Noise from large wind turbines (with focus on low frequencies)

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Overview of presentation

- Human perception of low-frequency noise and infrasound.
- Analysis of low-frequency noise and infrasound from wind turbines.
- Conclusions.

Human perception of low-frequency noise and infrasound

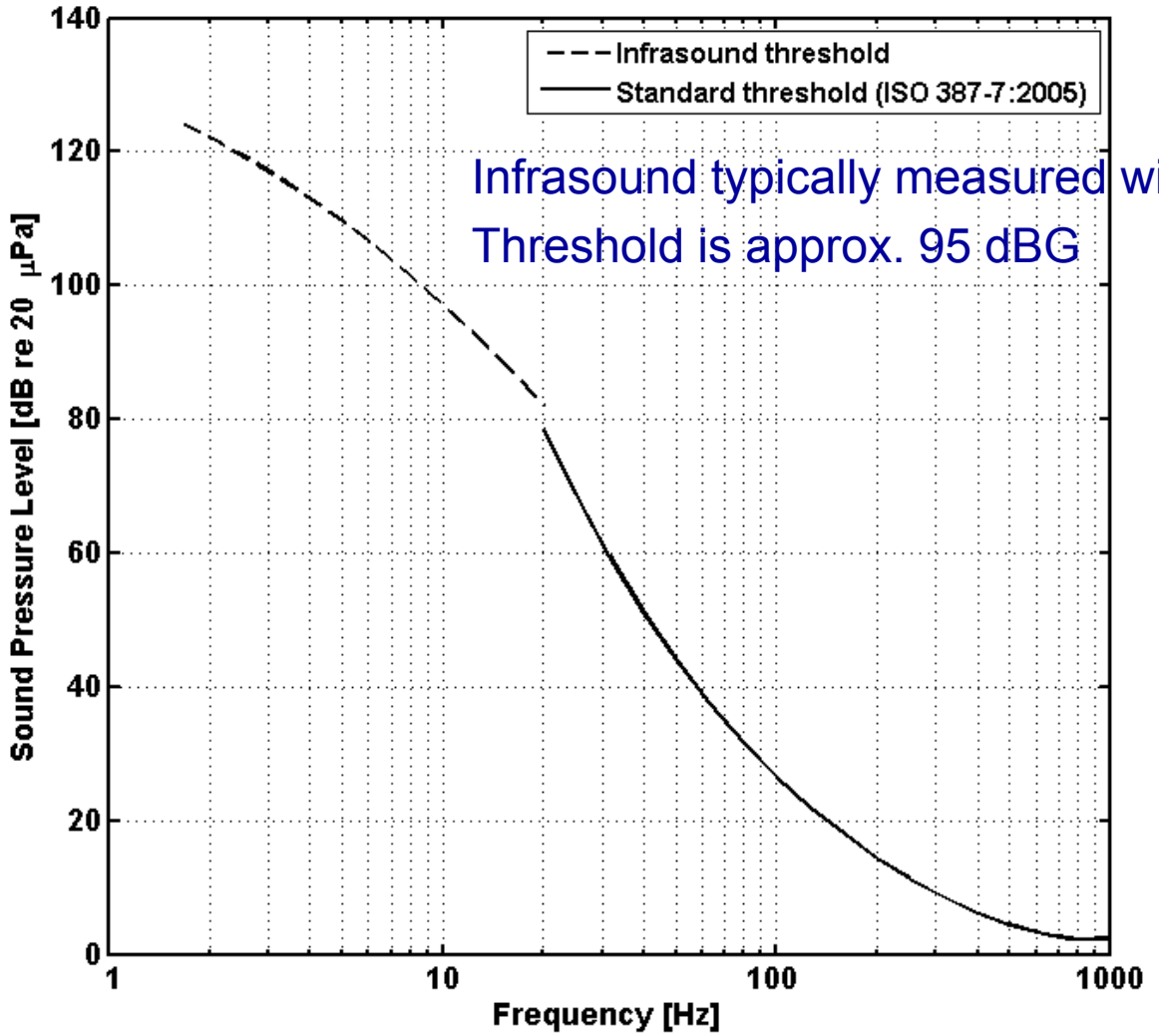
What is low-frequency sound

- Low-frequency sound: frequencies below 200 Hz
- Infrasound: frequencies below 20 Hz.
- Typical sources of low-frequency sound:
  - Engines
  - Compressors
  - Ventilation systems

  ...
  - Wind
  - Ocean
  - Earthquakes

  ...

General hearing threshold

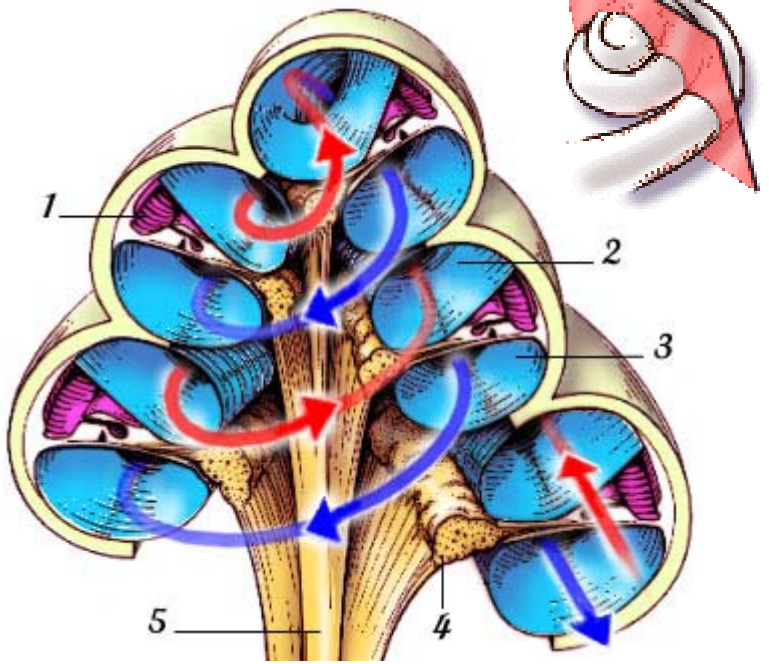


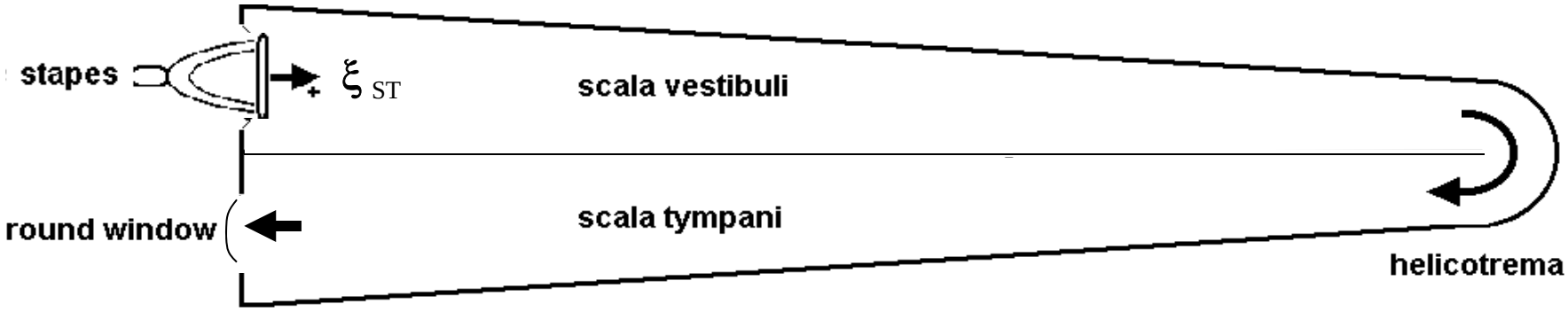
Infrasound typically measured with G-weighting

Threshold is approx. 95 dBG

Basilar membrane at LF

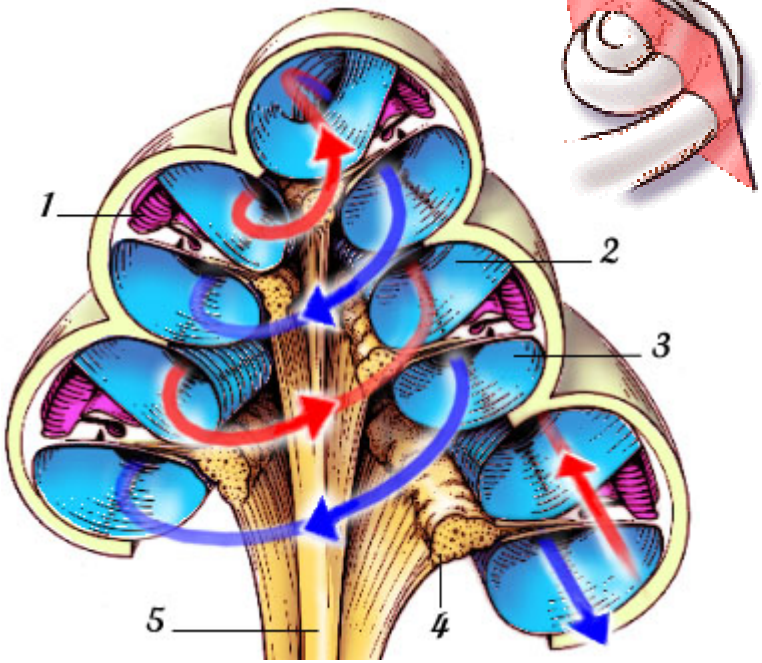
For static pressure (f = 0 Hz)

