Estimating the radiated underwater noise of seagoing platforms: The physics behind signal analytic approaches

Carsten Zerbs, Andreas Müller, Ingmar Pascher
Müller-BBM, Hamburg and Planegg (near Munich)

Introduction

- Modelling the acoustic signature of ships – requirements, assumptions for different tasks.
- Two examples:
  - UWRN predictions in the (early) design phase
  - Calculating estimates of the acoustic signature
- In both examples, assumptions and simplifications must be made
  - Data reduction
  - Simple description of the source, transfer behaviour and radiation
  - Minimization of the number of measurement positions
  - …

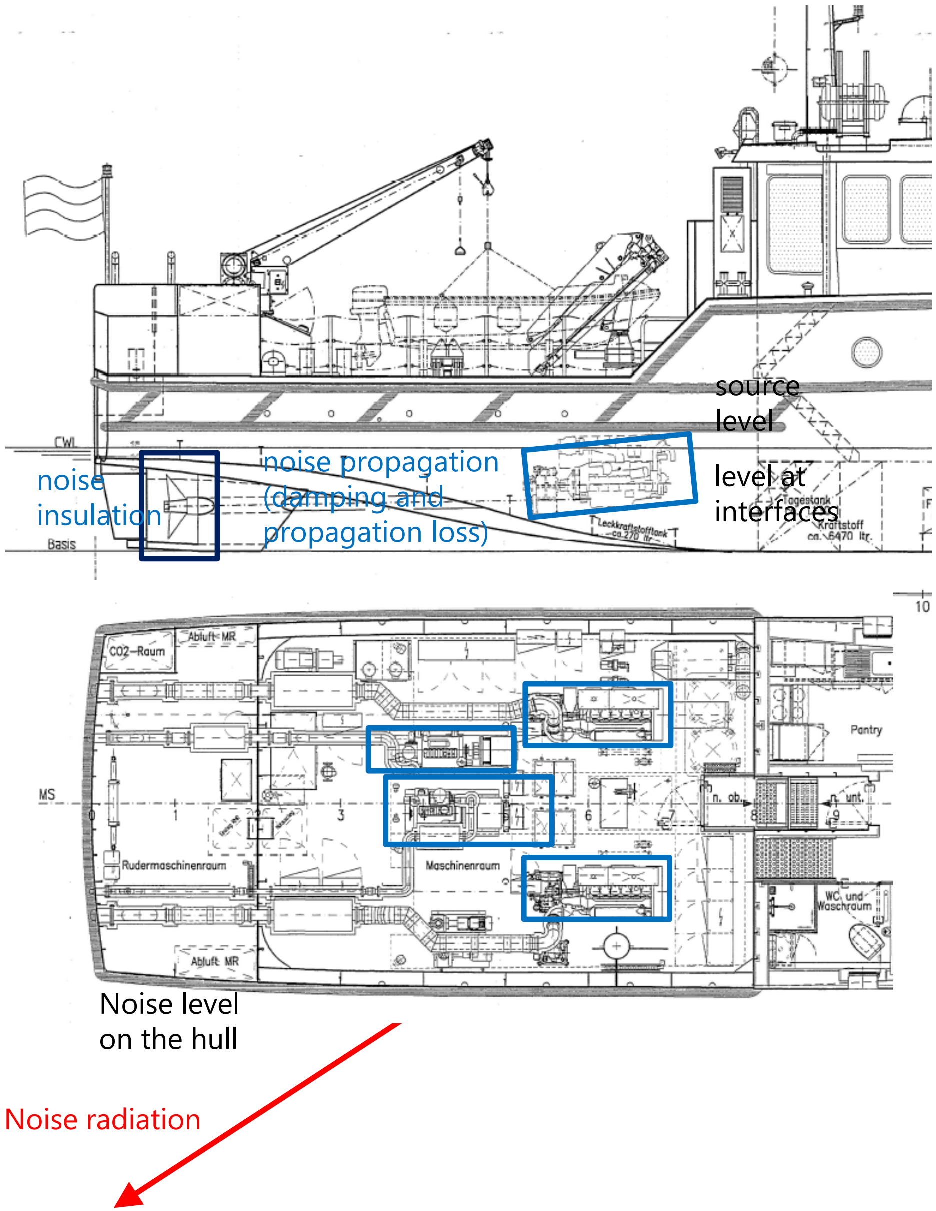
Underwater Noise Prediction Techniques

- Underwater noise predictions of the underwater radiated noise of ships are required in different project phases.
- *Design stage* for new ships
  - Prediction of underwater radiated noise based on
  - Relatively sparse information on:
    - Machinery
    - Ship structure: foundation, hull design, …
    - Noise insulation: elastic decoupling of machinery, acoustic insulation
- *Operational phase*
  - Calculated estimates of the current signature, based on measurement: SBN of noise source
- Predictions in both phases require some assumptions and simplifications, but …

Typical situation

Noise sources on vessels

- (Diesel-) generators
- Propulsion motor
- Auxiliary equipment (hydraulic compressors, cooling compressors pumps, …)
- AC
- Propeller, other drives (pump jet, …)
- Fluid-structure-coupling – excitation of ship structure by fluid / flow



Acoustic requirements

System requirements	according to	Standards, regulations (examples)	Objectives
Airborne noise (Noise level in rooms)	Standards, regulations, specification	BV 0450 (2003) STANAG 4294, IMO, (MIL-STD 740-1)	Workplace safety speech intelligibility recreation
Vibrations	Standards, regulations, specification	ISO 6954 (2000) (MIL-STD 740-2)	Workplace safety Comfort
Target level	**Navy (specifications), regulations**	**ICES 209**	**min. detection range, Safety of crew and ship, objects of protection**
Sonar self noise	Manufacturer / navy		Signal-noise-ration of sonar system

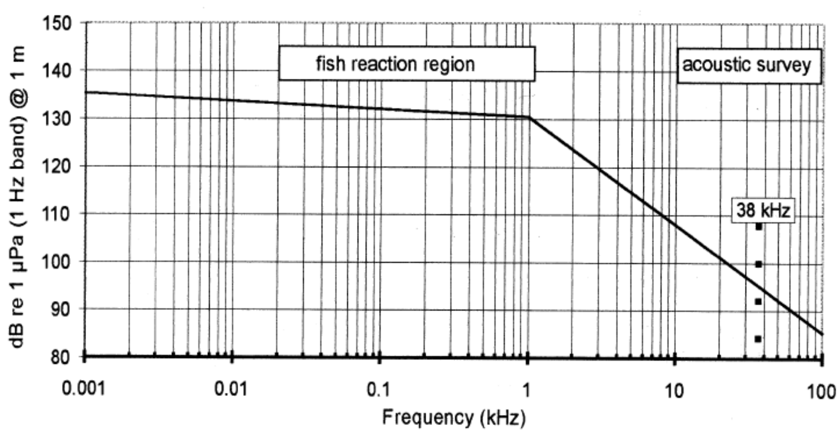
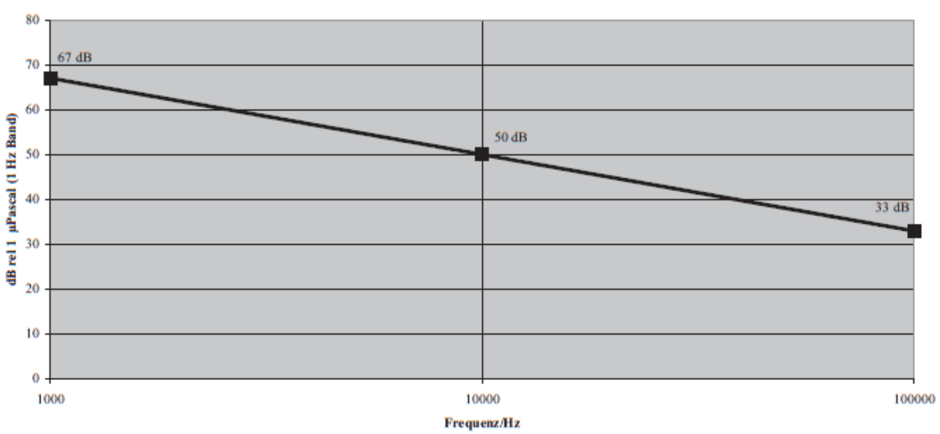


Figure 22. Proposed underwater radiated noise specification at 11 knots free-running for all vessels used in fisheries research.

