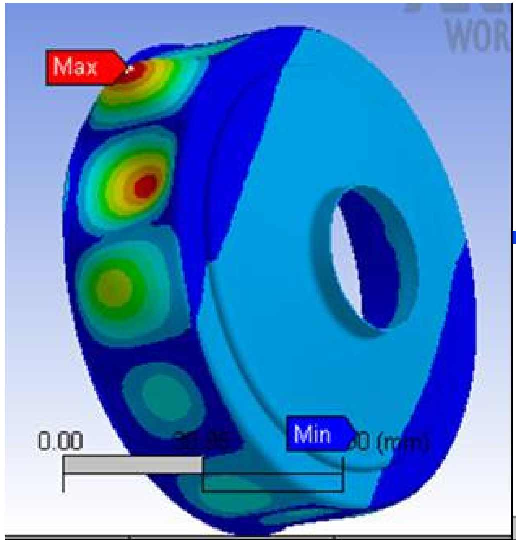
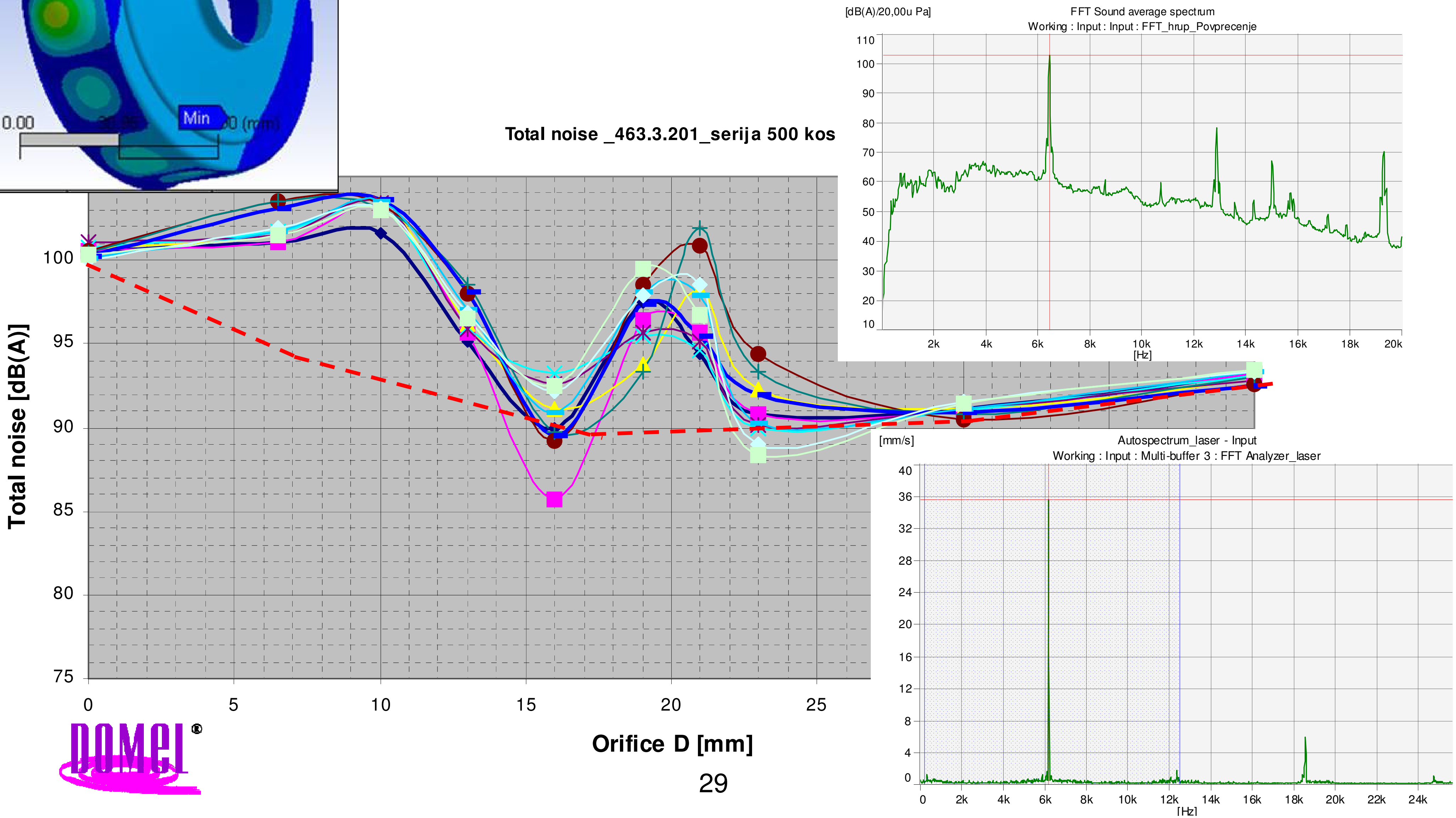


Total noise level in the relation to the airflow – typical example of the motor with a resonance



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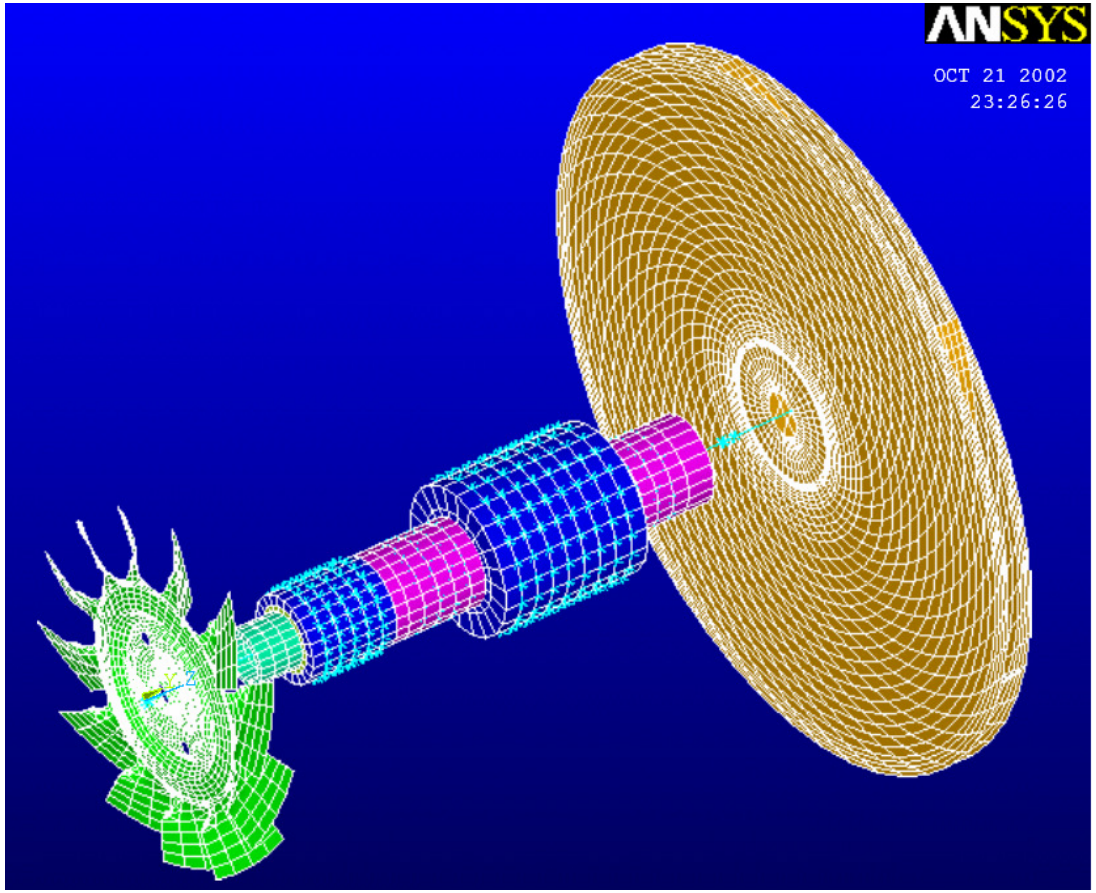
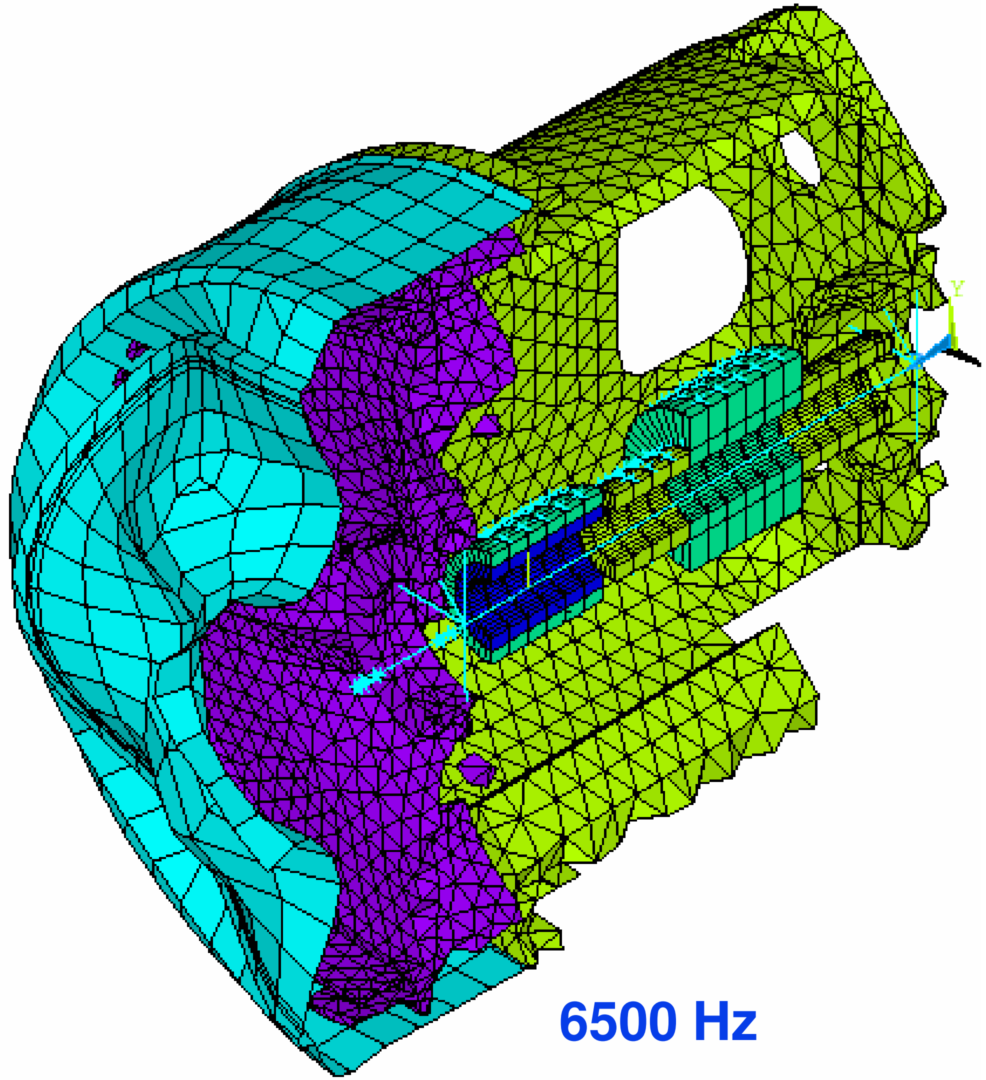
Numerical Simulations
Mechanics (LADISK, FS)

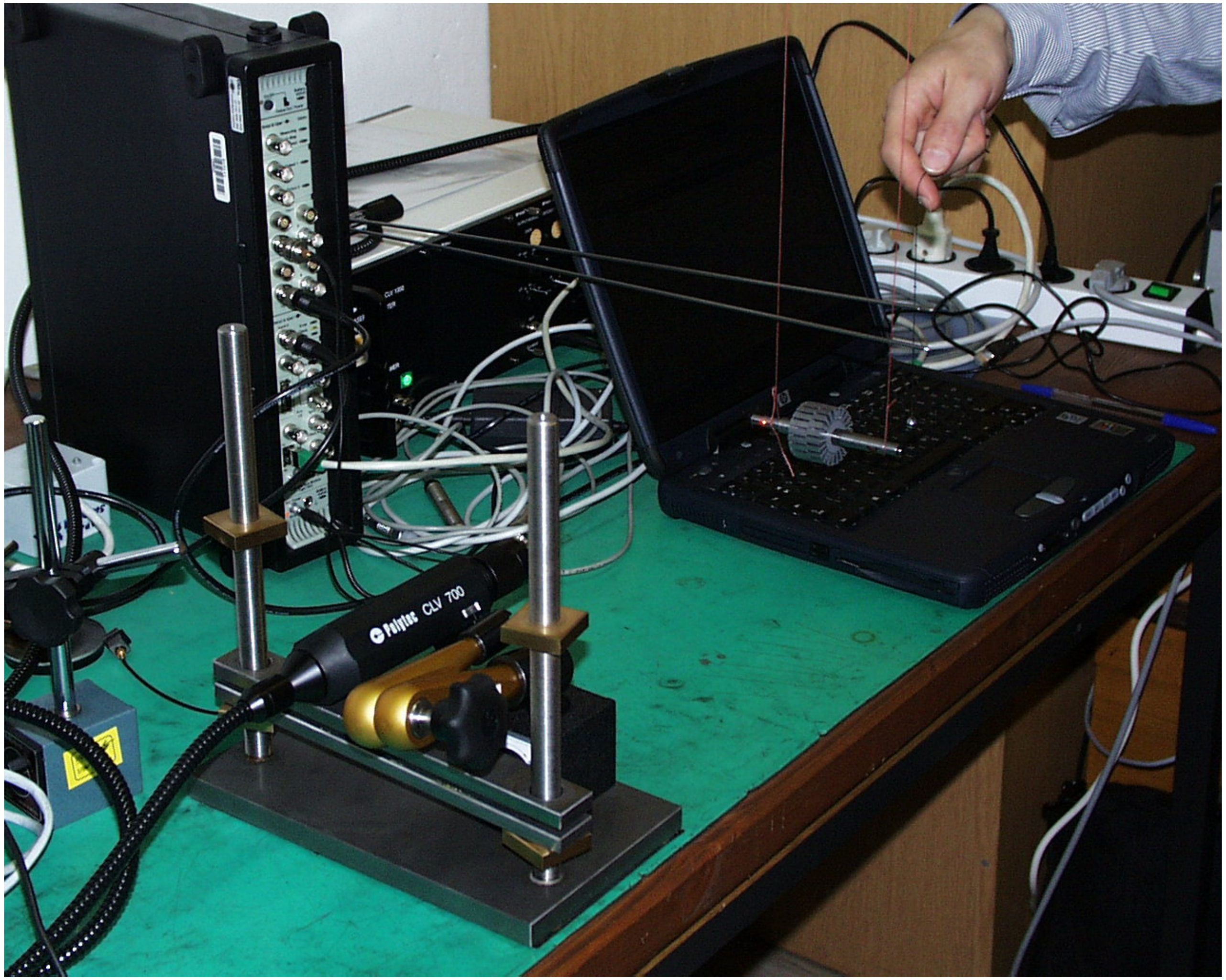




6500 Hz

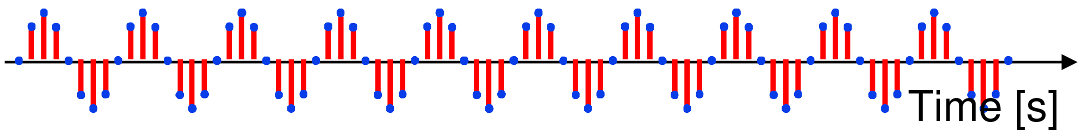
Measurements:
Laser vibrometer

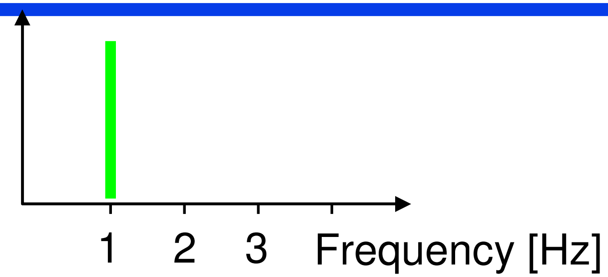
- Bruel&Kaer Pulse system
- Contact less laser measurements of vibrations
  - Small parts
  - During rotation

