Specialist Committee on Hydrodynamic Noise

27TH ITTC • Copenhagen

Membership

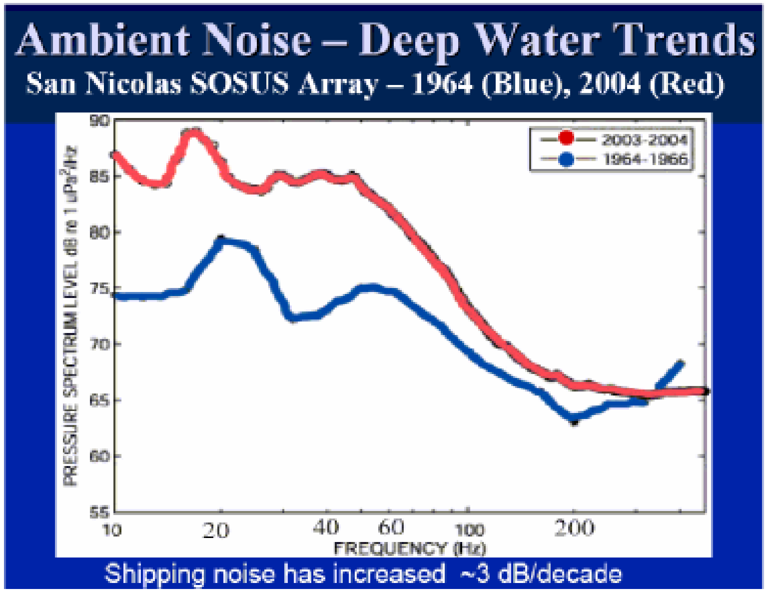
- Herbert Bretschneider HSVA, Germany
- Johan Bosschers (secretary) MARIN, Netherlands
- Gil Hwan Choi, Hyundai HI, Korea
- Elena Ciappi (chair) CNR-INSEAN, Italy
- Theodore Farabee NSWCCD, USA
- Chiharu Kawakita Mitsubishi Heavy Ind., Japan
- Denghai Tang CSSRC, China

Terms of reference from the 26th ITTC

- Create an overview of the characteristics of hydrodynamic noise sources (including machinery and equipment, e.g. sonars) and its influence to marine environment.
- Create an overview of existing national and international regulations regarding hydrodynamic noise.
- Check the existing methods and develop relevant guidelines for performing both model and full scale noise measurements.
- Identify scale effects in prediction of hydrodynamically generated noise (flow noise, cavitation noise....).
- Examine the possibilities to predict full scale values (correlation and operational requirements).

Underwater noise

Over last few years an increase of the low frequency level of the deep ocean ambient noise has been observed (Andrew et al. 2002, McDonald et al. 2006)



This is often related to the increase of ship traffic (Ainslie 2011) and have a significant impact on the marine biodiversity.

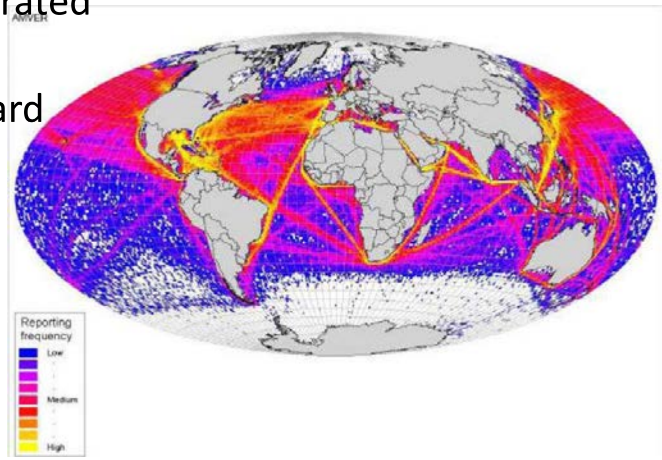
The acoustic pollution is dangerous for fish and marine mammals because causes:

- Masking of communication
- Disorientation
- Habitat displacement
- Permanent hearing loss and physical trauma for high intensity source level (e.g. sonar, airguns)

The occurence and the severity of these effects depends on: frequency and intensity of the received source, duration of exposure

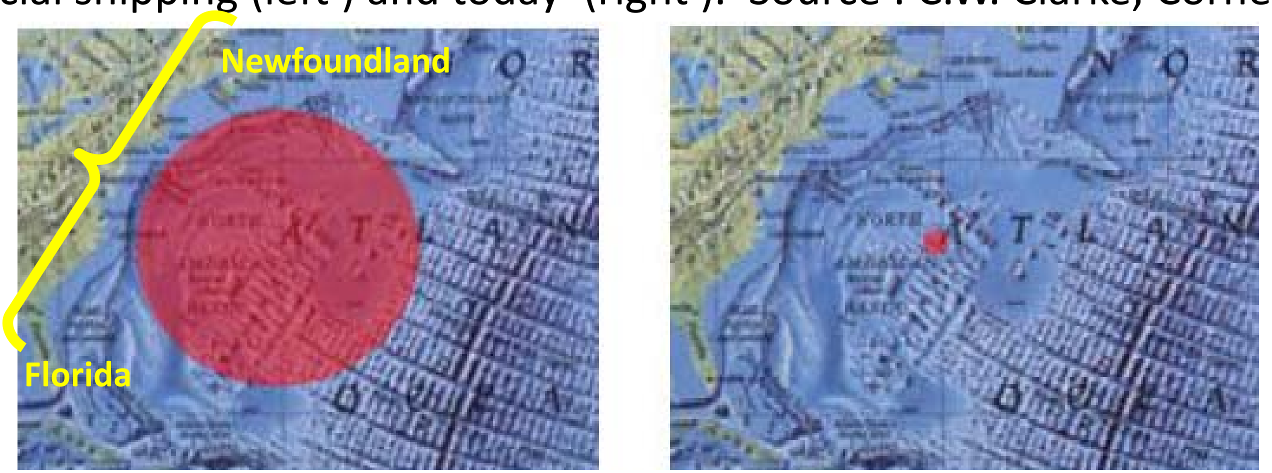
Underwater noise

A map of the ship generated underwater noise
source: U.S. Coast Guard



Reduced ship traffic in a bay in Canada, resulted in a decrease of the low-frequency underwater noise levels and a simultaneous decrease of stress hormones of whales within that bay (Rolland et al. 2011)