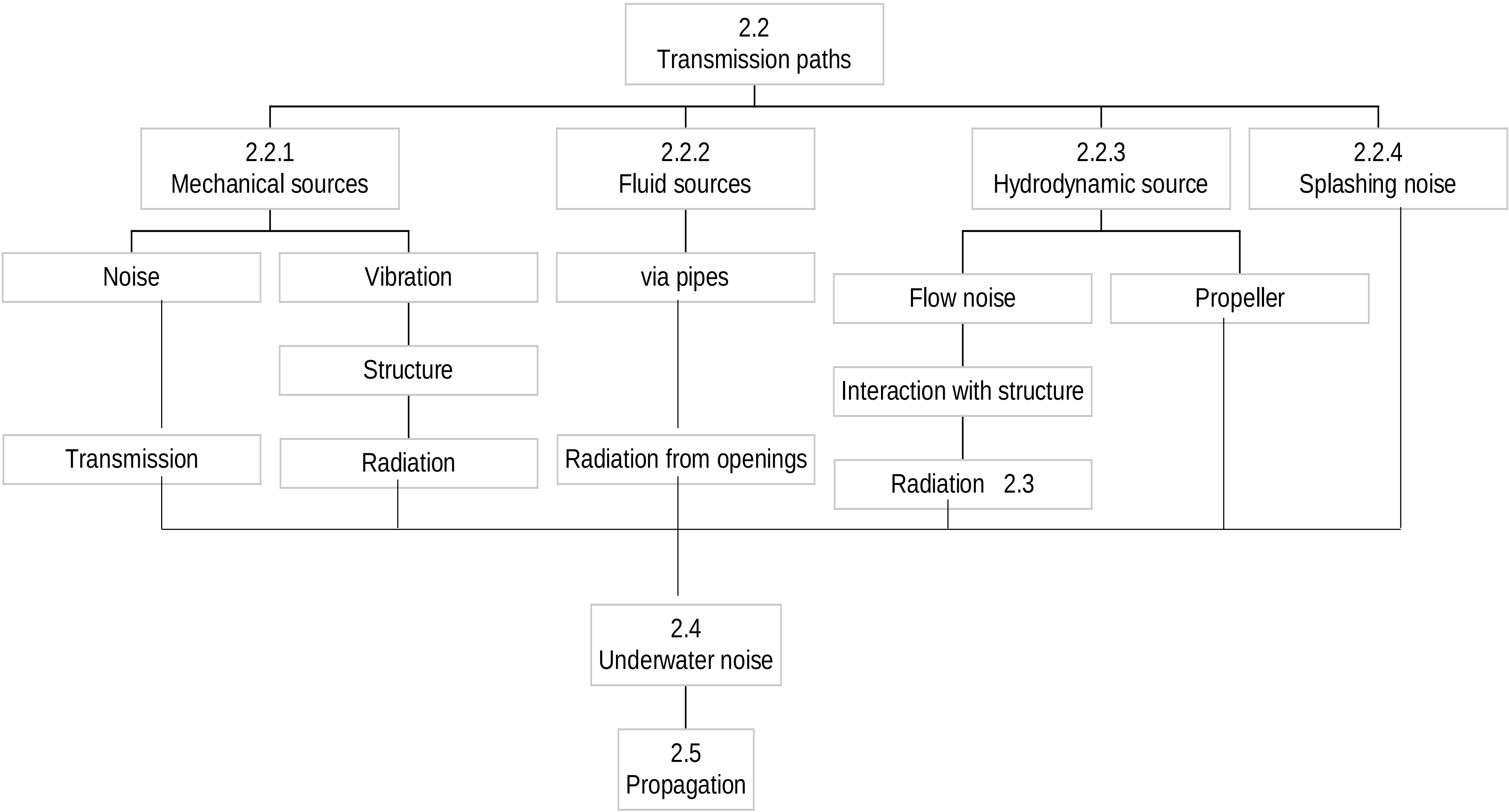


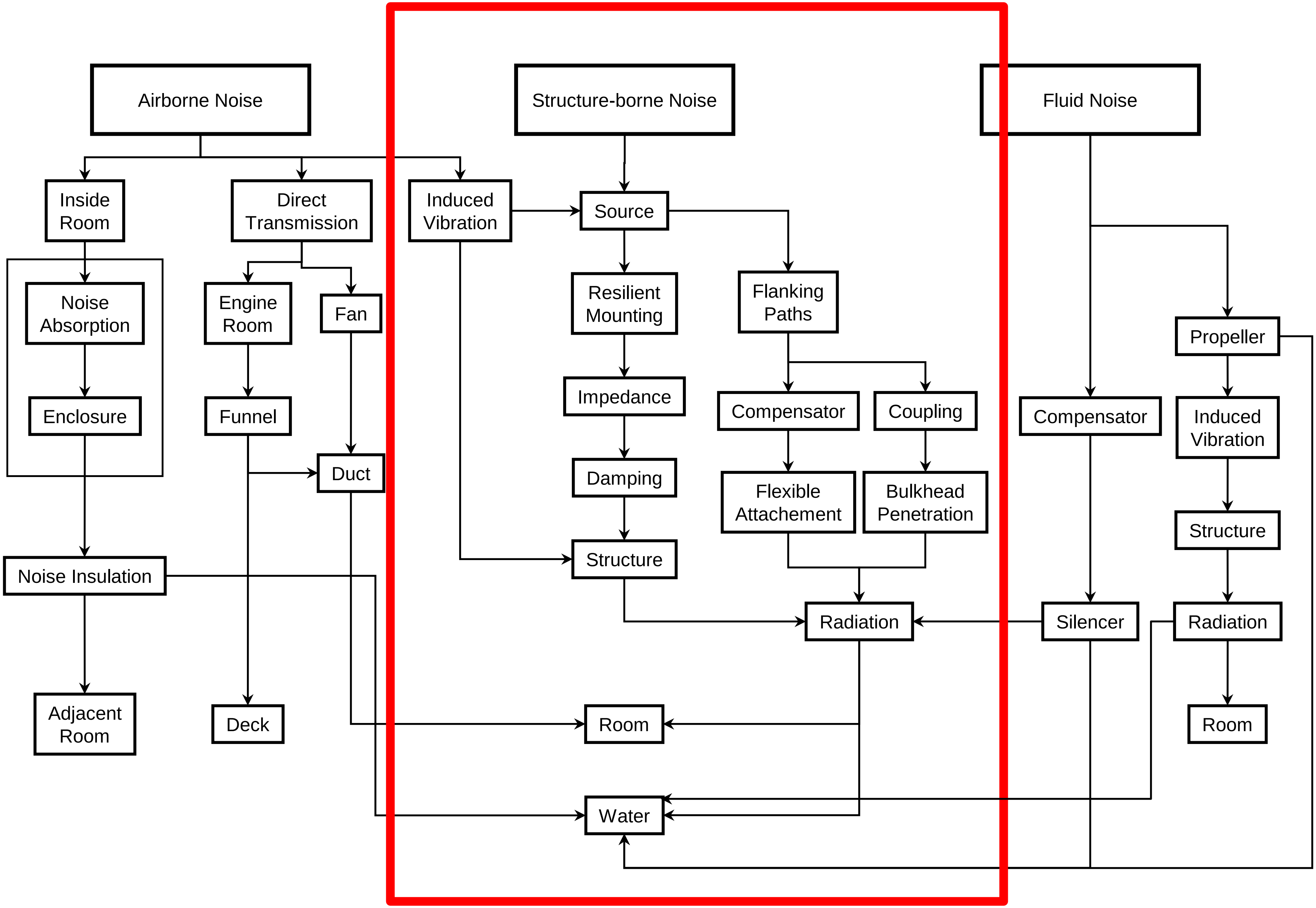
Design Phase
Requirements on Noise Prediction

Requirements on predictions during design phase

- Accuracy
  - Depending on the project phase, at least to a certain extent
  - It is important, that differences between variants are considered accurately (relative accuracy – improvements and degradation)
    - For example, the early design phase, sound insulating measures have to be configured and compared
- Flexibility
  - Simple setup
  - If input data is not available, a data base of typical variants is required (noise sources, impedances, mounting elements, ..., radiation efficiencies)
  - Fast calculation. For the assessment of variants, quick repetition of calculation for modifications is required
  - Allows integration of new results (e. g. results from numerical simulations of sub-structures, results from test stands, ...