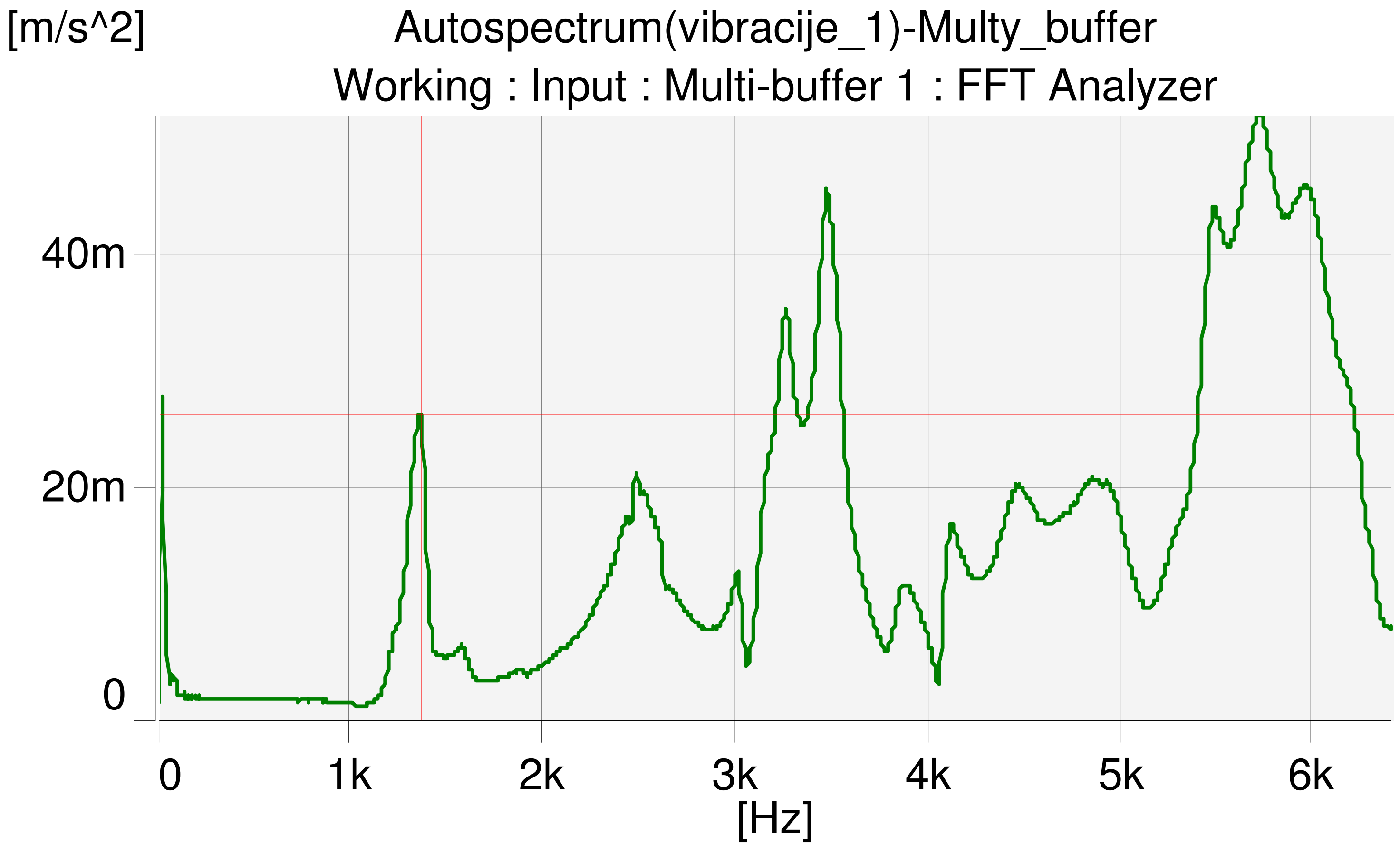


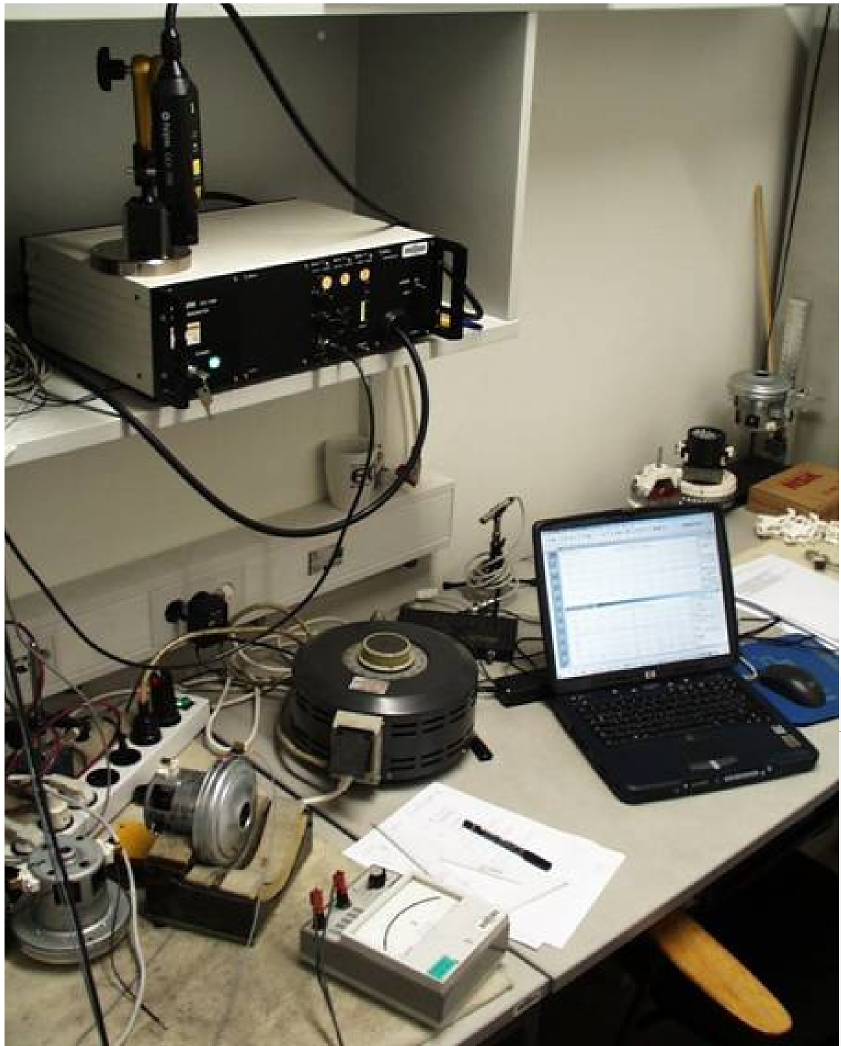
Frequency spectrum - FFT

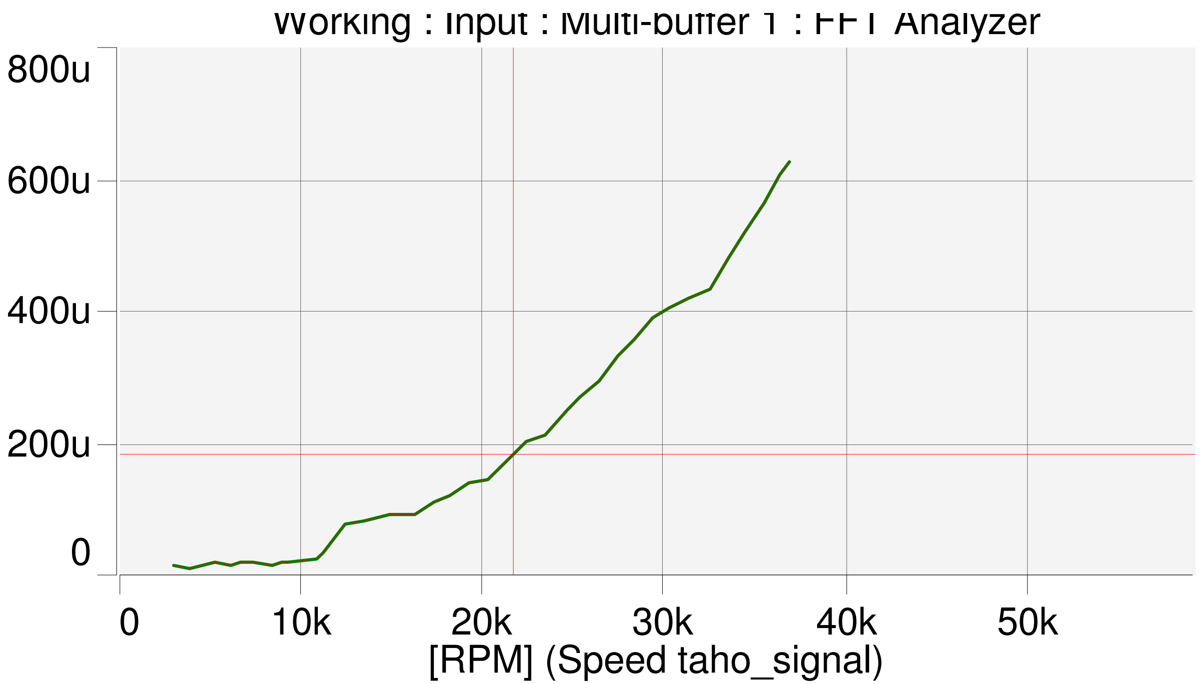
Response in time domain.

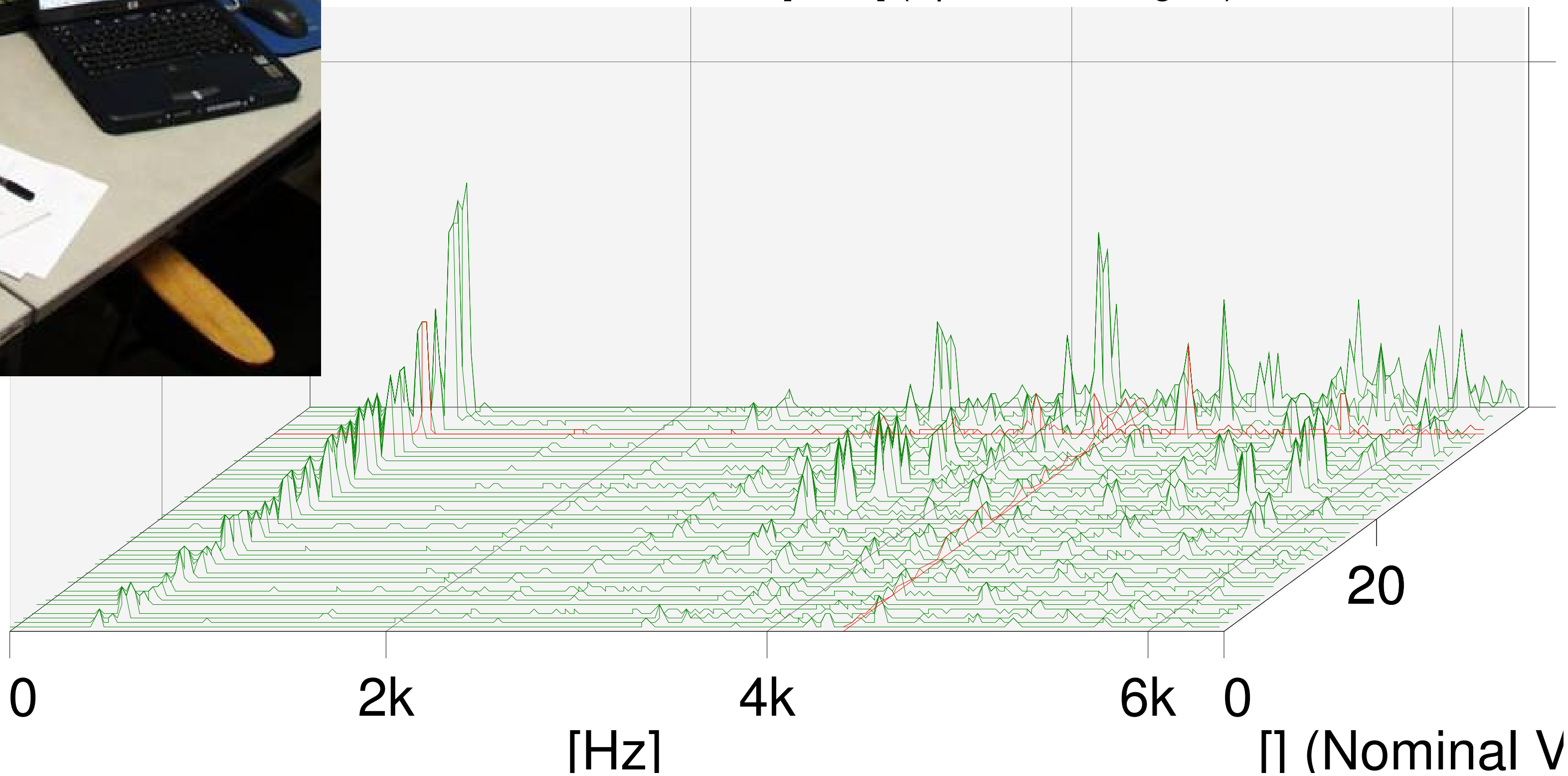










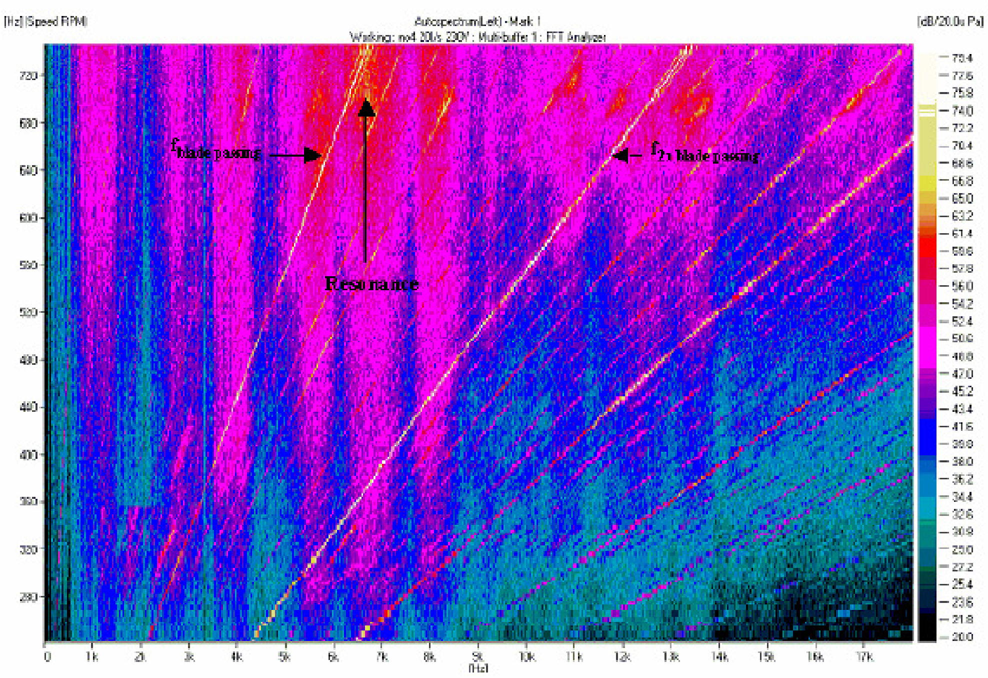


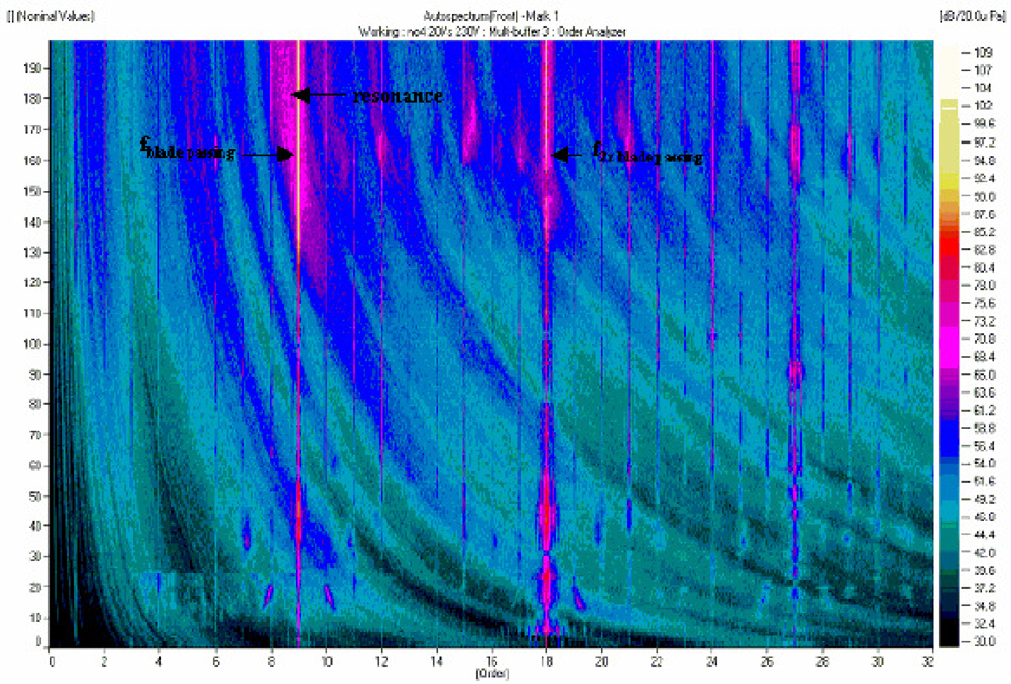
Run up analyses

Run up analysis
to determine possible resonances

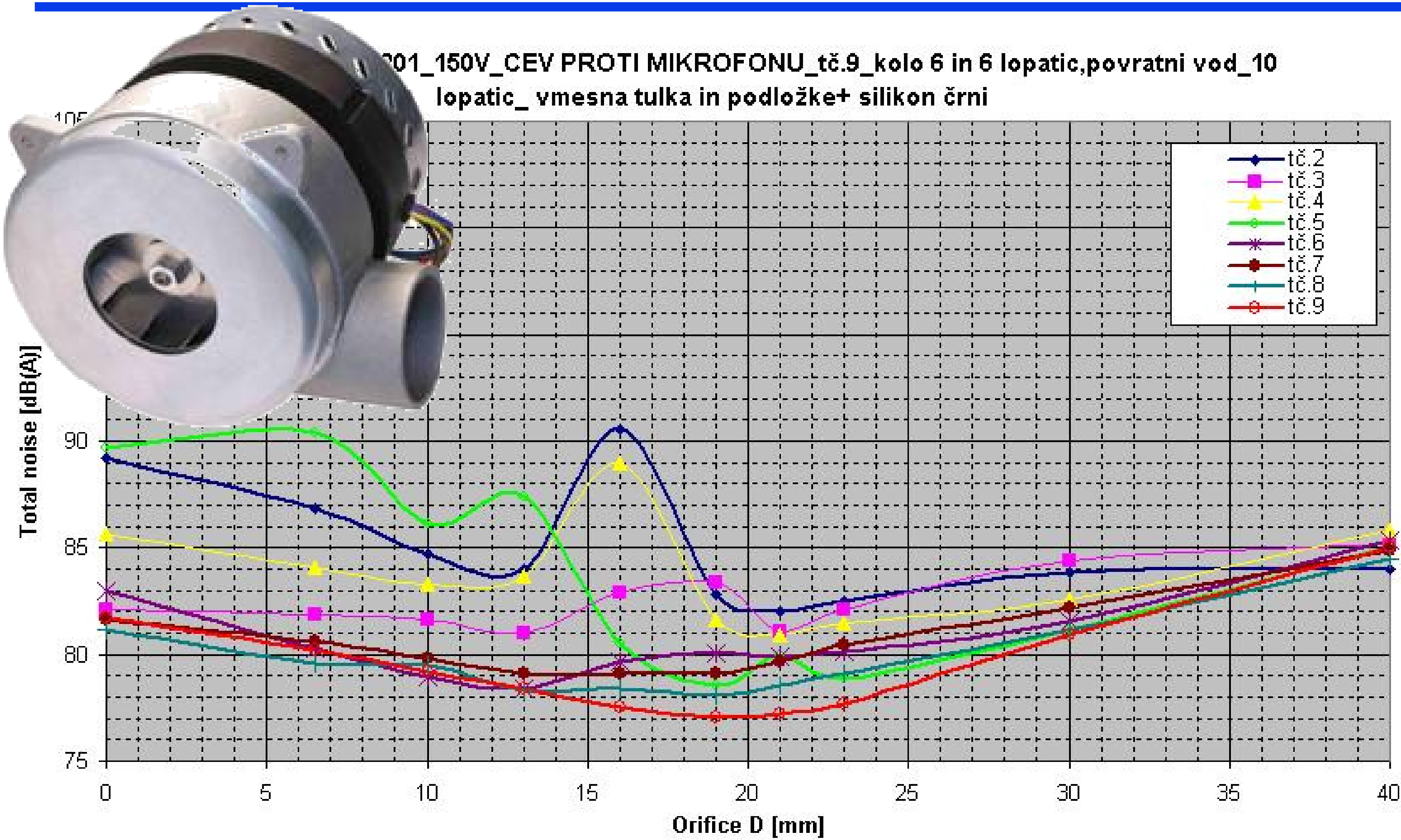
Sound pressure spectrum as
a function of frequency (x-axis) and speed (y- axis)