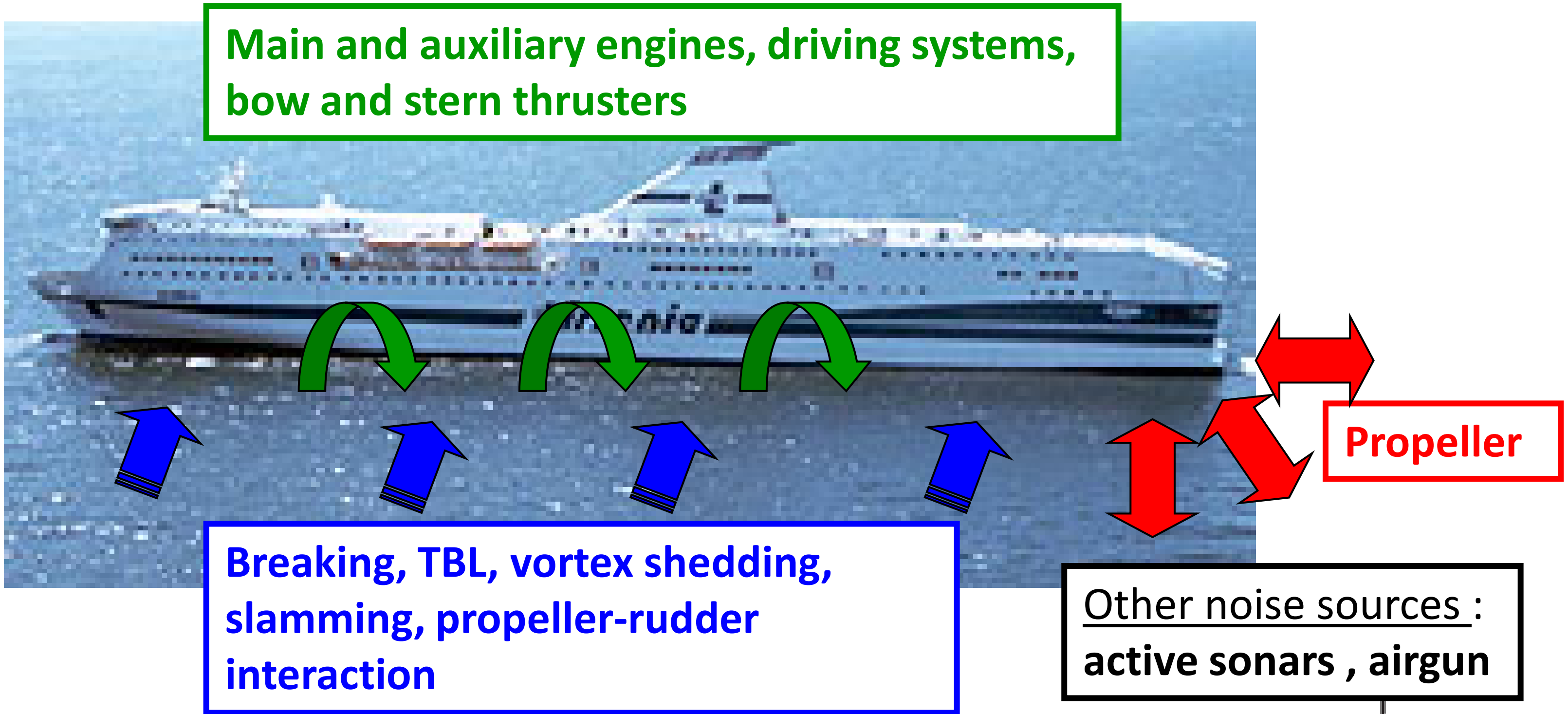
Estimated reduction in whale communication range: prior to the advent of commercial shipping (left) and today (right). Source : C.W. Clarke, Cornell Univ.



Noise sources

Underwater noise emission of vessels can be grouped into three major classes:

- Machinery noise comprising propulsion and auxiliary components
- Propeller noise caused by flow phenomena related to propeller operation and interaction with the vessel hull
- Hydrodynamic noise caused by flow of water along the ship hull and behind the vessel