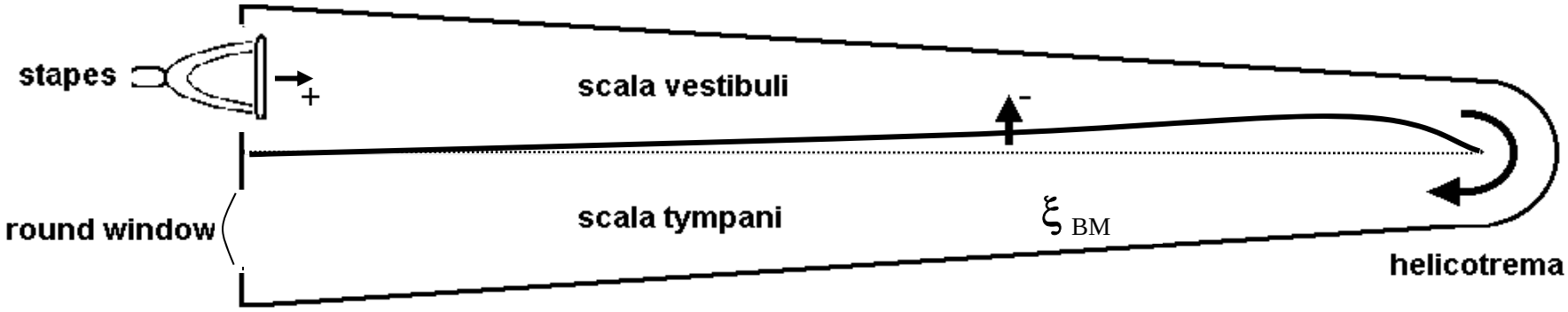




Basilar membrane at LF

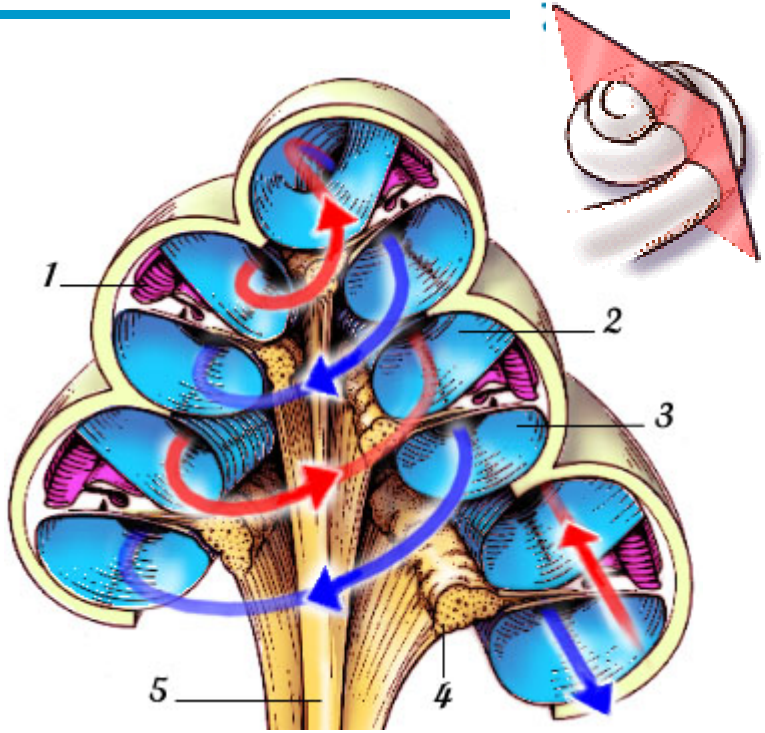
For lowest frequencies ($0 < f < f_B$):

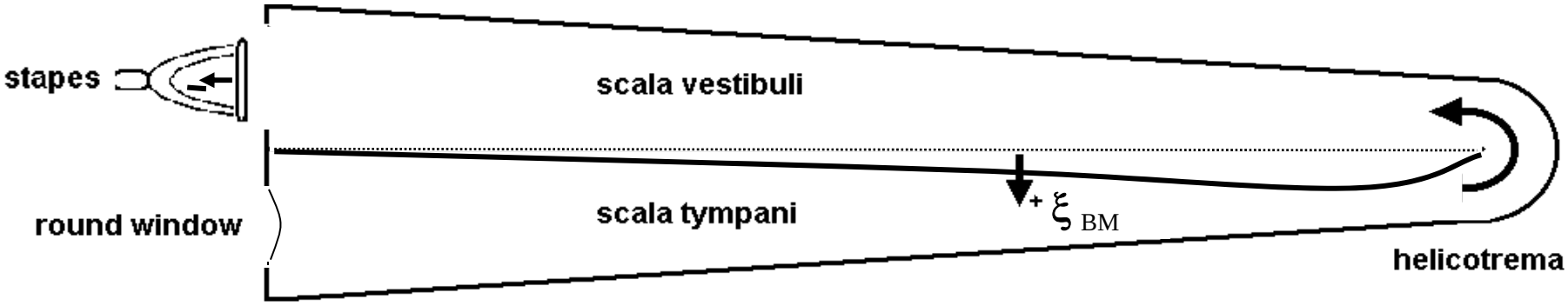




Basilar membrane at LF

For lowest frequencies ($0 < f < f_B$):

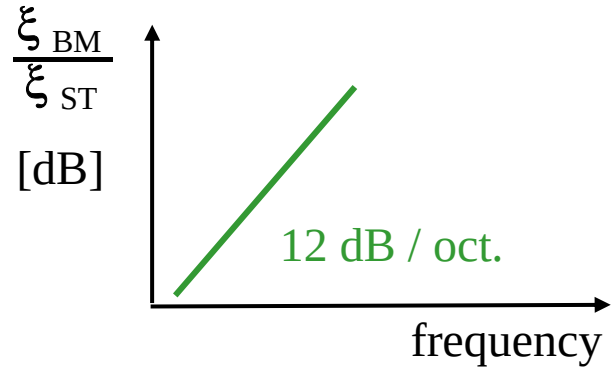


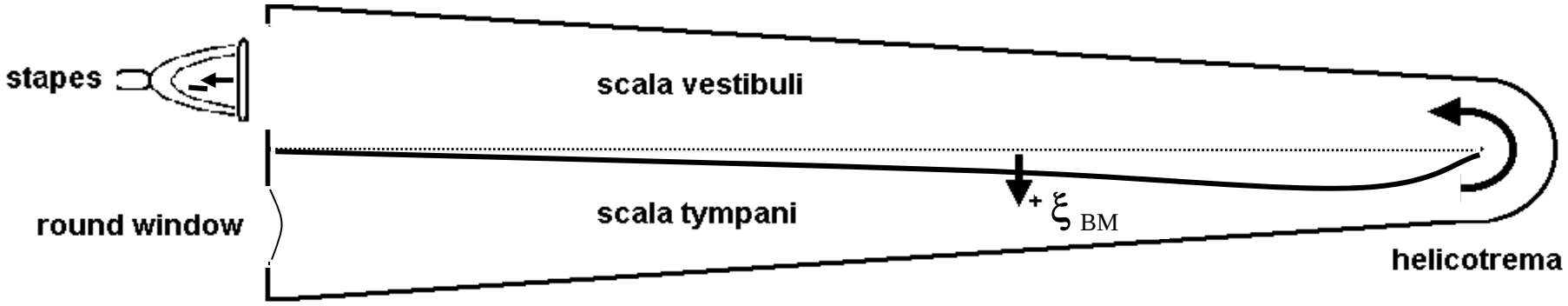


Basilar membrane at LF

For lowest frequencies ($0 < f < f_B$):

Mass-Dominated Impedance

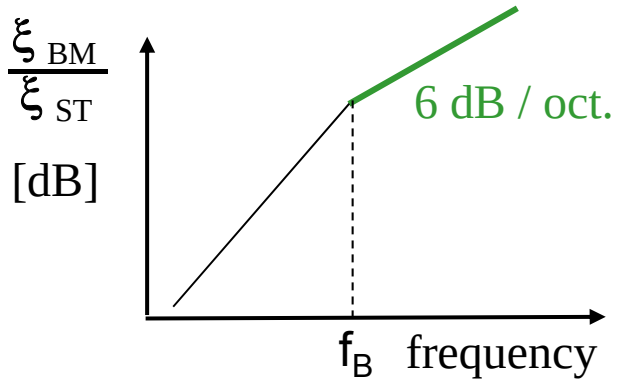


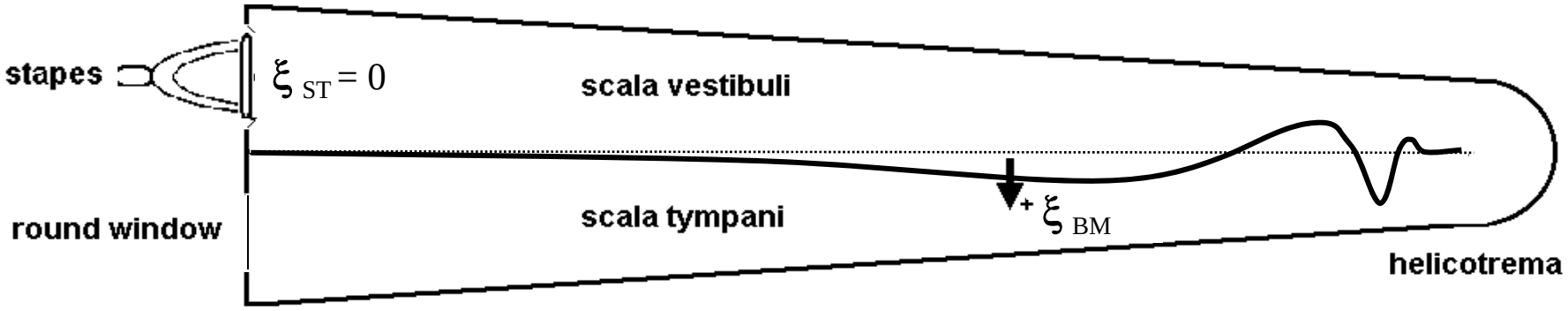


Basilar membrane at LF

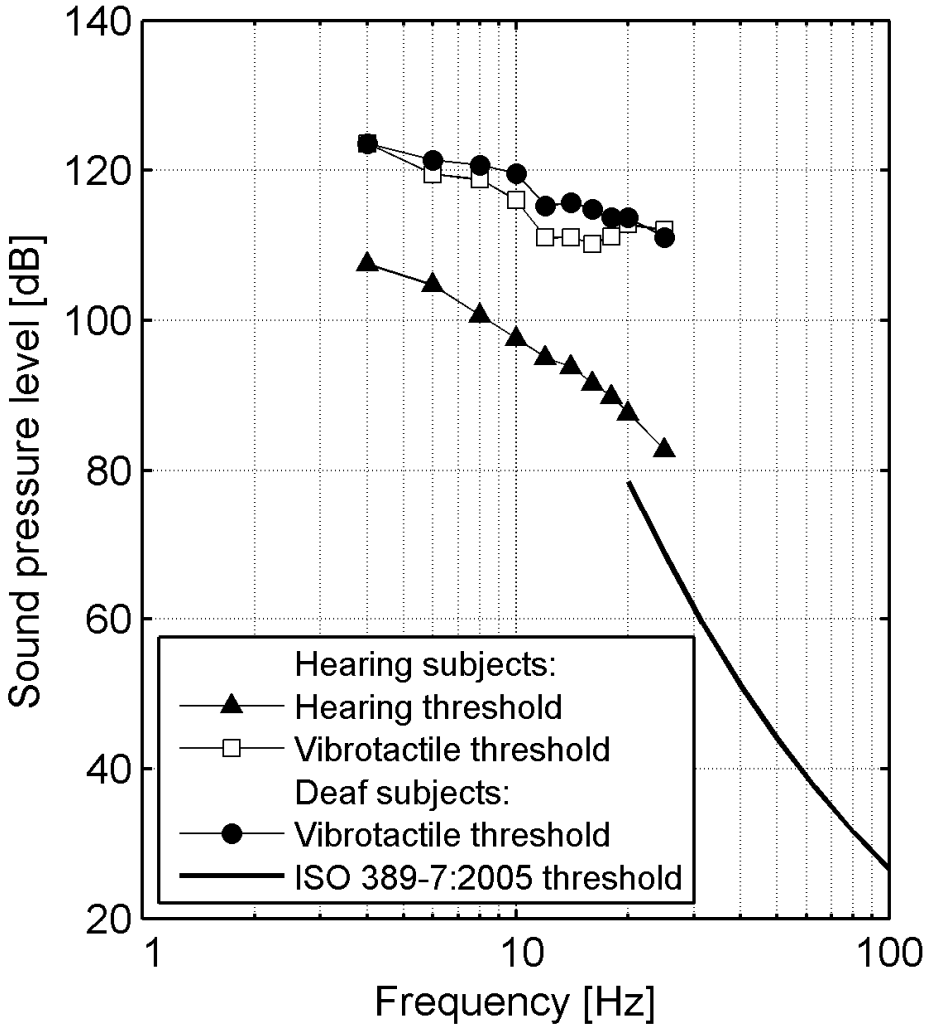
For low frequencies ($f_B < f$):