Order tracking analysis
Harmonics – x axis

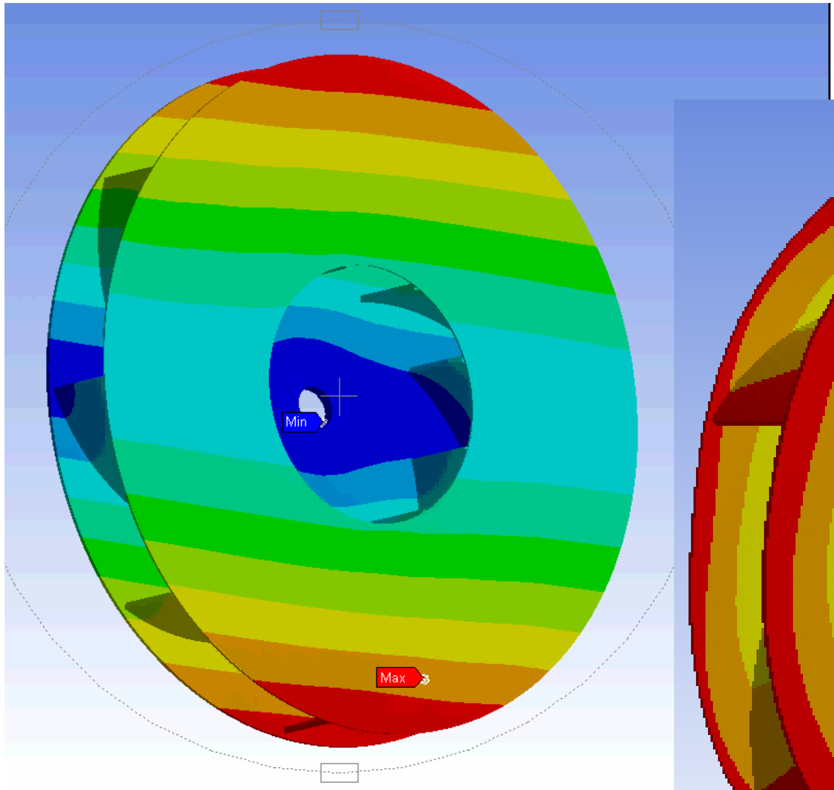




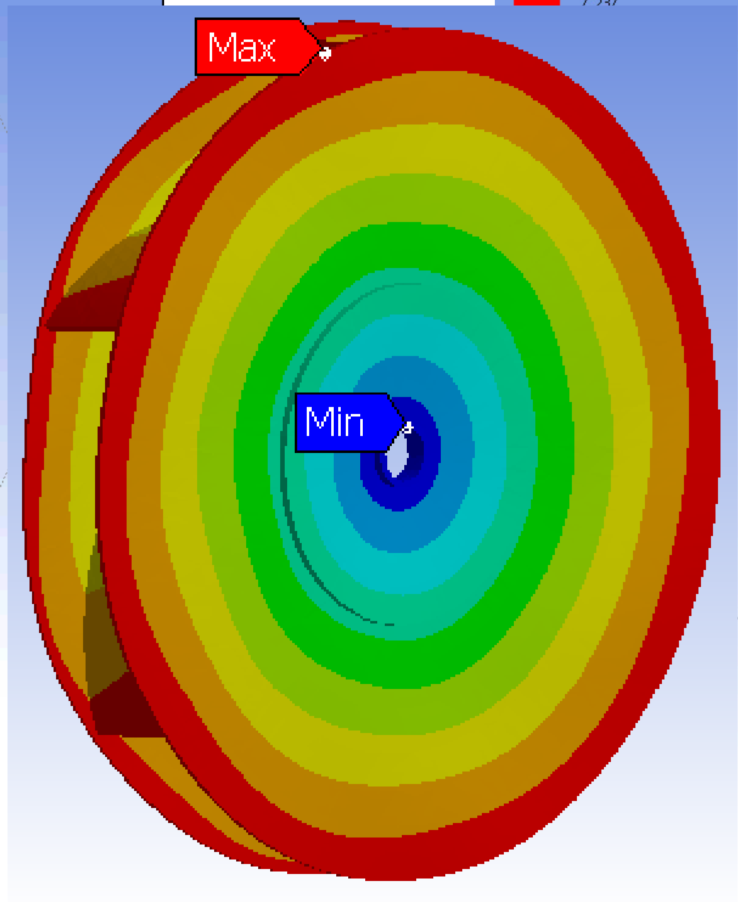
Case study: impeller resonance



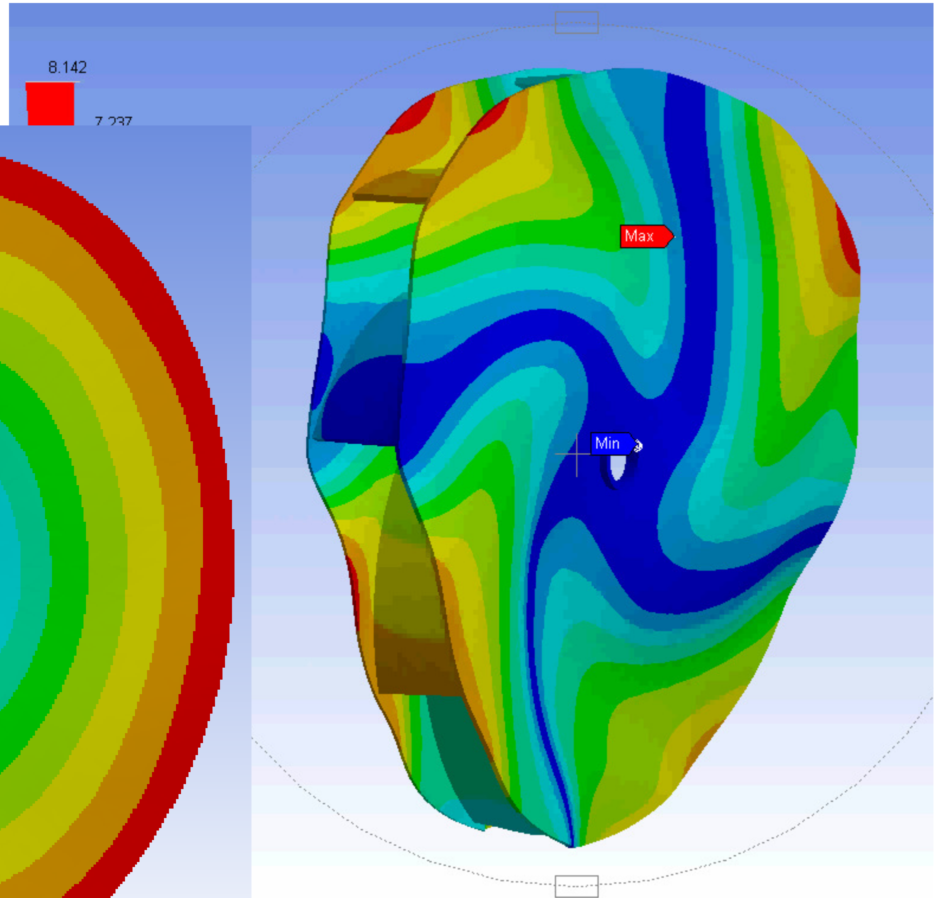
Impeller natural modes of vibrations



1. mode: 350 Hz

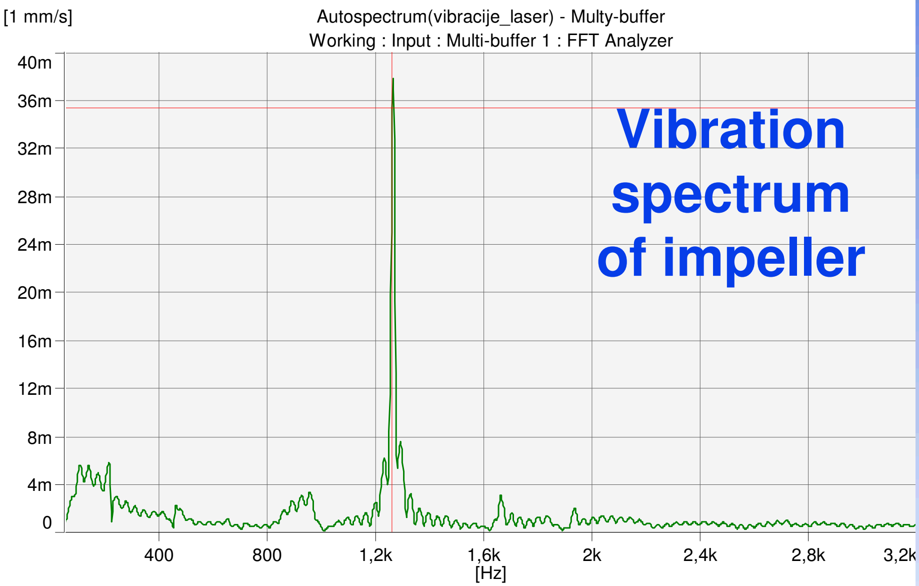


3. mode: 1280 Hz

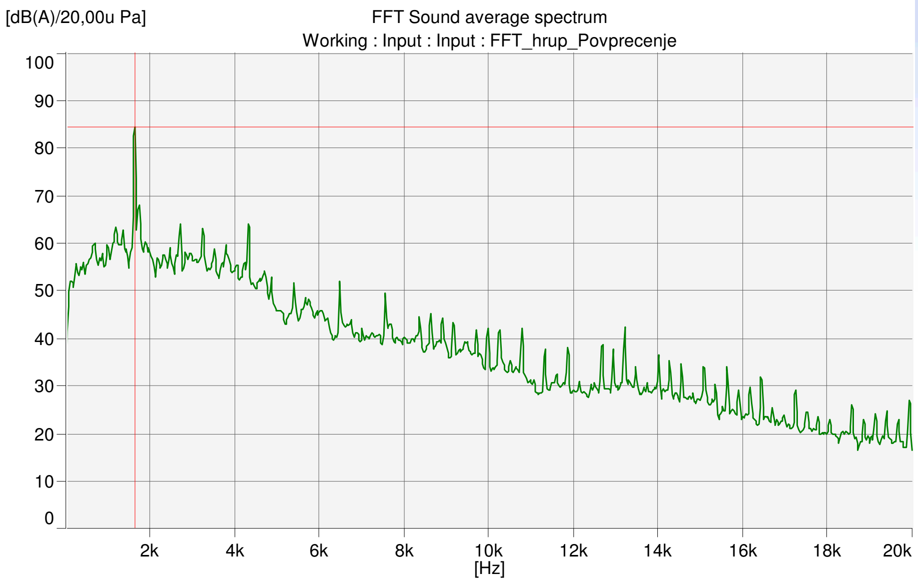


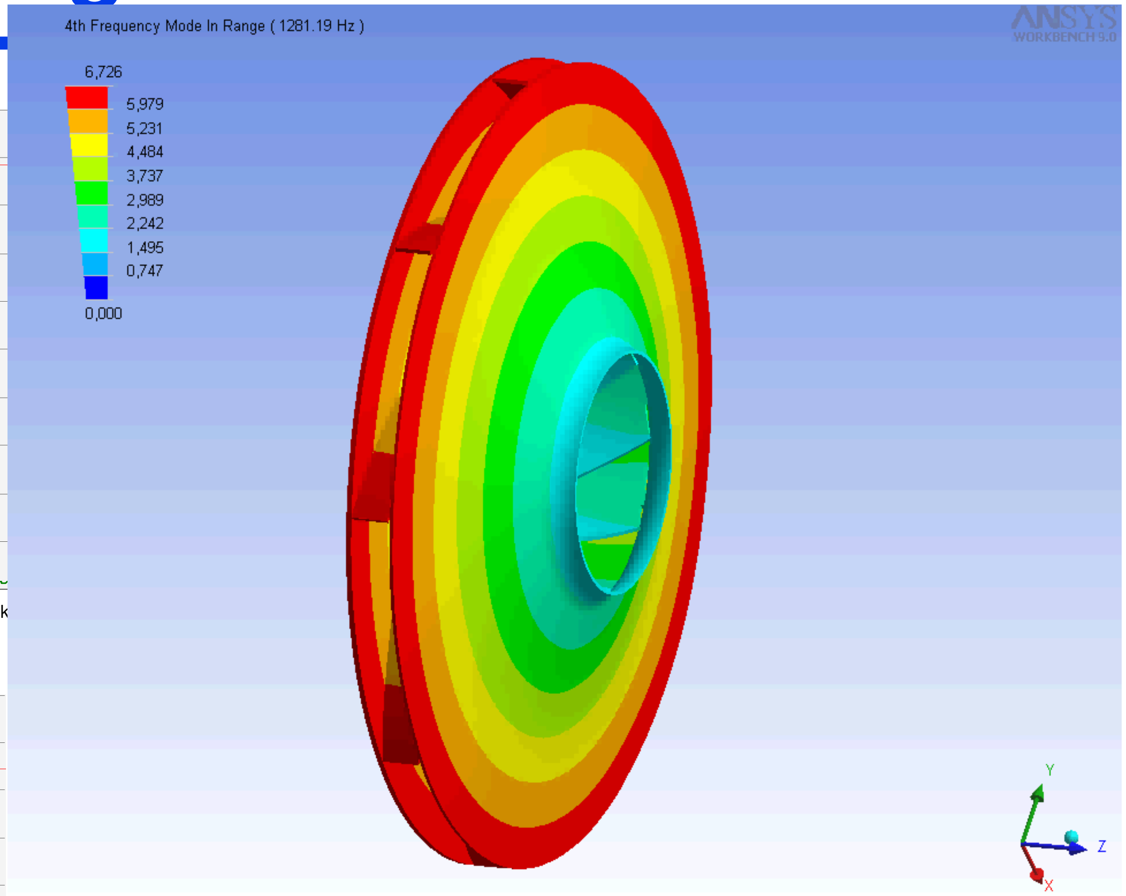
5. mode: 2670 Hz

Vibrations spectrum of impulse excitation in tangential direction



Vibration spectrum of impeller

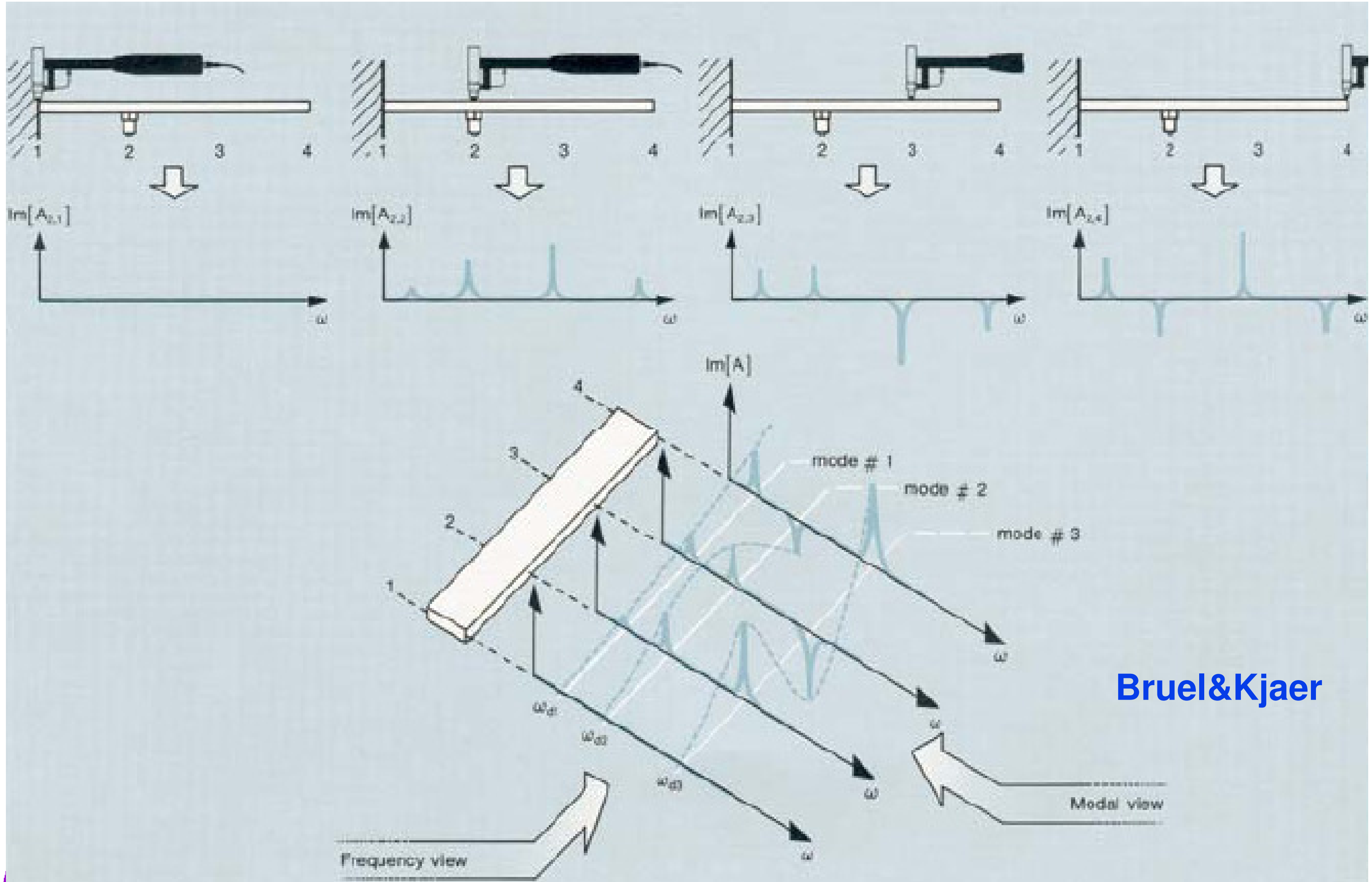




Sound Spectrum of the EC motor

Brushless or EC motor has six moment pulses per one revolution
It is an excetition force

Modal analyses I



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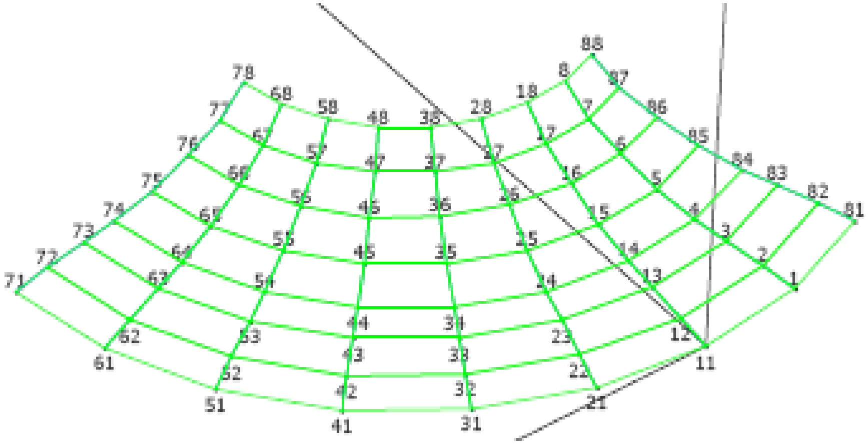
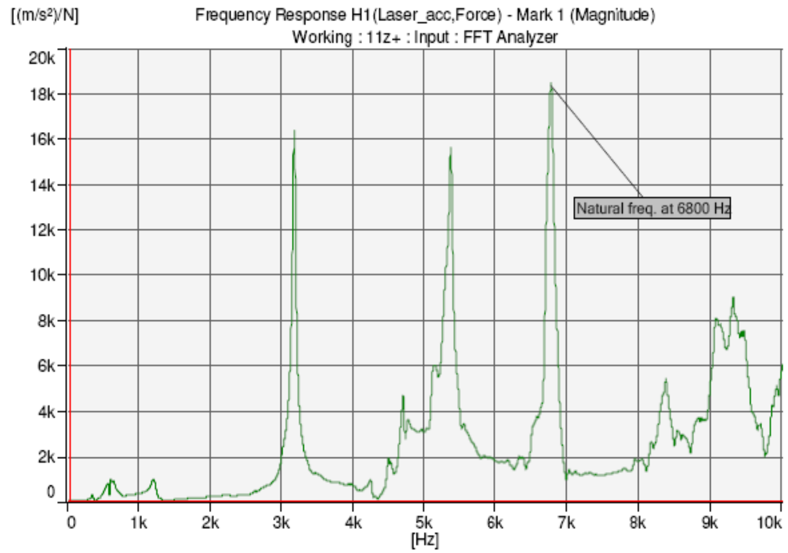
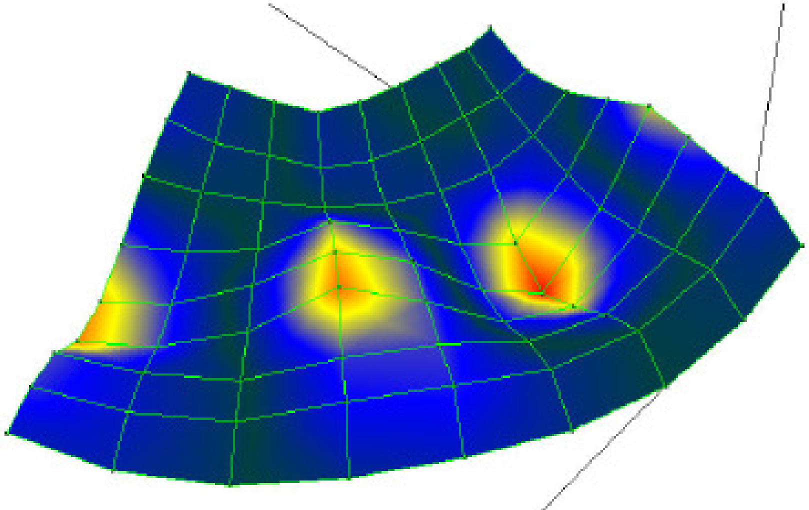
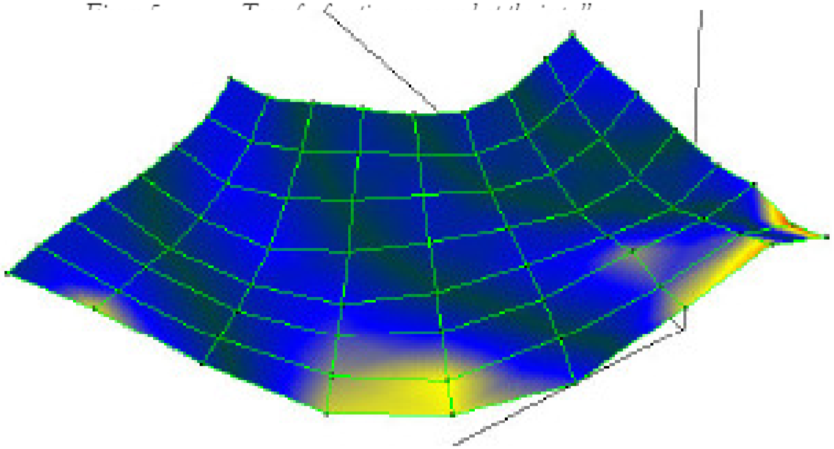
Modal analyses II (ATC, Drachten)