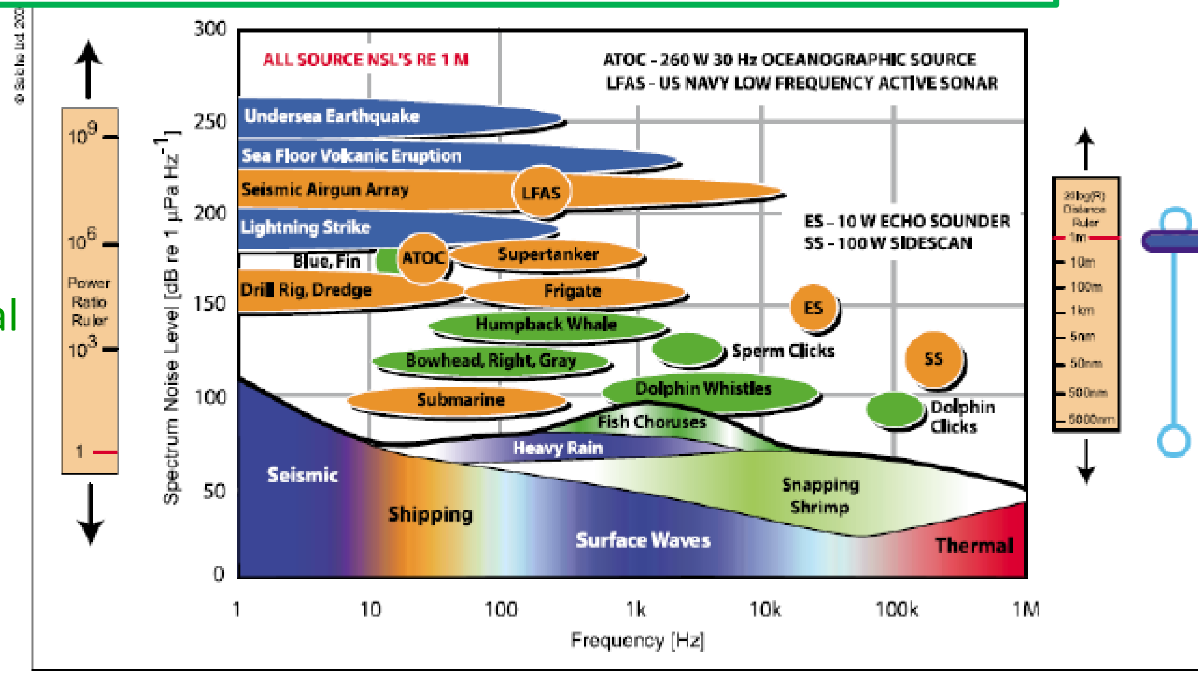


Other noise sources : **active sonars , airgun**

Sound level effects

Received levels:
>120 dB behavioral changes
>150 dB severe behavioral disruption and TTS (Temporary Threshold Shift)
>180 dB PTS (Permanent Threshold Shift)

Sound levels from anthropogenic and natural sound sources



Low frequency (little propagation loss), high intensity signals (airguns, sonars) are recognised to be the most dangerous, little is known about the effects of long term exposure to lower noise levels at low frequency (*i.e.* shipping).

Classification of noise sources

- **military active sonars and airguns** pose the most dangerous impact to the marine biodiversity (necessarily high amplitude sources)
- at **high frequencies** propeller cavitation is the most dominant noise source
- at **low frequencies** noise spectrum is dominated by machinery noise or cavitation noise depending on the amount of cavitation, type of machinery and applied noise reduction measures. Below the cavitation inception speed, ship noise is generally due to vibration and noise from main and auxiliary machinery equipment and the gearing box
- **flow noise** might be important for high speed and when effective mitigation measures have been applied to reduce propeller and machinery noise

Ship noise spectrum has both tonal components (blade frequency, firing rates, piston slap etc.) and a broadband character (cavitation, turbulence in pumps, friction etc..)

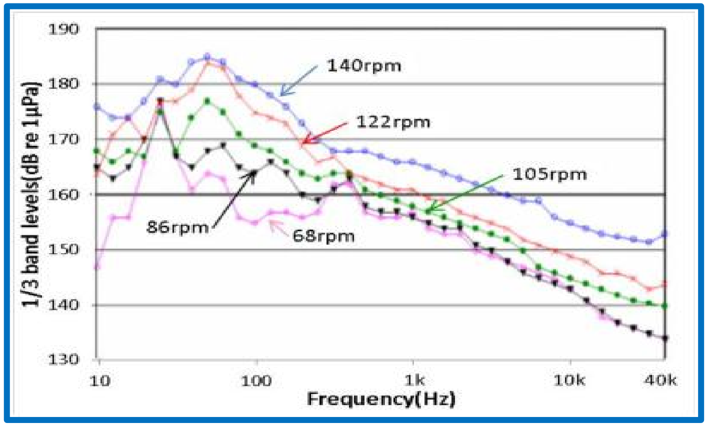
Shipping noise

Large ships: loud and low frequency signature, broadband source levels are generally in the range of 180 to 195 dB

Small to mid-size vessels : almost same frequency range, broadband source levels are generally lower 165 to 180 dB

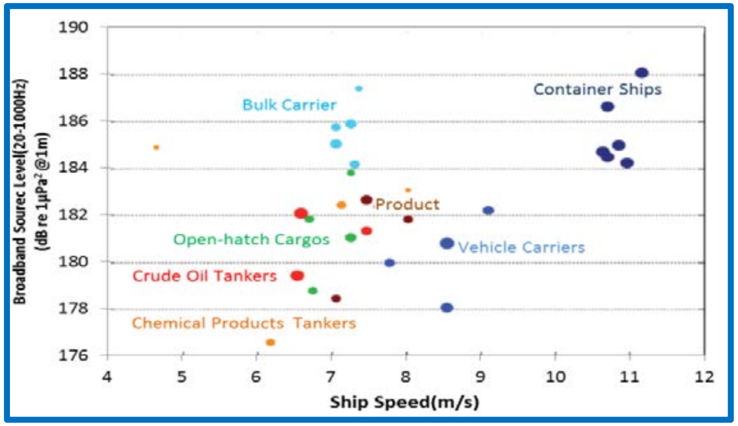
the maximum levels for both is reached in the frequency range of 10 to 125 Hz

(from Arveson and Vendittis, 2000)



Spectra for a **bulk cargo ship** (length 173 m and displacement of 25,515 tons, powered by a direct drive low speed diesel engine) at various speeds and propeller rotation rates

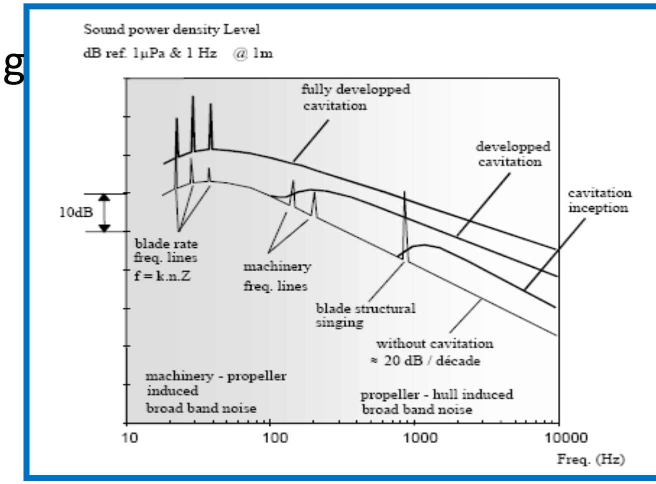
(from McKenna et al., 2012)



Broadband ship source level for **different ship-type**. Bubble size represents the relative size of the ship

Noise sources: non cavitating propeller noise

Noise spectra for non-cavitating and cavitating propeller



The sound pressure level of a non-cavitating propeller is less intense compared to a cavitating propeller

Tonal components

caused by the action of a propeller operating in the presence of upstream non-uniform wakes.