Travelling wave (Resistive)

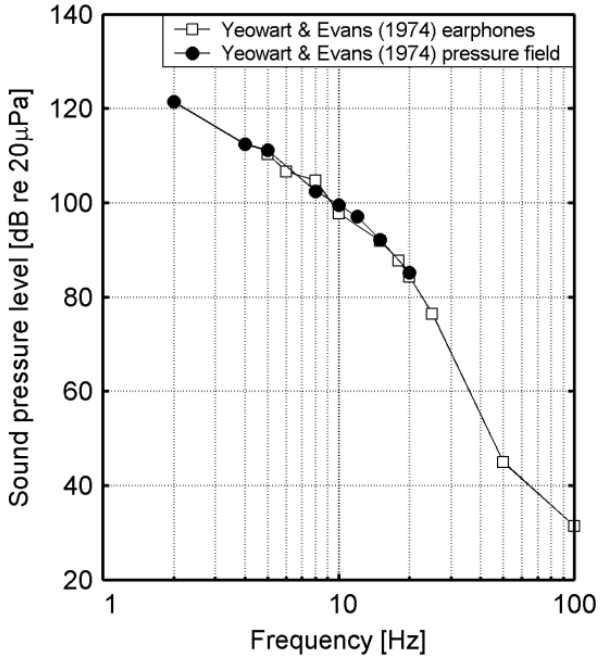




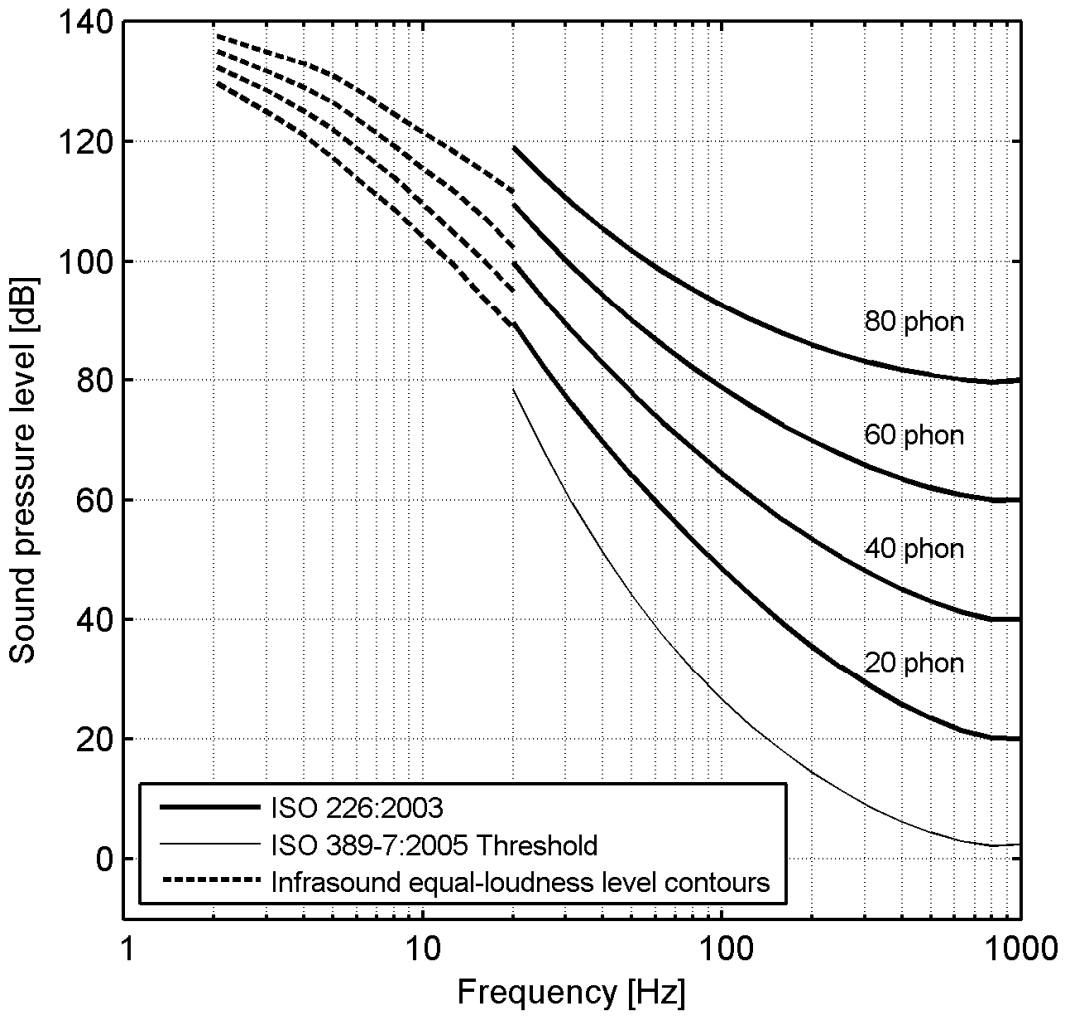
We sense with our ears



Landström U., Lundström R., Byström M. (1983), ***"Exposure to infrasound - Perception and changes in wakefulness"*****, J. Low Freq. Noise and Vib., Vol. 2(1), 1-11.**



Equal-loudness-level contours



LF-hearing summary

- Hearing threshold goes up at low frequencies.
- Infrasound is audible at very high levels.
- Hearing compressed at low frequencies:
  small level change -> large perceptual change.
- Sound (incl. infrasound) is primarily sensed with ears.
- At levels about 20 dB above our hearing threshold sound (incl. infrasound) is also felt as vibrations.
- Sound (incl. infrasound) below our hearing threshold is not detected and there is no scientific evidence that it can affect us in any harmfull way (e.g. vibro acoustic disease).
- But audible LF-noise (and infrasound) can cause annoyance and sleep disturbance, and thereby have negative health impact.

LF-hearing summary

- There are individual differences in our sensitivity. A LF-noise that is not audible by one person can be clearly audible and annoying for another person.
- Tonal noise is more annoying than non tonal noise.
- Impulsive noise is more annoying than non impulsive noise.
- Amplitude modulated noise is more annoying than non modulated noise.

Analysis of low-frequency noise and infrasound from wind turbines

Main questions

- What happens to the frequency spectrum as the size increases?
- What are the levels at the neighbours?
- What are the indoor levels at the neighbours?
- What are the characteristics of WTN.

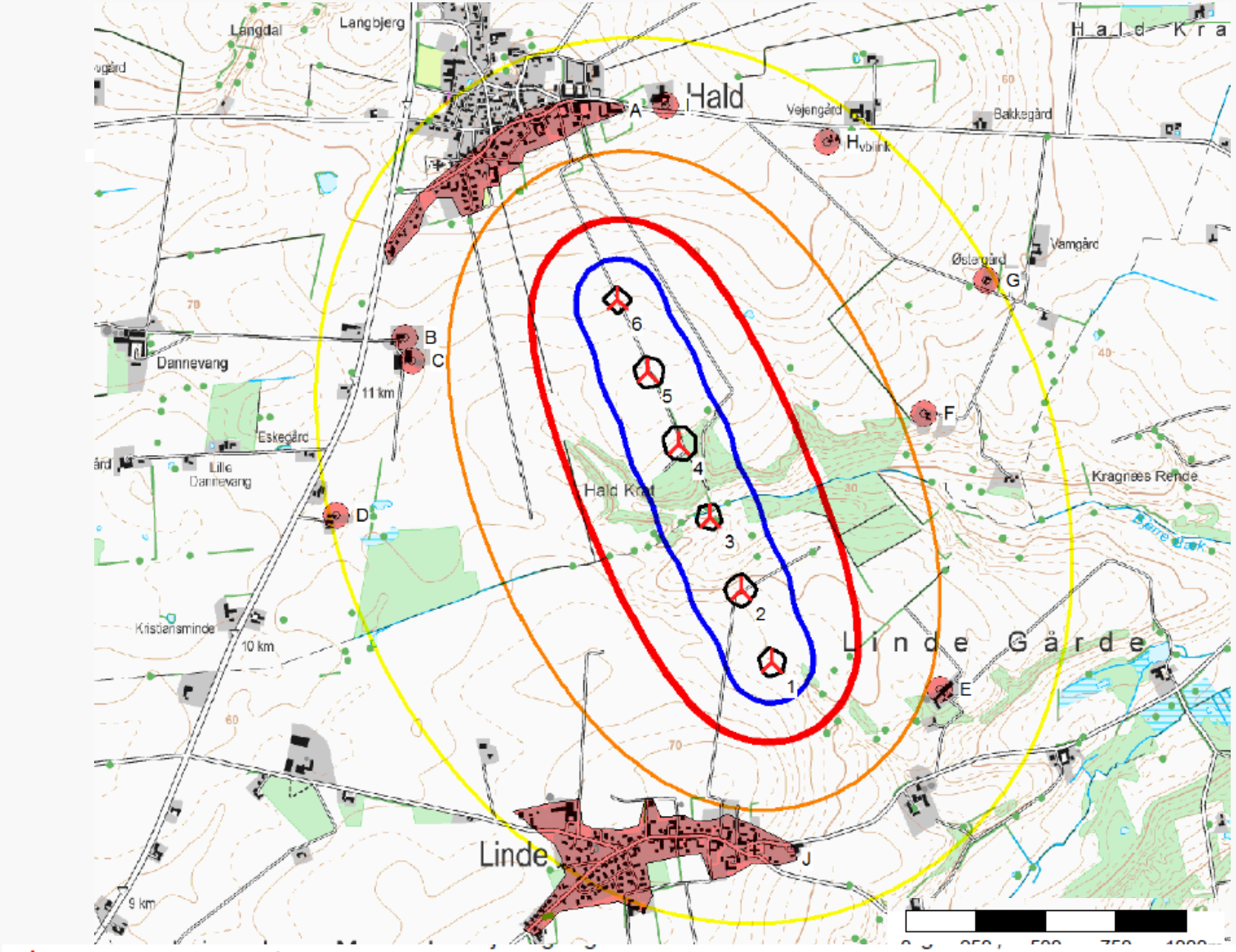
Noise regulations in Denmark

- When putting up new wind turbines, the impact on the surroundings must be assessed.
- Here it must be shown that the noise regulations will be fulfilled (from calculations):

