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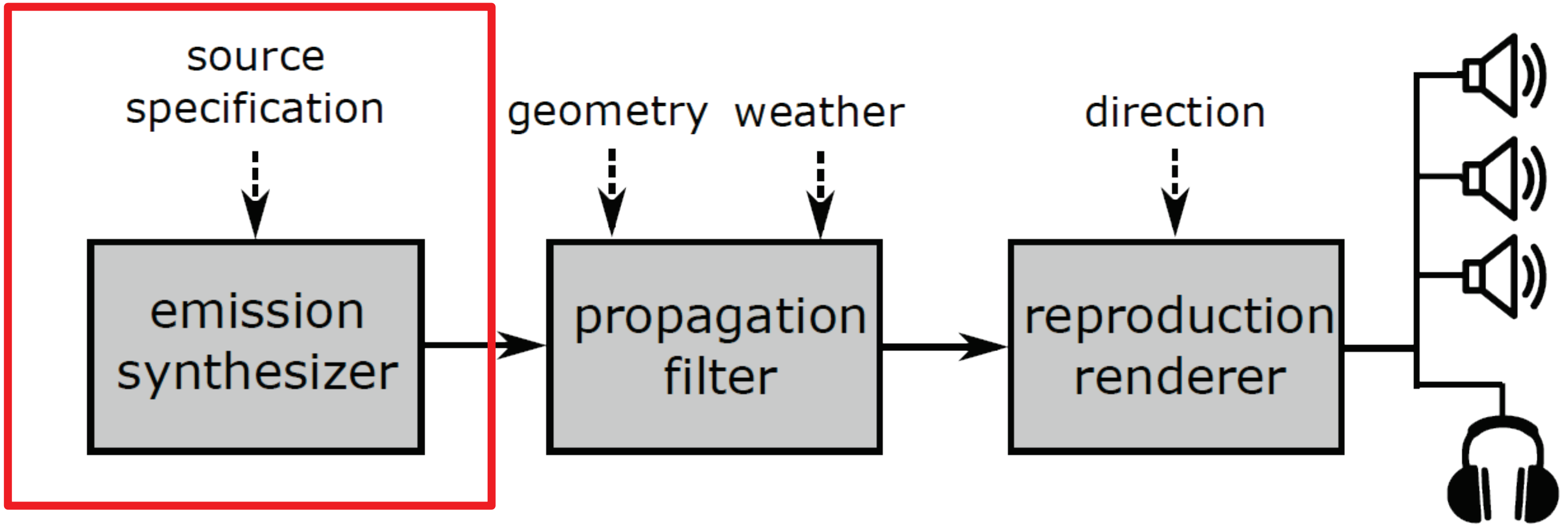
Acoustics II

Auralization: Sound synthesis

Reto Pieren

2024

Flexible auralization approach

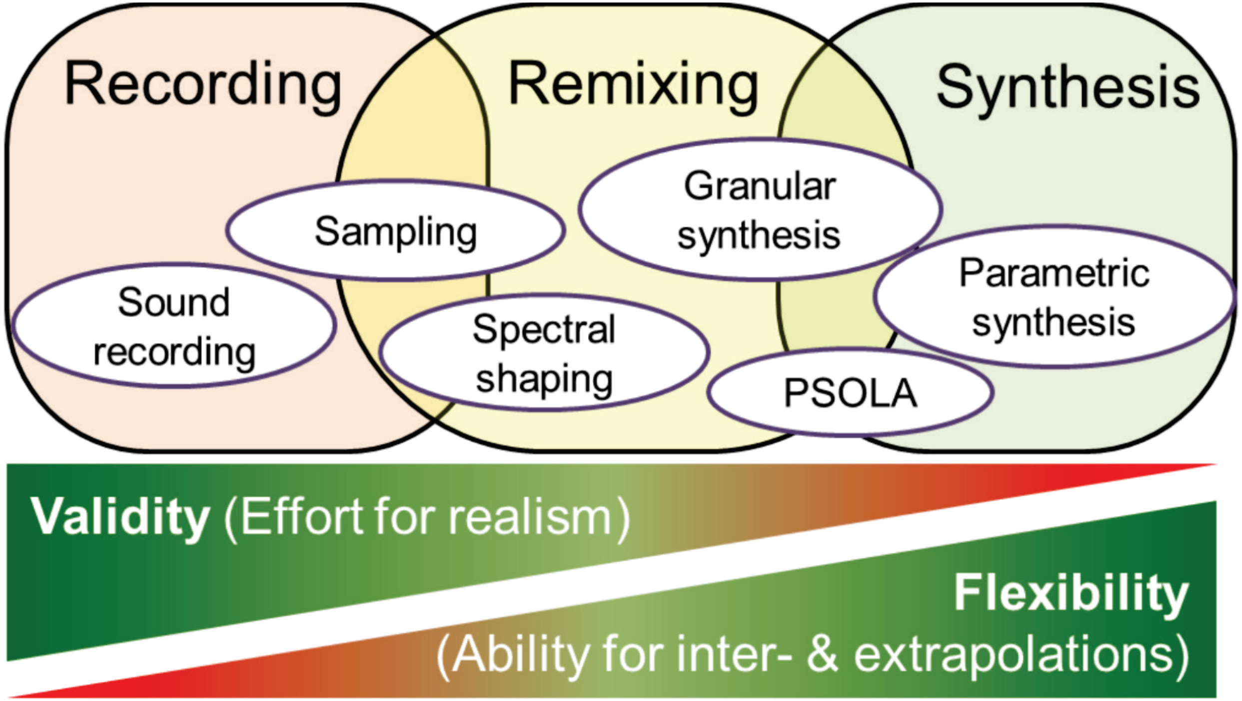


Sound synthesis

[Bilbao, S. 2009. Numerical Sound Synthesis. Wiley.

Smith, J.O. III 2011. Spectral Audio Signal Processing. W3K Publishing.]

Sound signal generation: Recording vs synthesis



Synthesis methods

1. Sample-based synthesis
   - Granular
   - PSOLA
2. Signal-based synthesis
   - Additive
   - Subtractive
   - Spectral Modelling
3. Physics-based synthesis

1. Sample-based synthesis

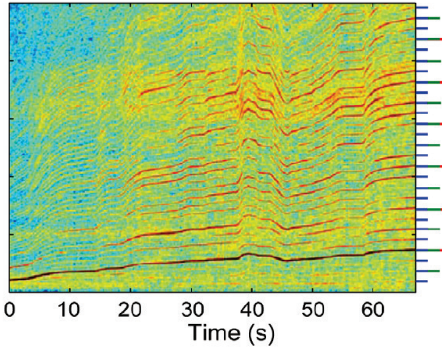
Granular synthesis

- Type of concatenative synthesis: concatenating existing audio samples in time
  1. Recorded signal segmented into short units (grains): 10 – 100 ms
  2. Enveloping amplitude of each grain
  3. Playback of overlapping, reordered, amplitude-scaled grains
- Keeps transients, spectral content and natural variations

Pitch-Synchronous OverLap and Add (PSOLA)

- Type of concatenative synthesis: harmonic signals
- Very short segments with respect to signal period

- Applications:
  - Speech
  - Musical instruments
  - Combustion engine of car



[Jagla, J. et al. 2012. Sample-based engine noise synthesis using an enhanced pitch-synchronous overlap-and-add method. Journal of the Acoustical Society of America, 132(5).]

- Keeps spectral content, natural variation
  → allows for pitch modification

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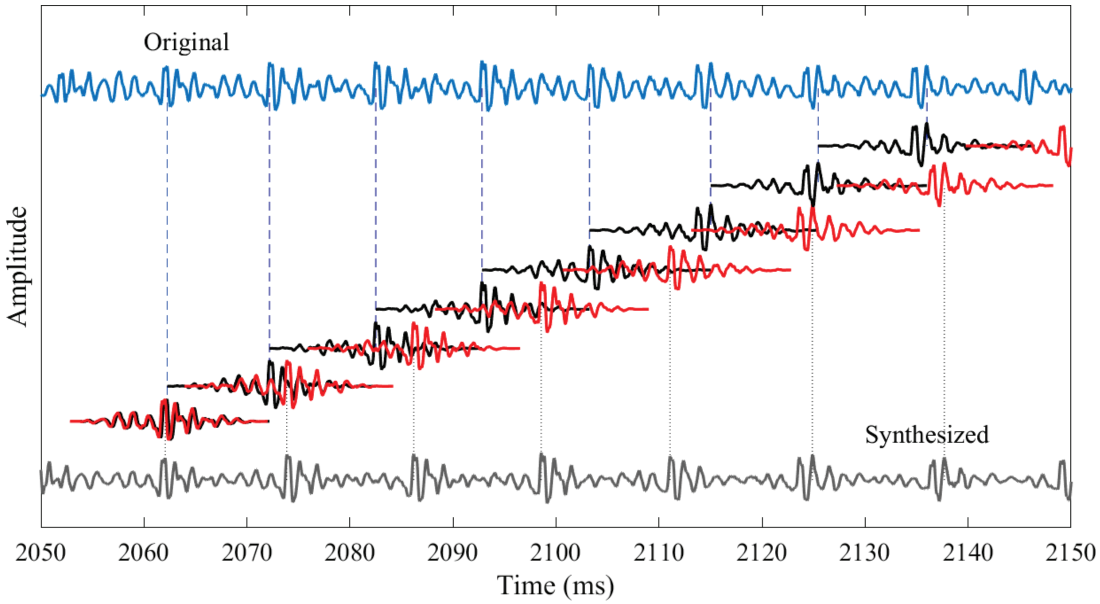
Pitch-Synchronous OverLap and Add (PSOLA)