Frequency range: blade frequencies, generally do not exceed 20 Hz (first 3 harmonics).

Model scale test: performed by measuring the fluctuating force on the propeller and then simulating the radiated noise.

Numerical simulations: BEM/RANS for noise sources and FW-H* in the time or in the frequency domain

* FW-H Ffowcs Williams –Hawkings (acoustic analogy approach)

Noise sources: non cavitating propeller noise

Continuous spectrum

Low frequency hydroacoustic forces are caused when the hull TBL on the vessel surface is ingested into the propulsor. High frequency hydroacoustic forces are caused when the local BL, formed on the blade surface, passes over the blade trailing edge

Frequency range: 1Hz-20 KHz

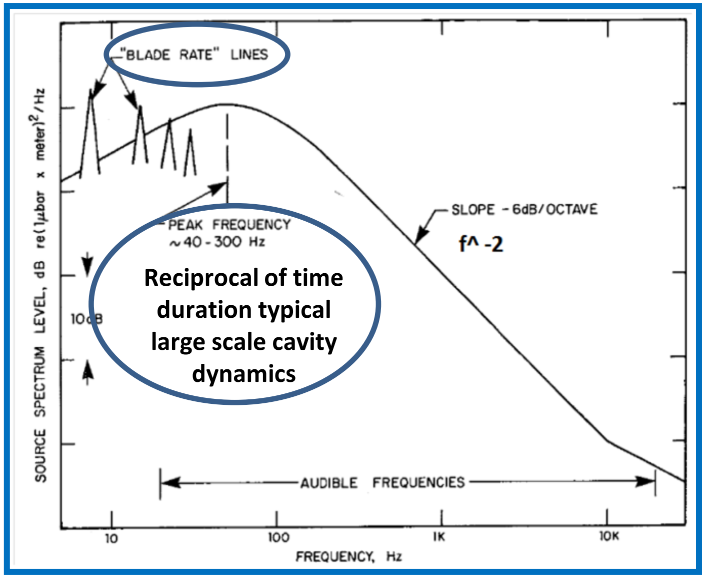
Model scale test: low noise facility can be used but the phenomenon strongly depends on Reynolds and Cauchy number, scaling methods have been proposed but **the correlation to full scale data is poor**.

Numerical simulations: LES/RANS + acoustical solver (Helmoltz/ FW-H) to understand which are the key hydrodynamic issues and the effect of the nonlinear terms in the near and in the far field. Semi-empirical methods are used for the high frequency.

Noise sources: cavitating propeller noise

Stylistic PSD of a cavitating propeller noise

Before the hump the PSD increases as f^4
After the hump (bubble collapse) decreases as f^{-2} *i.e.* by 6 dB/octave



Only part of noise spectrum can be described by the single bubble dynamics.
At high frequency the collective behavior and their interaction is important

Key parameters for noise: gas content, compressibility

Speed Scaling:

Fully developed cavitation $L_s \propto 10 \log_{10} V^6$ → Ship speed

Near cavitation inception Higher order dendence on speed

Noise sources: cavitating propeller noise

Flow Field Scaling:

Ship wake: geometrical similarity but different velocity vector, only mean velocity with mean thrust coefficients, **effects on the radiated noise level are unknown**

Cavitation number**:** is defined for a selected location on a propeller disc

Gas content: cushioning effect, an increase of gas content produce a decrement of spectrum amplitude and of the sound speed, at full scale may change significantly

Mach number: influence on the high frequency part of noise spectra but consequences of dissimilarity are unknown

Extrapolation from model to full scale

Frequency scaling

$$\frac{f_{fs}}{f_{ms}} = \frac{n_{fs}}{n_{ms}}\sqrt{\frac{\sigma_{fs}}{\sigma_{ms}}}$$

Noise level scaling (ITTC 87)

$$L_{fs} - L_{ms} = 20\log_{10}\left[\left(\frac{D_{fs}}{D_{ms}}\right)^{z}\left(\frac{r_{ms}}{r_{fs}}\right)^{x}\left(\frac{\sigma_{fs}}{\sigma_{ms}}\right)^{w}\left(\frac{n_{fs}D_{fs}}{n_{ms}D_{ms}}\right)^{y}\left(\frac{\rho_{fs}}{\rho_{ms}}\right)^{y/2}\right]$$

Noise sources: cavitating propeller noise

Numerical simulations:

Sheet cavitation tonal components: BEM/RANS /LES+FW-H
Sheet and tip vortex cavitation broadband: semi-empirical models (*e.g.* TVI- Tip Vortex Index for tip vortex cavitation noise) show a fair agreement with on board and far field full scale data; CFD with acoustic analogy has the capability but is still very demanding.

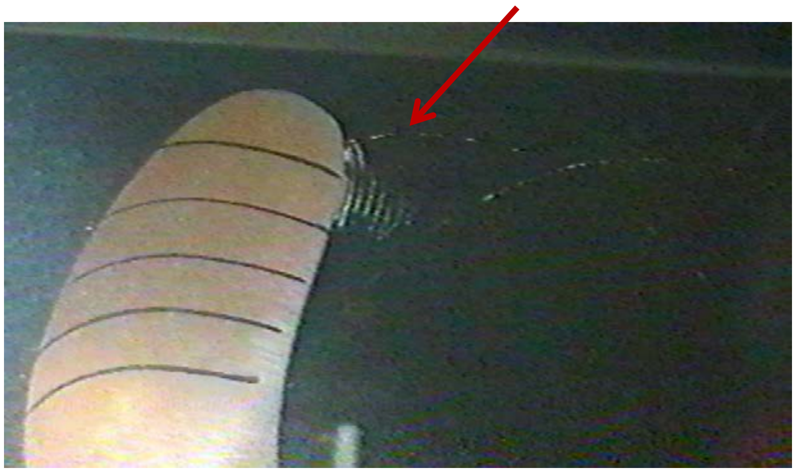
Summarizing:

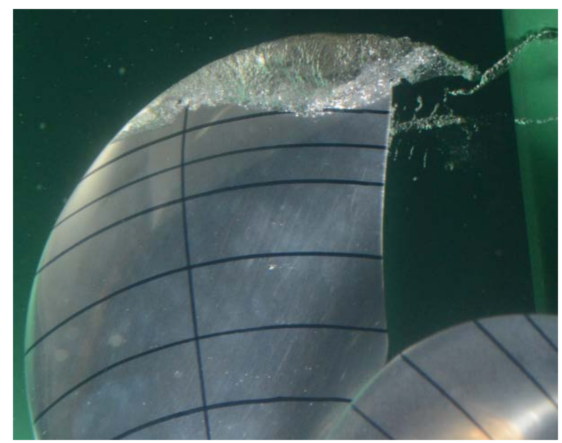
- It is impossible to achieve all similarities between model test and full scale and the environmental conditions of the test are often quite different from the full scale conditions.
- Computational prediction of cavitating flows is still a difficult task especially for the cases of instantaneously cavitating vortices or for the process of cavitation collapse. Possibilities and limitations for accurate noise predictions need to be further assessed

Noise sources: singing propeller

High pitch squeeling noise generated, usually in non cavitating conditions, by trailing edge vortex exciting blade vibration natural frequency (100 Hz-1.5 KHz) giving rise to one or more distinct tones of high amplitude. Sometimes is recognizable during flow visualization as white parallel stripes (induced cavitation)

Model scale test and numerical simulations: the phenomenon depends on details of trailing edge geometry and on damping therefore, is very difficult to replicate (identical propellers can have completely different singing behavior).





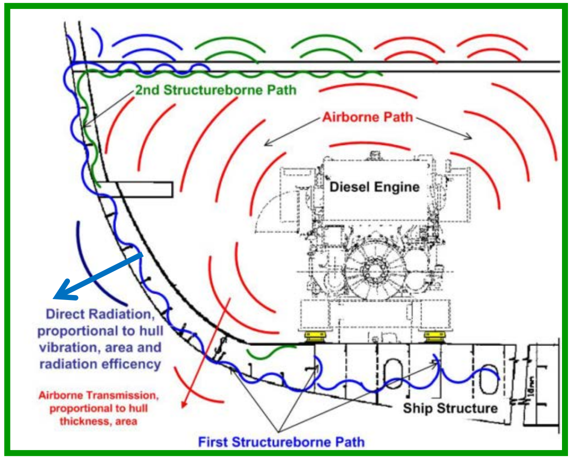
Noise sources: machinery noise

Machinery noise originates from the generation and transmission of mechanical **vibration and/or sound** from the many and different parts of a moving vessel.

Dominant at low frequency, below cavitation inception speed

There are three ways of noise transmission:

- **structure borne noise transmitted via foundations, pipes, and couplings**
- airborne noise, important for people working near the noise source
- exhaust gas chimney, important for noise above the water surface



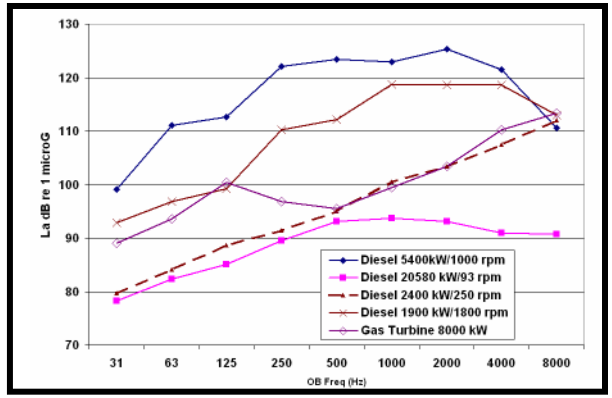
Main Engines: Diesel Engines geared or direct drive, Diesel-Electric, Steam and Gas Turbines Gas turbine-electric. Frequency range: few Hz-1 KHz

Auxiliary Machinery: Noise emission from auxiliary machinery covers the range 10 Hz to 5 KHz

Machinery Noise

Diesel vibration source levels usually scale as: **(power/weight)²**

heavy low speed diesels have lower source levels



Source levels for diesel engines (from Fisher and Brown, 2005)

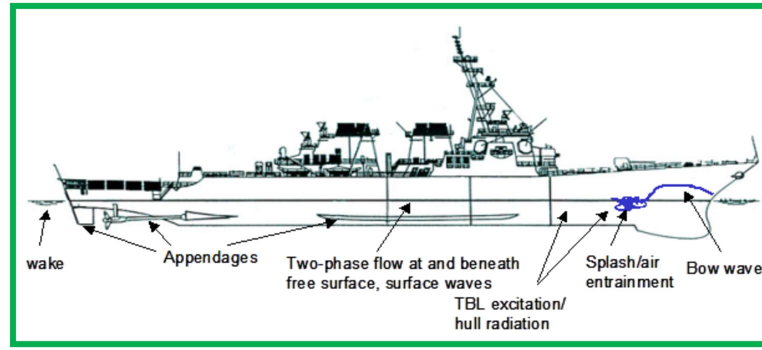
Medium size 4-stroke diesel engines are connected to the propeller shaft via a reduction gear and are usually resiliently mounted. The dominant noise is due to *"piston slap"* and occur at frequencies that depend upon ship speed. When used as a genset they operate at constant speed and thus mounts can be properly designed.