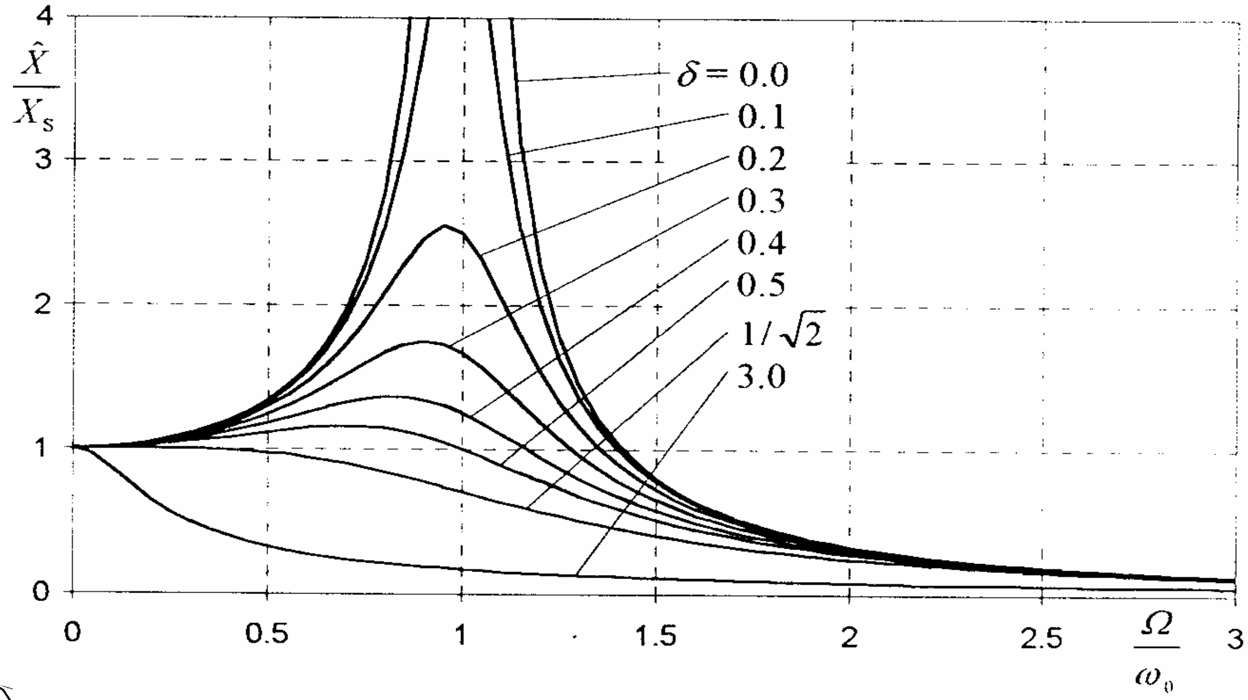


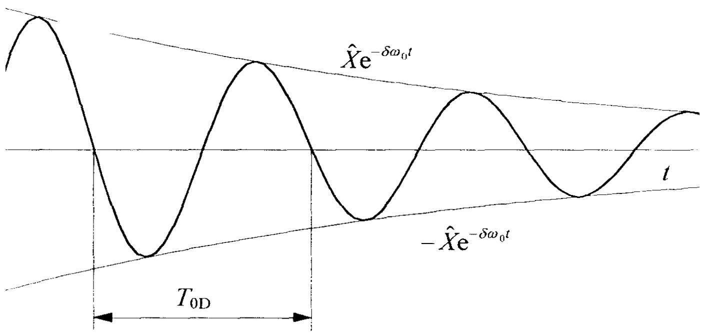


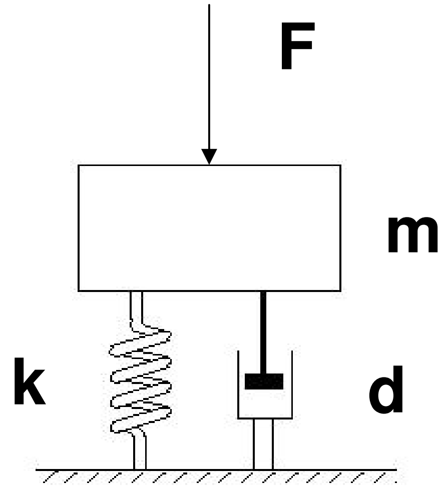


Mode shape of the impeller at 6.8 kHz

Damping of vibration







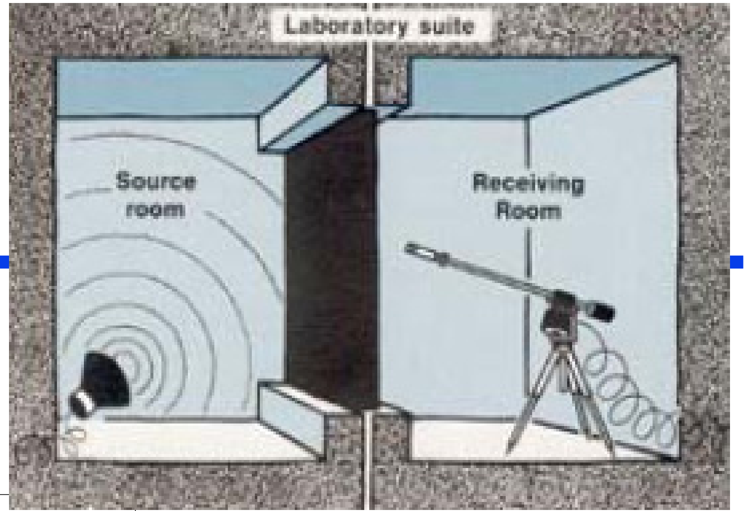
$w_n = \mathrm{sqrt}(\, k \;/\; m \,)$

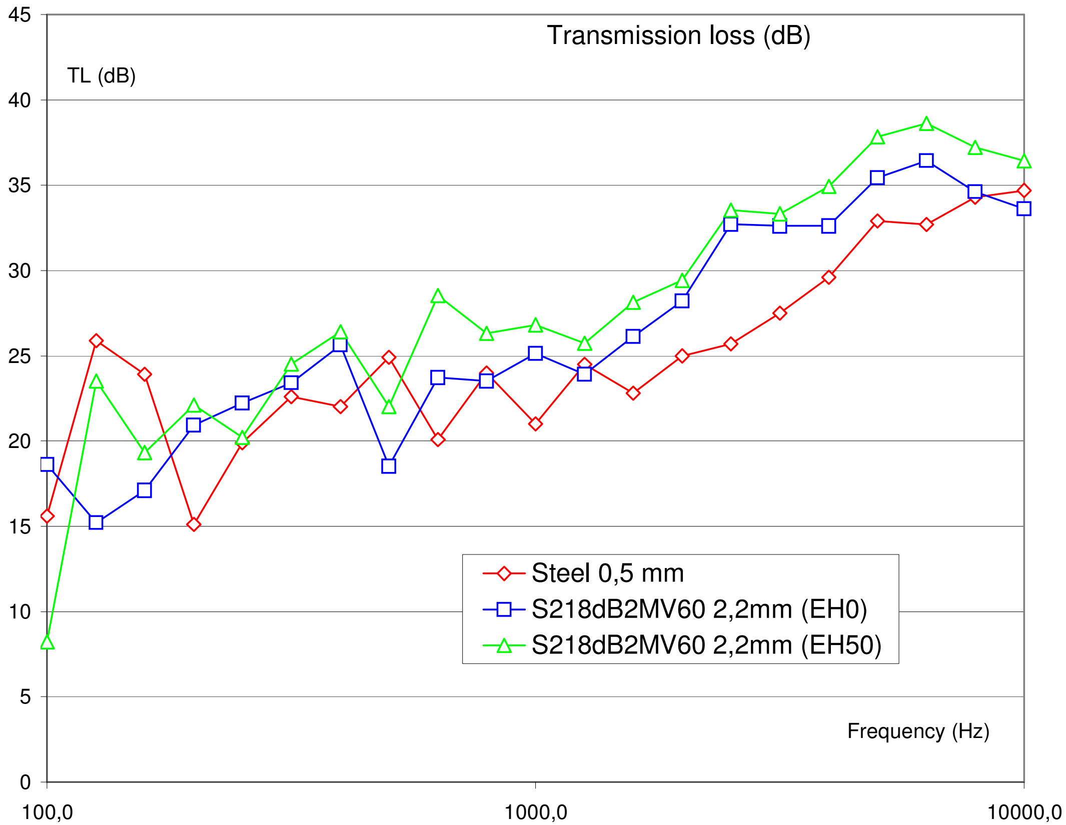
$w_{nd} = w_n \, \mathrm{sqrt}(1 - d^2)$

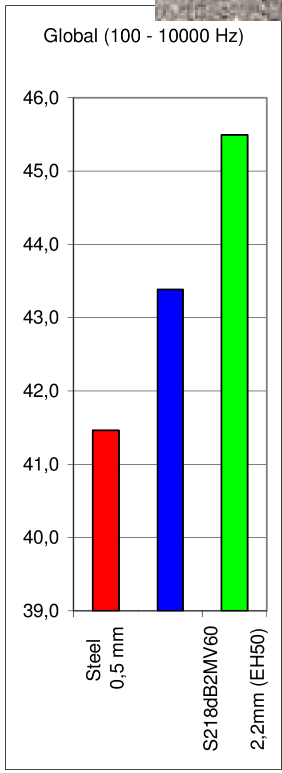
k – stiffness
m – mass
w_n – natural frequency
d – damping factor

Damping materials

Cover made from accustic polyamide





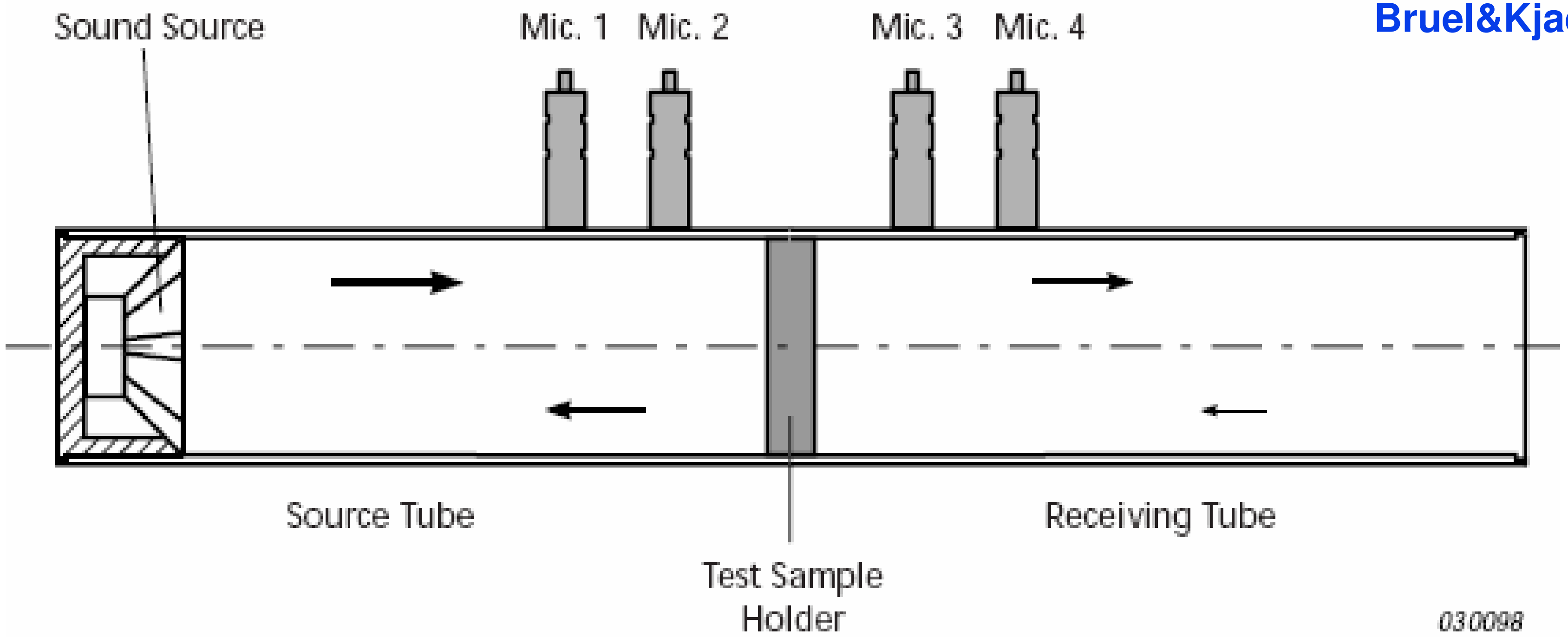


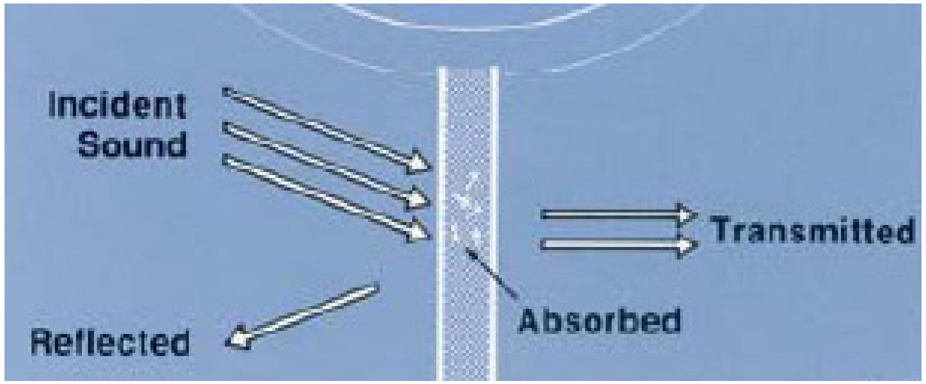
Steel 0.5mm Vs polyamide

With an high insulation grade as the the cover : **Improves by 3dB** the acoustic insulation in comparison with **the steel cover**

Transmision loss measurements

Bruel&Kjaer



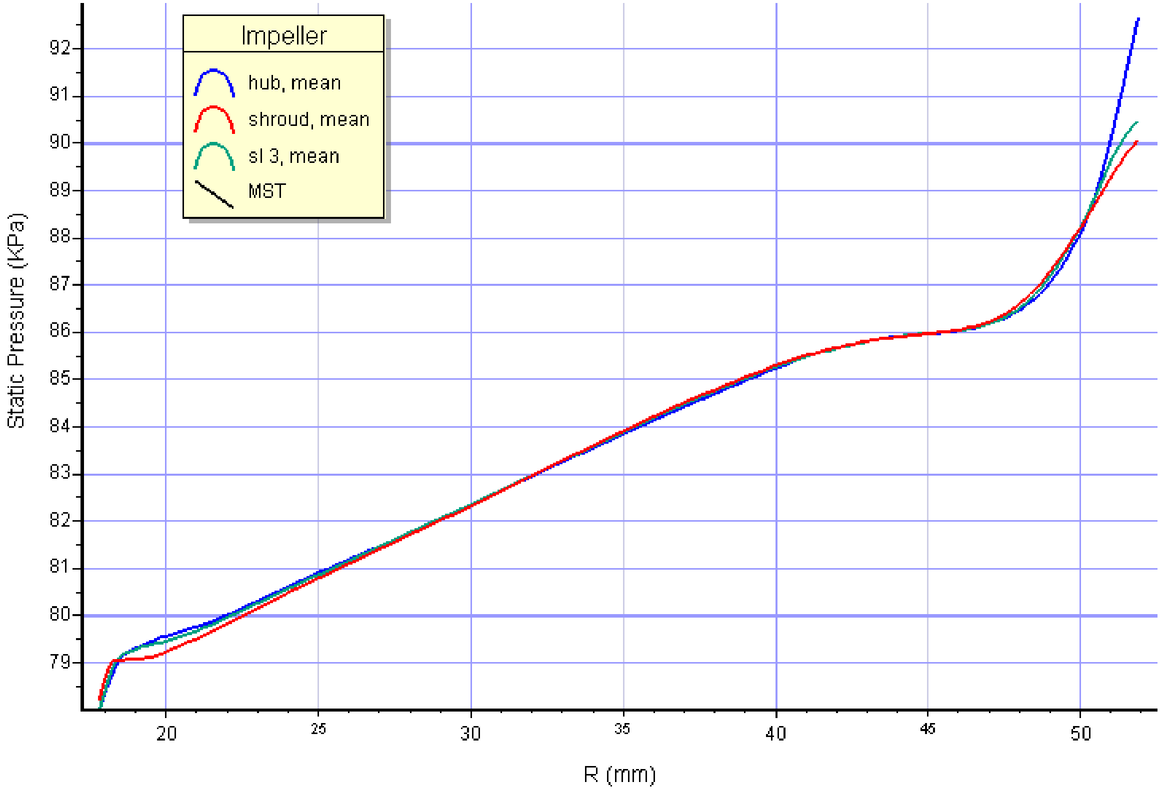


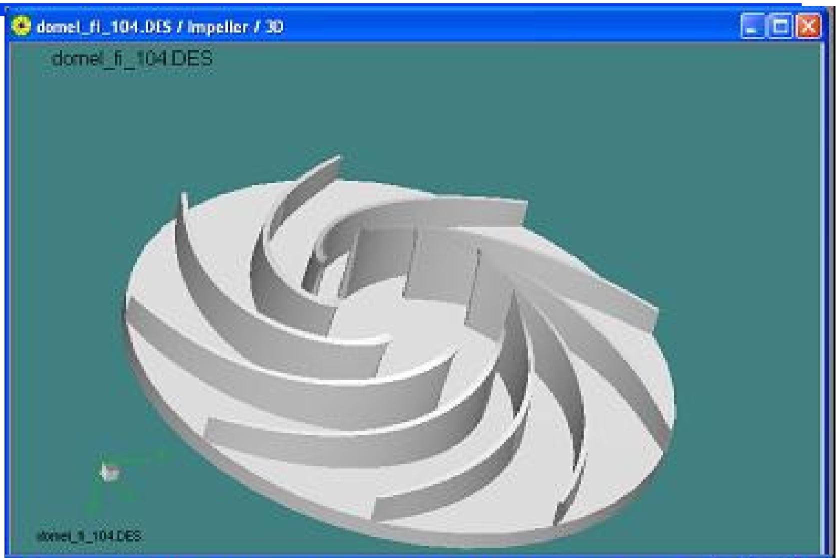
Noise sources

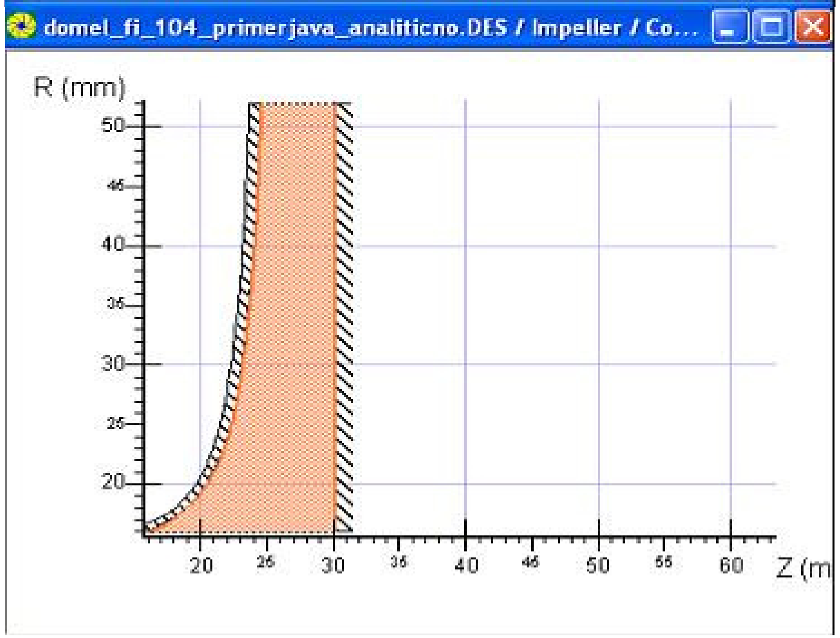
Aero-dynamic noise:

- blade passing frequency noise
  (fan and diffuser blade interaction)
- CFD calculation
- flow visualisation
- acustic camera