Area/windspeed	6 m/s	8 m/s
Houses in the countryside	42 dBA	44 dBA
Recreational areas and houses in residential areas	37 dBA	39 dBA

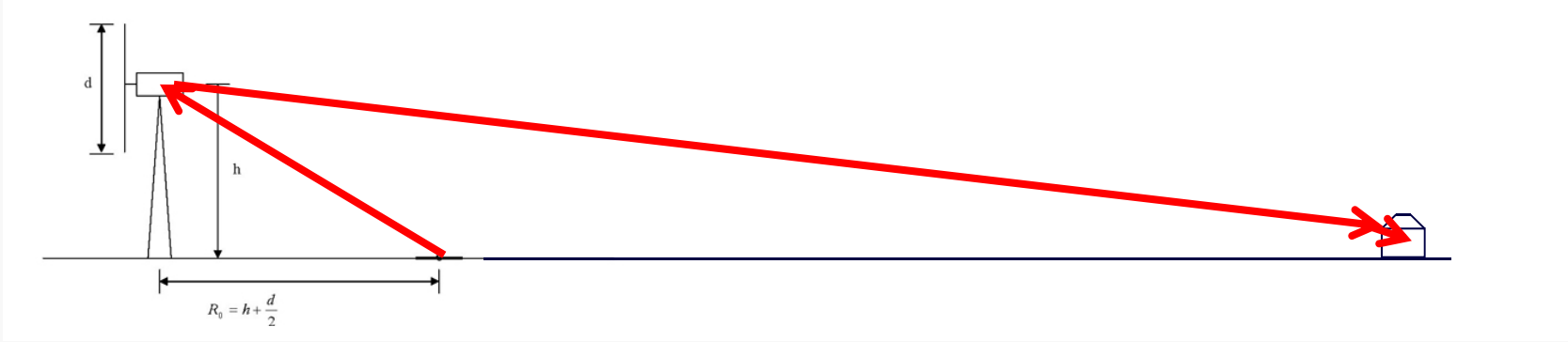
- If noise problems, when turbines are running:
  - measurements at wind turbine
  - calculate levels at neighbour.

  Here the uncertainty is subtracted from the measured/calculated levels.


Langdal
Langbjerg
Hald
Vejengård
Bakkegård
Hvbjerg
Østergård
Vamgård
Dannevang
Eskegård
Lille Dannevang
Hald Krat
Kragnæs Rende
Kristiansminde
Linde Gårde
Linde
11 km
10 km
9 km
A
B
C
D
E
F
G
J
1
2
3
4
5
6
Ny mølle
Støjfølsomt område
Højde over havoverflade fra aktivt linie objekt
34,0 dB(A)
39,0 dB(A)
44,0 dB(A)
49,0 dB(A)
54,0 dB(A)

Overview of the study

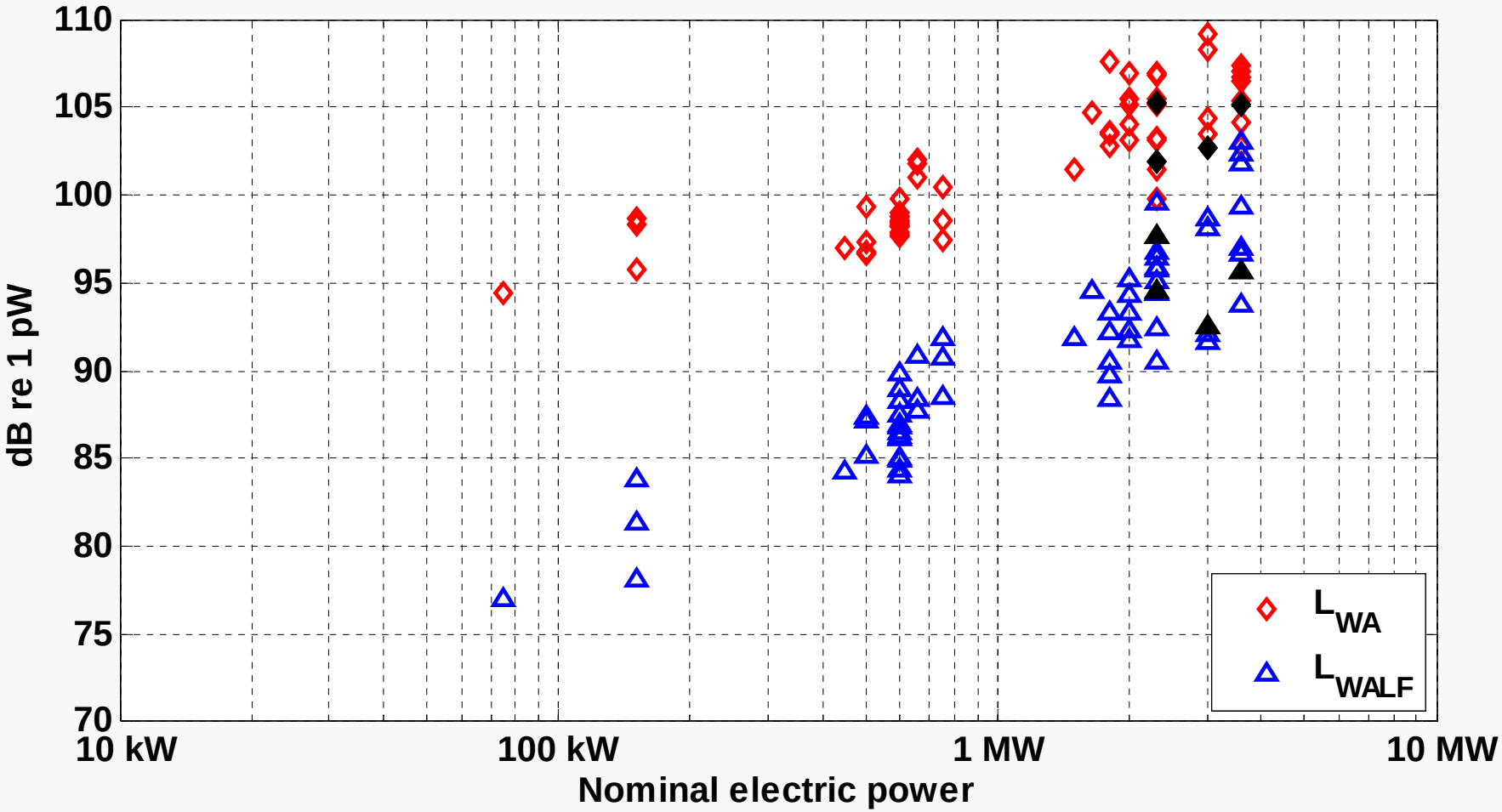
- Analysis of wind turbine noise data (8 m/s) (measurements done by Delta.)
- Compare small ≤ 2 MW with large (>2 MW).
- Estimate levels at potential neighbours.
- Indoor sound levels estimated.



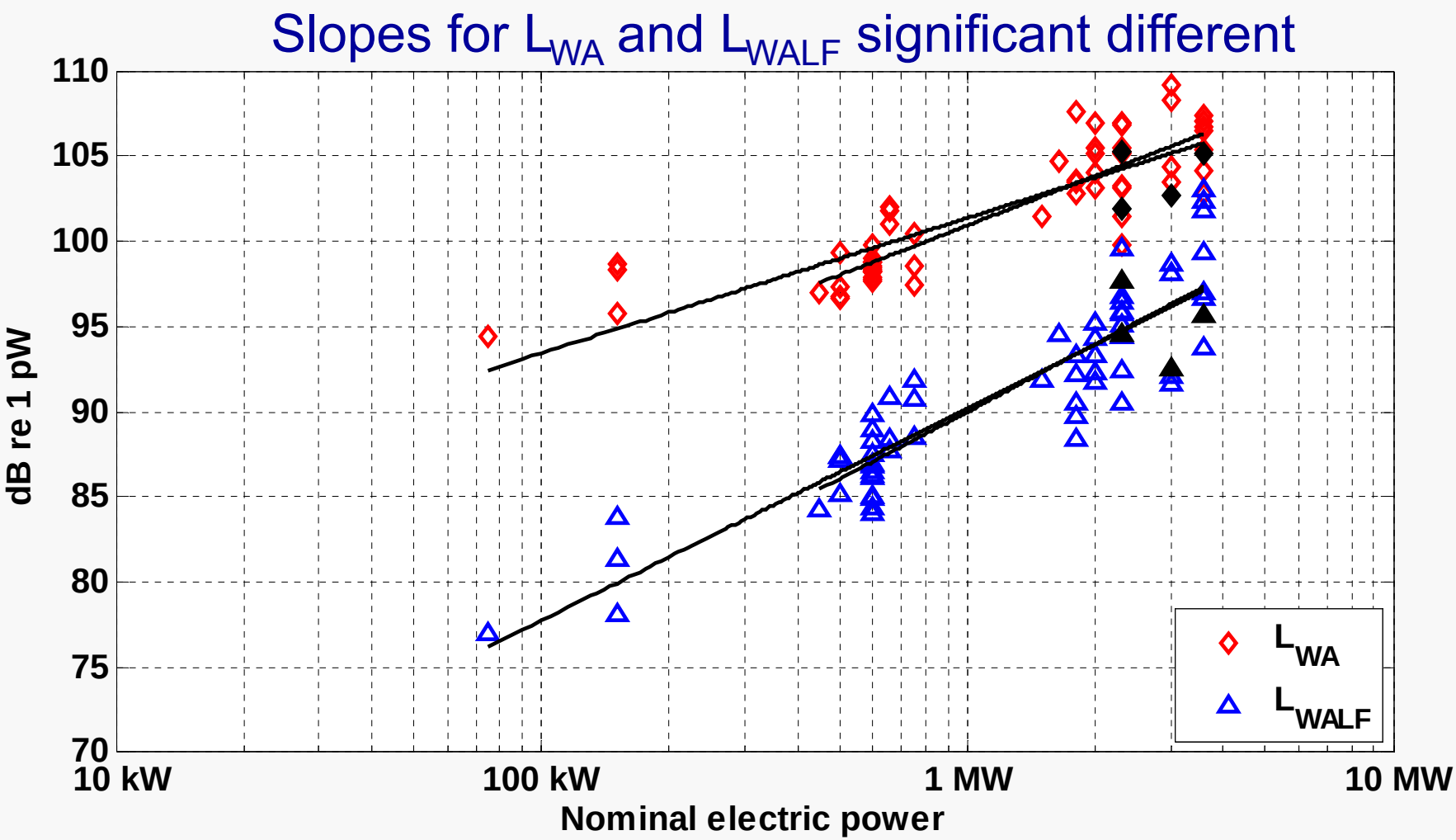
For more details

- Henrik Møller, Christian Sejer Pedersen, Steffen Pedersen, *"Lavfrekvent støj fra store vindmøller – opdateret 2011",* Sektion for Akustik, Aalborg Universitet, ISBN 978-87-92328-63-2
  (in Danish)
- Can be downloaded from this page:
  http://www.es.aau.dk/sections/acoustics/press/opdateret-rapport-om-stoej-fra-vindmoeller/
- Henrik Møller, Christian Sejer Pedersen, *"Low-frequency noise from large wind turbines",* Journal of Acoustical Society of America, **129**, 6, 2011, pp. 3727-3744.
  (in English, but on a smaller data set)