- Processing: Pitch estimation, segmentation, weighting, adding



[https://wiki.aalto.fi/display/ITSP/Introduction+to+Speech+Processing]

2. Signal-based synthesis

Signal-based synthesis

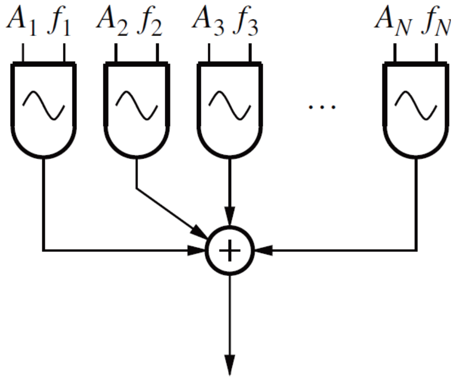
- Parametric synthesis
- Creating audio signal from scratch
- Full control
- Full flexibility
- Not necessarily related to physical sound generation mechanisms

Additive synthesis

Additive synthesis

- Inspired by Fourier series («Fourier synthesis»)
- Sinusoidal model: Sum of sinusoids (stationary case):

$$x(t) = \sum_{i=1}^{N} A_i \sin(2\pi f_i t + \theta_i)$$



Additive synthesis: Variations in time

- Instantaneous (time-dependent) frequency of signal $\sin(\varphi(t))$ with oscillation phase φ:

$$f(t) \triangleq \frac{1}{2\pi}\frac{d\varphi}{dt}$$

- Instantaneous phase (= oscillation phase):

$$\varphi_i(f_i, t) = 2\pi \int_{-\infty}^{t} f_i(\tau)d\tau = \varphi_{i,0} + 2\pi \int_{0}^{t} f_i(\tau)d\tau$$

- Time-varying amplitude, frequency and phase:

$$x(t) = \sum_{i=1}^{N} A_i(t)\sin\left(\varphi_i(f_i, t) + \theta_i(t)\right)$$

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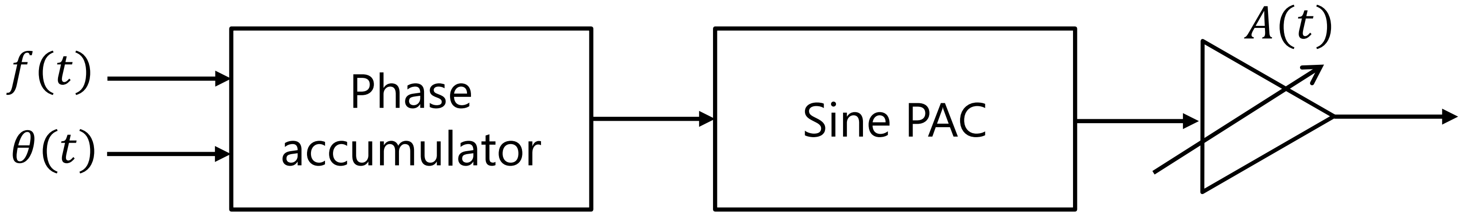
Additive synthesis: Digital realization by Numerically Controlled Oscillator (NCO)

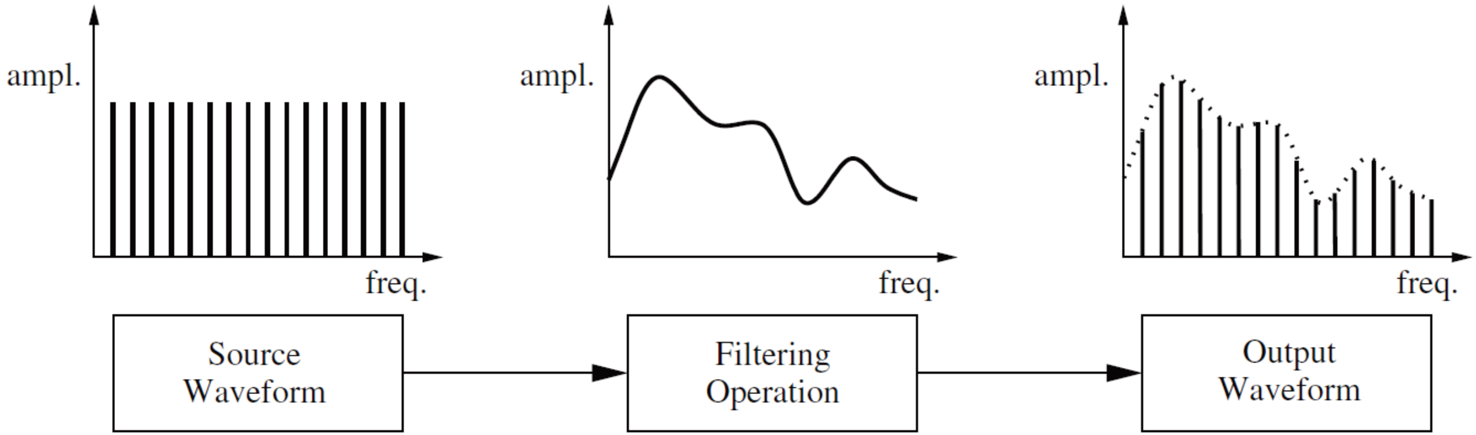
- 2 stages: Phase accumulator and Phase-to-Amplitude Converter (PAC)



- Advantages
  - Flexible and robust
  - Direct and linear control of frequency, phase and amplitude
- For real-time processing:
  - Lookup table with interpolation for sine function (wavetable)
  - Polynomial approximation for sine function

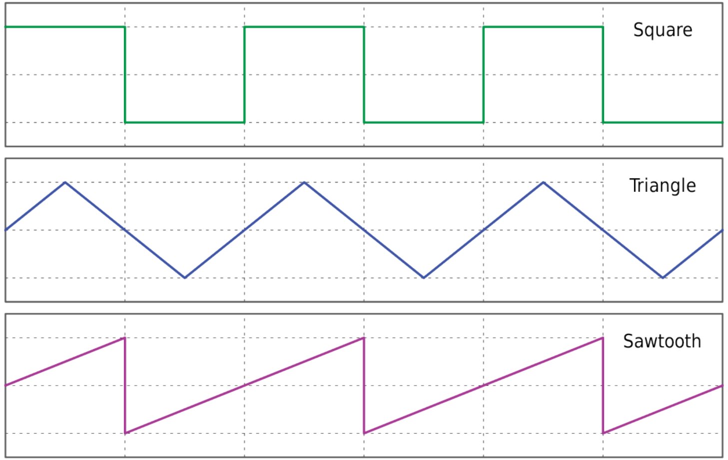
Subtractive synthesis

Subtractive synthesis



Subtractive synthesis

- Broadband basic waveform + filter
- For musical applications typically:
  - Non-sinusoidal periodic waveforms
  - Fundamental + many harmonics
  - Square, triangle, sawtooth wave
- For environmental noise applications typically:
  - Noise or noise-like signals



Noise signals

- Noise = random signal
  - Creation by random process
  - Random phase relations within signal
- DC-free: average amplitude = 0

- White noise:
  - constant Power Spectral Density (PSD) → analogy to white light
  - equal intensity at *all* frequncies
  - *all* frequencies equally frequent

White noise generation: Discrete-time

- Realization: Vector of random numbers with zero mean and finite variance σ^2

- Statistically independent samples → Power spectrum independent of frequency
  - Because: autocorrelation $R_{ww} = \sigma^2\delta(t)$

$$S_{ww}(f) = \mathcal{F}(R_{ww}) = \sigma^2$$

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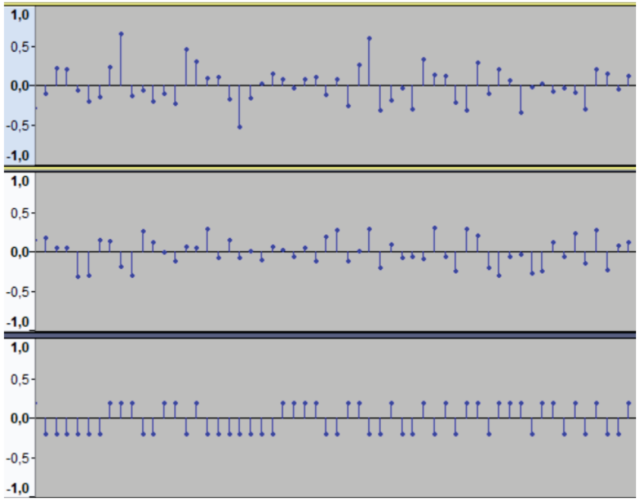
White noise generation: Discrete-time

- Different amplitude distributions
  - Gaussian (White Gaussian Noise)
  - Uniform
  - Binary