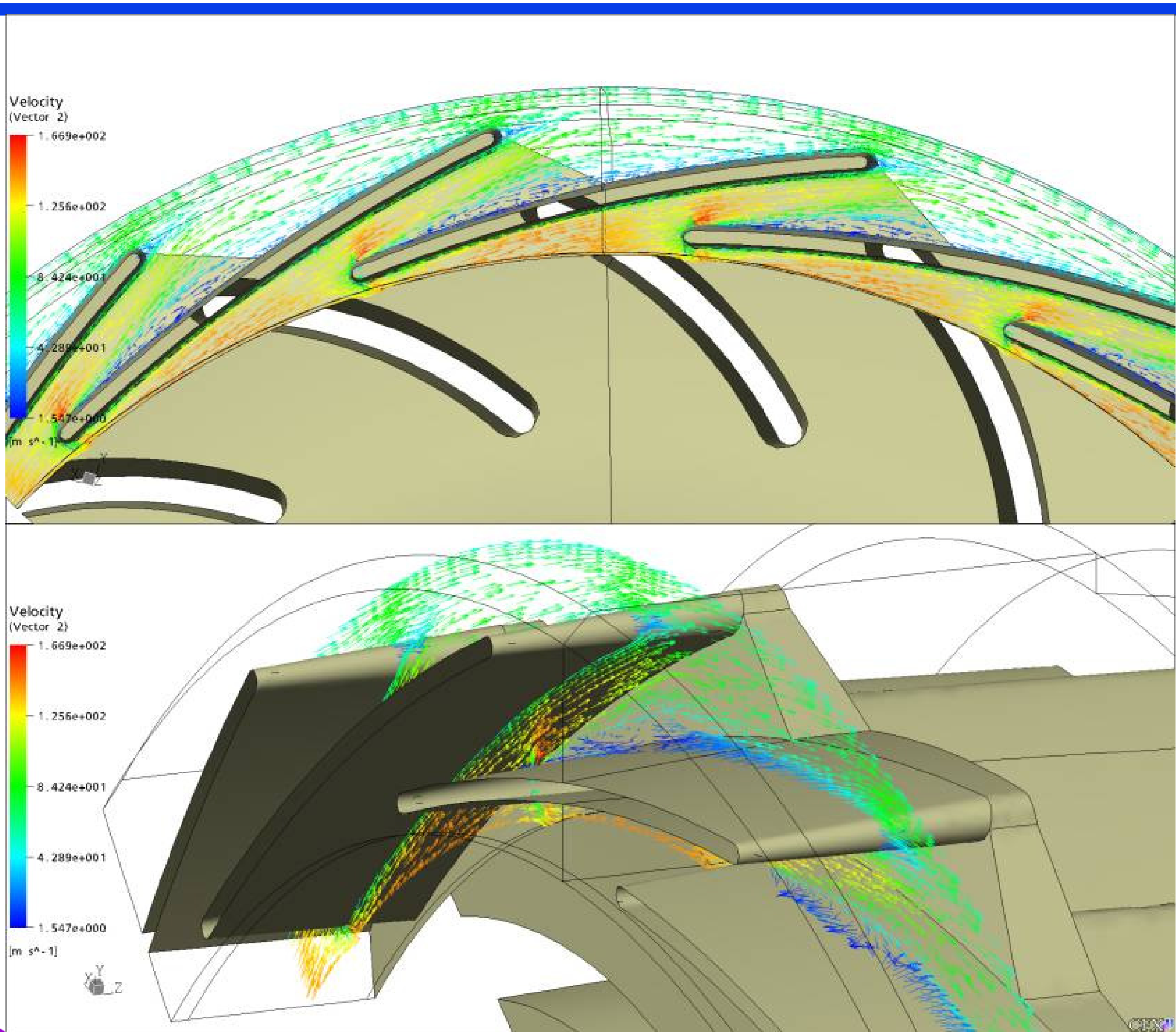
Aerodynamic calculations of impeller and diffuser geometry







CFD analyses of Global motor, CFX software
LECAD, Faculty of Mechanical Engineering Ljubljana



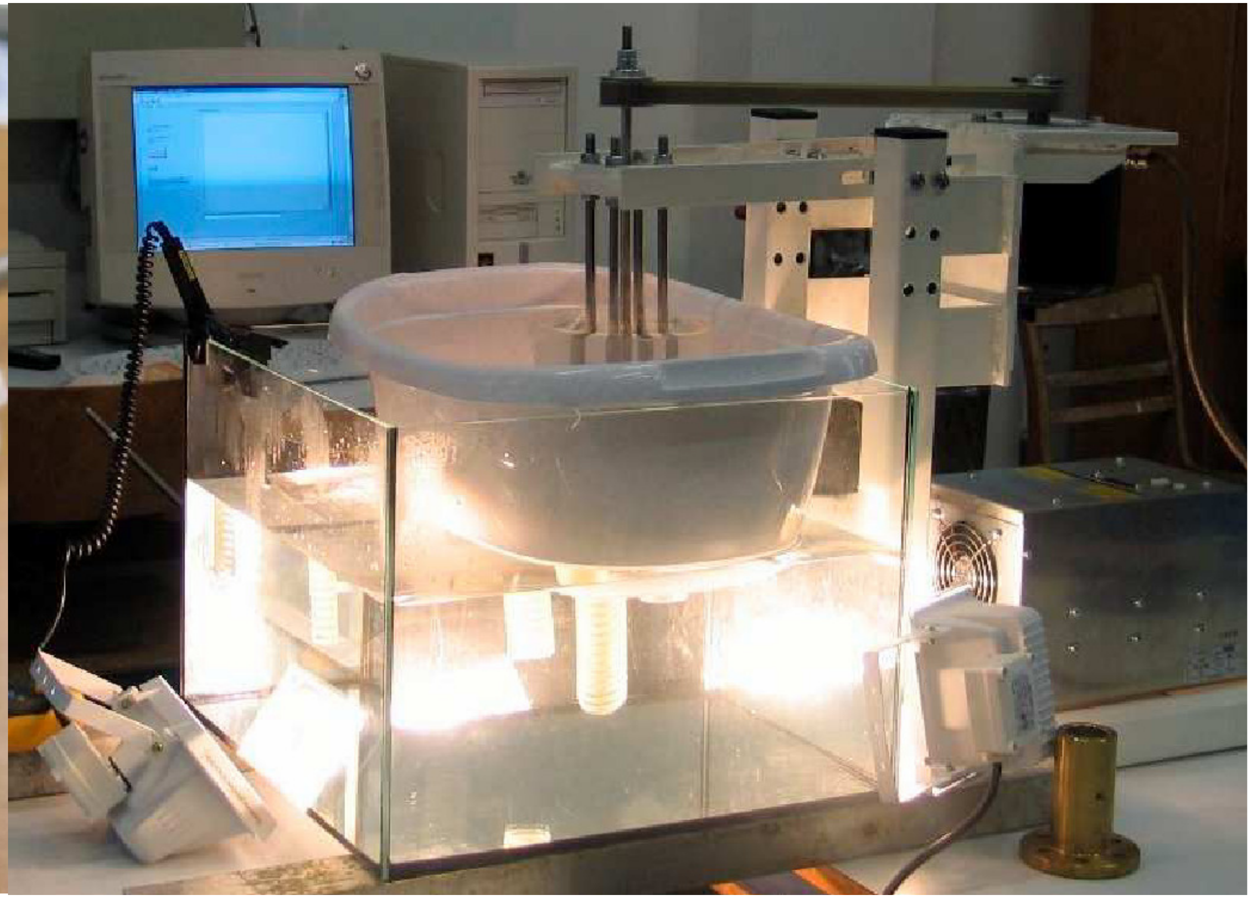
Matjaž Šubelj, LECAD

K-ε turbolence Model

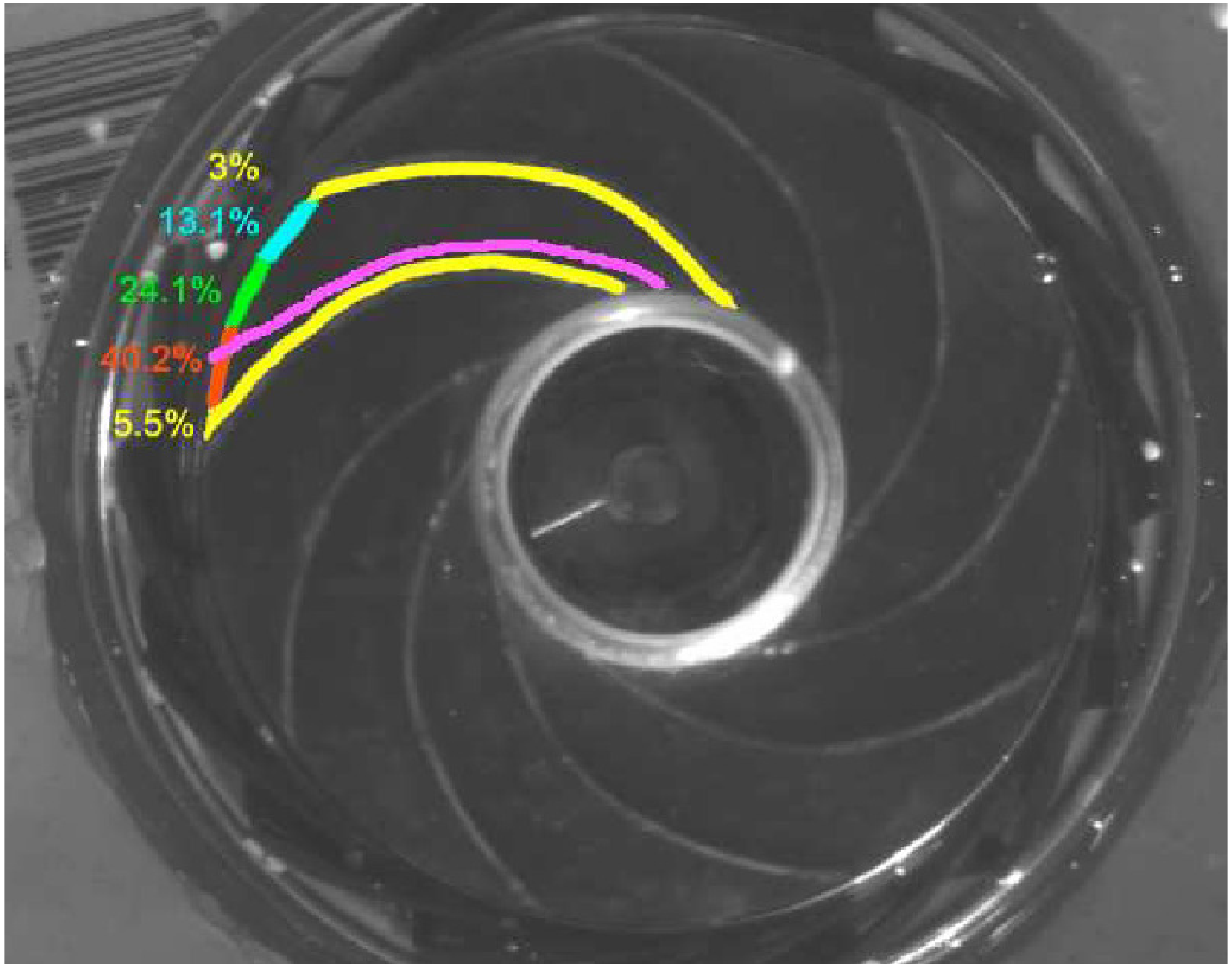
Airflow 29 l/s (orifice fi19)

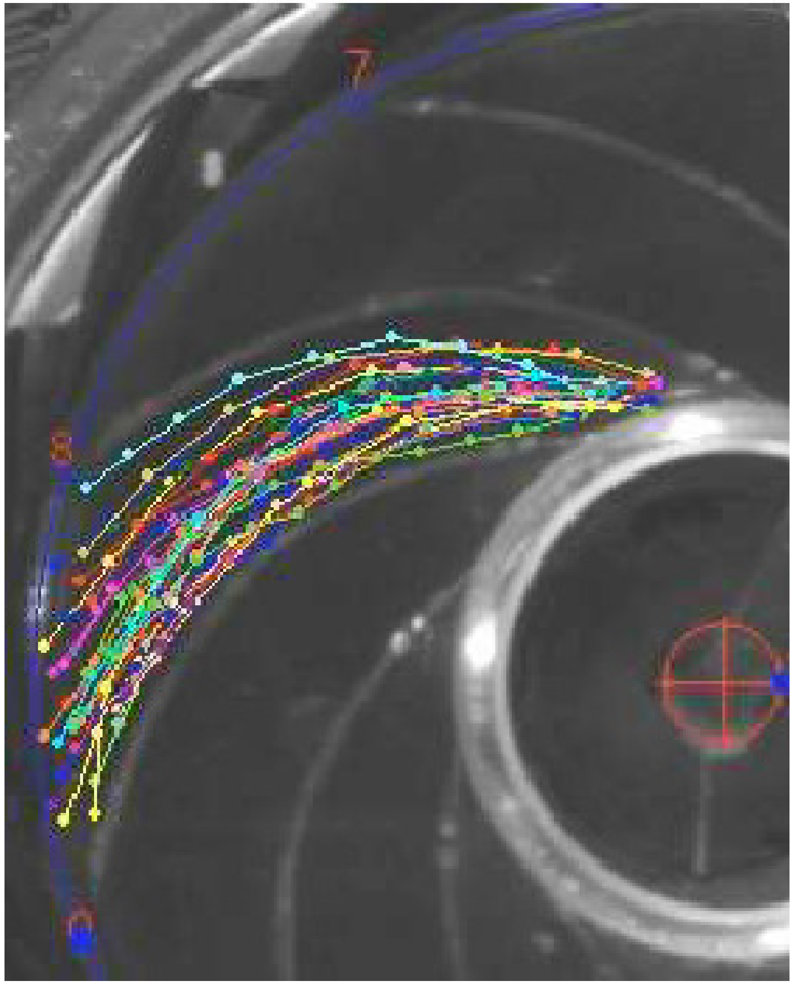
Visualization of the airflow

Janez Rihtarsic, LECAD, FME Ljubljana



Visualization of the airflow
Janez Rihtarsic, LECAD, FME Ljubljana





Results of powder applying

Improved inlet of the motor

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Measurements:
Test-rig for rapid examinations of VCM’s

- on-line monitoring of motors or impellers only
- rapid examination
- high flexibility
- according to several standards

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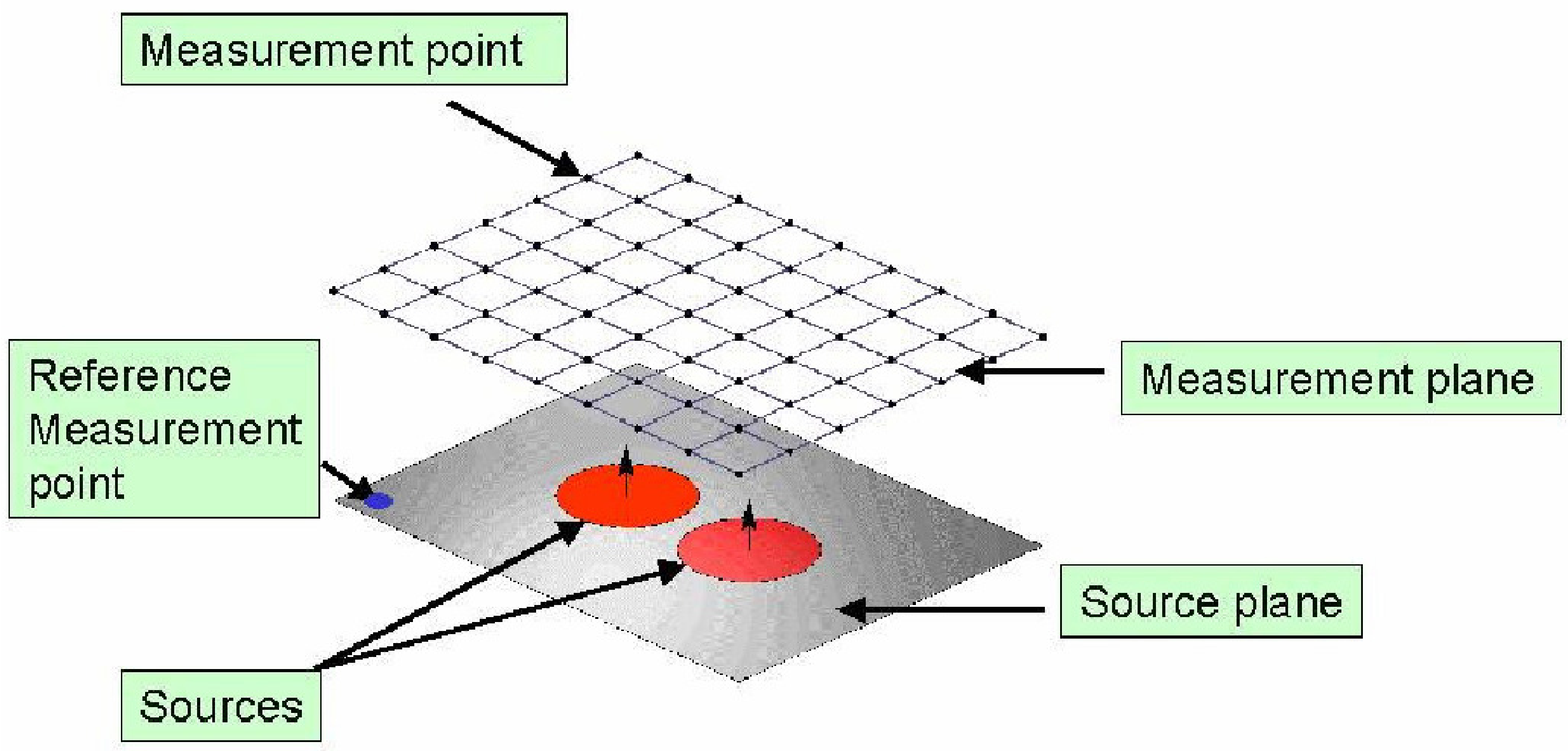
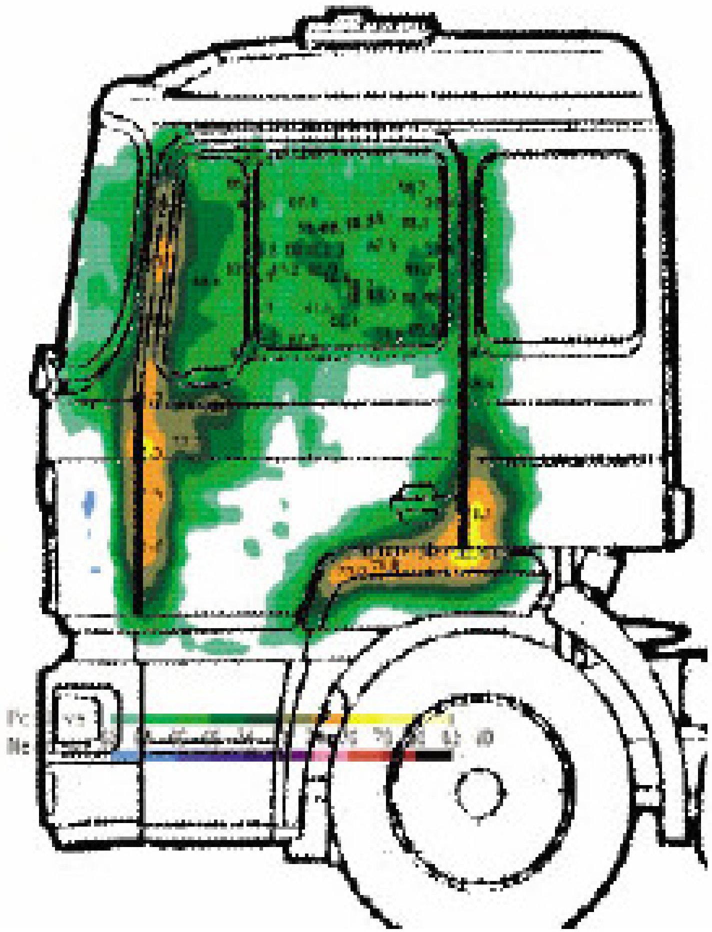
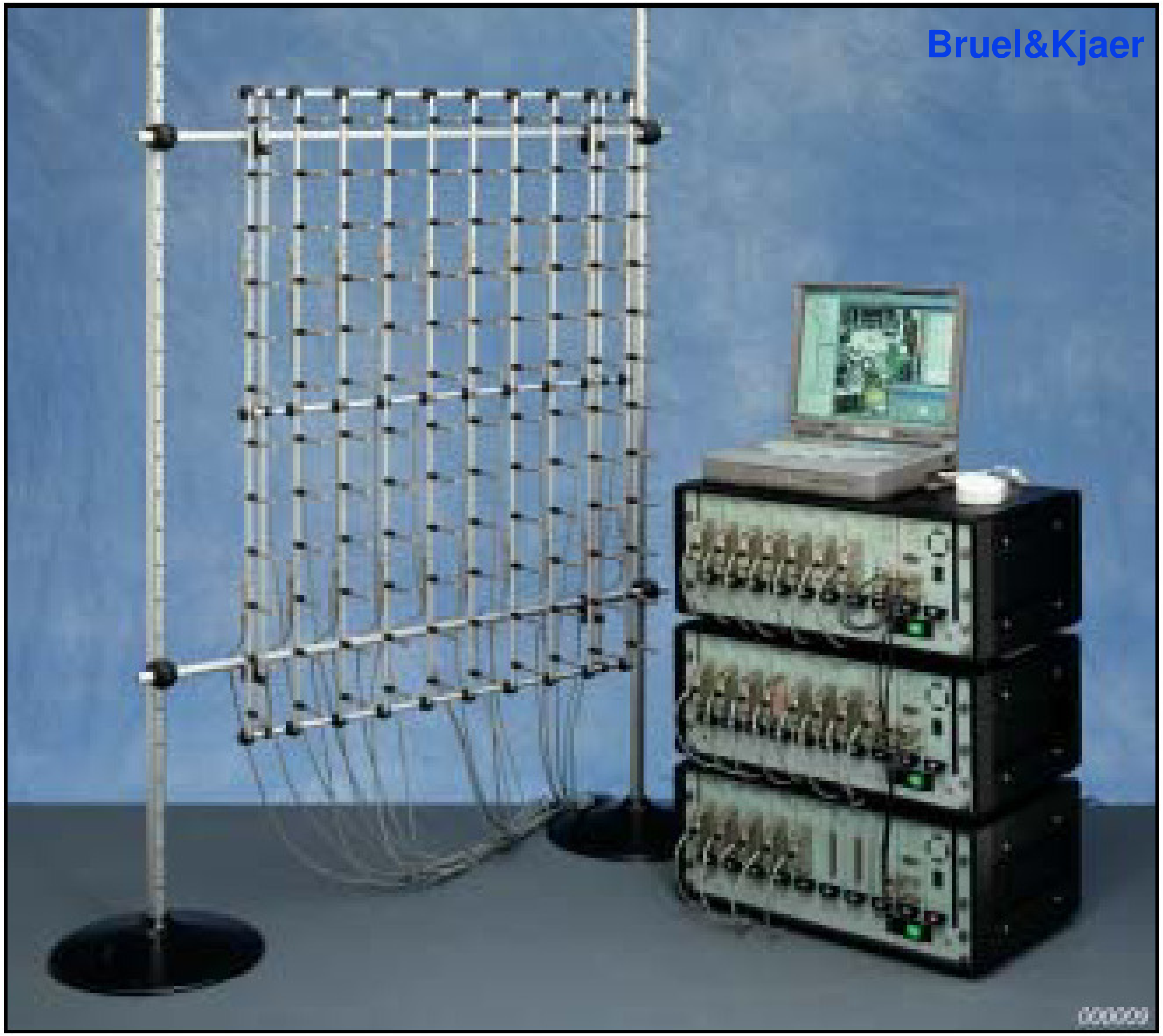
Acoustic camera
principles of measurements (ATC)