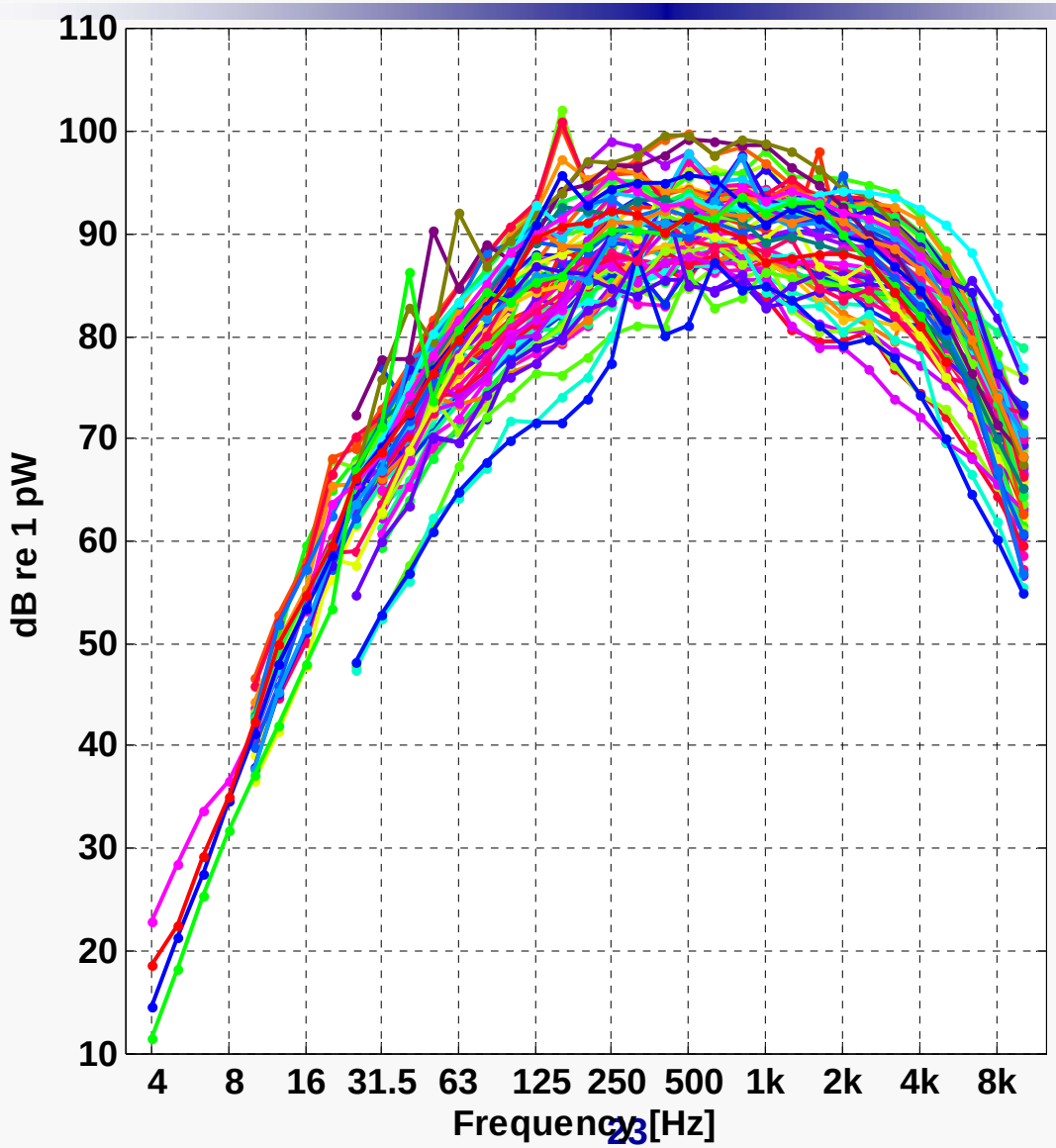
L_{WA} , L_{WALF} vs size



L_{WA} , L_{WALF} vs size

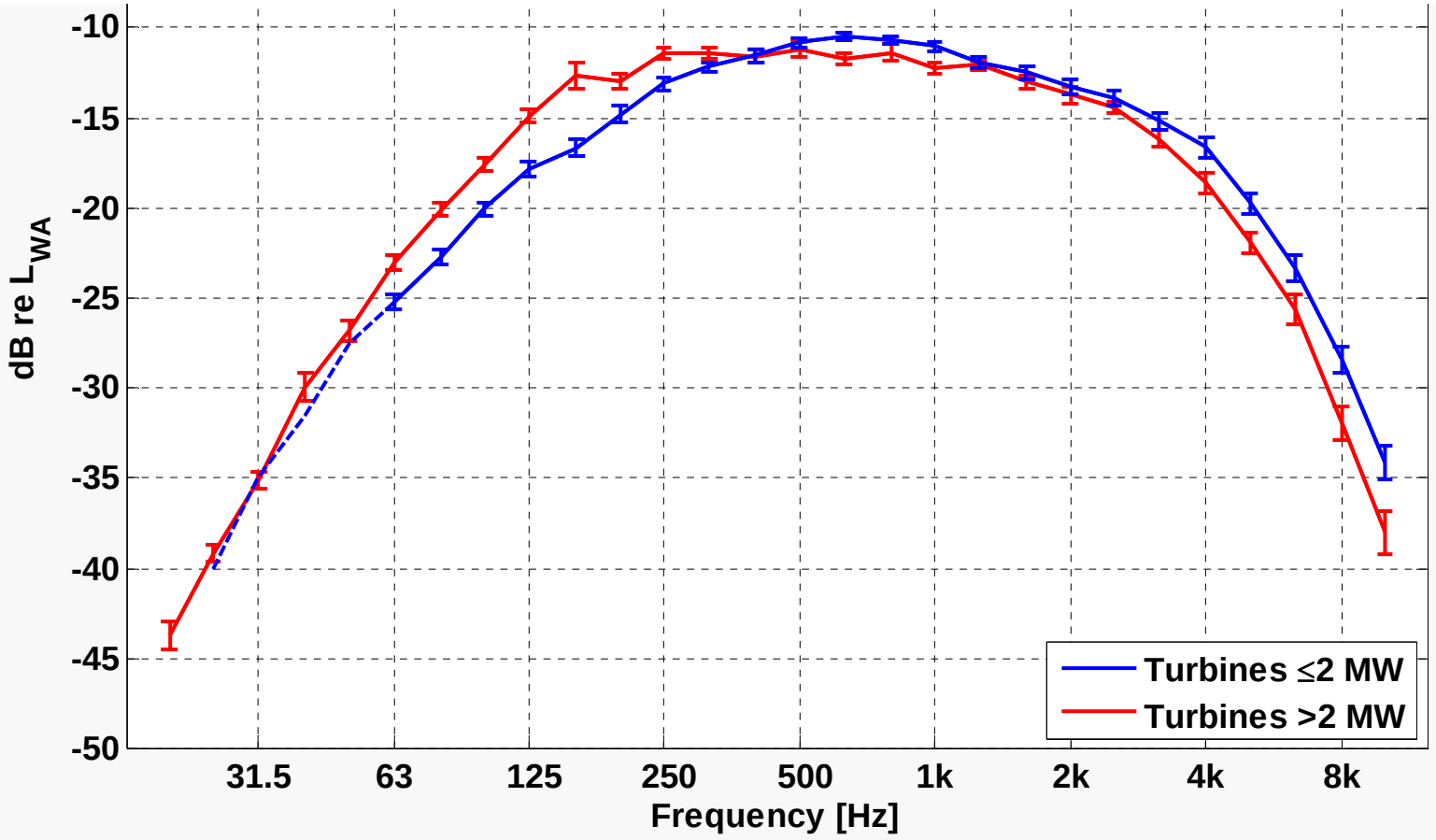


Spectrum – all turbines

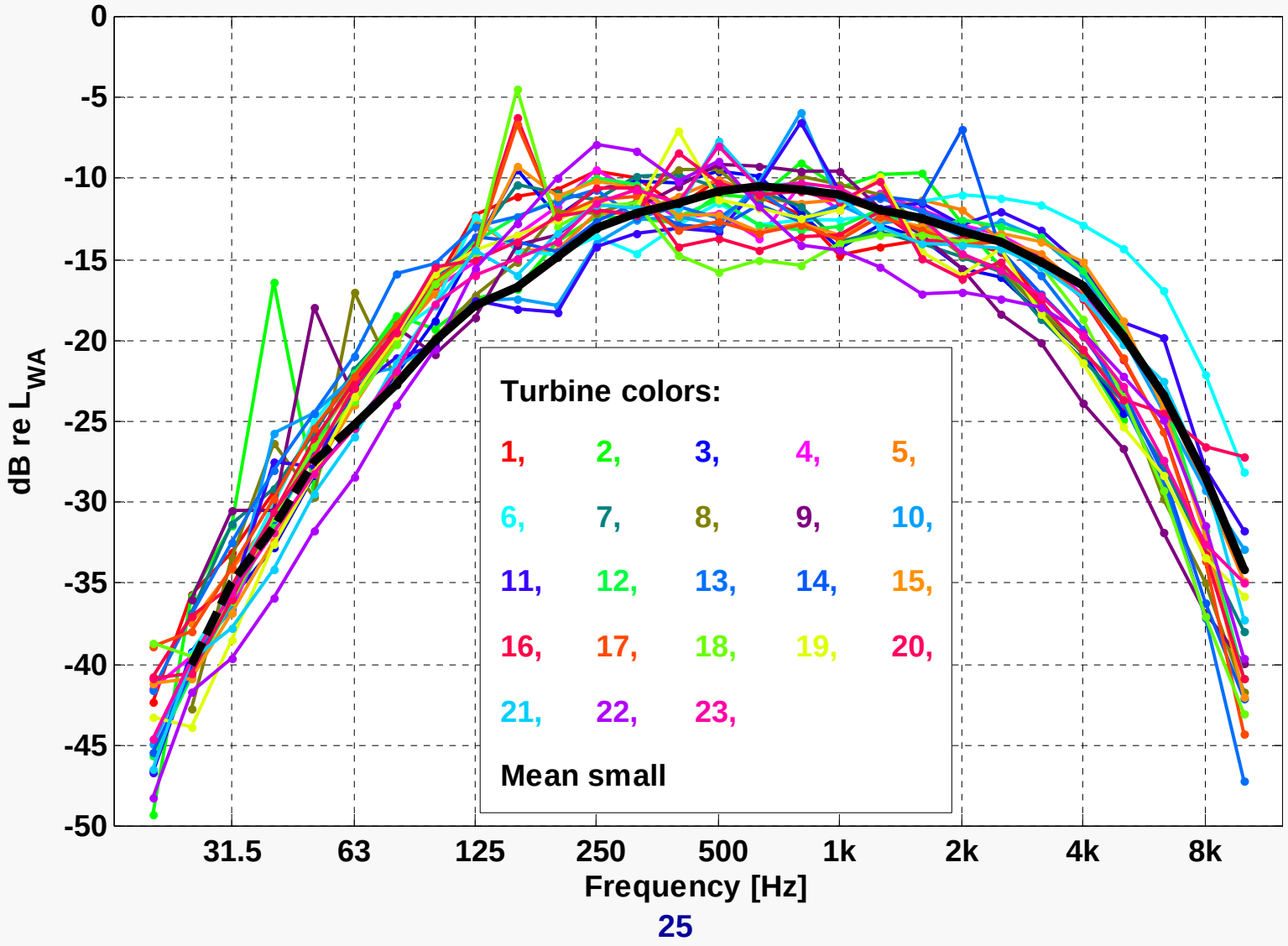


Normalized: small vs large

Significant difference: 63-250 Hz, 630 Hz, 1000 Hz and 4-10 kHz.
(also at 315 Hz if four smallest turbines discarded)