Even large direct drive electric motors and rotatory machinery (main engines and auxiliary) are quiet if compared with reduction gears and piston engines

→ **medium speed diesel** dominate noise spectrum

Noise sources: flow noise

Flow noise sources might be important for **high speed (above 30 Knots)** and only if **strong mitigation measures** have been applied to reduce cavitation and machinery effects



Wavebreaking the noise is caused by oscillating air bubbles and clouds of air bubbles and depends on the amount of air entrained and the bubble size distribution. **The noise is influenced by** Froude number, Weber number, Reynolds number, turbulence intensity and water quality which complicate scaled model tests (scale size limitation). **Frequency range:** 100 Hz 10 KHz

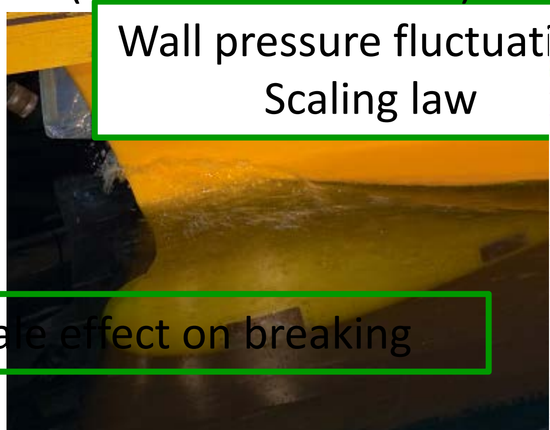
TBL rather inefficient for underwater direct radiations. More efficient in presence of rigid surfaces or when exciting flexible structures. Most important for selfnoise detected by the on board sensors. **Frequency range**: few Hz-1 KHz

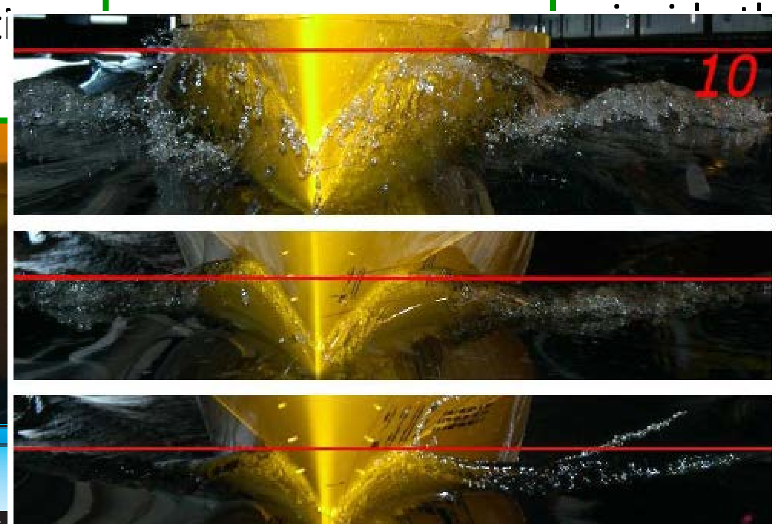
Scaling laws exist at least in nearly canonical conditions

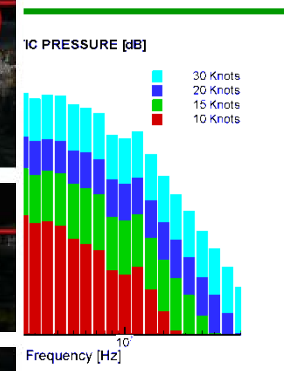
Full scale radiated noise ... e sonar dome

Wall pressure fluctuati...

Scaling law







Scale effect on breaking

Noise sources: active sonars

The impact to the ocean environment depends on the sonar's purpose since this determines the sonar's frequency range, source strength, and mode of operation
Low frequency (100Hz-1 KHz), medium (up to 8 KHz), high (above 8 KHz)

Active military sonars (AMS) : most of AMS used for warefare operate at low and medium frequency. Those operating at low frequency pose the greatest impact because there is little propagation loss. Submarines sonars are powerful but seldom used, sonar of surface vessels can operate continuously at low frequency with an effective source strength of up to 235 dB.

Active Sonar Echo-Sounder & Active Navigation Sonar:

- Depth sounders and fathometers: medium to high frequency, low source level
- Fish finders: high freq (depending on fish size), low source level
- Searchlight sonars, which includes side-scan sonars, and acoustic cameras: high frequency, low source levels
- Acoustic Doppler current profilers for high accuracy measurement of speed: high frequency, low source levels
- Sonar system used for underwater acoustic communications: medium frequency, low to medium source strengths

Noise sources: airguns

The peak pressure reaches values of about 230 dB (re: 1µPa at 1m), with a spectrum that is of broadband type. Most airgun noise occurs in the range below 1 kHz with increasing levels at lower frequencies with a maximum typically below 100 Hz.

Regulations

Anthropogenic noise emissions in the sea has been analysed only in recent years mainly at a regional level, in particular for restricted areas where there is a higher concentration of species of marine mammals or fishes.

The regional, national and international regulations do not specify acceptable underwater source levels but instead restrict activities that can harass or harm marine animals and suggest technologies and operational modes that can reduce underwater noise radiation.

International Framework: United Nations Convention on the Law of the Sea-**UNCLOS**, **IMO**, International Council for the Exploration of the Sea-**ICES**, Convention on the Conservation of Migratory Species of Wild Animals -**CMS** etc.

Regional and National Framework: **EU**, The Convention for the Protection of the Marine Environment of the North-East Atlantic - the **OSPAR Convention**, the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas-**ASCOBANS**, the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area - **ACCOBAMS**, **United States**, etc.

Regulations

International Framework: The Marine Environment Protection Committee (MEPC) of the International Maritime Organisation (IMO)

2008 : noise from commercial shipping is indicated as an high priority item and a Correspondence Group with the task to *identify and address ways to minimize the introduction of incidental noise into the marine environment and to develop non mandatory technical guidelines for ship-quieting technologies as well as navigation and operational practices* has been established.

2009 : the Corresponding Group stated that noise in the low frequency range (10 Hz to 1 kHz) has the biggest impact on the marine biodiversity. Different noise control technologies were discussed and an overall noise reduction of about 20 dB can be achieved through optimization of machinery and propeller noise mechanisms.

2014 : approved the *"Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life"*, MEPC 66/17 (2013). These non-mandatory Guidelines are intended to provide general advice about reduction of underwater noise and focus on the primary sources of underwater noise such as associated with propellers, hull form, onboard machinery, and operational aspects. A specific section discusses the use of CFD, FEM and SEA

Regulations

Regional and National Framework : EU

2004 : EU Parliament adopted a Resolution on the environmental effects of high-intensity active naval sonar.