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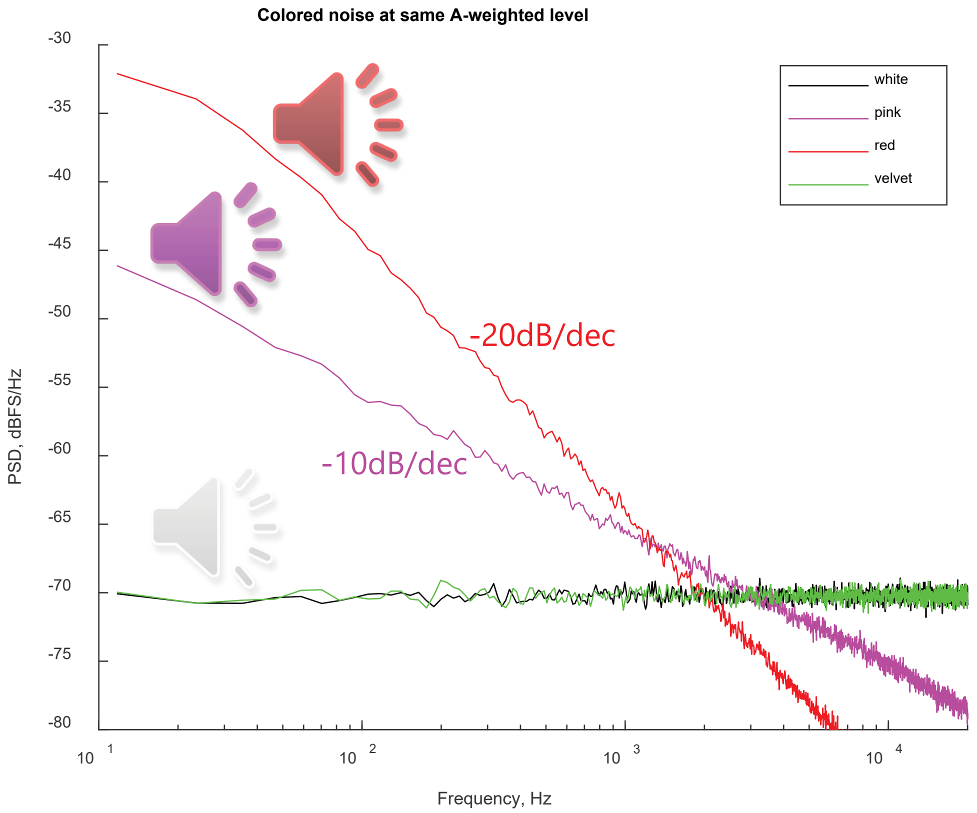
Colored noise



Red noise

- Brownian/red noise:
  - Analogy to red light
  - Created by Brownian motion process (random walk)
  - Power spectral density: $S(f) \sim \frac{1}{f^2}$
  - Power drops -6dB/oct
- Infinite power at 0 Hz → in practice saturation at low frequencies

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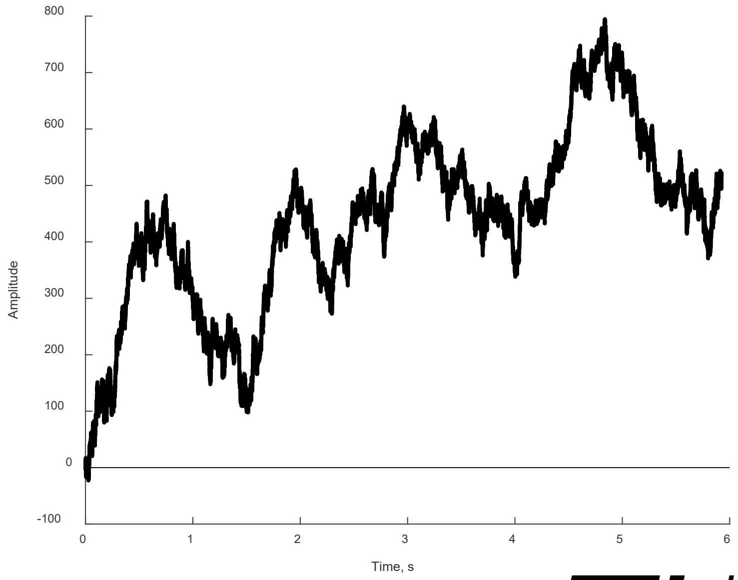
Red noise generation: Discrete-time

- How to generate red noise?
- Idea 1: Random walk: Statistically independent amplitude *increments* between samples
- Realization:
  - new sample = previous sample + random offset
  - = cumulative integration of white noise
  - Problem: signal «wandering off» Solution: *leaky* integrator



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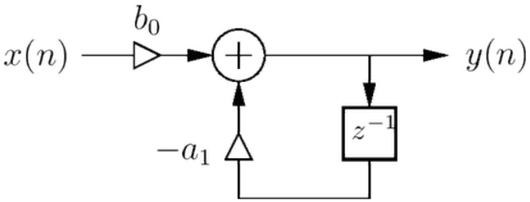
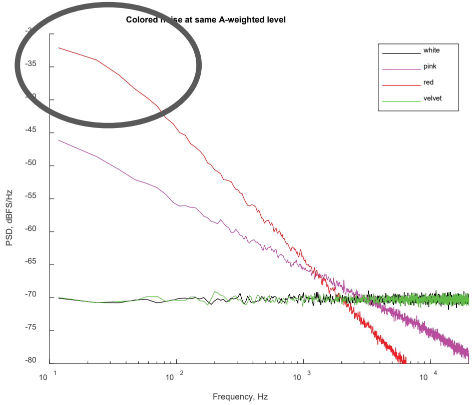
Red noise generation: Discrete-time

- Idea 2: Filtering of white noise
  - -6dB/oct → stopband of 1st order lowpass filter
  - Choose corner frequency well below relevant frequency range





$$b_0 = \frac{1}{1 + \frac{f_s}{2\pi f_c}} \quad a_1 = b_0 - 1$$

- Sampling rate 48kHz, corner frequency 20 Hz → -a1 = 0.9974

→ slightly dampened feedback → = leaking of integrator

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Pink noise generation

- Pink noise
  - Occurs often in nature → good starting point
  - Same power in frequency bands of constant relative bandwidth
  - Power spectral density: $S(f) \sim \frac{1}{f}$
  - Power drops -3dB/oct
- No exact solution, no simple elementary filter with -3dB/oct
- Different algorithms available

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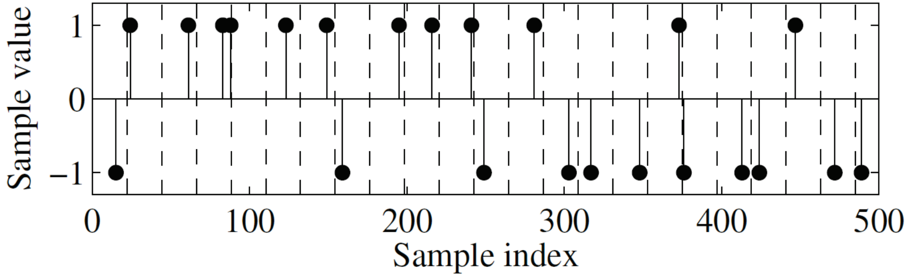
Velvet noise generation

- Sparse pseudo-random noise with white-like spectrum
- Applications in artificial reverberation (and more?)
- Discrete signal values: -1,0,1
- Only few non-zero amplitudes



[Välimäki, V. et al 2013. A Perceptual Study on Velvet Noise and its Variants at different Pulse Densities. IEEE Transactions on Audio Speech and Language Processing, 2013]

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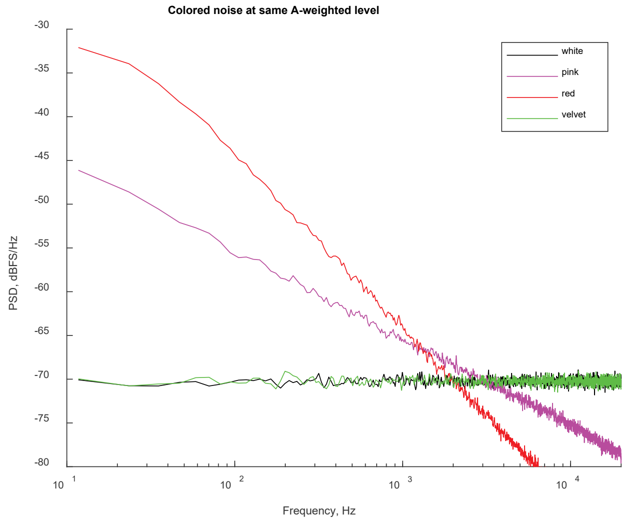
Velvet noise generation

- Parameter: spike density
- Velvet noise (4000 spikes/s) vs. white noise
- Sounds smoother than white noise…

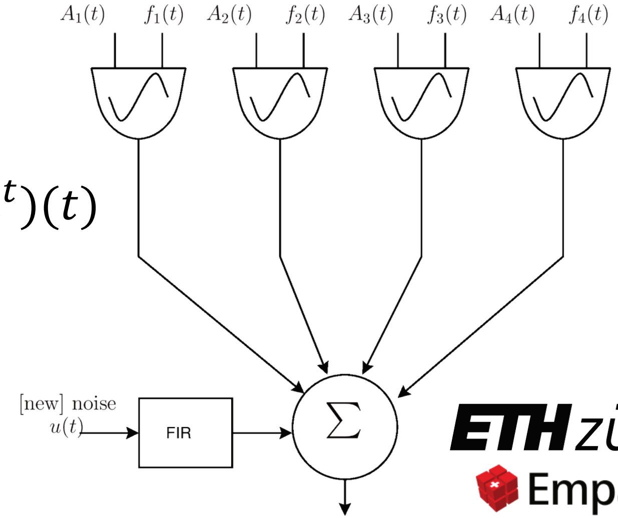


Spectral modeling synthesis

Spectral modeling synthesis (SMS)

- Combination of additive and subtractive synthesis
- Modelling time-varying spectra as combination of deterministic and stochastic component
- Sum of sinusoids plus colored noise

$$x(t) = \sum_{i=1}^{N} A_i(t)\sin[\varphi_i(f_i, t) + \theta_i(t)] + (u * h^t)(t)$$