Classification of noise sources and propagation paths





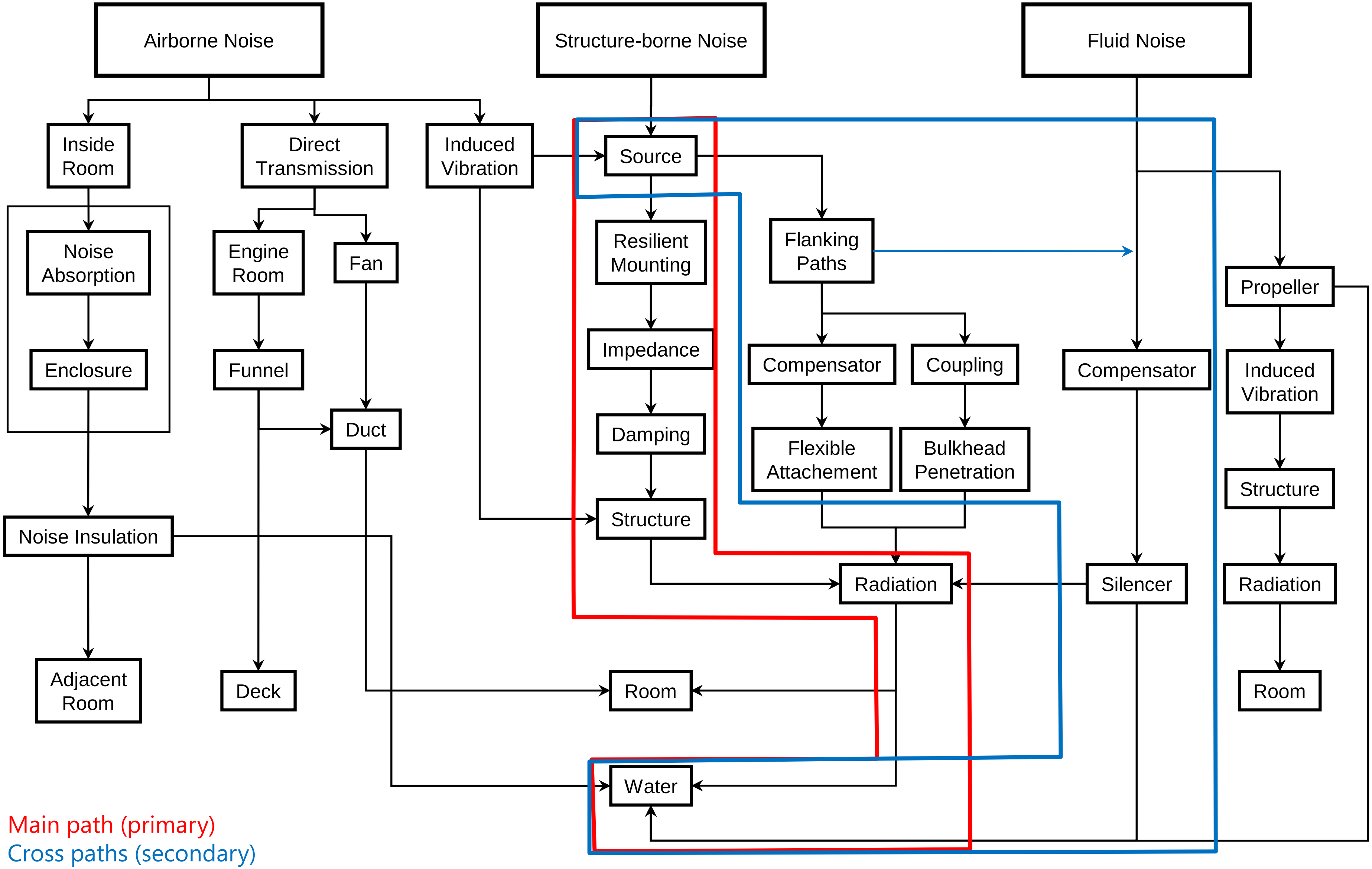
Airborne Noise
Structure-borne Noise
Fluid Noise
Inside Room
Direct Transmission
Induced Vibration
Source
Noise Absorption
Engine Room
Fan
Resilient Mounting
Flanking Paths
Propeller
Enclosure
Funnel
Impedance
Compensator
Coupling
Compensator
Induced Vibration
Duct
Damping
Flexible Attachement
Bulkhead Penetration
Structure
Noise Insulation
Structure
Radiation
Silencer
Radiation
Adjacent Room
Deck
Room
Room
Water

Early-design-phase prediction models

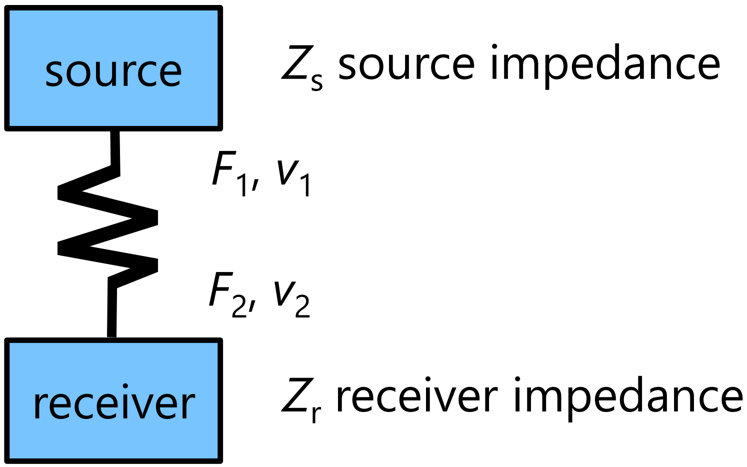
- Required properties for the description of sound generation and sound propagation
  - Properties of noise sources: source impedance, “source levels”
  - Transfer properties
- Simplifications
  - Calculation in the spectral domain, but
  - Input data (source spectra) and transfer functions are given in 1/3rd octave bands
  - No phase dependency is considered
    Calculations: transfer behaviour as level difference, superposition of contributions as level sum (energetic addition)
  - Models are restricted to the description of sound propagation via the *primary* (or main) paths, i. e. from the noise source via mounting, the ship structure and the hull into the surrounding water
  - Secondary (cross-) paths are often neglected

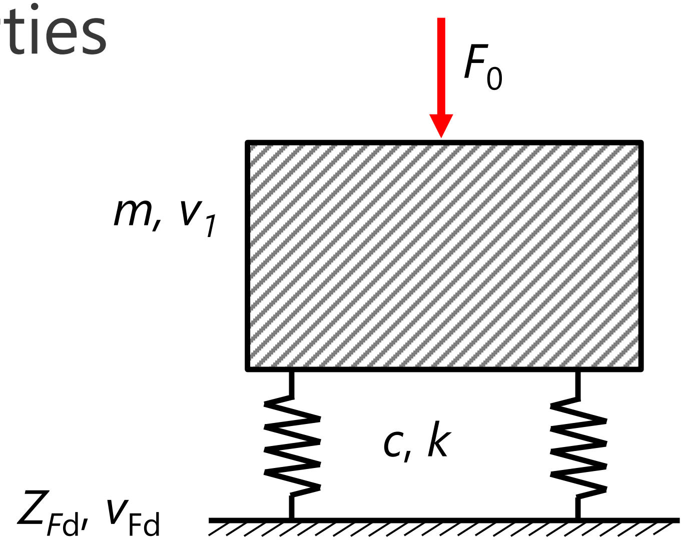
Early-design-phase prediction models

- Semi-empirical models are applied: measurement data is combined with
  - experimental data
  - or “typical data”
  - Typical transfer functions
    - Insulation of an elastic mounting – described as level difference
    - Input an transfer impedance – level difference
    - Propagation loss in the structure
      - Radiating area
    - Radiation efficiency
  - Transfer functions which are sometimes neglected in the early design phase
    - Secondary paths: pipelines, canal, hoses, cabling


Airborne Noise
Structure-borne Noise
Fluid Noise
Inside Room
Direct Transmission
Induced Vibration
Source
Noise Absorption
Engine Room
Fan
Resilient Mounting
Flanking Paths
Propeller
Enclosure
Funnel
Impedance
Compensator
Coupling
Compensator
Induced Vibration
Duct
Damping
Flexible Attachement
Bulkhead Penetration
Structure
Noise Insulation
Structure
Radiation
Silencer
Radiation
Adjacent Room
Deck
Room
Room
Water
Main path (primary)
Cross paths (secondary)

Example: source and transfer properties





$$\begin{pmatrix} F_1 \\ F_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

1 DOF oscillator $m\ddot{x} + c\dot{x} + kx = F(t) = F_0 e^{j\omega t}$

$$\frac{v_1}{v_{Fd}} = \frac{Z_{Spr} + Z_{Fd}}{Z_{Spr}} = 1 + \frac{Z_{Fd}}{Z_{Spr}}$$