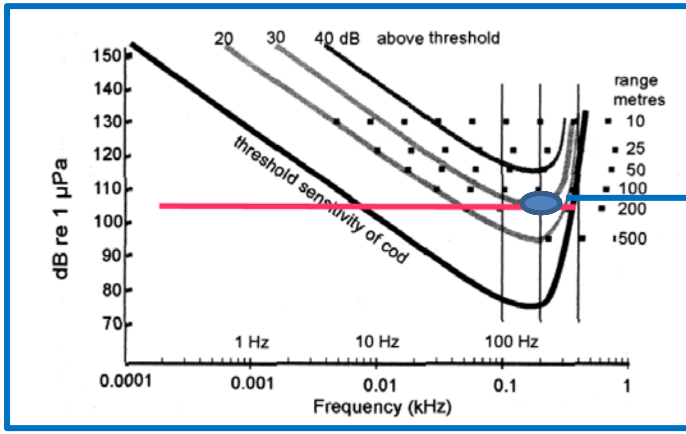
2008 : the EU Marine Strategy Framework Directive specifically mentions the problem of noise pollution and represents the first international legal instrument to explicitly include anthropogenic underwater noise within the definition of pollution (Article 3 (8)), which needs to be properly mitigated in order to achieve the **good environmental status** (**GES**) of European marine waters by 2020 (Article 1). The Directive identifies 11 environmental descriptors to achieve (GES), and the **11th** is related to underwater noise.

2010 : the EU Commission Decision provides the descriptor (11.2) for 'continuous low frequency noise' (as generated by shipping): "*Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate*". This Directive is enforced from 2014 and all member states are obliged to provide an evaluation of the "good status" of their seas based on those descriptors.

Standards

ICES (International Council for the Exploration of the Sea) **methodology (1995) for research vessel**

Cod audiogram



200 Hz (frequency of maximum sensitivity) on the curve 30 dB above thresold curve (limit of behavioral effects appearance)

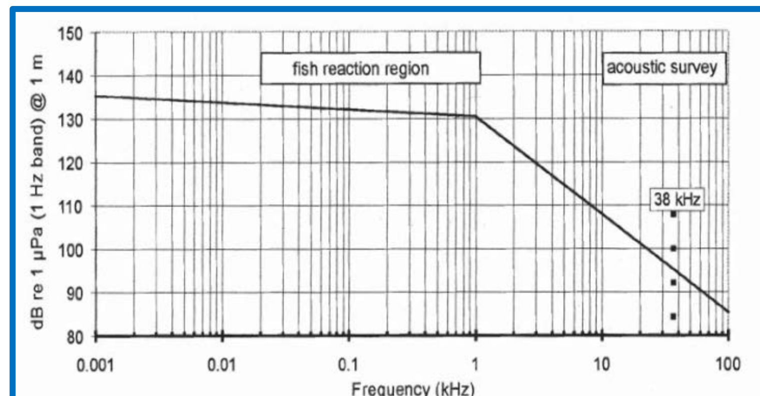
$$1\ \text{Hz} \leq f \leq 1\ \text{kHz}$$

$$SL = 135 - 1.66 \log_{10}\left({}^{f_{\text{Hz}}}/_{1\ \text{Hz}}\right)$$

$$1\ \text{kHz} < f \leq 100\ \text{kHz}$$

$$SL = 130 - 22 \log_{10}\left({}^{f_{\text{Hz}}}/_{1\ \text{kHz}}\right)$$

Underwater noise source level (SL) spectrum



Standards

DNV Silent Class Notation (2010)

First Class Notation that set limits for underwater radiated noise

Five categories have been considered:

i) Acoustic (ships involved in hydro-acoustic measures);
ii) Seismic (ships involved in seismic surveys);
iii) Fishery (commercial fishing);
iv) Research (fishery research);
v) Environmental (any vessel which require controlled environmental noise emission)

Different curves are given depending on the operational conditions of the ship, they report maximum allowable noise levels versus frequency (1/3 octave resolution). The curve relative to research vessels substantially corresponds to the low frequency ICES one except for the format

Hydrodynamic noise

Part II Survey and Guidelines

- Full Scale noise measurements
  - Guideline 7.5-04-04-01
  - Results survey
- Model Scale noise measurements
  - Guideline 7.5-01-01-05
  - Results survey

Guidelines Full Scale Measurements

- Purpose: provide general procedures and methodologies
- Recommendation to follow
  - ISO/PAS 17208-1:2012(E), deep water
  - ISO standard for shallow water in development
- ITTC guidelines discuss procedures following
  - ISO/PAS 17208-1:2012(E)
  - ANSI/ASA S12.64-2009
  - DNV Silent Class notation, 2010

Survey Full Scale noise measurements

- Results not in draft report, available at registration desk
- 11 organizations responded (**6 ITTC-members**)
  - France: DCNS — ship yard
  - Germany: WTD71 — navy
  - Italy: **CETENA** — research & consultancy (R&C)
  - Japan: **MHI, Mitsui Lab.** — ship yards
  - Korea: **KRISO, HHI** — R&C, ship yard
  - Netherlands: TNO, DMO — R&C, navy
  - Spain: TSI — consultancy
  - USA: **NSWC/CD** — navy

topics FS measurements

Guidelines

- Normative references
- Measurement requirements and procedures
- Data acquisition, Processing and Uncertainties
- Required and recommended data

Survey

- Site and test set-up
- Propeller/hull info
- Hydrophones
- Data acquisition and processing
- Correction procedures