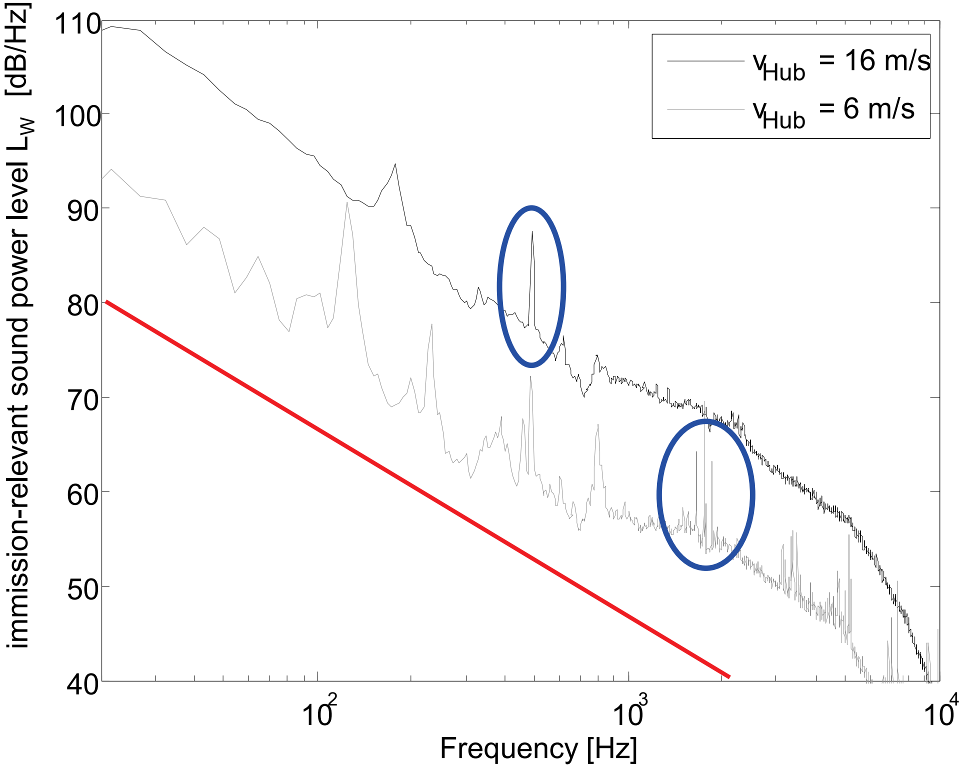
[Serra, X. & Smith III, J. 1990. Spectral Modeling Synthesis: A Sound Analysis/Synthesis System Based on a Deterministic plus Stochastic Decomposition. Computer Music Journal, 14(4).]

Example:
Wind turbine noise

[Pieren, R., Heutschi, K. et al. 2014. Auralization of Wind Turbine Noise: Emission Synthesis, Acta Acustica united with Acustica, 100]

Wind turbine source sound characteristics

- Sound signal characteristics
  - Red-like spectrum
  - Discrete tones
  - Amplitude modulations



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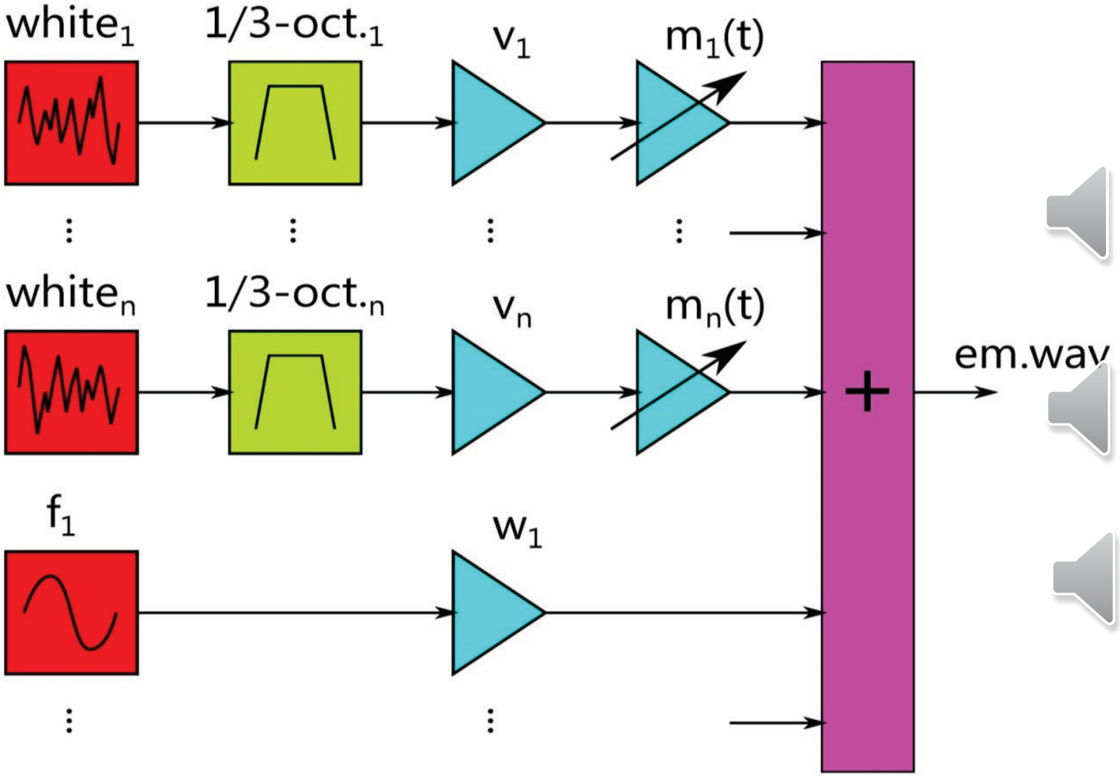
Wind turbine sound synthesis using SMS



Recording
(Vestas V90-2MW
Strong wind, 150 m distance)

Synthesis

Synthesis
(increased AM)

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Application: Auralization of virtual wind farms

100 m

200 m

350 m

600 m

Example: Passenger car noise

[Pieren, R., Bütler, T. & Heutschi, K. 2016. Auralization of accelerating passenger cars using spectral modeling synthesis. Applied Sciences, 6(1).]

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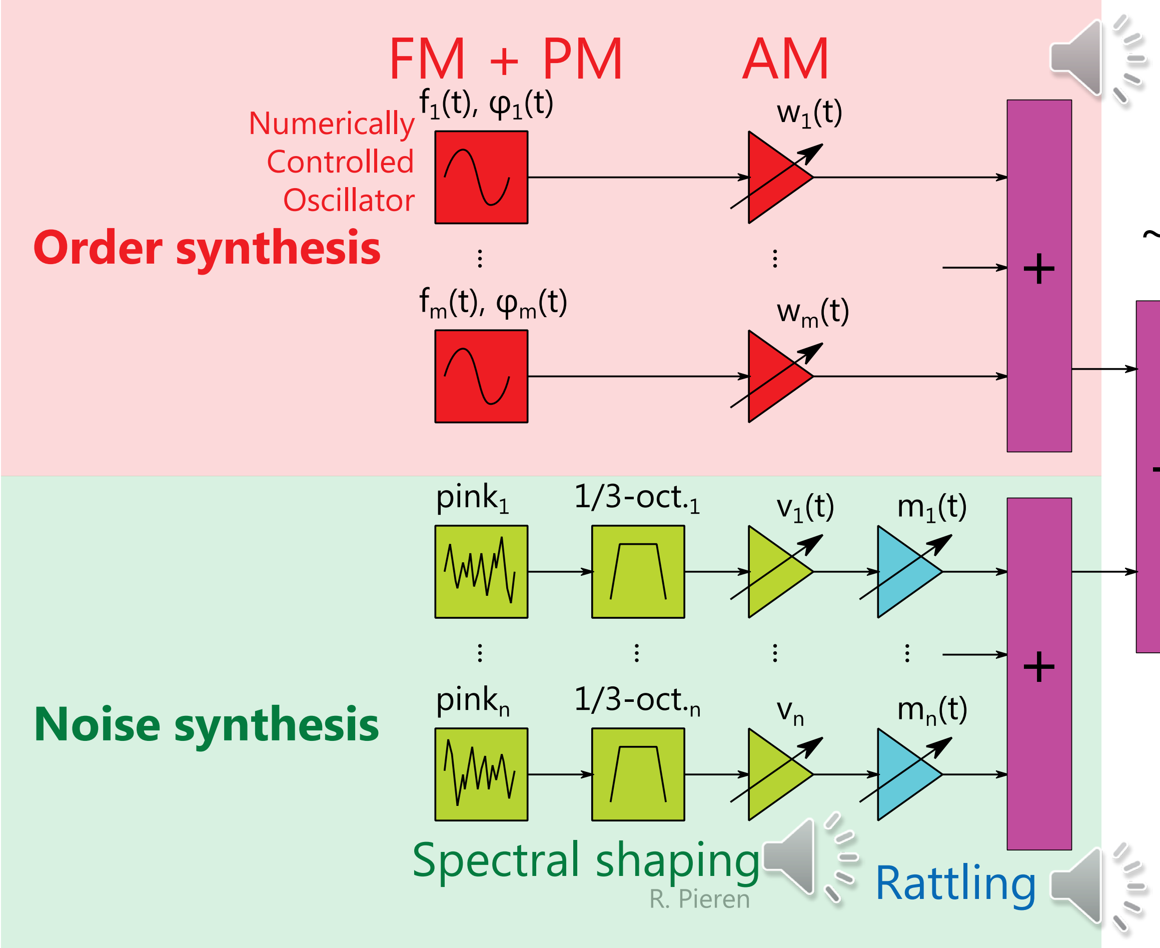
Passenger car sound synthesis