$$Z_{Fd} \gg Z_{Spr} \qquad \frac{v_1}{v_{Fd}} \approx \frac{Z_{Fd}}{Z_{Spr}}$$

Source and transfer properties have to be considered in 3 dimensions

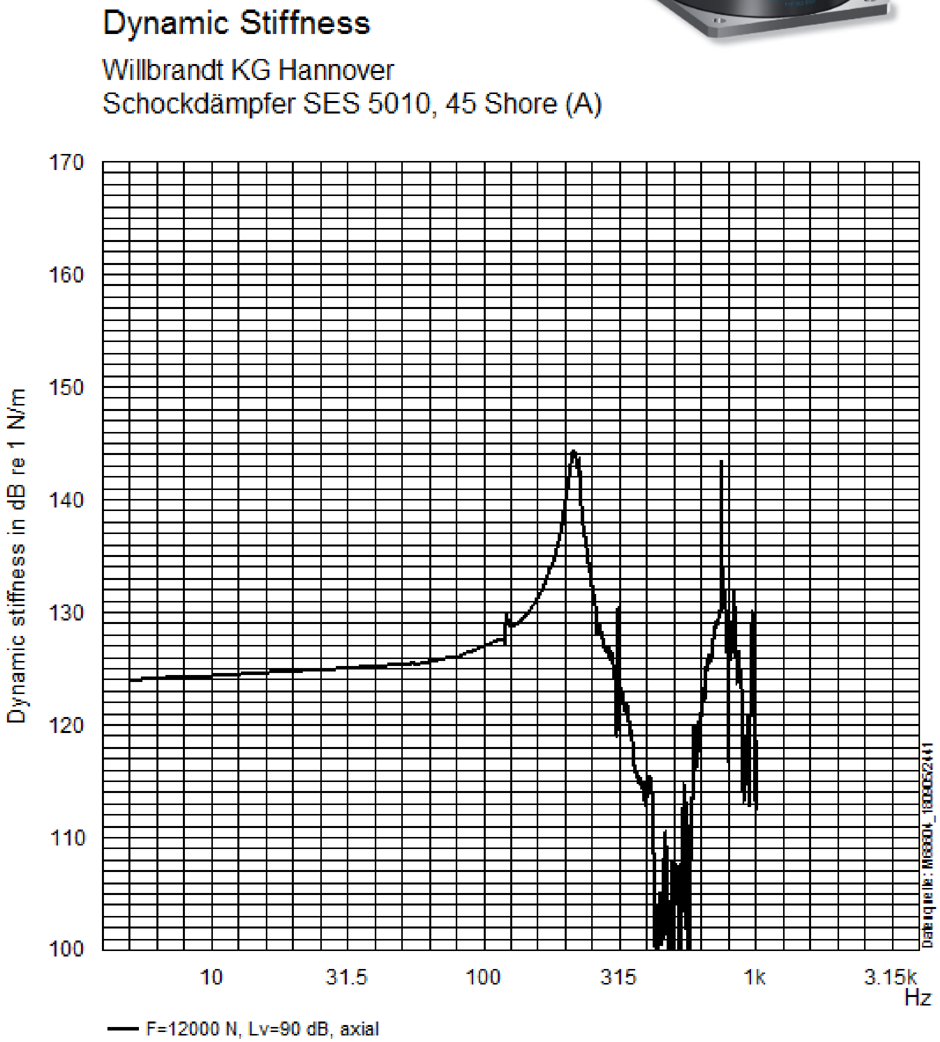
Transfer stiffness of spring elements

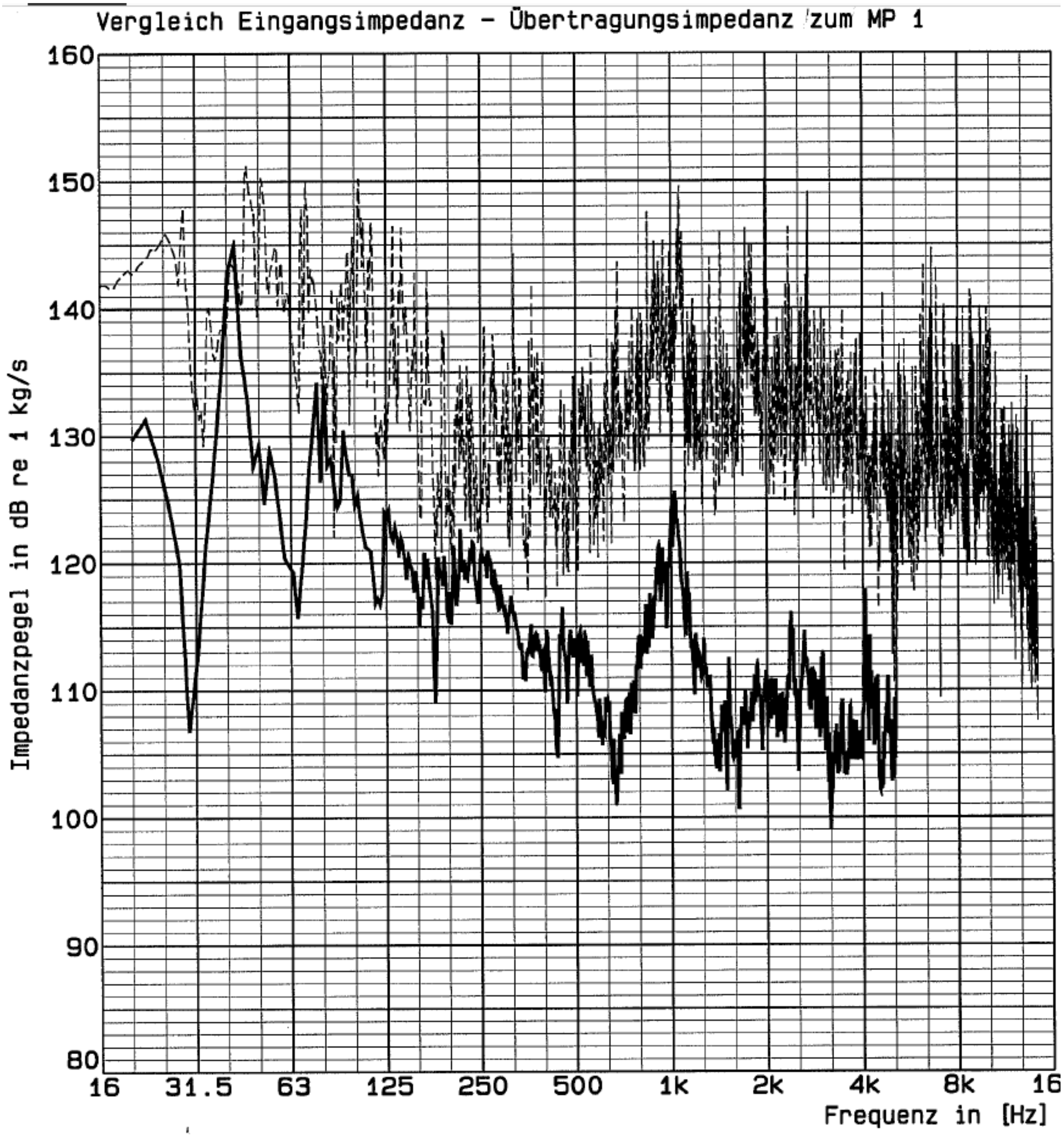
- With the definition of the impedance, the velocity of the foundation becomes

$$v_{\mathrm{Fd}} = \frac{\tilde{F}_{\mathrm{out}}}{Z_{\mathrm{Fd}}} = v_1 \cdot \frac{s_{dyn} / \omega}{Z_{\mathrm{Fd}}}$$

$$\frac{v_{Fd}}{v_1} \approx \frac{Z_{Sp}}{Z_{Fd}} \ll 1$$

- The ratio of s_{dyn}/ω is also defined as an impedance quantity (*dynamic transfer spring impedance*)
- The dynamic spring stiffness s_{dyn} is available for many elastic elements (e. g. in manufacturer catalogue)





Transfer impedance (to hull)

Input impedance (foundation)

Radiation efficency

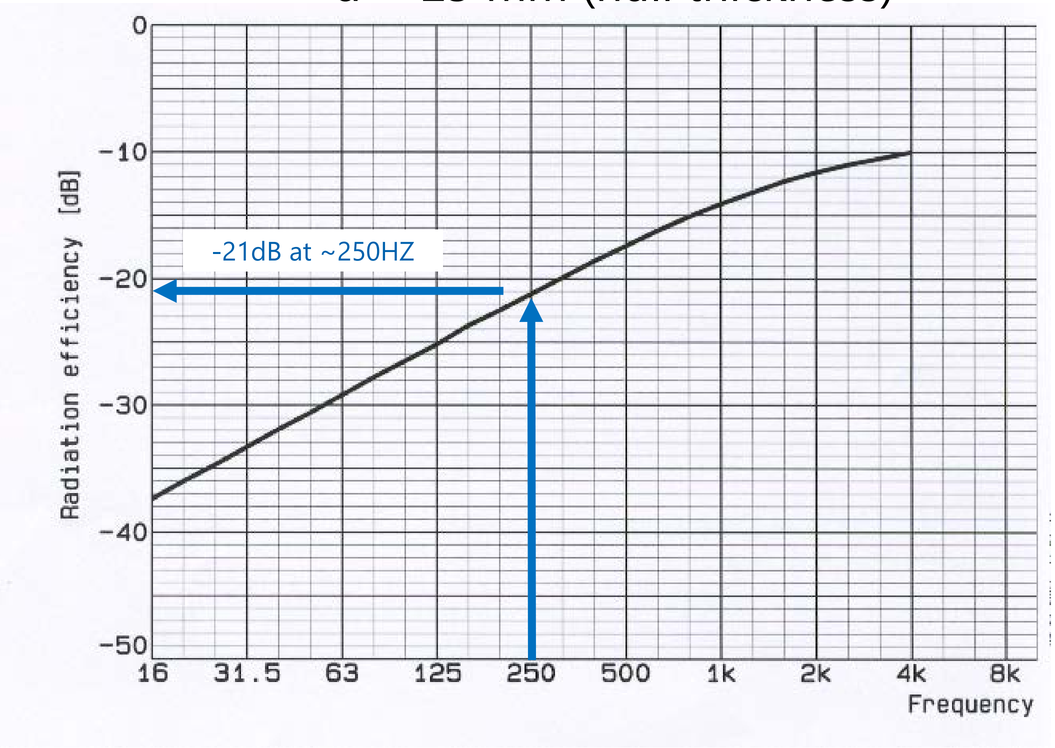
- The radiated underwater noise caused by hull vibration is