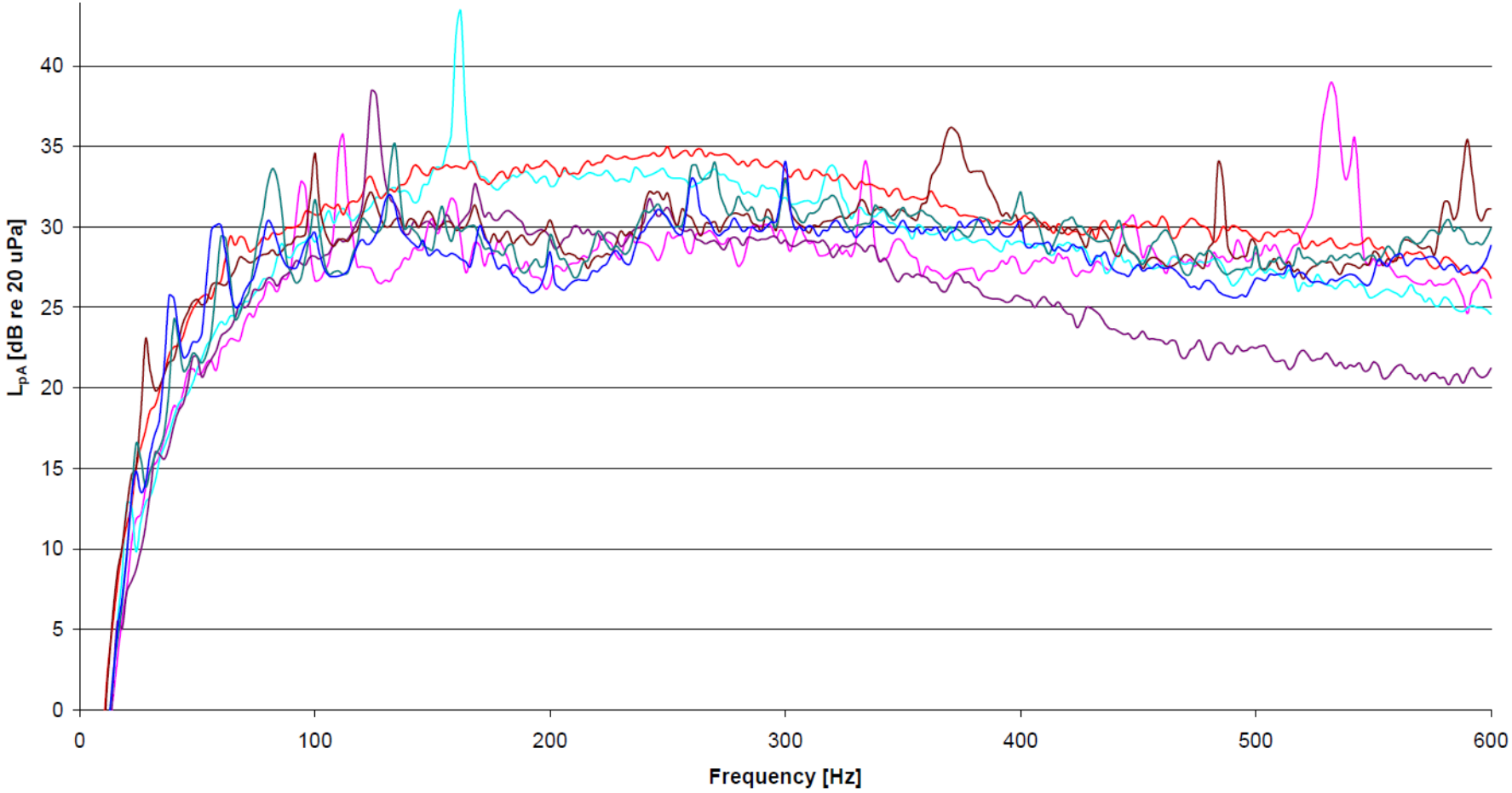


Normalized: large vs mean small



LF tones – From 7 turbines

Figure from EFP-06 project – Low Frequency Noise from Large Wind Turbines, Final Report. AV 1272/10, 21 November 2010

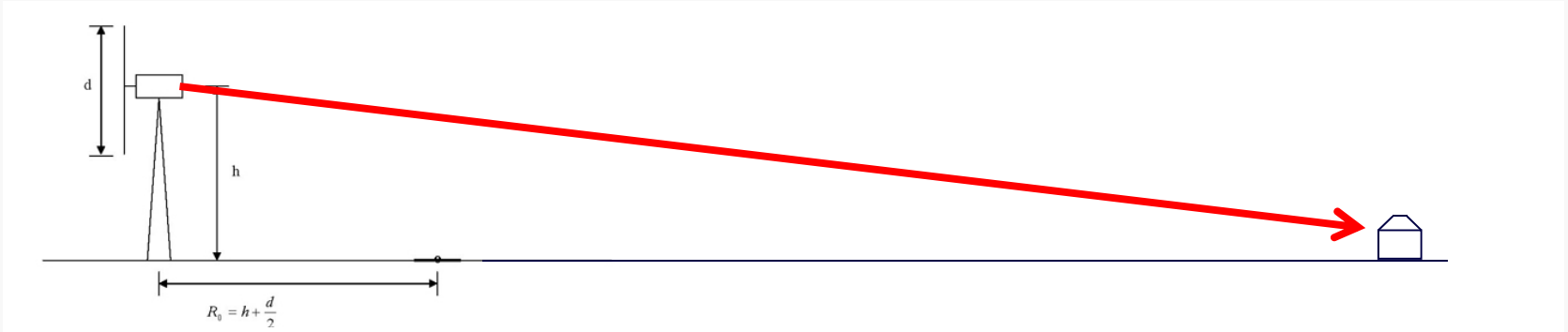


Sound at neighbours

- A-weighted sound pressure level at neighbours

$$L_p = L_{WA} - 20\ \text{dB} \cdot \log_{10}\left(\frac{d}{1\ \text{m}}\right) - 11\ \text{dB} - \alpha \cdot d + 1.5\ \text{dB}$$

Atm. abs. ground reflection



Based on figure from: Bekendtgørelse om støj fra vindmøller (BEK nr 1518 af 14/12/2006)

Outdoor at distance: L_p = 44 dBA (wind park)

Turbine	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Distance[m]	530	546	831	759	585	672	631	1241	1142	579	624	791
L_{pA} [dB]	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0
L_{pALF} [dB]	37.9	35.9	38.1	36.8	37.2	38.4	38.0	36.3	36.3	34.5	34.5	37.8
L_{pALF}-L_{pA} [dB]	-6.1	-8.1	-5.9	-7.2	-6.8	-5.6	-6.0	-7.7	-7.7	-9.5	-9.5	-6.2
L_{pG} [dB]	**68.4**	**63.9**	**64.6**	**67.4**								
Turbine	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Small**
Distance[m]	695	528	934	1078	1033	1033	487	375	805	1045	771	406
L_{pA} [dB]	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0
L_{pALF} [dB]	38.4	37.2	39.0	40.8	40.6	41.8	36.4	36.0	35.8	35.5	35.4	33.9
L_{pALF}-L_{pA} [dB]	-5.6	-6.8	-5.0	-3.2	-3.4	-2.2	-7.6	-8.0	-8.2	-8.5	-8.6	-10.1

35 dBA reasonable outdoor limit?

- Limits in Denmark for WTN:
  44 dBA (at 8 m/s)
  39 dBA (at 8 m/s) for noise sensitive areas
- Pedersen and Waye [61] 35 dBA:
  - % of highly annoyed persons increases above 5 %, and
  % of annoyed persons increases above 10 % [62].
- Pedersen and Nielsen [63] recommended minimum distance to neighbours so that the wind turbine noise would be below 33-38 dBA.
- A limit of 35 dBA is used for wind turbines, e.g. in Sweden for quiet areas. It is also the evening/night limit for recreational areas in Denmark for industrial noise.

[61] E. Pedersen, K. P. Waye, ”Perception and annoyance due to wind turbine noise – a doseresponse relationship”, J. Acoust. Soc. Am., 116 (6), 3460-3470, 2004.