- Separate synthesis of
  - Tyre/road interaction sound and
  - Propulsion sound:

Examples	Recording	Synthesis
Petrol-engined car full load at 2000 rpm back mic		
Diesel-engined car idling at 1500 rpm front mic		

Propulsion sound synthesis using SMS



~200 parameters

Sweep:
900→2700 rpm

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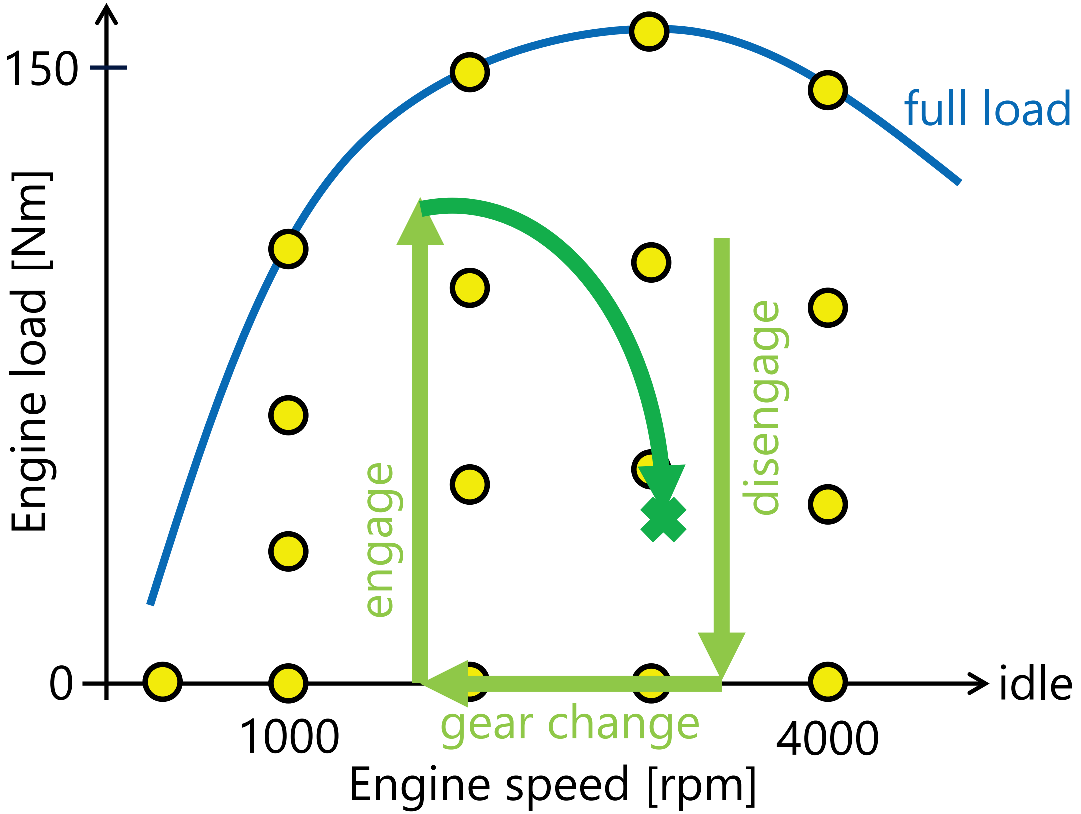
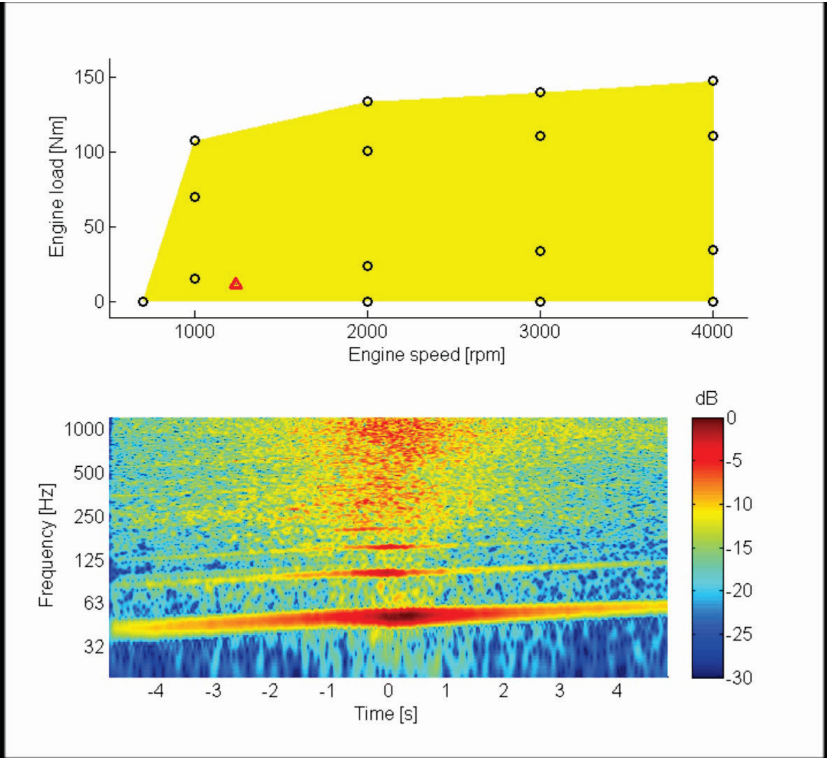
Chassis dynamometer measuring points



Auralization of accelerating passenger car

0.5 m/s², eco driving style



Ford Focus 1.8i, Michelin Alpin A4, 7→50 km/h

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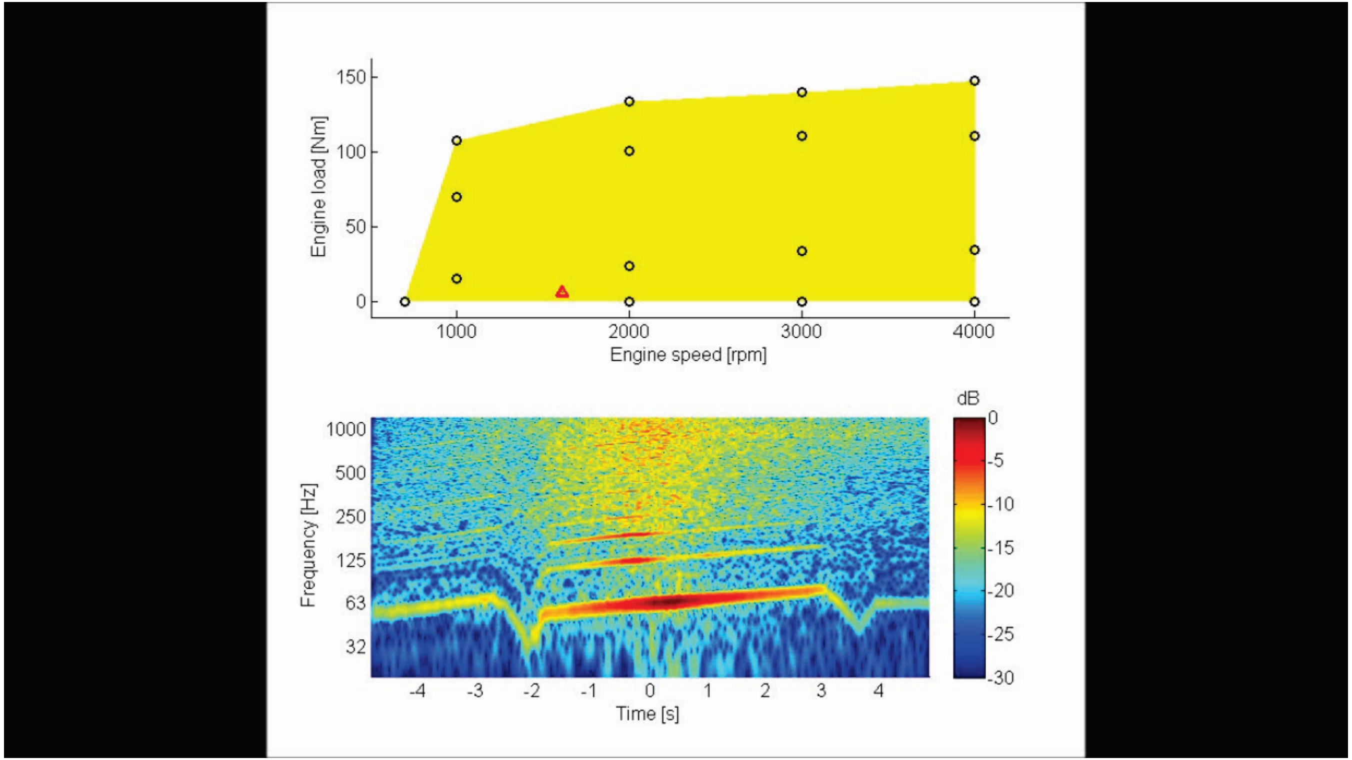
Auralization of accelerating passenger car