$$p^2 = (\rho \cdot c)_W^2 \cdot \sigma \cdot \frac{S_R}{S_M} \cdot v$$

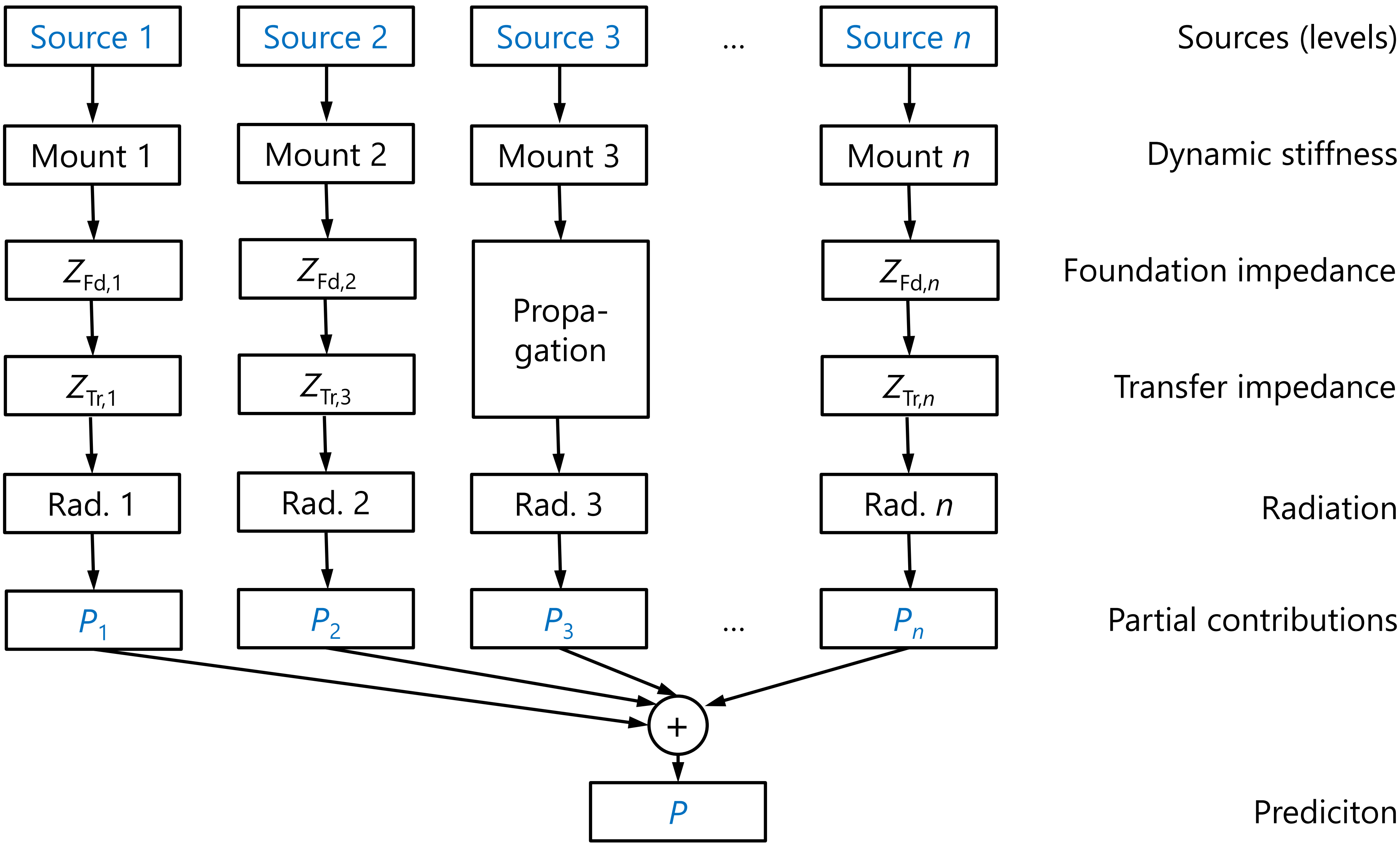
S_R = radiating area
S_M = measuring area

- The radiation efficiency can be taken from tables or estimated via rules of thumb

Example: l = 0.45 m (frame distance)
d = 25 mm (hull thickness)



Simplified URN prediction model



Signature Monitoring Requirements on Noise Estimates

Monitoring of the acoustic signature of ships

- Real-time-monitoring the acoustic signature of ship means calculating an (online-) prediction of the radiated UWN
- Different *signal analytic* methods and algorithms algorithms were investigated and implemented (only to mention some keywords).
  - Principal Component Analysis (PCA),
    "Classical" Transfer Path Analysis
    Operational Transfer Path Analysis (OTPA),
    Energetic Transfer Path Analysis (ETPA)
- Implementation of the prediction model required several steps
  - Calibration measurements: simultaneous measurement of excitation (on board) and signature, typical: Heggernes test trial
  - Data adjustment (lab)
  - Building the model, implementing on the on-board measurement system

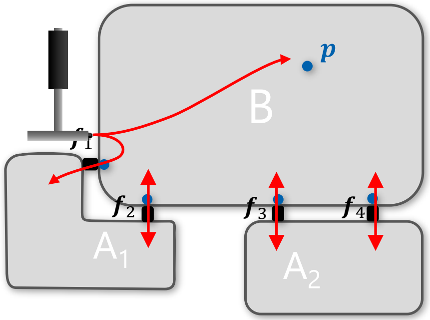
(O) TPA – motivation, application, goals

System analysis for

- Troubleshooting
- Product planning
- Quality assurance
- Sound design
- System characterization
- Contribution analysis

- Possible application:
- Automotive acoustics
  - Interior noise
  - Exterior noise
- Rail vehicles
- Agricultural engines
- **Ships**

Some aspects of classic TPA: transfer functions

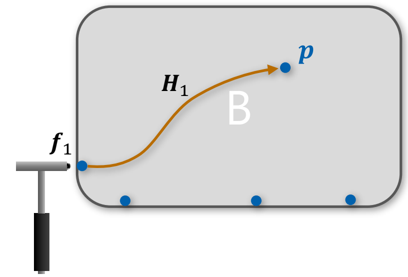


In operation:

- Simultaneous excitation of all forces

FRF measurement

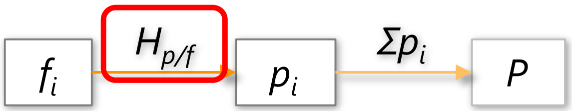
- Single replacement force f_i a position *I*
  Response p has no other source



- Excitation by hammer or shaker
- All positions measured subsequently
- $H_\mathrm{i} = p/f_i$ [Pa/N]

Measurements at the isolated system

- All other forces have to be zero
- To avoid crosstalk between adjacent measurement positions

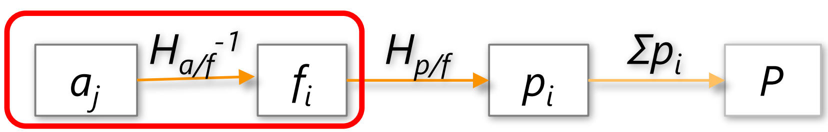


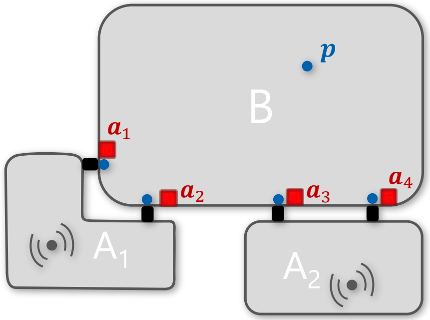
Indirect estimation of operational forces

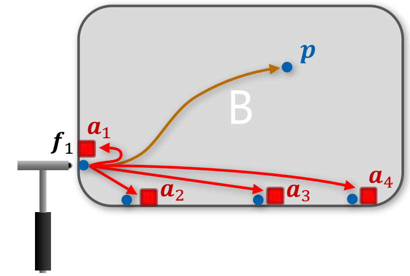
Matrix inversion

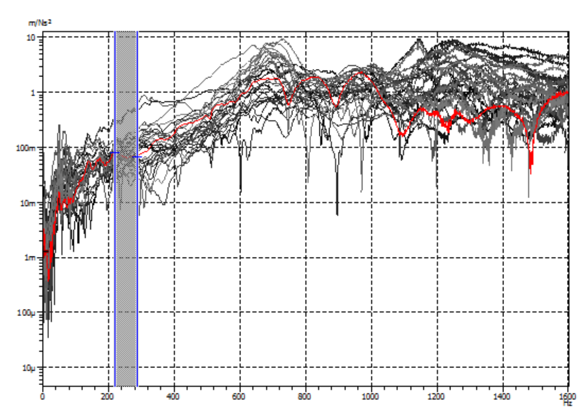
- Measurement of “indicator” or interface accelerations in operation
- Measurement of all transfer functions $H_{a/f}=\{a_j/f_i\}$
- Inversion of the accelerance matrix

$$\boldsymbol{H}_{a/f}^{-1} = \begin{bmatrix} a_1/f_1 & a_1/f_2 & \cdots & a_1/f_n \\ a_2/f_1 & a_2/f_2 & & a_2/f_n \\ \vdots & & \ddots & \vdots \\ a_m/f_1 & a_m/f_2 & \cdots & a_m/f_n \end{bmatrix}^{-1}$$