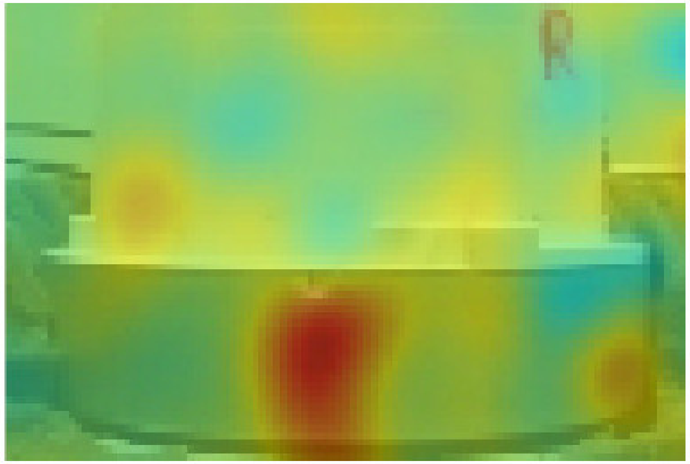


Array of microphones / sound camera

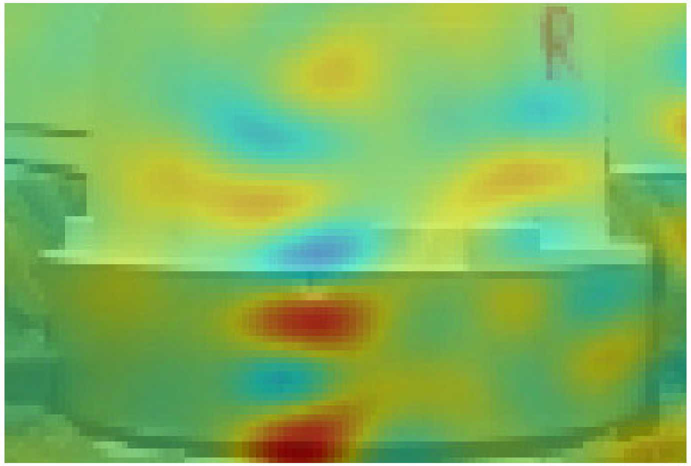




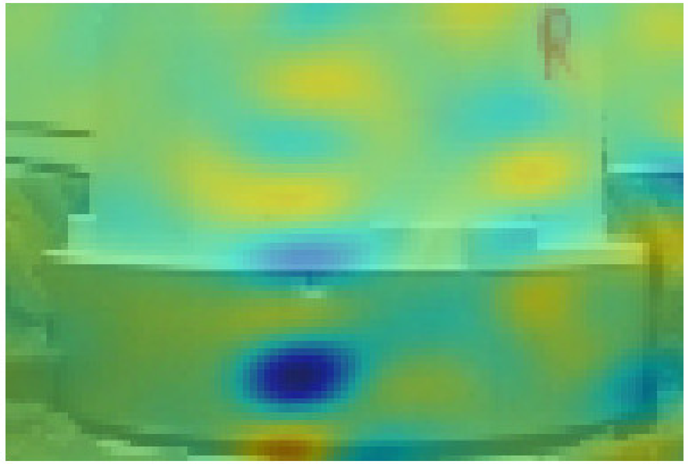
Acoustic camera 3 (Philips, ATC)
left side, blade passing frequency, airflow 20 l/sec



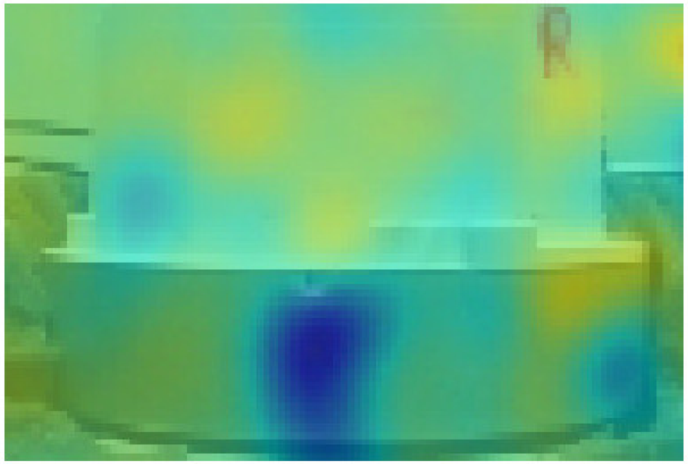
0 degrees



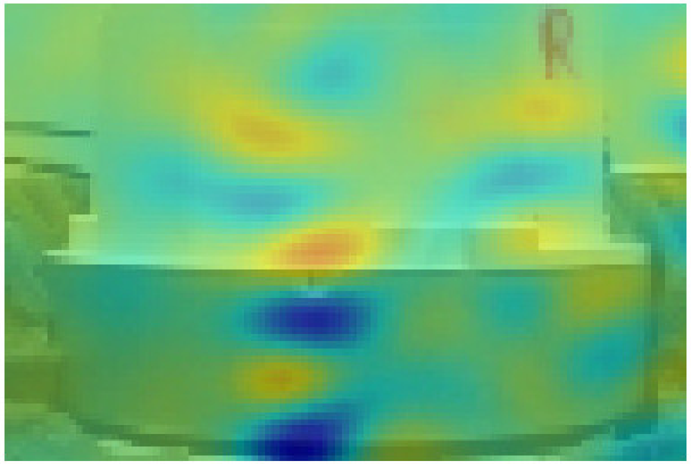
60 degrees



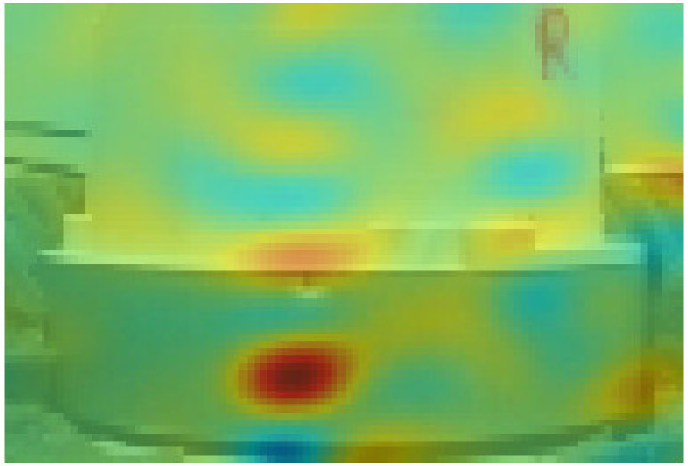
120 degrees



180 degrees



240 degrees



300 degrees

Standing wave experiment setup

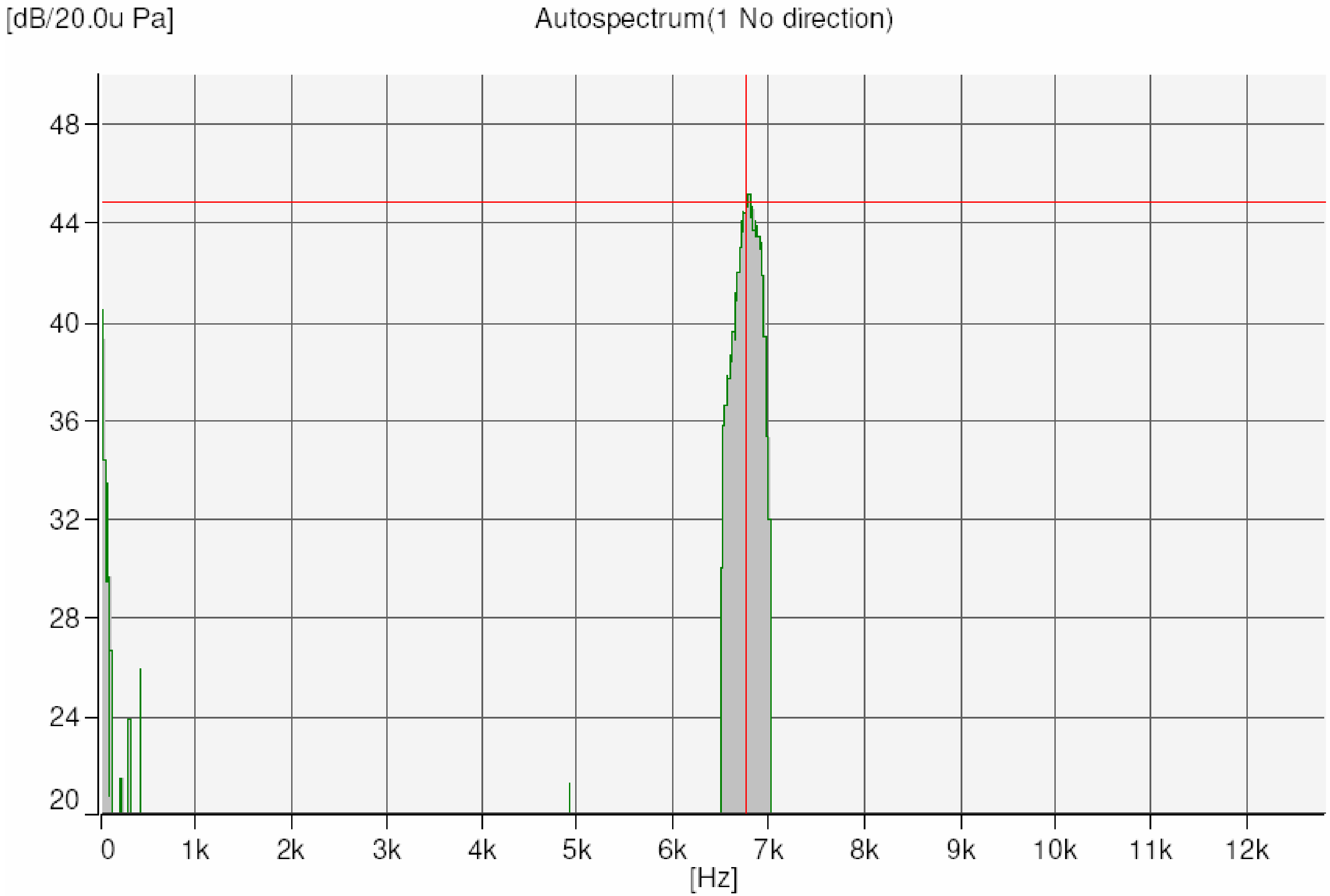
Signal generator (sweep sinus or random broadband noise)

microphone

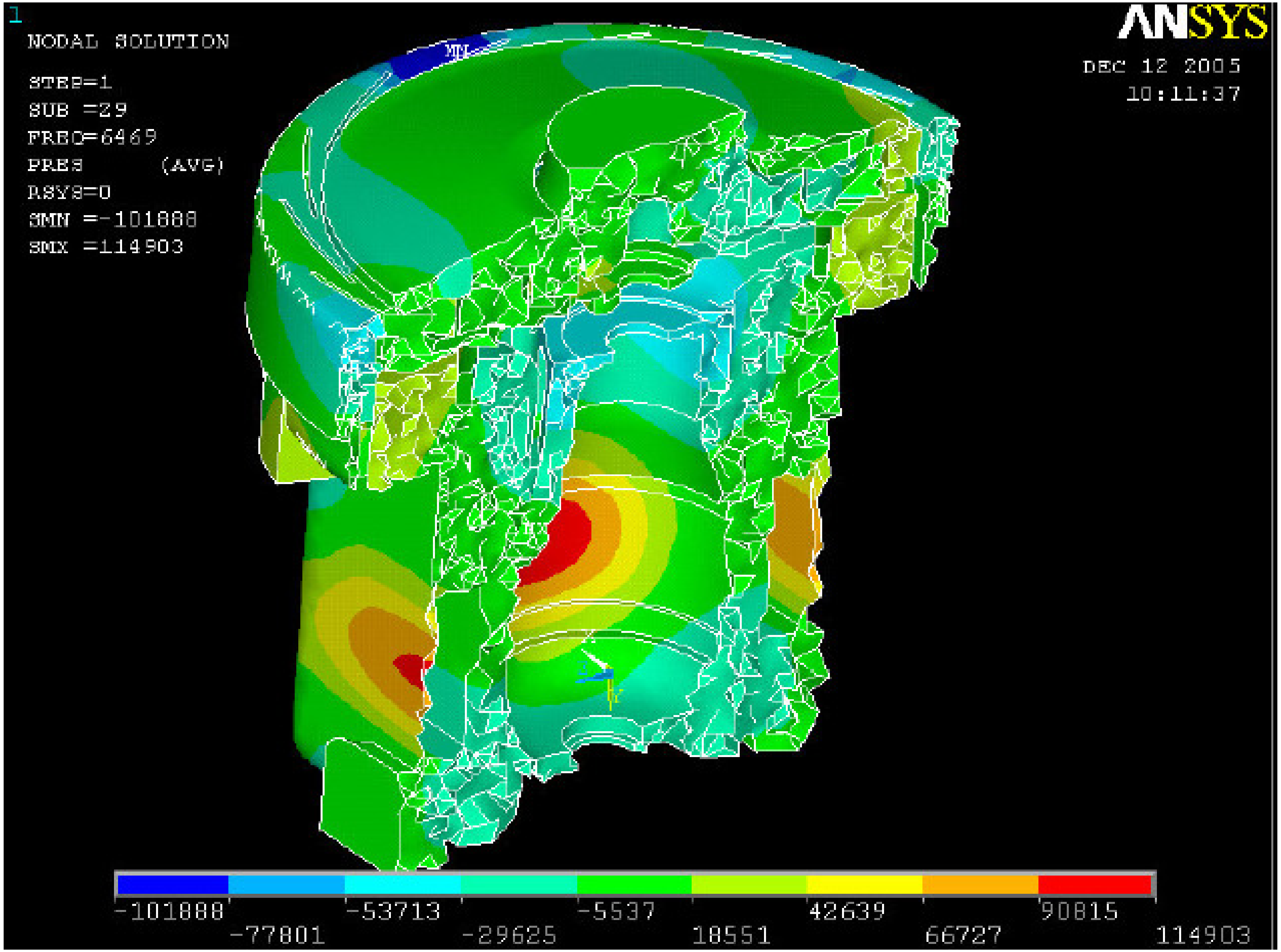
Speaker

Standing wave
Sound measurement

Peak hold measurement (peak overlap)



Standing wave
FEM calculation (ATC, Drachten)



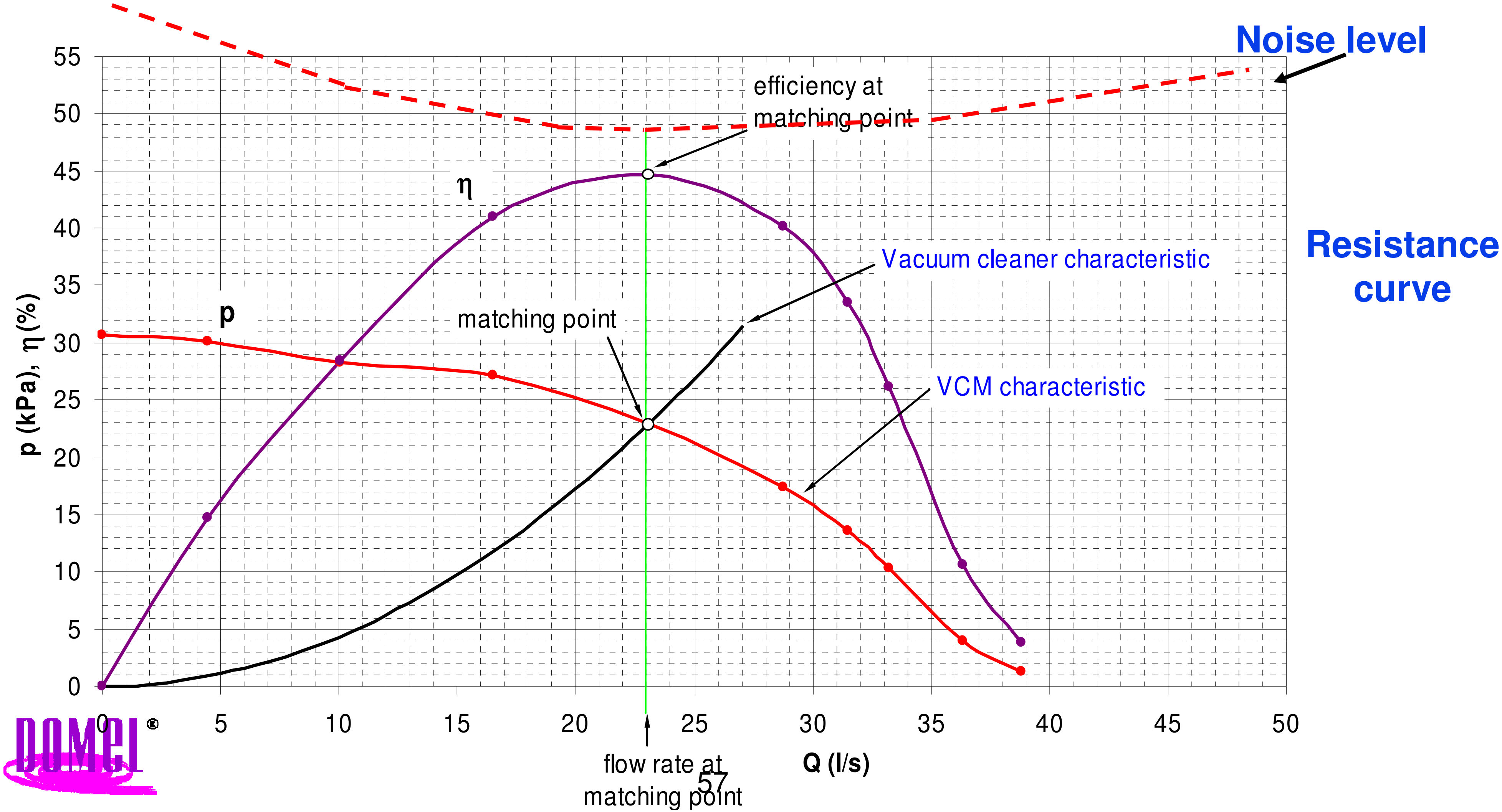
Noise level reduction

Case study:

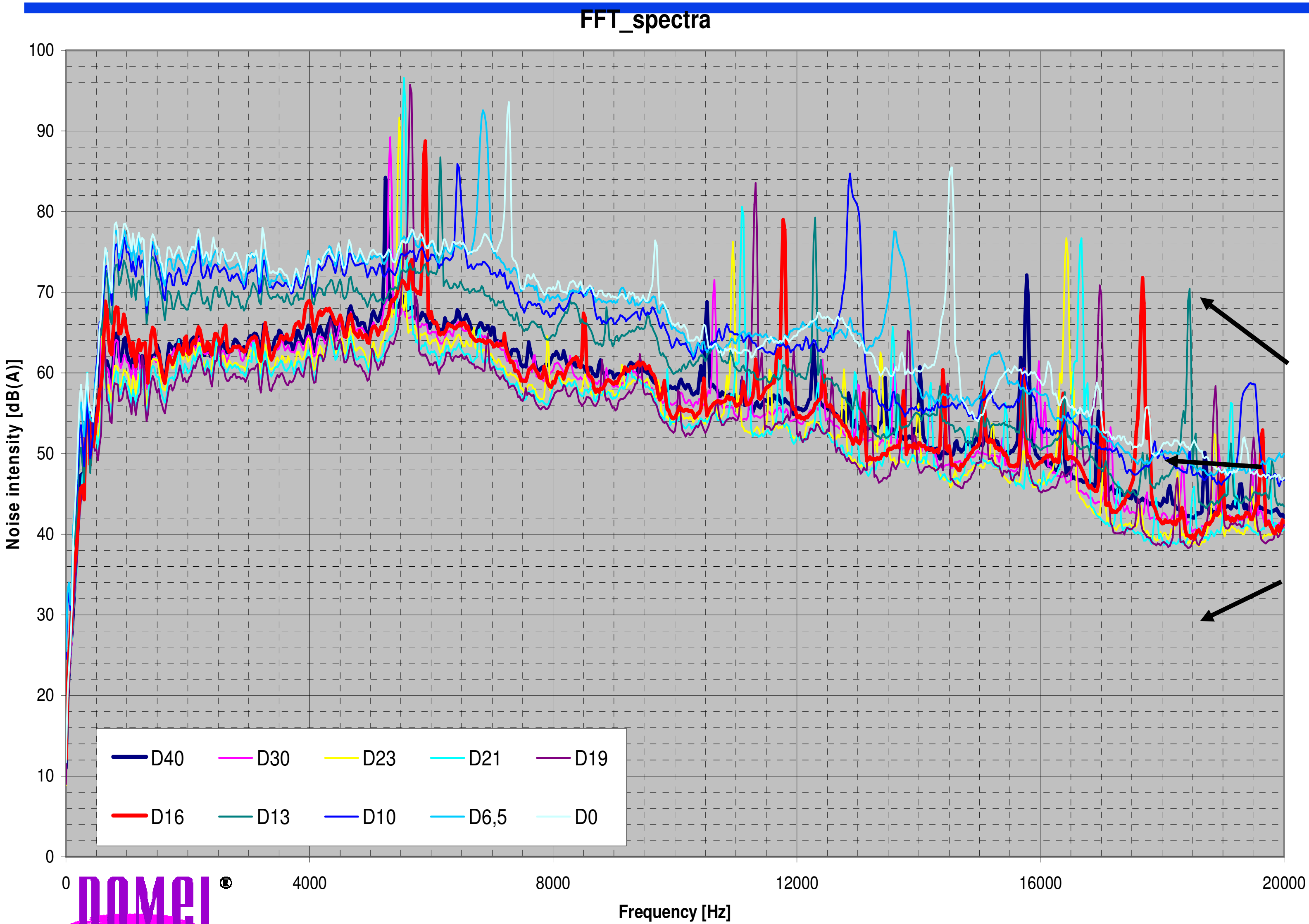
- Good maching between vaccum cleaner and motor
- Impeller design
- Helmholtz resonator

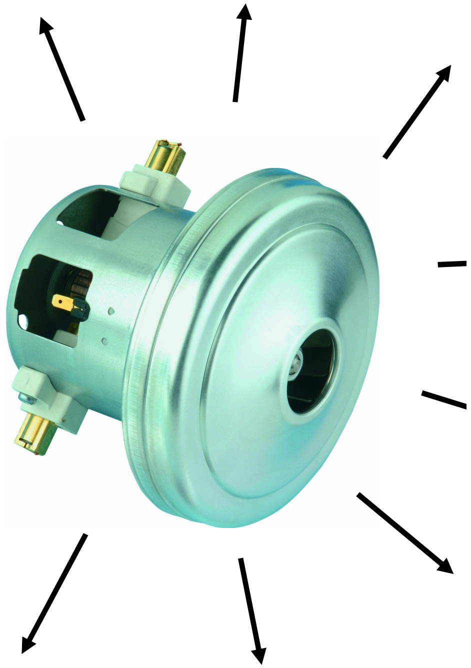
Good Matching between vacuum cleaner and Motor reduces noise level

- **Matching point: pressure produced by the VCM = pressure loss through the vacuum cleaner**

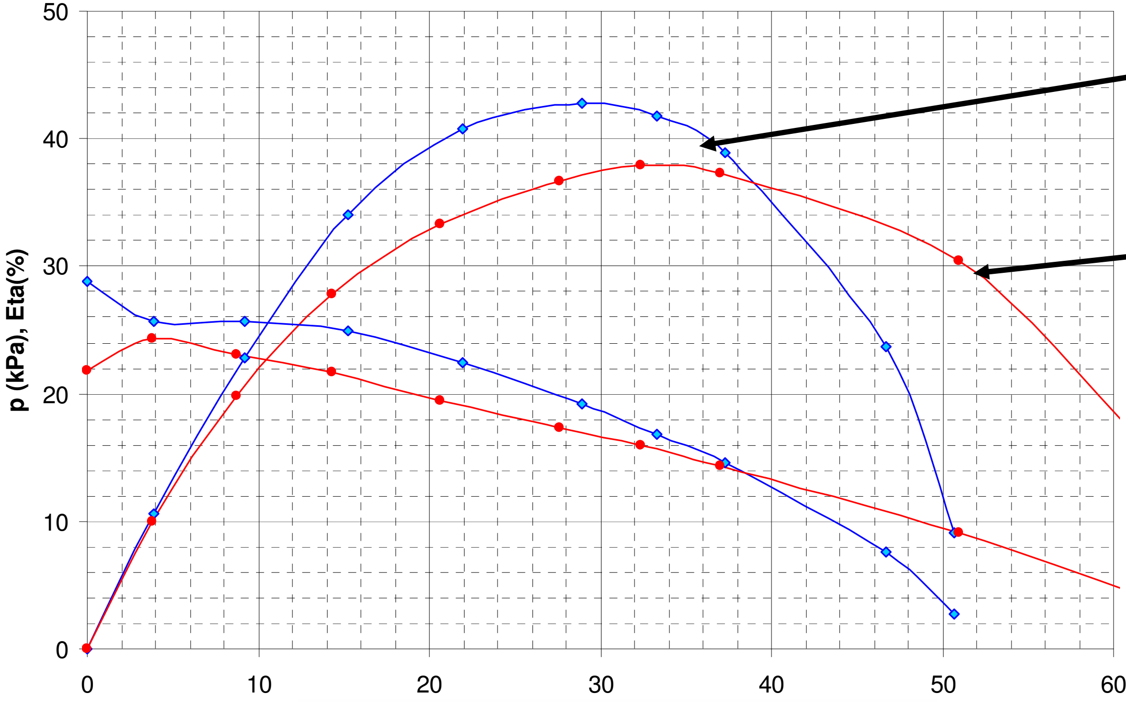


Sound spectrum / total level / annoying peaks





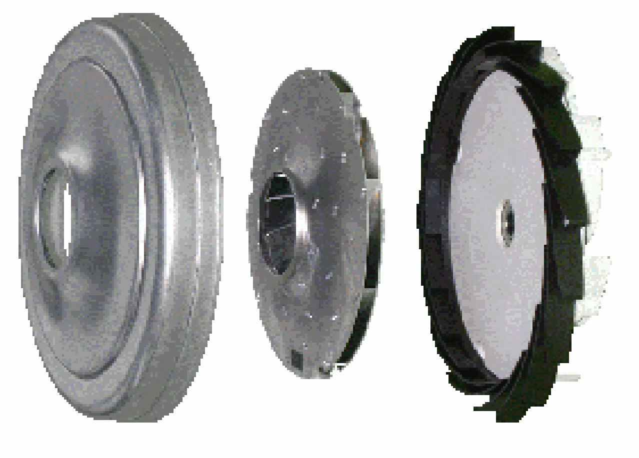
Diffuser removal - 2

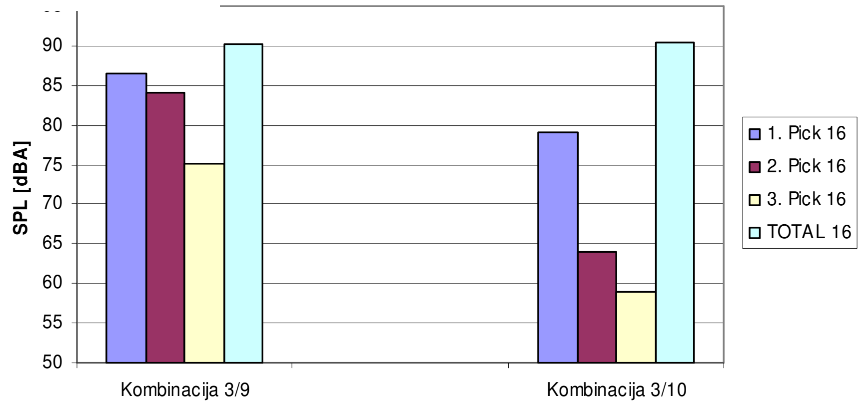


Original VCM with diffuser

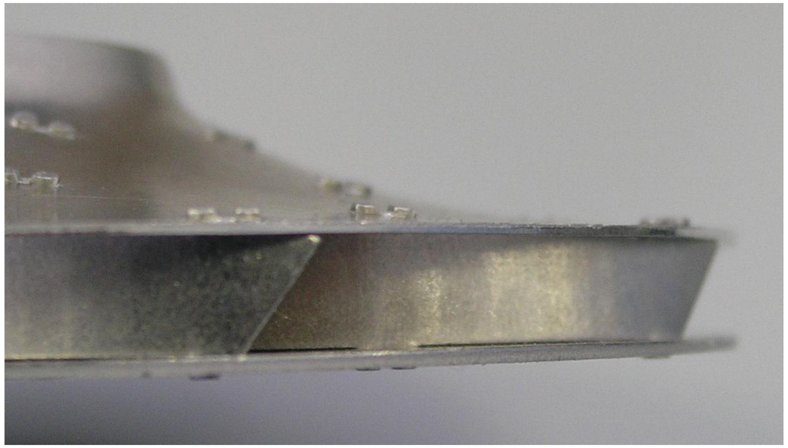
VCM without vaned diffuser

Broadband noise increase

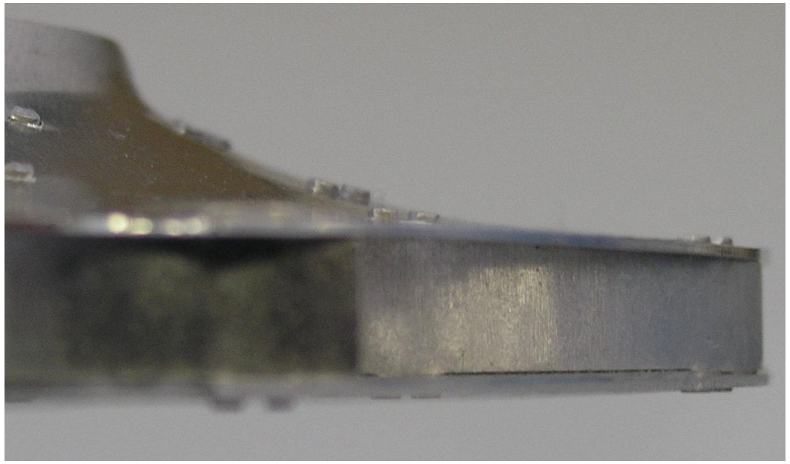




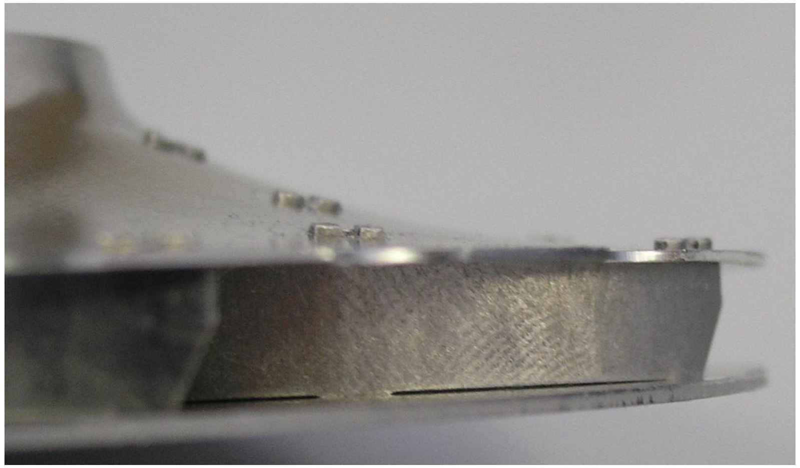
Impeller blade cut (462)



Inclination down



Standard blade



Step + Inclination down

Improved performance at low airflow with blade cut **Inclination down**

Small influence on noise

Impeller geometry variation
Taguchi experiment

1 – shorter blade (cut)
A – 0.0 mm (current)
B – 2.0 mm
C – 4.0 mm

2 – impeller exit width
A – 6.3 mm - (current impeller fi 90)
B – 5.7 mm (input width (6.3 mm))
C – 5.0 mm ((input width (6.3 mm))

3 – shape of exit blade
A – blade cut with inclination 30 degrees
B – streight cut (current)

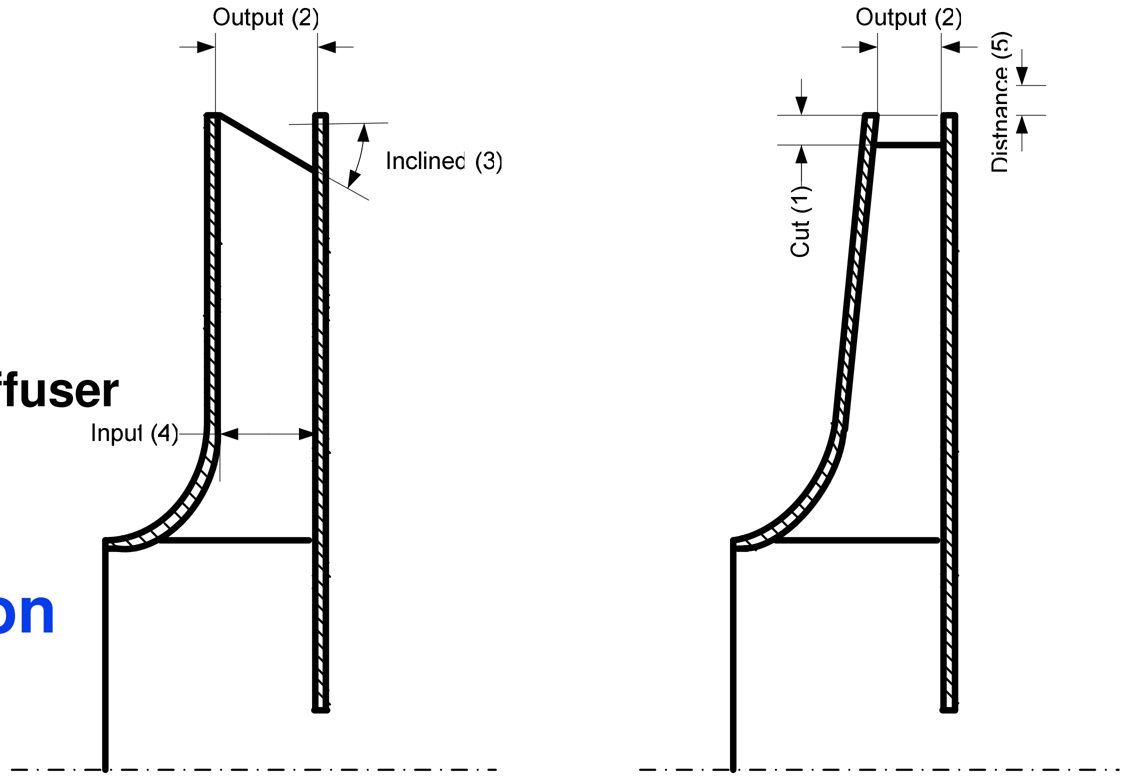
4 – impeller input width
A – 6.3 mm - (current impeller fi 90)
B – 8.0 mm

5 – distance between impeller and diffuser
A – 1 mm - (current impeller fi 90)
B – 0.5 mm (bigger impeller diameter)

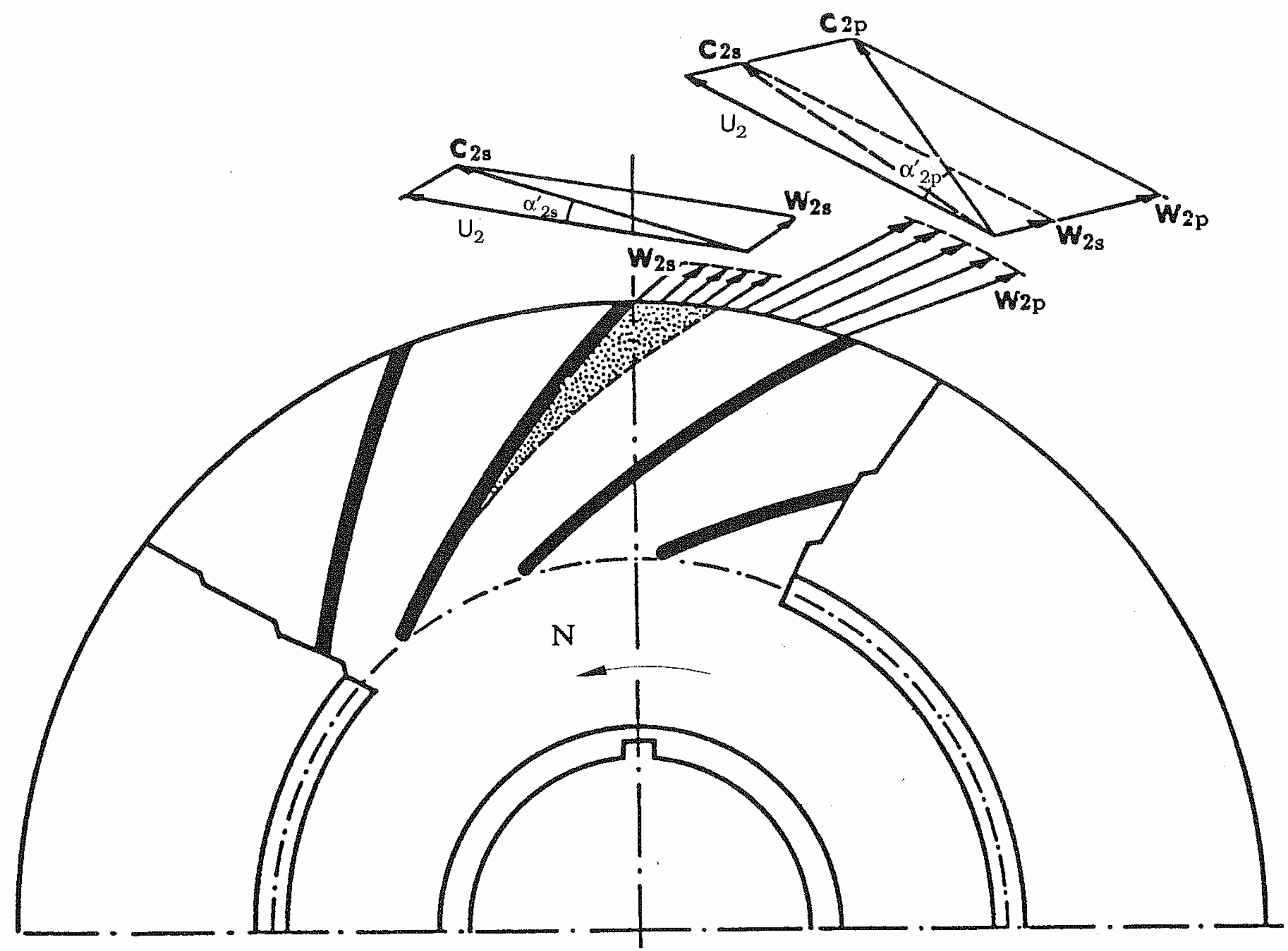
Result: 3 dB noise reduction

- Taguchi system

Prepared on the base of experiences and literature review

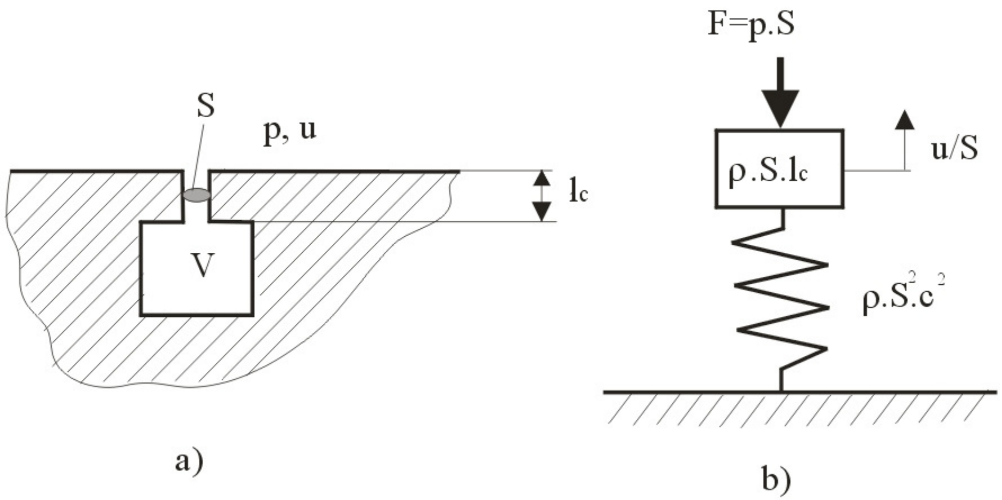


Primary and secondary flow: reason for Blade Passing Frequency



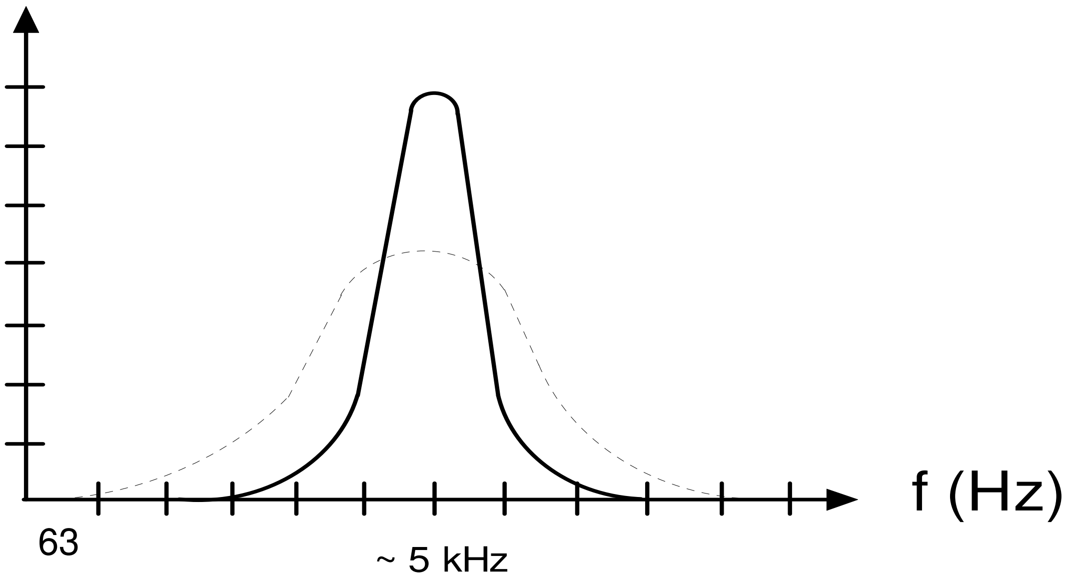
Helmholtz Resonator – technical principle