1.0 m/s², medium driving style



Ford Focus 1.8i, Michelin Alpin A4, 7→50 km/h

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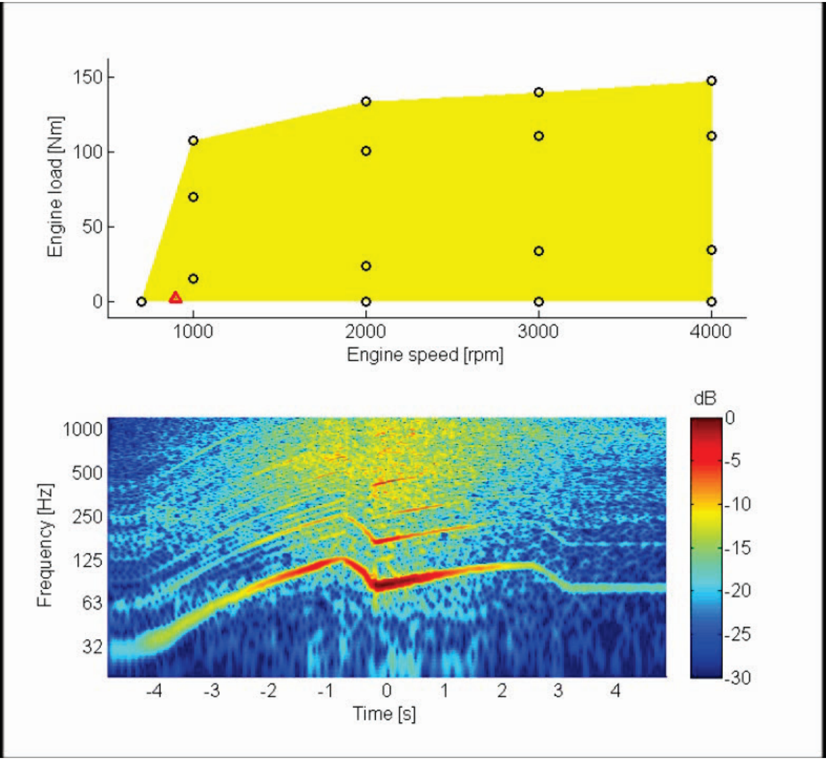
Auralization of accelerating passenger car

2.0 m/s², sportive driving style



Ford Focus 1.8i,
Michelin Alpin A4,
7→50 km/h

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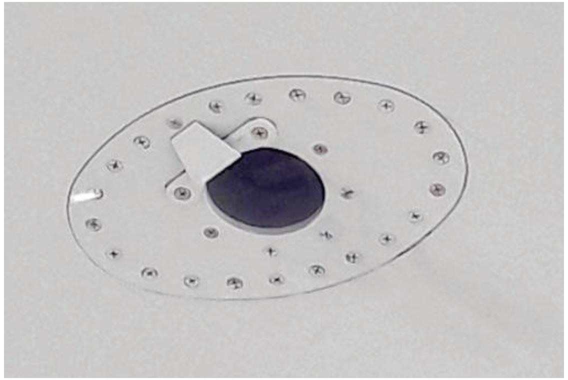
Example:
Aircraft noise

[Pieren, R., et al. 2019. Improving future low-noise aircraft technologies using experimental perception-based evaluation of synthetic flyovers. Science of the Total Environment, 692.]

Aircraft noise: Cavity tones

- Parasitic, narrow-band aeroacoustic airframe noise source
- Airflow-excited Helmholtz resonators
- Best documented case:
  - Wing cavity tones in A320 family
  - 4 openings in lower wing surface (FOPP)

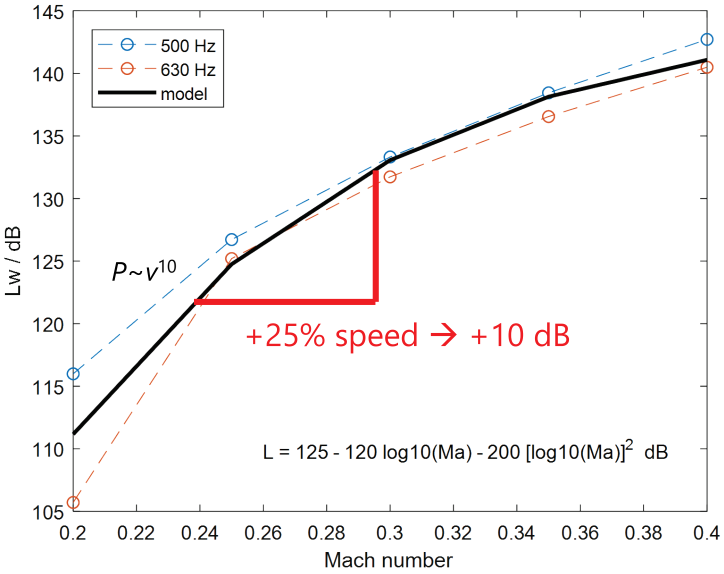


Fuel tank Over Pressure equalization Port (FOPP) of A320 with installed vortex generator

Recording of approaching aircraft:

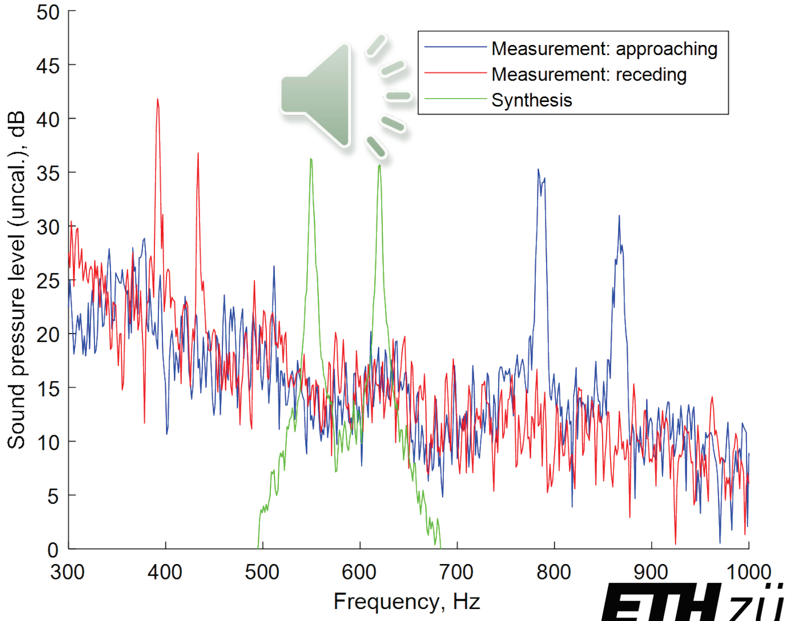
Aircraft noise: Cavity tones

- Measurement data on A320 family:
  - Two frequency components around 600 Hz
  - Bandwidth 1–3 Hz
  - Sound power: strong airspeed dependence



Aircraft noise: Cavity tone synthesis

- Subtractive synthesis using resonance filters
  - Controlled peak frequencies, bandwidths and powers
  - Stochastic phase relations



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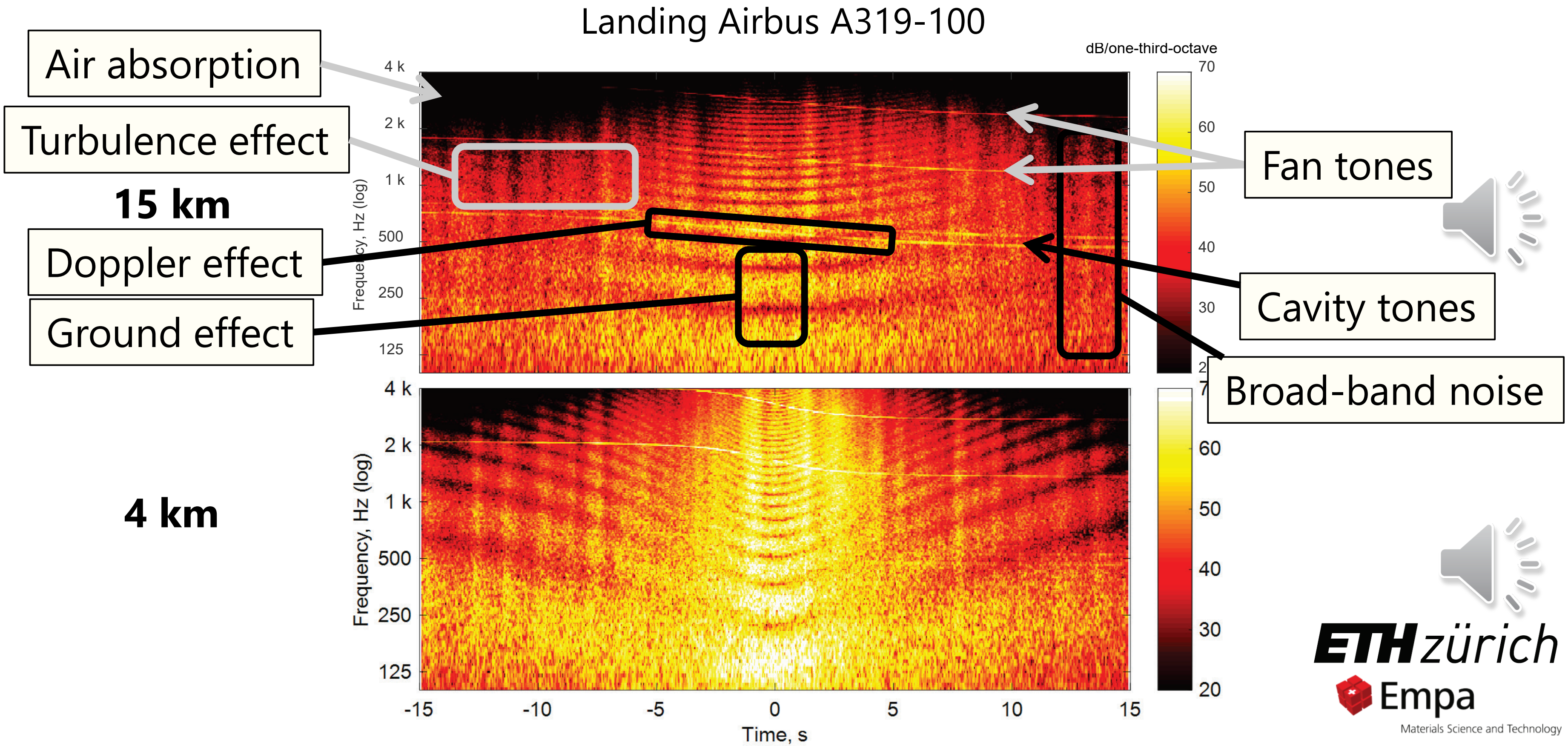
Sounds of virtual aircraft flyovers



3. Physics-based synthesis

Physics-based synthesis

- Simulation of physical sound generation processes
- Mainly used for musical instruments
  - Stringed instruments using delay lines or FDTD
  - Percussion
  - Voice, but still with limited quality

Example:
Railway noise synthesis

[Pieren, R., Heutschi, K., et al. 2017. Auralization of railway noise: Emission synthesis of rolling and impact noise. Applied Acoustics, 127.]