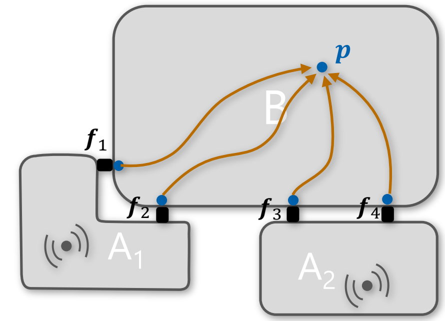






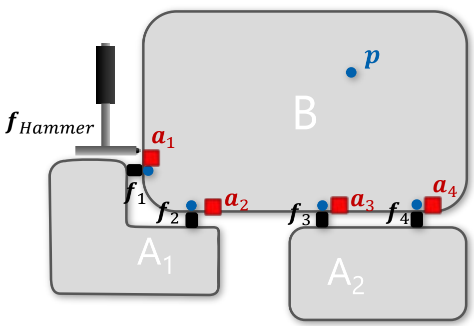


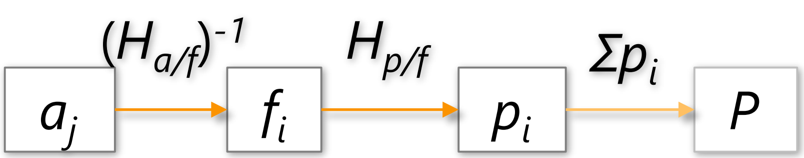
Classical TPA, matrix inversion

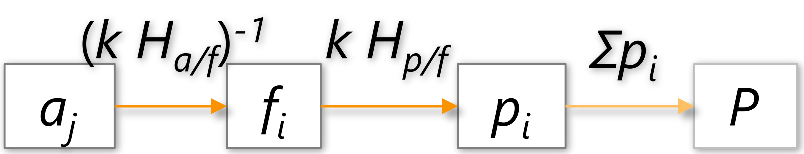


Summary

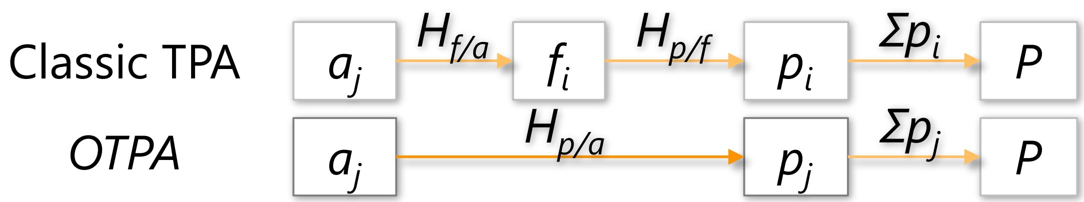
- Indirect estimation of interface forces
- Very time-consuming
- Multi-stage determination of sound contributions. High complexity → prone to errors
- Transfer functions do not describe actual operation
- But: method also provides the interface forces suitable for comparison with simulation







Operational TPA



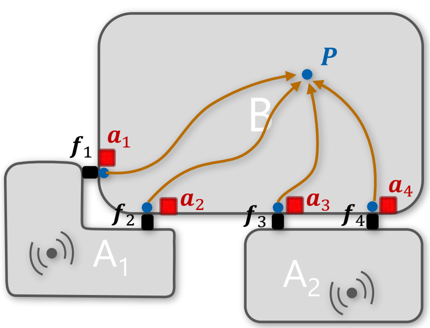
Indirect estimation of operational forces at "indicator positions"

Sound contributions for indicator-positions

Calculation of path contributions from operational measurements

Requirements

- Multiple, different excitations
- Suitable "path indicators" (intefaces)



Mathematical concept of the operational TPA

Source and response signals in operation

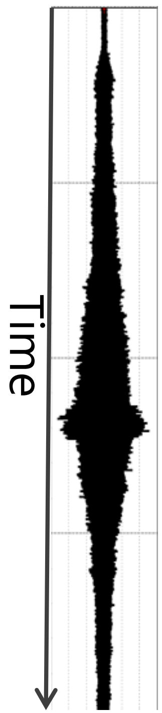
Linear system
$P = A \cdot H$

Variation of excitation

Solution of the linear system by PCA (principal component analysis)

A^{-1}: pseudo-inverse of A

Source signals | Transfer functions | Response signals



$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} \end{bmatrix} \cdot \begin{bmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \end{bmatrix}$$