$$f\ [Hz] = c / (2\pi) \sqrt{(S / l V)}$$

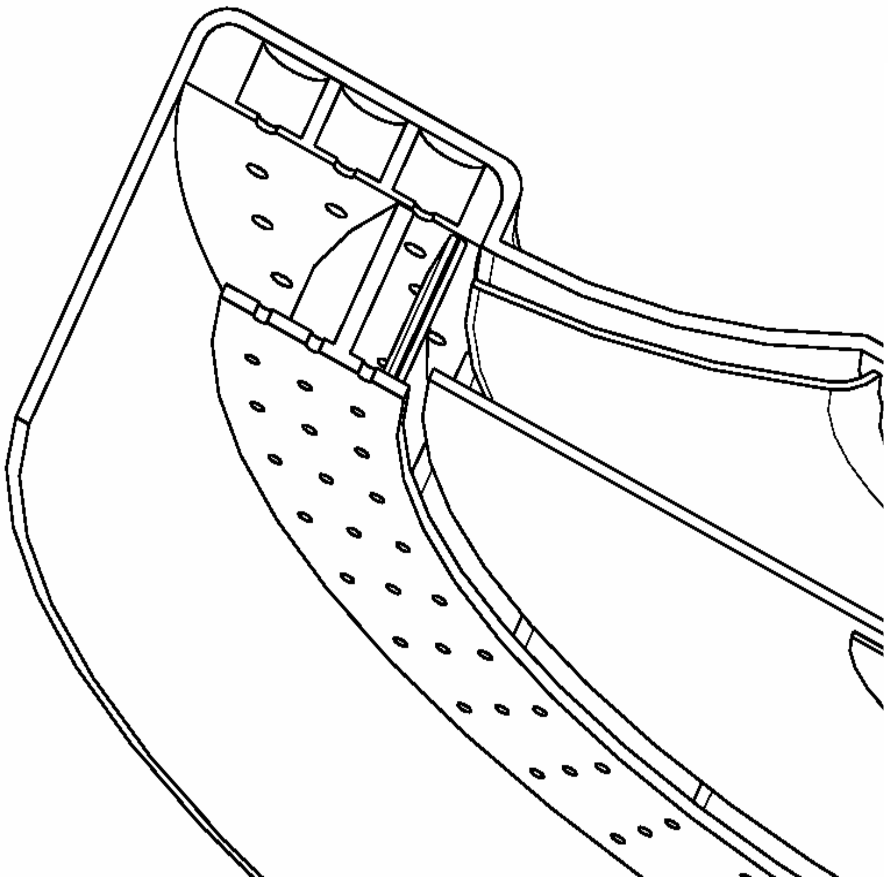


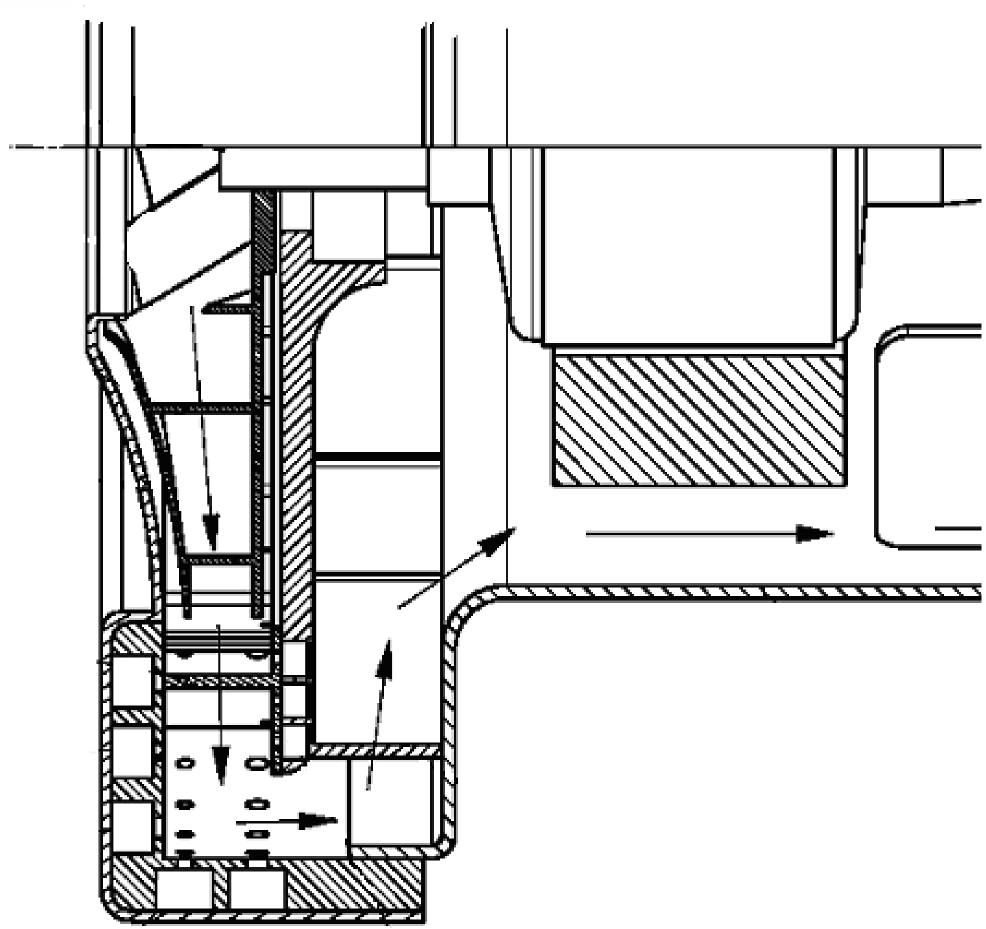
f [Hz] - resonator frequency
c [m/s] – sound speed
S [m^2] - size of orifice
l [m] - neck size
V [m^3] – volume of resonator

Resonator absorbs energy at resonating frequency



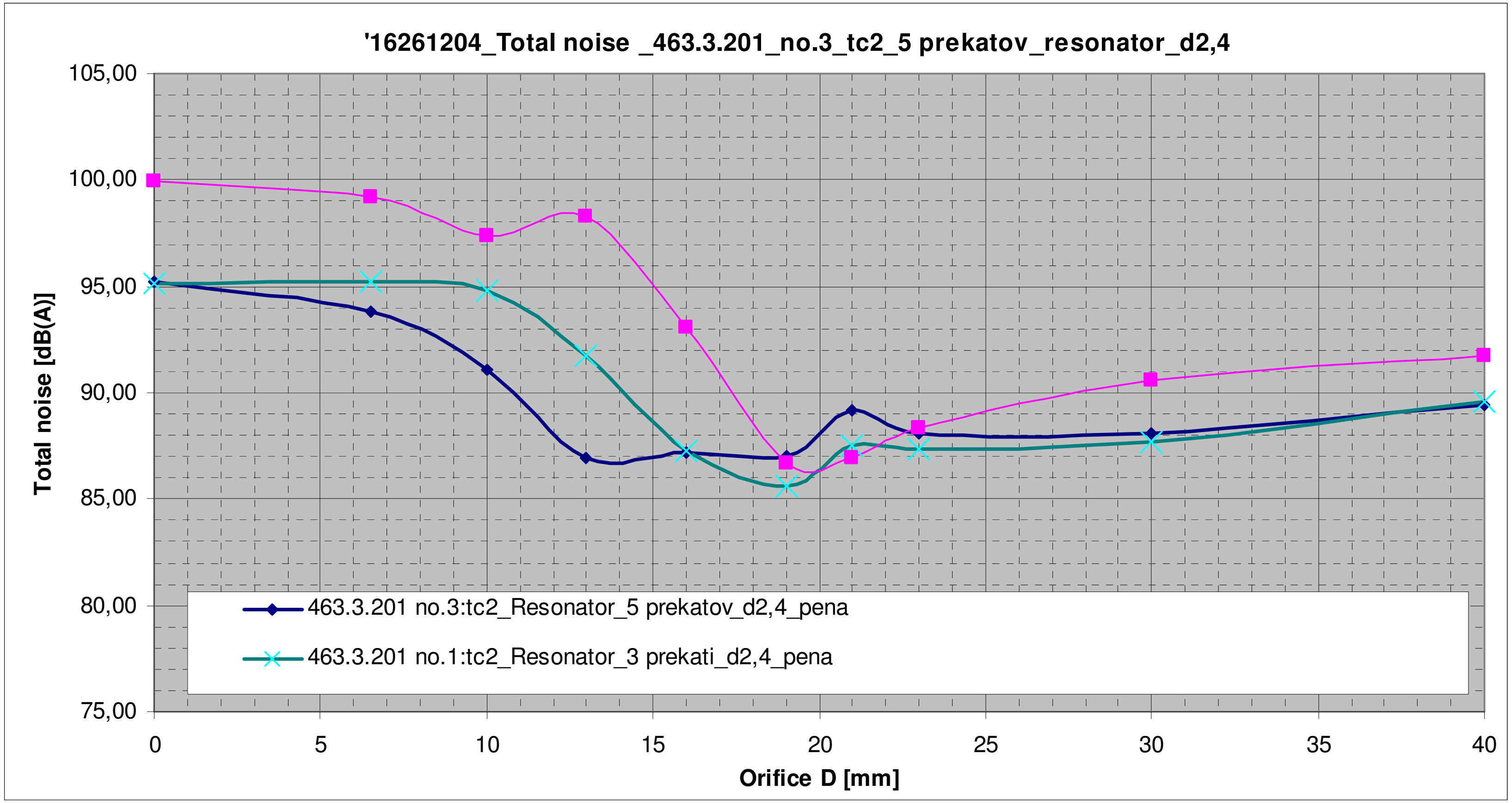
Resonator – implementation detail





Resonator and total noise level

Pink line -VCM without resonator



Noise control

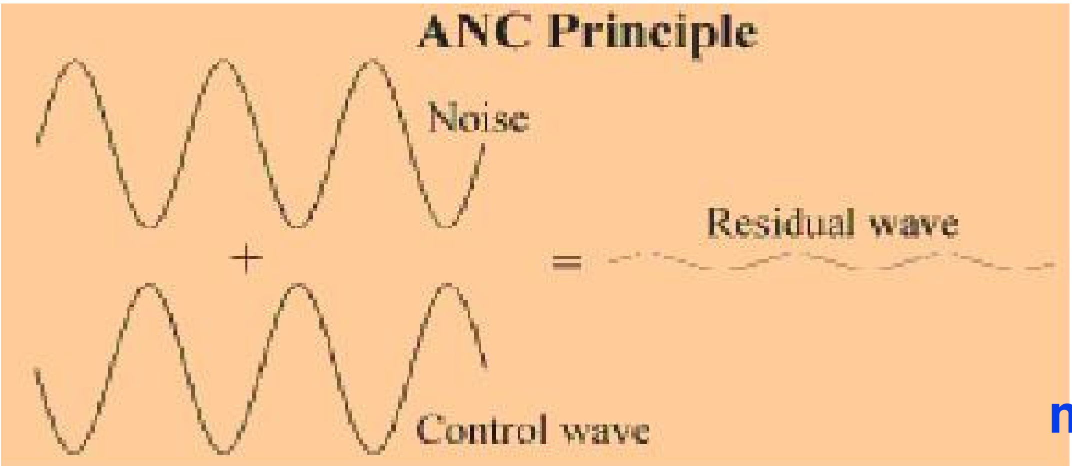
Active noise control

Active noise control I

- Idea comes from 1930's, more development in 1950's
- several commercial application in the last 15 years (from simple headphone (cancel low-frequency noise) , vehicle cabins, military applications in helicopter)

Physical principle:

- Control wave have the same amplitude and shifted phase therefore is the noise eliminated or significantly reduced.
- active noise cancellation (ANC) and
- active structural-acoustic control (ASAC)



Experiment of ANC with two microphones from Virginia university

Active noise control II

- Active noise control is more efficient at lower frequencies (< 1000 Hz)
- Passive damping is more efficient at higher frequencies (> 1000 Hz)

LIMITATIONS:

Costs of the advanced equipment
(microphone, speaker, feedback control system)

Efficiency depend on many circumstances:

- ANC works best for sound fields that are spatially simple

Controlling a spatially complicated sound field is beyond today's techn.

It is easier to control noise in an enclosed space

- Broadband noise is harder to control than tonal noise
- ANC works best when the wavelength is long compared to the dimensions of its surroundings (500 Hz => 0.68 m)

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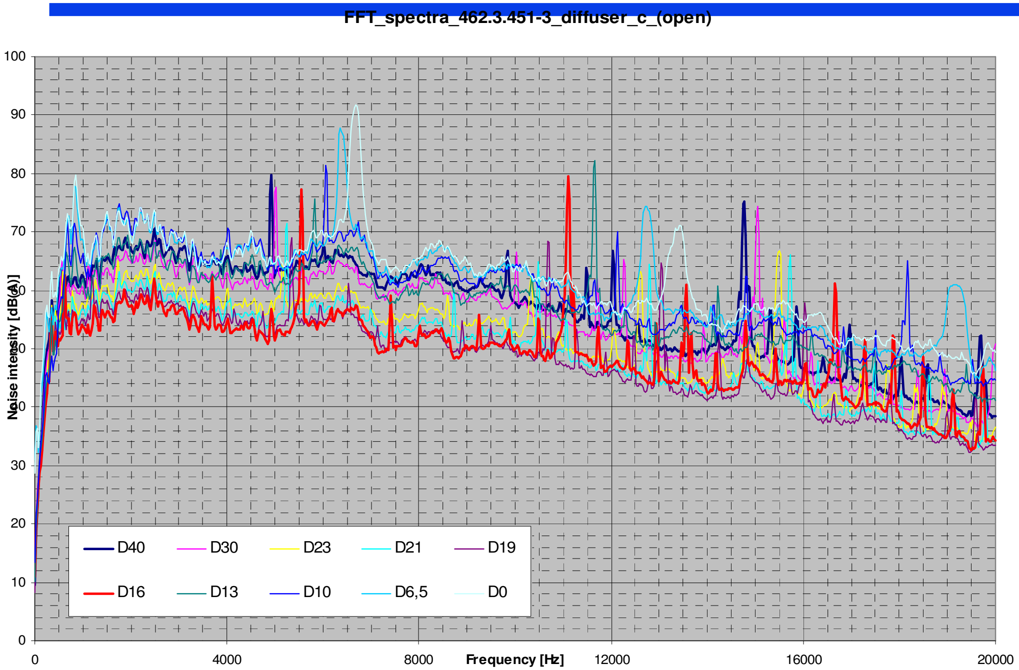
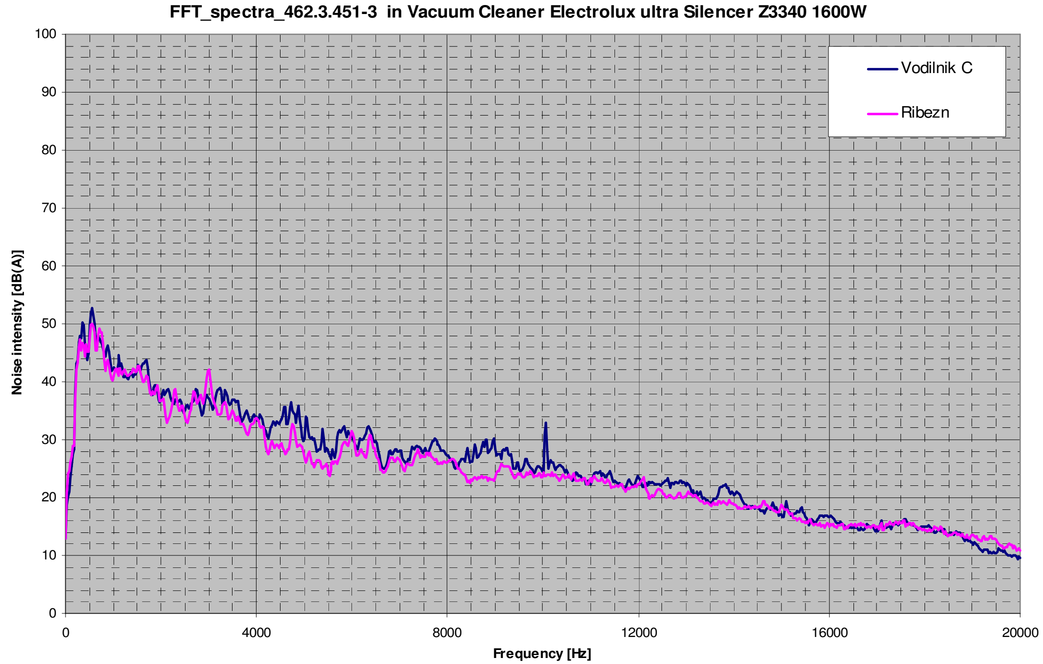
Application of ANC and EC motors





- **Running project: application of ANC to EC motors**

Active noise control is more efficient at lower frequencies (< 1000 Hz)
=> this is the speed of rotation and dominated peak

Use of ANC for reduction of rotating speed frequency at 400 Hz
ANC will be applied inside the motor or inside the appliance

Conclusions

Noise reduction is possible through:

- **Integrated approach**
- **Understanding physical background of the noise sources**
- **Advanced numerical and measurement methods**
- **Innovative solutions**

- **Close cooperation between motor and appliance manufacturer**

information: www.domel.com

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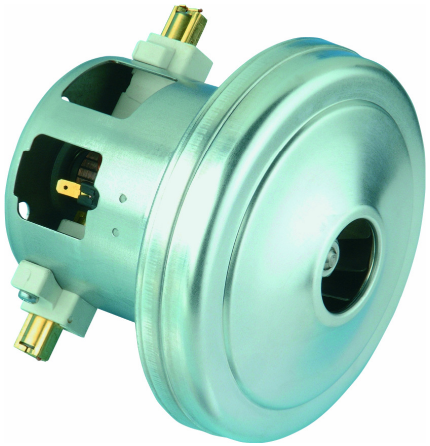
http://www.burger.si/SLOIndex.htm

http://www.burger.si/SLOIndex.htm



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