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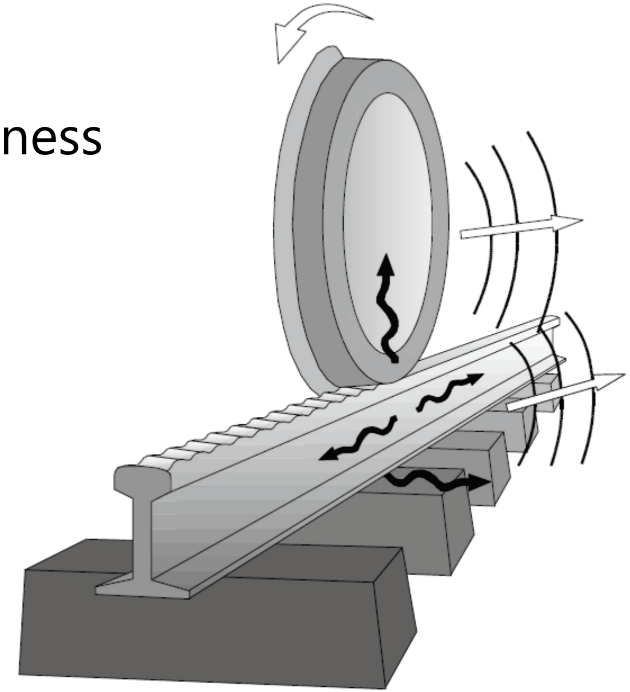
Railway noise synthesis: Rolling noise

- Most relevant source
- Wheel and rail unevenness leading to vibrations



[Thompson, D. 2008. Railway Noise and Vibration. Elsevier Science.]

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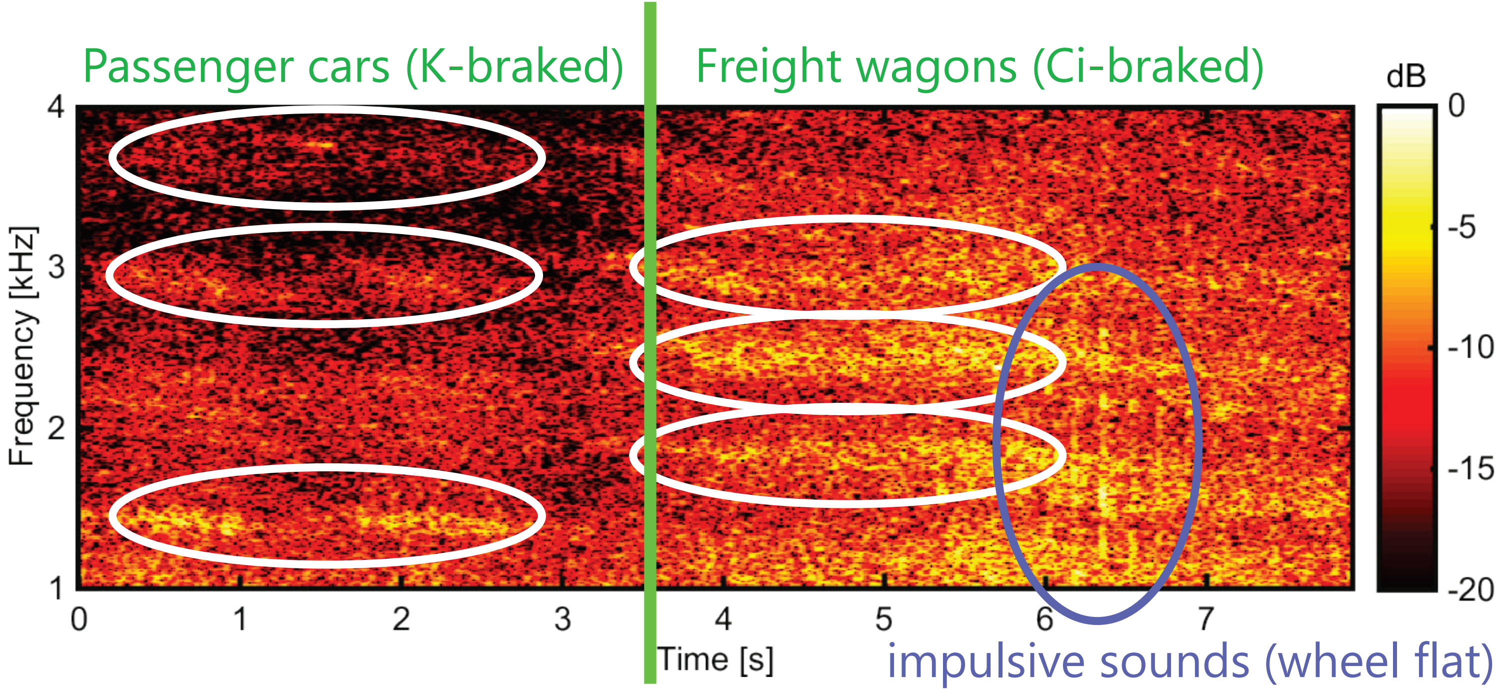
Railway noise synthesis: Spectro-temporal patterns

Train passby: Excerpt of sound pressure recorded at 7.5 m



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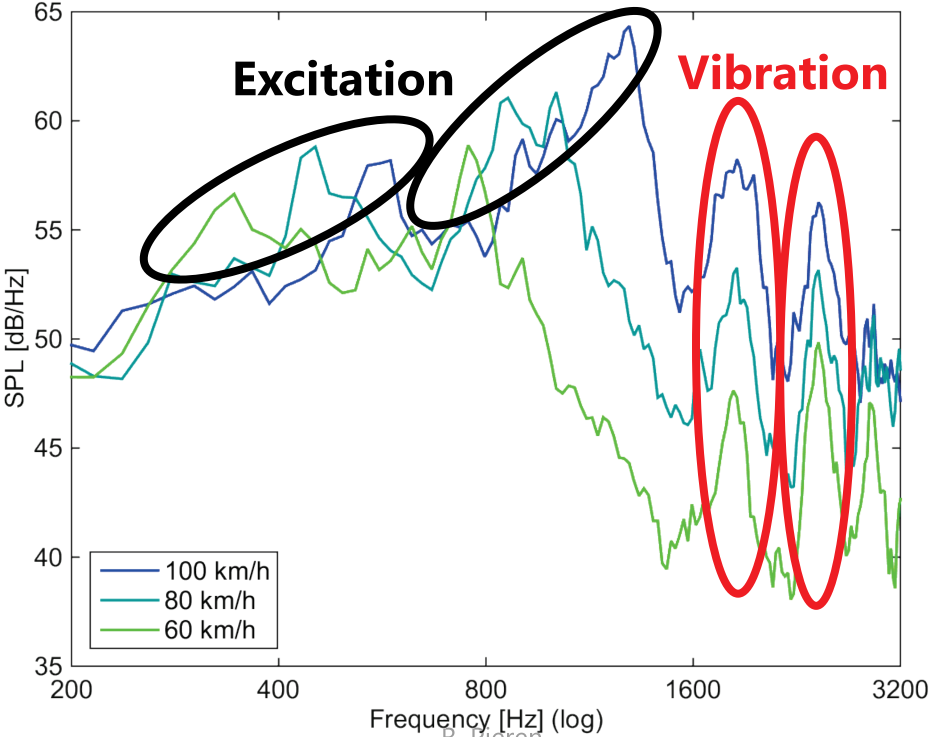
Railway noise synthesis: Spectro-temporal patterns