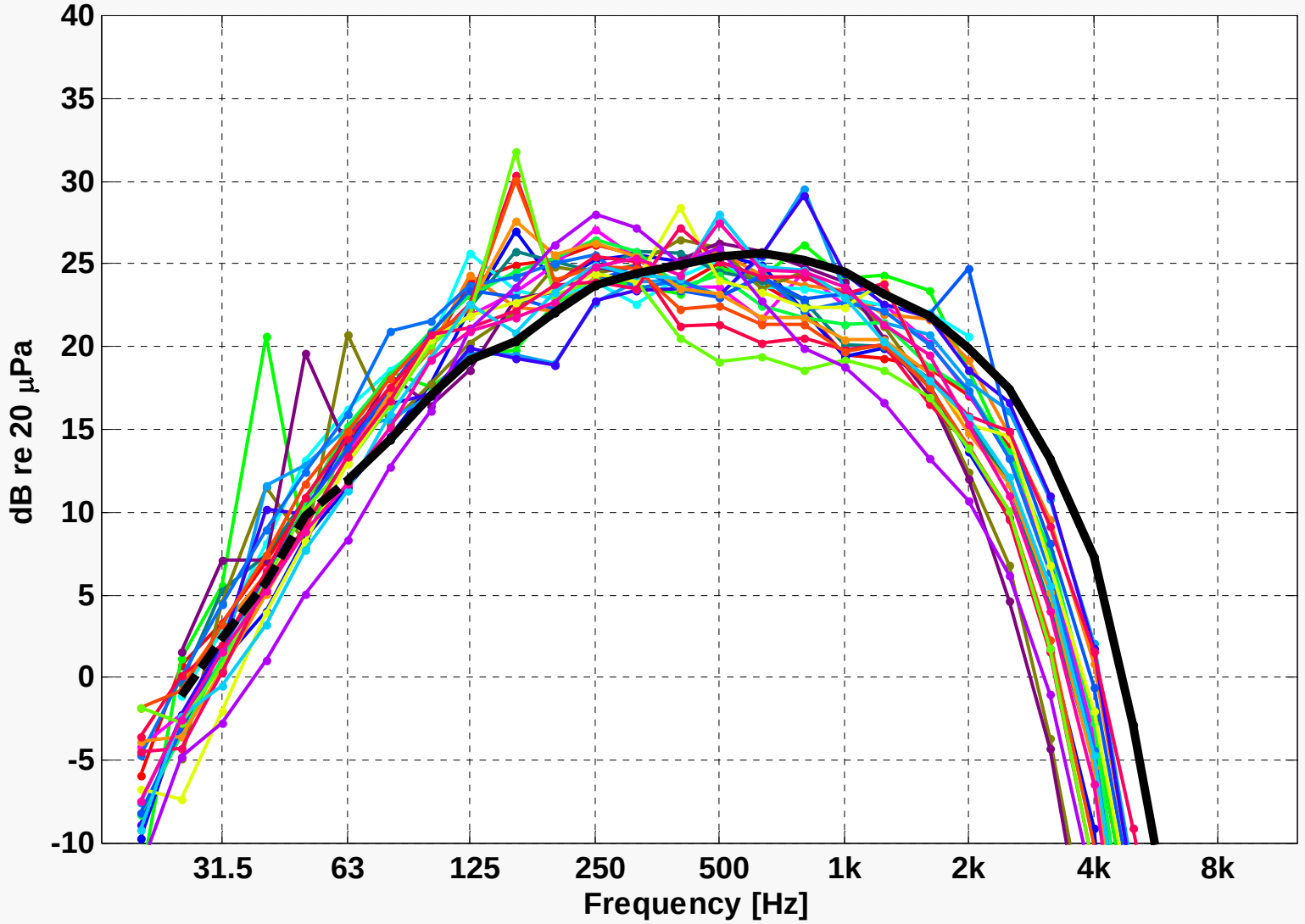
[62] E. Pedersen, F. van den Berg, R. Bakker, J. Bouma, ”Response to noise from modern windfarms in The Netherlands”, J. Acoust. Soc. Am., 126 (2), 634-643, 2009.

[63] T. H. Pedersen, K. S. Nielsen, ”Genevirkning af støj fra vindmøller”, Rapport 150, Delta Akustik & Vibration, 1996.

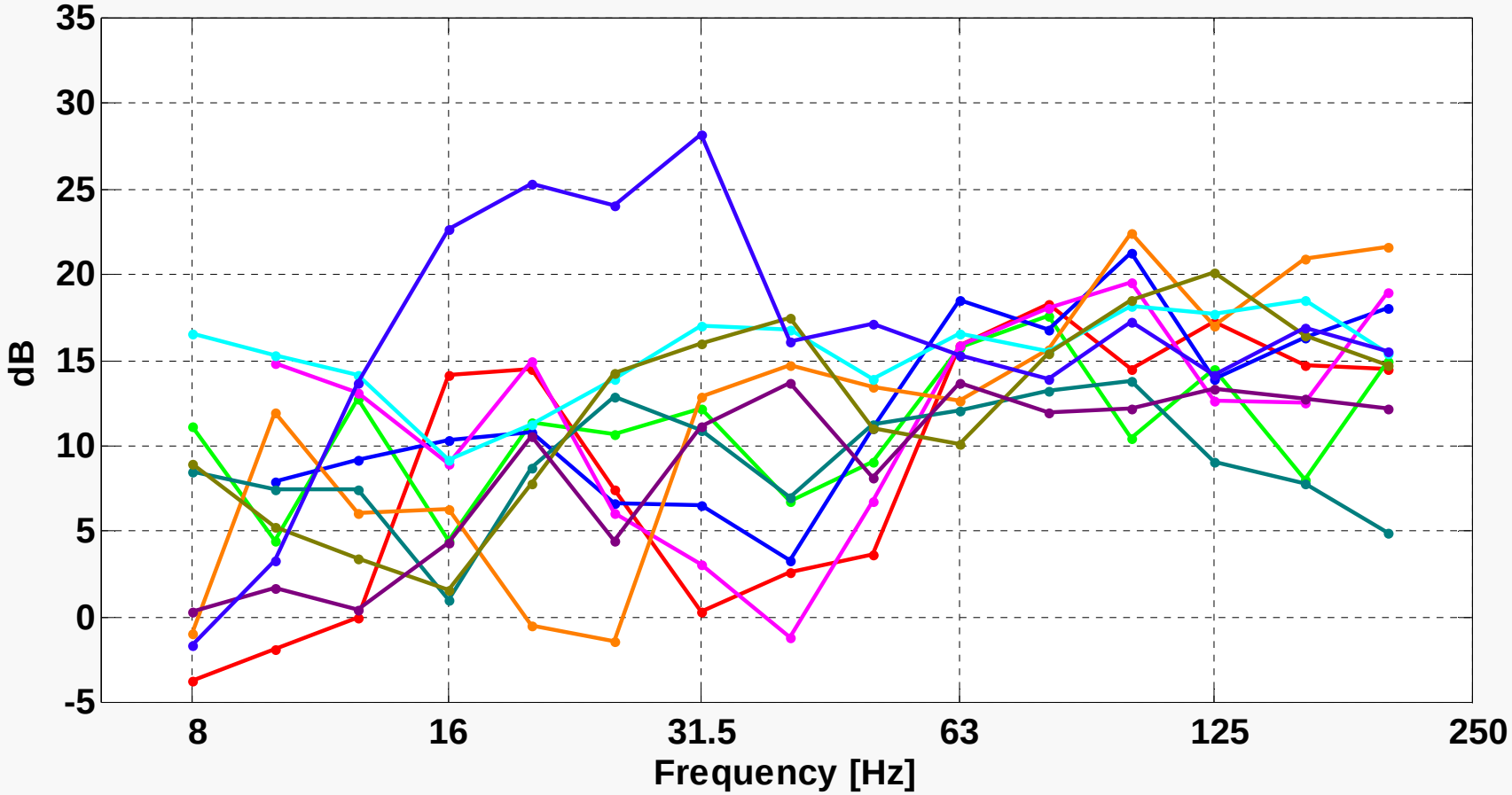
Outdoor at distance: L_p = 35 dBA

Turbine	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Distance[m]	629	647	879	822	678	758	713	1227	1144	676	715	847
L_{pA} [dB]	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} [dB]	28.8	26.7	28.9	27.6	28.0	29.1	28.8	27.0	27.0	25.3	25.2	28.6
L_{pALF}-L_{pA} [dB]	-6.2	-8.3	-6.1	-7.4	-7.0	-5.9	-6.2	-8.0	-8.0	-9.7	-9.8	-6.4
L_{pG} [dB]	**59.1**	**54.5**	**55.0**	**58.0**								
Turbine	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Small**
Distance[m]	768	631	962	1078	1042	1038	594	495	861	1054	834	464
L_{pA} [dB]	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} [dB]	29.2	28.0	29.8	31.7	31.5	32.7	27.2	26.9	26.5	26.3	26.2	24.8
L_{pALF}-L_{pA} [dB]	-5.8	-7.0	-5.2	-3.3	-3.5	-2.3	-7.8	-8.1	-8.5	-8.7	-8.8	-10.2

Outdoor at distance: L_p = 35 dBA



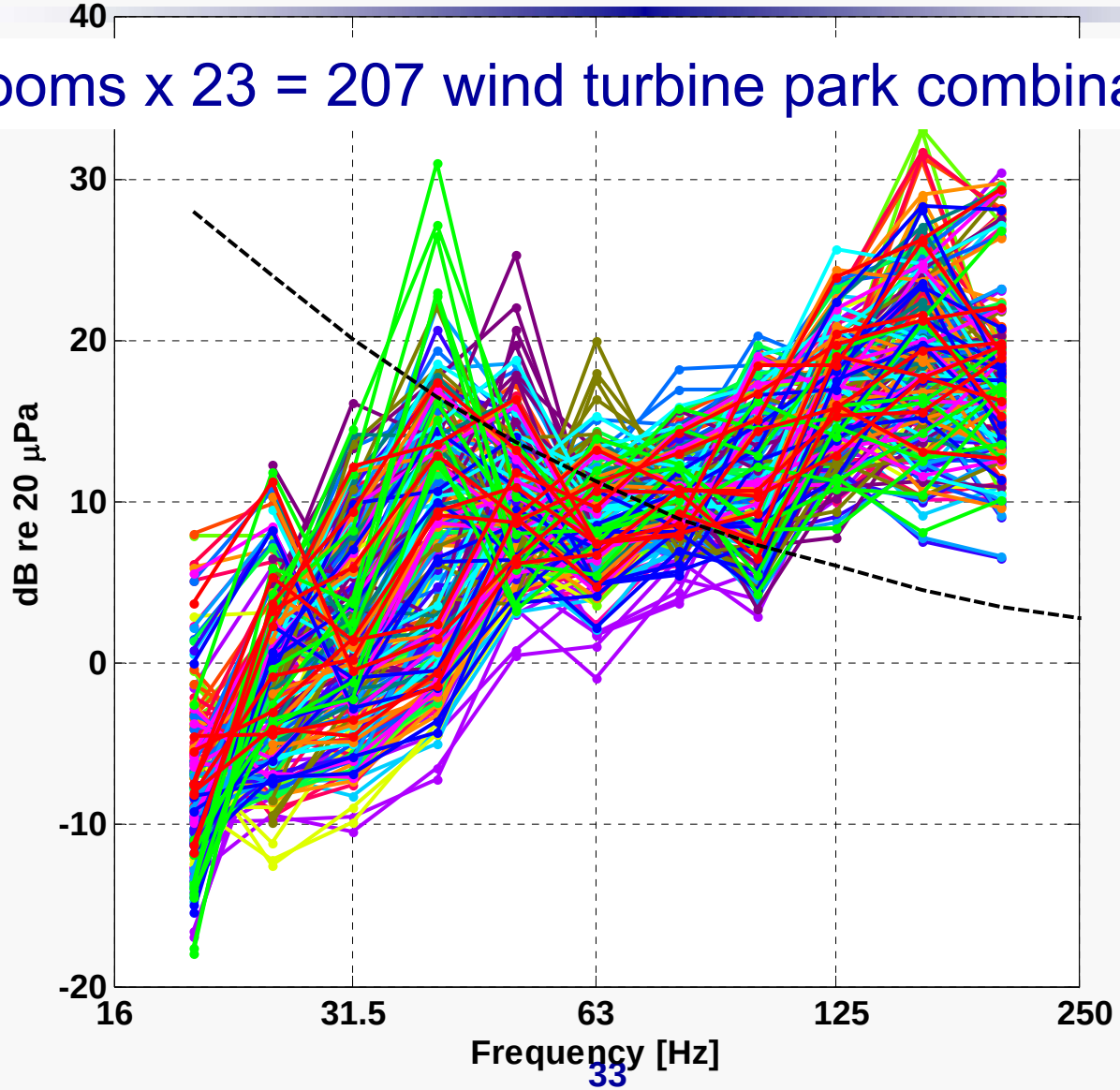
Sound insulation (closed windows)