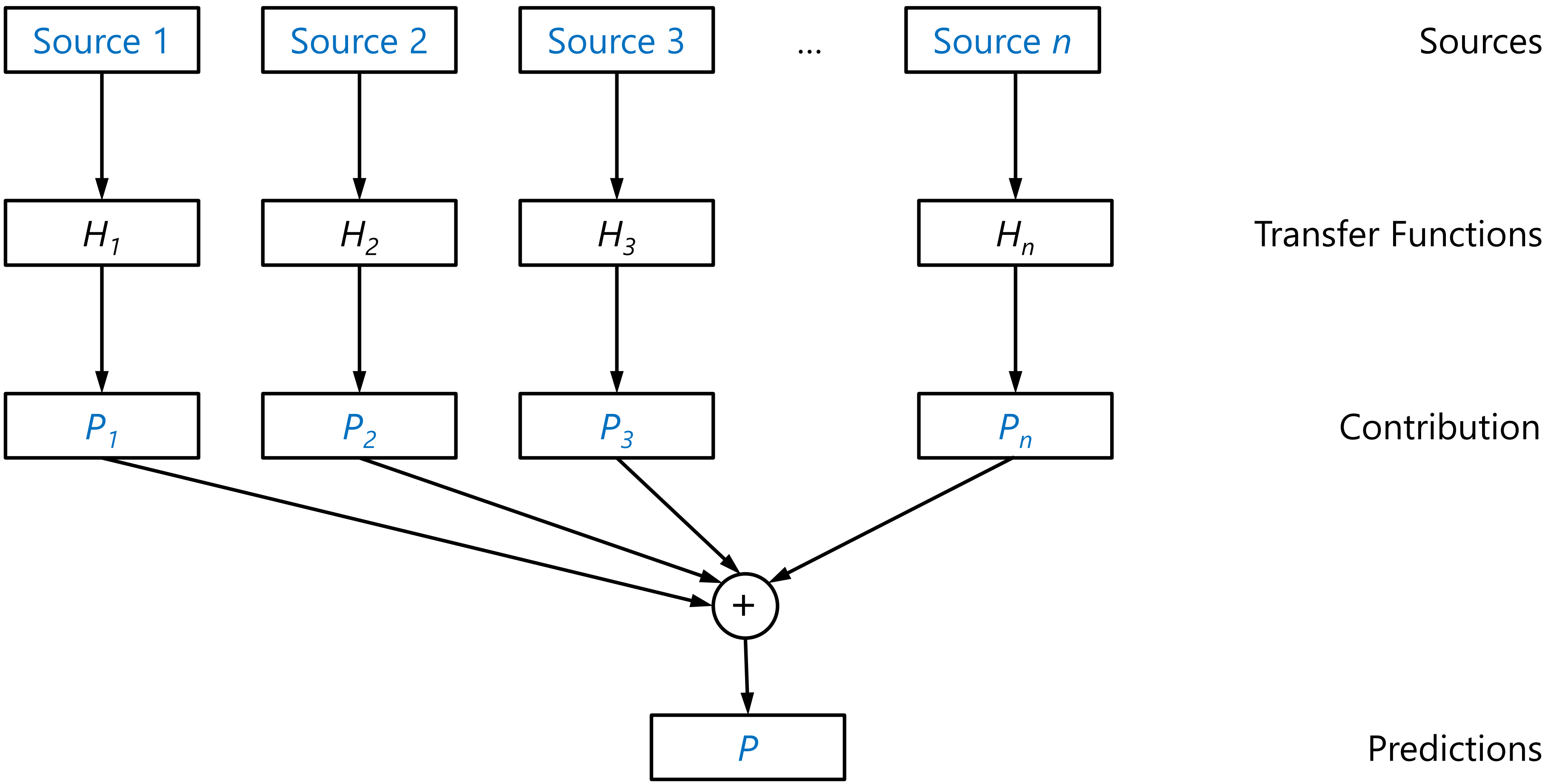
Frequency

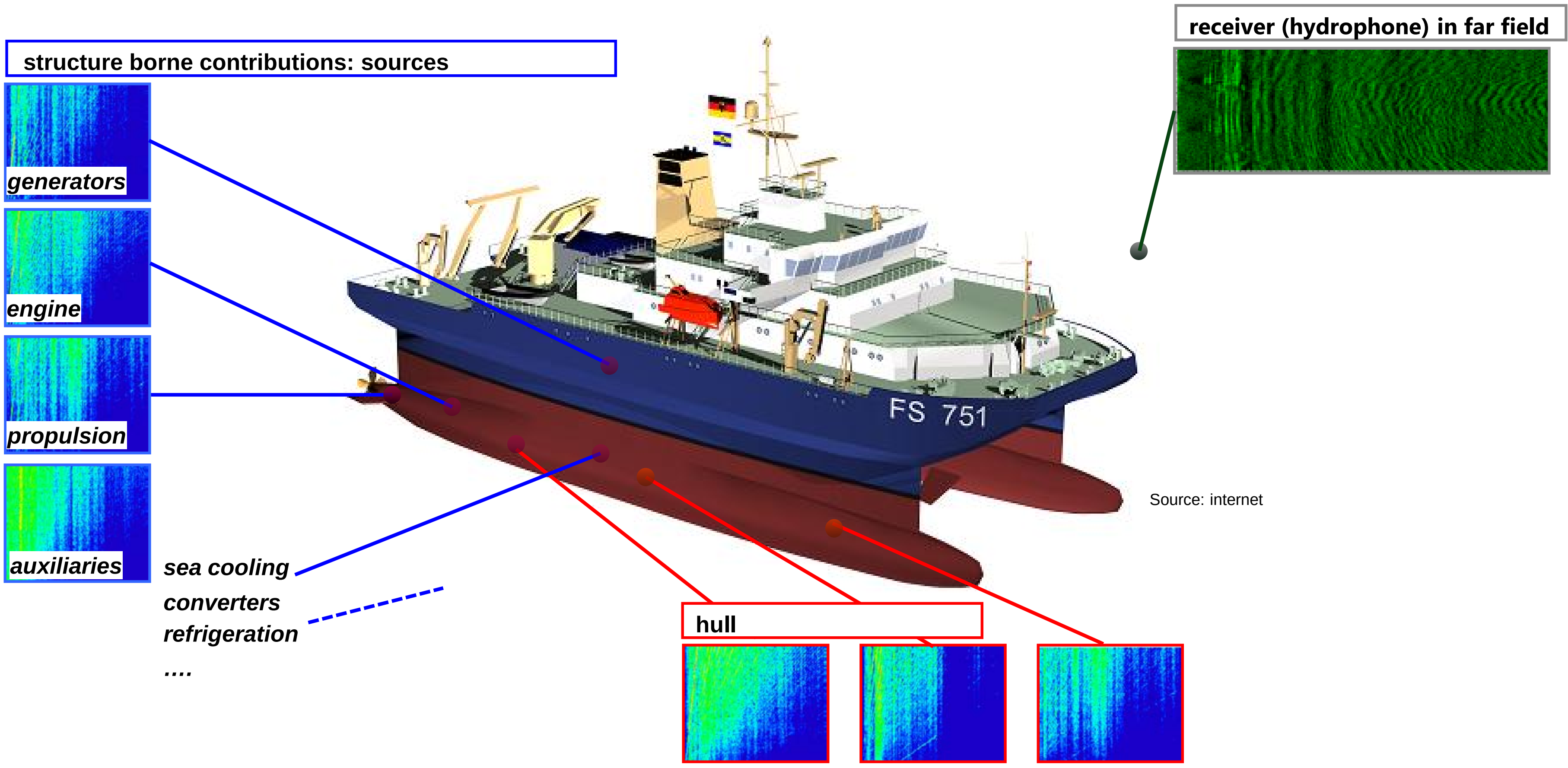
Source spectra A, target spectra P, transfer functions H

↓ measurement steps (spectra), parameter time: e.g. 7

→ measurement positions: e.g. 5

Signal analytic model from OTPA



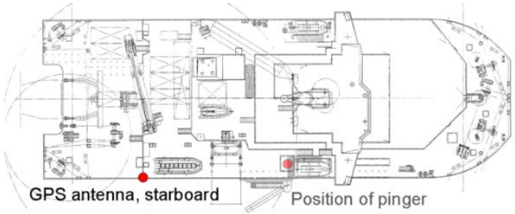


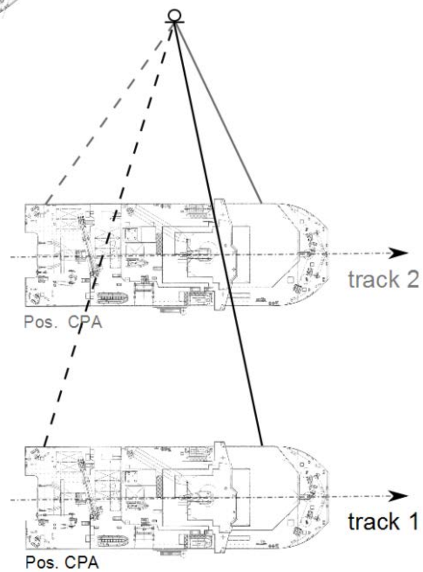
Capture sound contributions for different operating condition, for internal (acceleration sensors) or external receivers (hydrophones). Only operational data required.

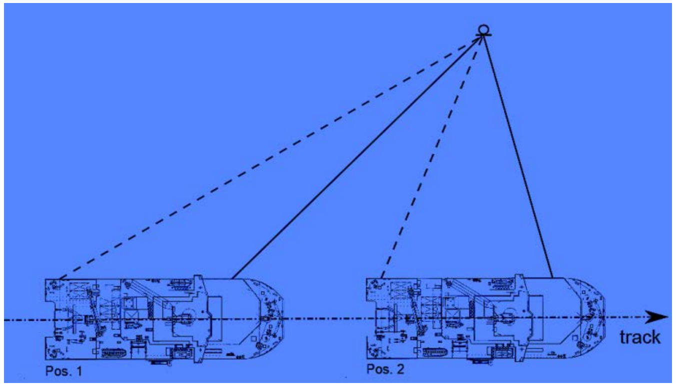
Capturing operational measurement data for ships

OTPA data:

- Realistic data can only be measured in operation (propeller, propulsion, flow noise)
- Data must be measured with two different systems (sources on ship, hydrophone(s) as receiver
- Measurement of test range (Aschau, Heggernes)
- Measurement with floating receiver (hydrophones on buoy)
- Post-processing: synchronization of data sets

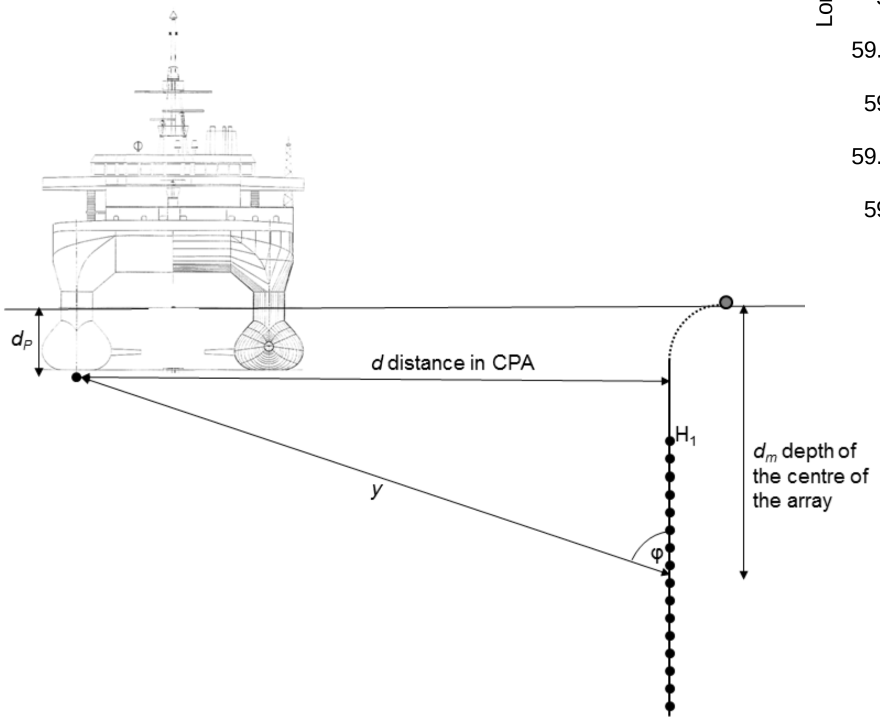


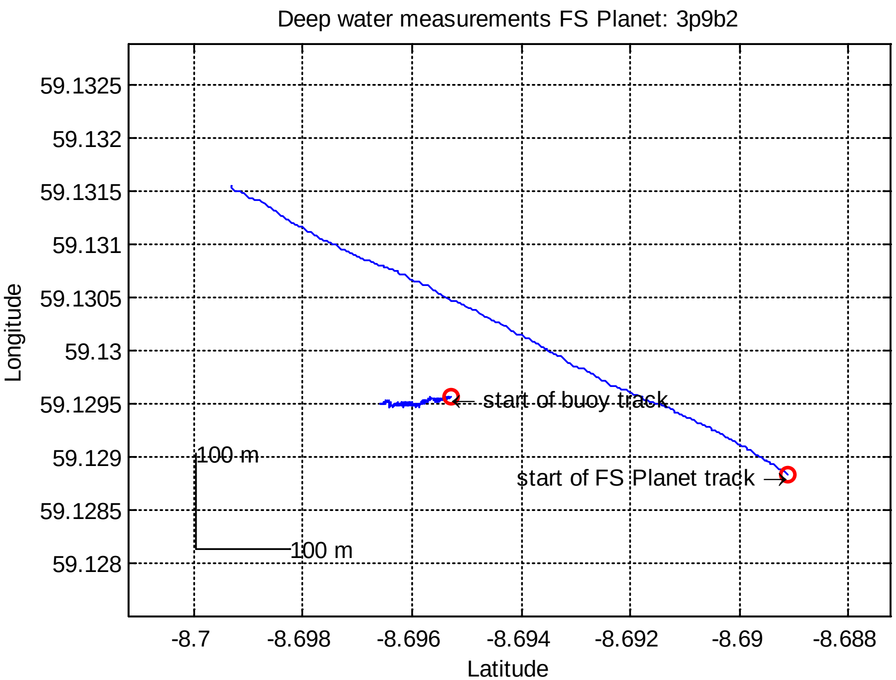




Deep water measurements

Ship is passing a floating buoy.