SPL spectra of flat freight wagons at different travelling speeds



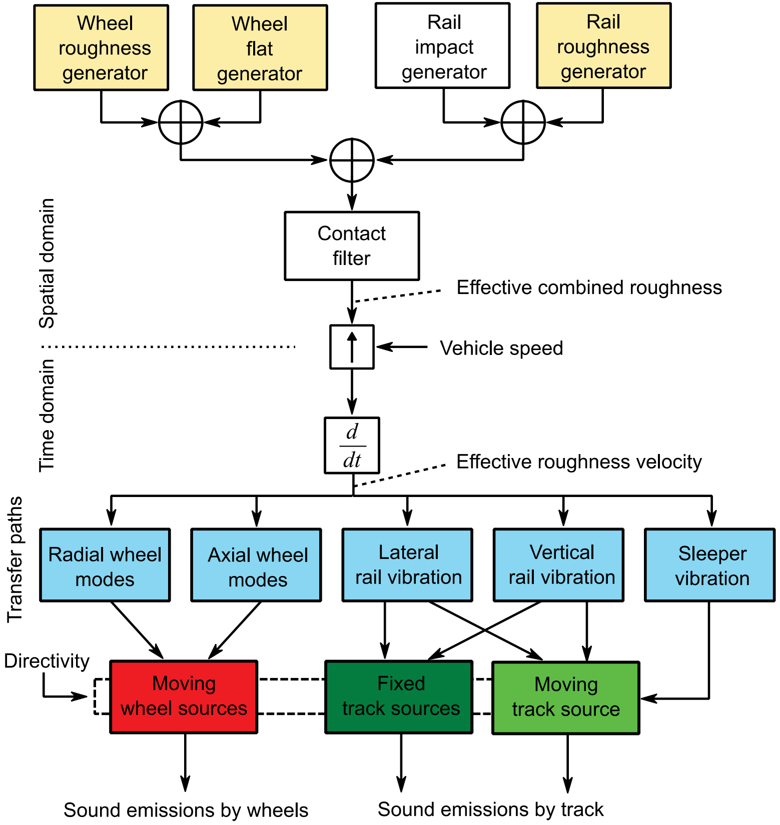
Railway rolling noise synthesis: Approach

- Excitation and vibration related effects → Motivation for a physics-based approach

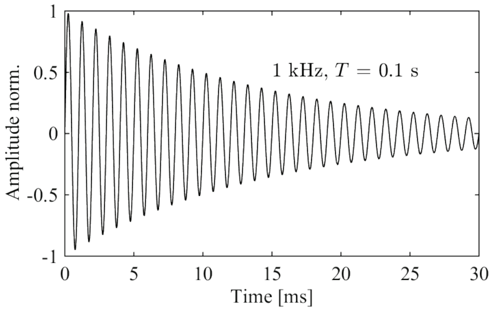
Physical approach

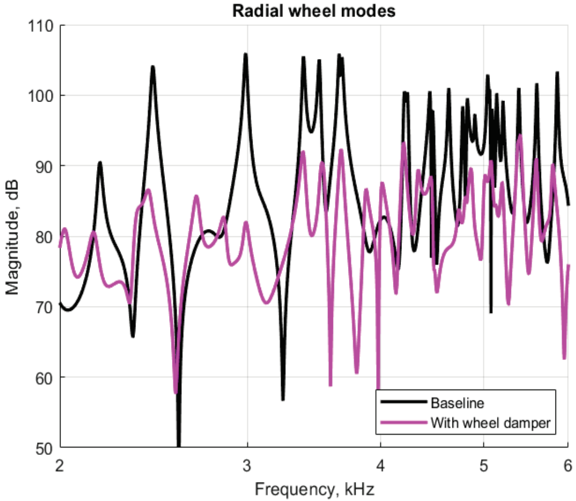
1. Generation of surface microstructure of rail and wheels
2. Determination of mechanical excitation of track-wheel structure
3. Transformation from spatial into time domain
4. Modal behaviour of the structure
5. Radiation

Railway rolling noise synthesis



Modal resonator





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Horizon 2020 European Union Funding for Research & Innovation

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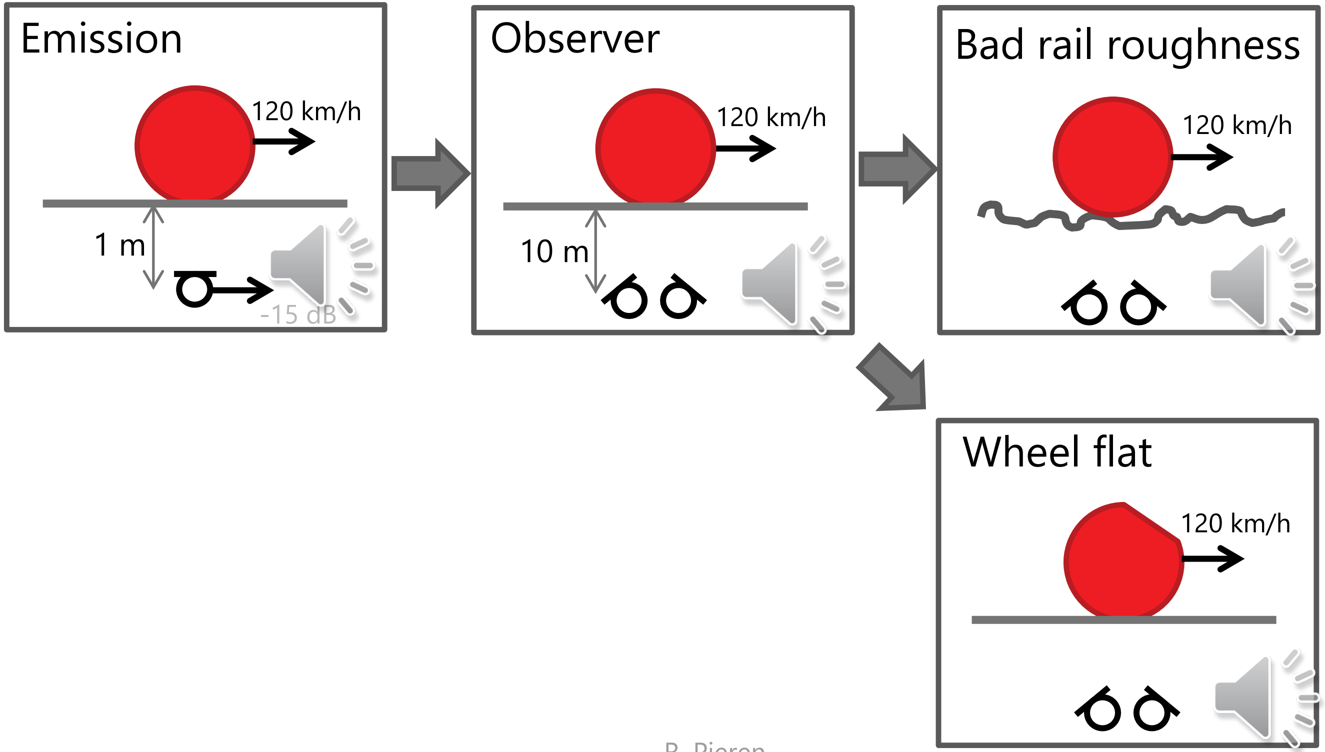
Railway rolling noise synthesis: Examples



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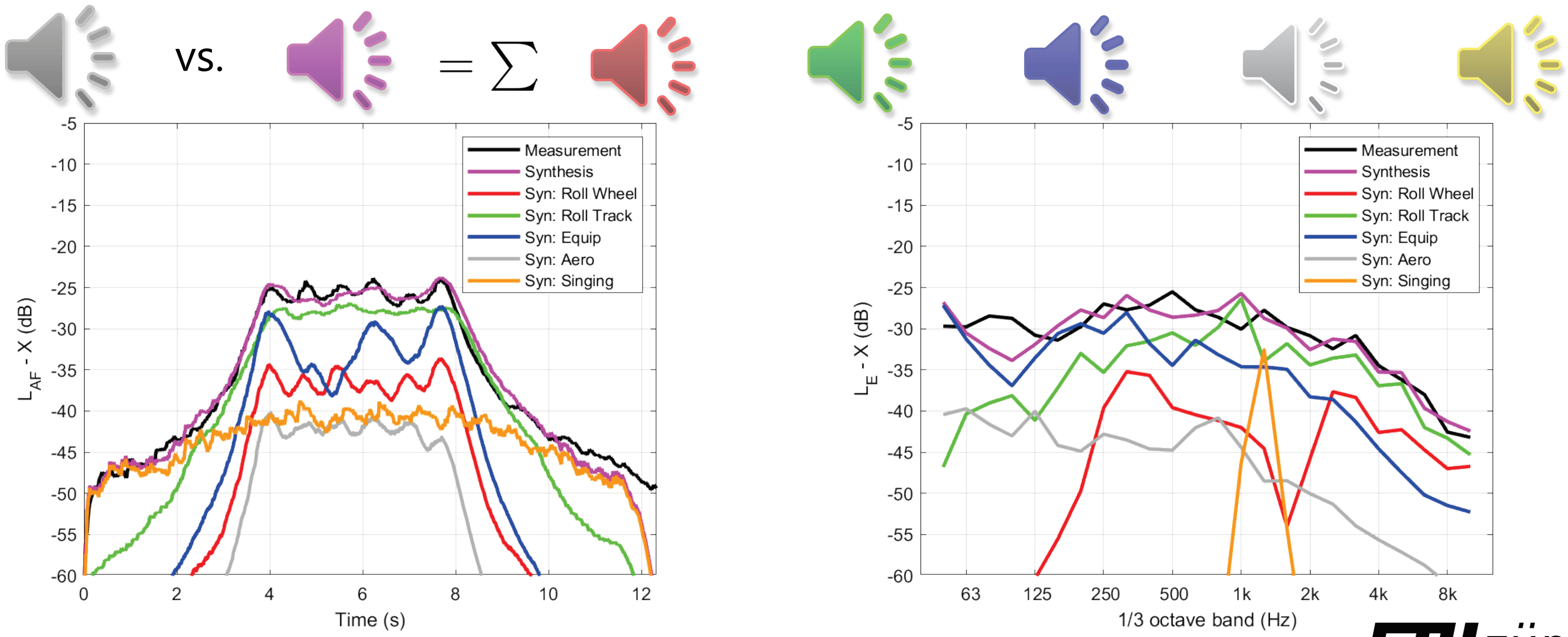
Train pass-by noise synthesis example



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