10 rooms (5 different houses)

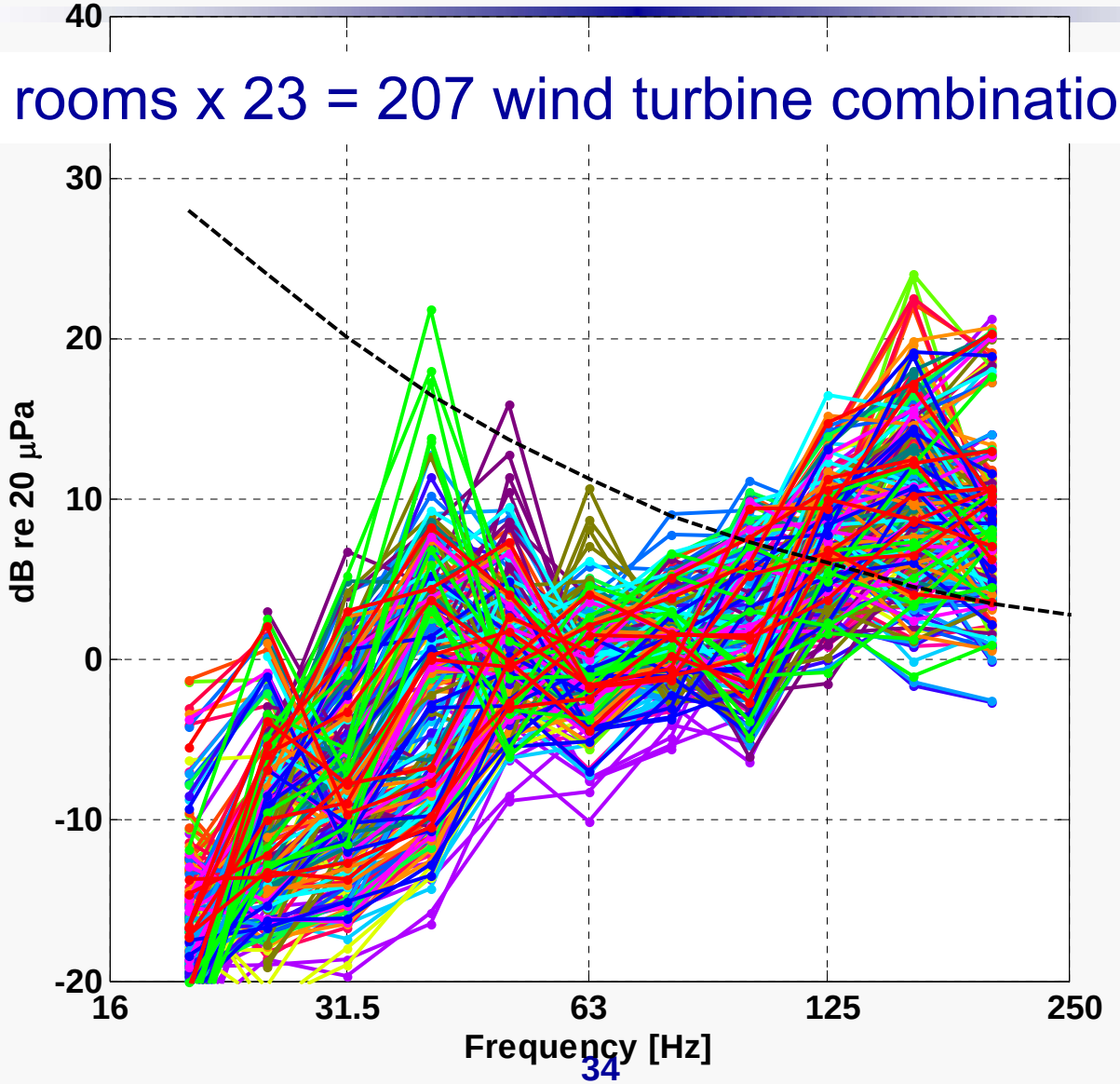
Indoor spectrum (L_p = 44dBA outdoor wind farm)

9 rooms x 23 = 207 wind turbine park combinations



Indoor spectrum (L_p = 35dBA outdoor)

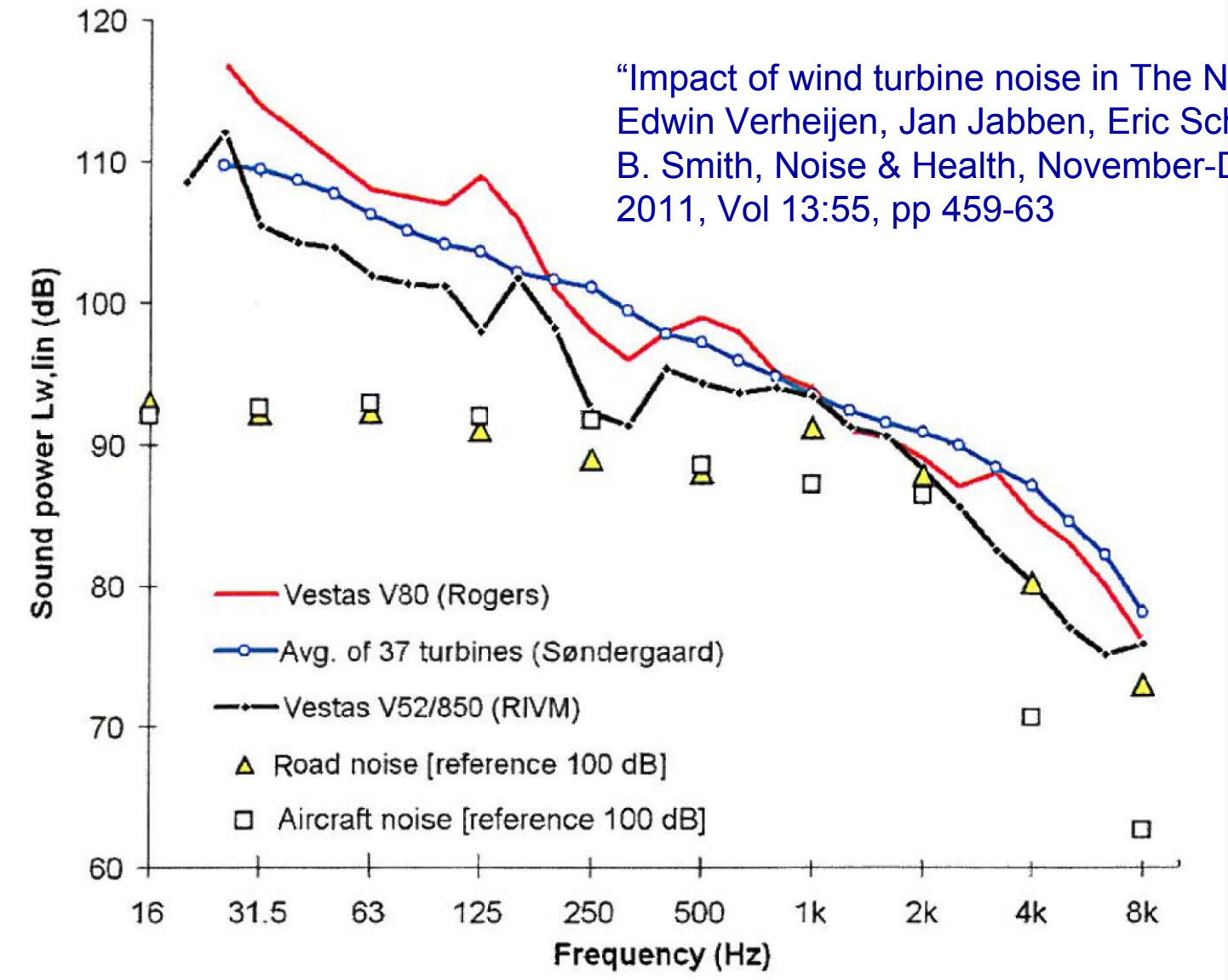
9 rooms x 23 = 207 wind turbine combinations



Indoor levels summary

- If 35 dBA outdoor, then potential audible LF-noise in most room/turbine combinations.
- If 44 dBA outdoor, then audible LF-noise in all combinations.
- And Danish LFN-limit of 20 dBA,LF is exceeded for single 1/3-octave bands in 100 of the 207 combinations.
- Therefore the limit of 20 dBA,LF is expected to be exceeded in even more turbine/room combinations.

WTN vs road and aircraft noise



"Impact of wind turbine noise in The Netherlands", Edwin Verheijen, Jan Jabben, Eric Schreurs, Kevin B. Smith, Noise & Health, November-December 2011, Vol 13:55, pp 459-63

Conclusions

Conclusions

- We sense LF-noise and infrasound primarily with our ears – much higher levels needed before we feel it.
- Modern wind turbines do not emit infrasound levels that are audible at typical distances.
- However, modern wind turbines do emit audible low-frequency noise.
- And larger wind turbines emit higher levels, and relatively more low-frequency noise than small wind turbines.
- LF-noise is attenuated less by the atmosphere and structures.
- LF-noise is more easily transmitted into buildings.
- Due to atmospheric absorption larger distances gives relative more LF vs MF/HF content.
- Consequently noise from future larger turbines is expected to be even more LF dominated at the neighbours.

Conclusions continued

- There are tonal components that probably originate from the gears.
- Indoor levels depend much on turbine/room combination.
- Danish outdoor limit of 44 dB does not prevent audible LF-noise from large turbines indoor.
- And the limit does not prevent the LF-noise from exceeding the limits that are used for other noise sources.
- Special atmospheric conditions can give less attenuation with distance, which might explain case stories about audible LF-noise at very long distances.
- And the load on the wings changes with different atmospheric conditions, which can change the noise character.
- There are large uncertainties in estimating levels at neighbours. Therefore a safety margin should be applied in future planning.

Conclusions continued

- There are no direct physical effect of WTN on people.
- All effects of WTN are indirect from e.g. noise annoyance and sleep disturbance.
- Since WTN can contain both tonal components, amplitude modulation, impulsiveness and LF-noise it is potentially more annoying than other typical noises like traffic noise.