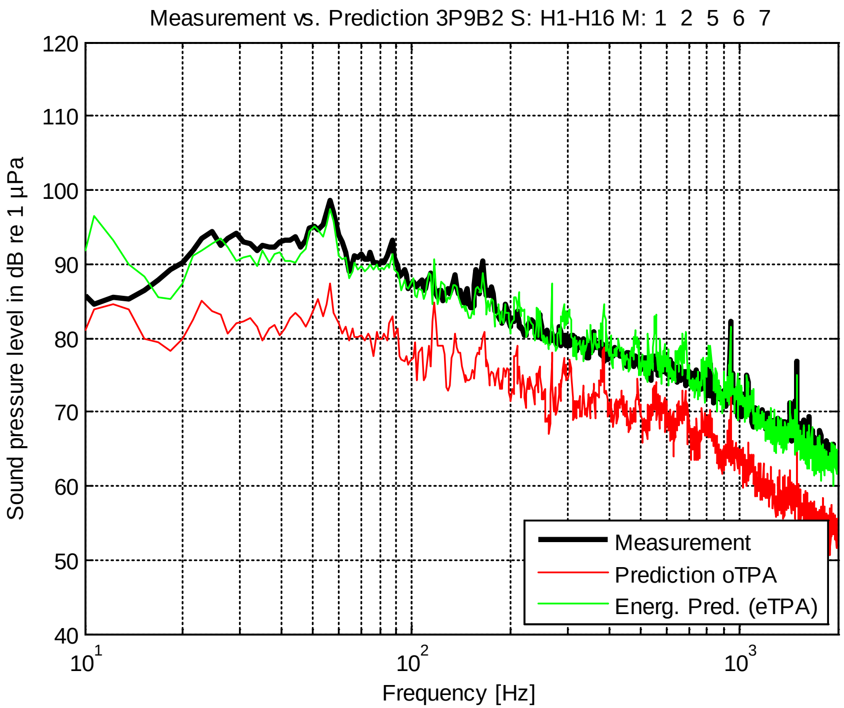


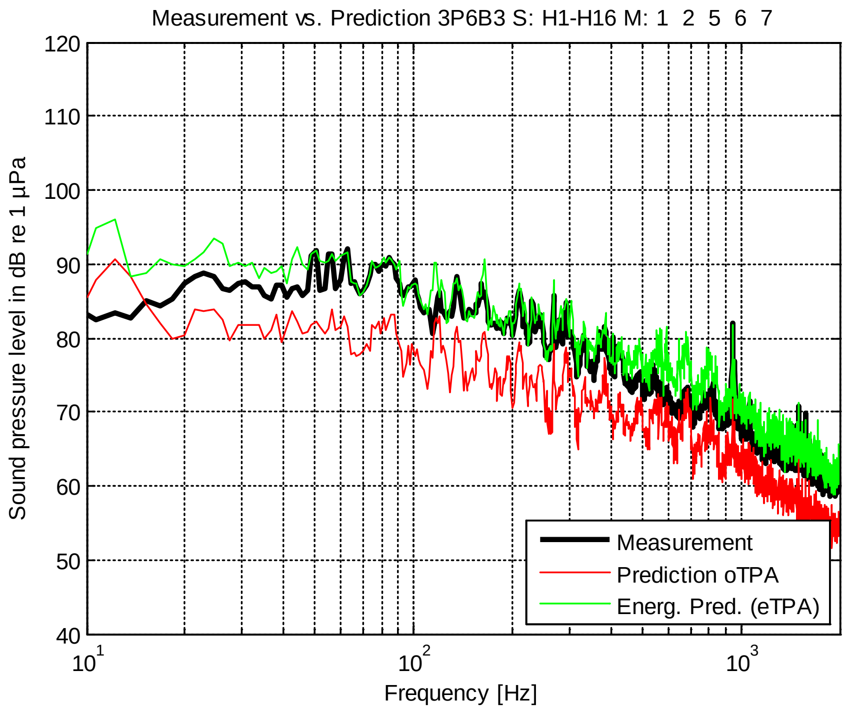
Sensors:

Single hydrophone or hydrophone array

Synchronization of data based on GPS data or information from pinger signal (transit time)

Some results





Datensatz DS 1: 3P9B2
Sensors: Array (16)
Modell aus DS 1,2,5,6,7

Datensatz DS 2: 3P6B3
Sensoren: Array (16)
Model aus DS 1,2,5,6,7

$$p_{\text{pred}}(f) = \sum_{n=1}^{N} H_n(f) \cdot a_{\text{n}}(f)$$

$$\left|p_{\text{energetic}}(f)\right|^2 = \sum_{n=1}^{N} w_n(f) \cdot \left|a_{\text{n}}(f)\right|^2$$

OTPA for ships: requirements and simplifications

- To reduce the complexity of the measurement sensor network, single sources are typically covered by only one (or two) sensors (assumption: excitation is coherent for sensor positions)
- Models should be constructed only for similar stages of sound propagation, e. g.
  - Sources – UWN
  - Sources – Hull
    monitoring of sound transfer
  - Hull – UWN
- To measure flow noise, measurement positions (MP) on the hull are required
- MP on the hull should also cover the influence of
  - all relevant on-board noise sources
  - Propeller noise (may be also measured on the thrust bearing or by external sensors)
  - Rudders
- Therefore the design of a sensor network should be carefully planned

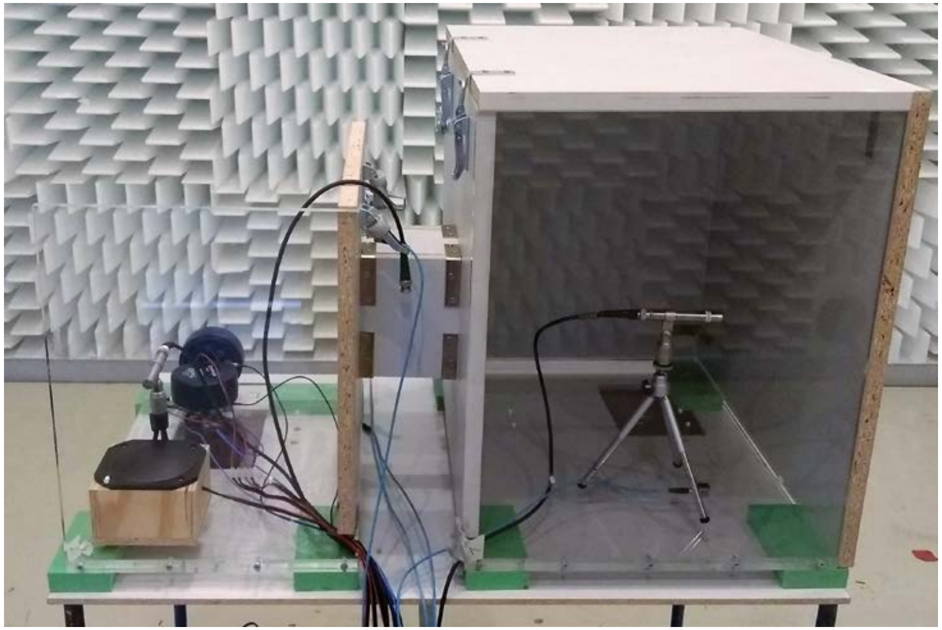
Properties of acoustic ship signature monitoring

- Properties and restrictions of the OTPA (and of signature monitoring) result from the facts
  - that a signal analytic approach is used
  - and that the number of sensors applied has to be restricted
  - system description by FRFs is restricted by the operating excitations and responses are used
- Physical properties of sound transfer “collapse” in transfer functions
  - For a detailed analysis of a system or troubleshooting, additional concepts from the classical TPA might be required

Possible improvements

- Many noise sources generate only at single frequencies: equipment running at fixed operational speed(s). The signature consists in frequency lines, rpm and harmonics
- The transfer behaviour source to receiver can only be calculated at these frequencies. Workarounds are considered:
- Measure equipment during starting phase (forced run-up)
- Apply additional external excitation, e. g. by shaker or impact hammer

- Investigated in a Master’s theses at MBBM (Lucas Heidemann, Investigations on operational transfer path analysis in combination with additional artificial excitation by the use of a physical model)



Summary

- Predictions for the underwater radiated noise of ships
- Some concepts for different project stages and phase
  - Design phase
  - Monitoring
- Have different advantages and limitations

Thank you for your attention

www.MuellerBBM.de