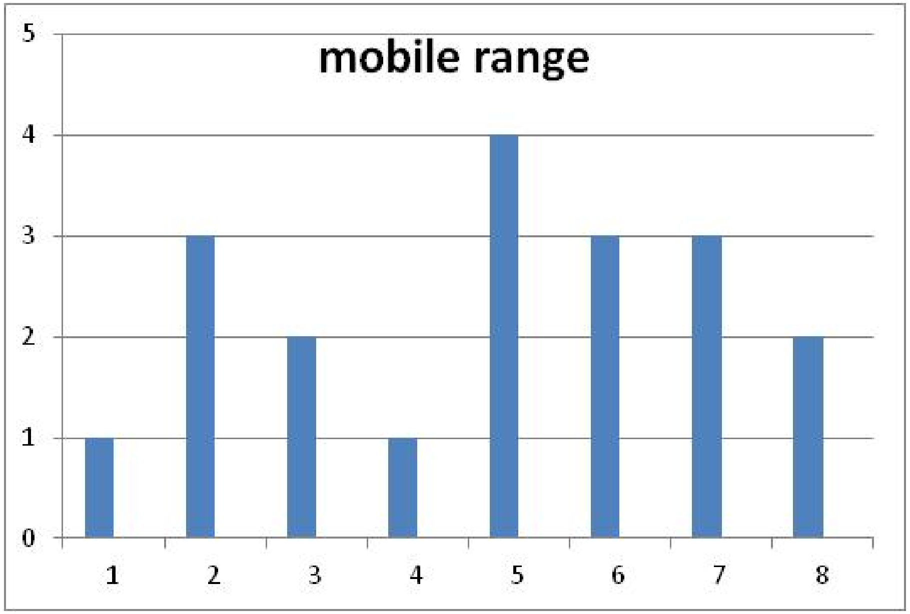
ISO/PAS 17208

Grade	A	B	C
Grade name	**Precision method**	**Engineering method**	**Survey method**
Achievable measurement uncertainty	1,5 dB	3,0 dB	4,0 dB
Measurement repeatability	± 1,0 dB	± 2,0 dB	± 3,0 dB
Bandwidth	One-third-octave band		
Frequency range (one-third-octave bands)	10 Hz to 50 000 Hz	20 to 25 000 Hz	50 Hz to 10 000 Hz
Narrowband measurements	Required	Required	As needed
Number of hydrophones	Three	Three	One
Hydrophone geometry	Figure 1	Figure 1	Figure 2
Nominal hydrophone depth(s)	15°, 30°, 45° angle	15°, 30°, 45° angle	20° ± 5° angle (see 5.4)
Minimum water depth	Greater of 300 m or 3x overall ship length	Greater of 150 m or 1,5x overall ship length	Greater of 75 m or 1x overall ship length
Minimum distance at closest point of approach (CPA)	Greater of 100 m or 1x overall ship length		

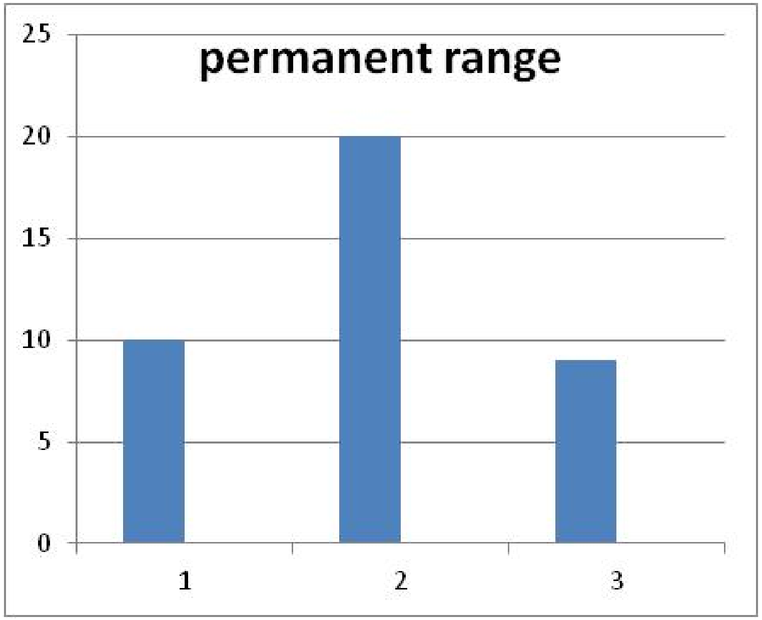
FS survey – 1. Site and test set-up

- 3 fixed locations (navies), shallow (20 m) and deep water (400+ m)
- 8 mobile equipments
- Depth of hydrophones: 14 – 300 m
- Horz. distance ship cpa: 30, 50, 80, 100, 200 m.
- Max allowable sea state: 2 – 3
- Some check surface condition of propeller and hull, 50% polish propeller

FS survey – 3. #Hydrophones



Survey responder #



Survey responder #

Grade name	Precision method	Engineering method	Survey method
Number of hydrophones	Three	Three	One

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ISO-standard, beam aspect

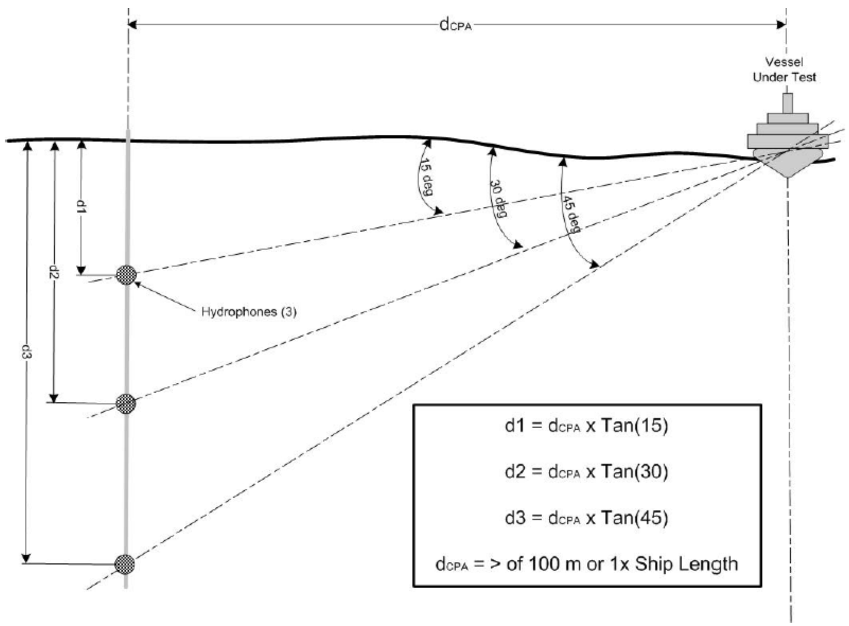
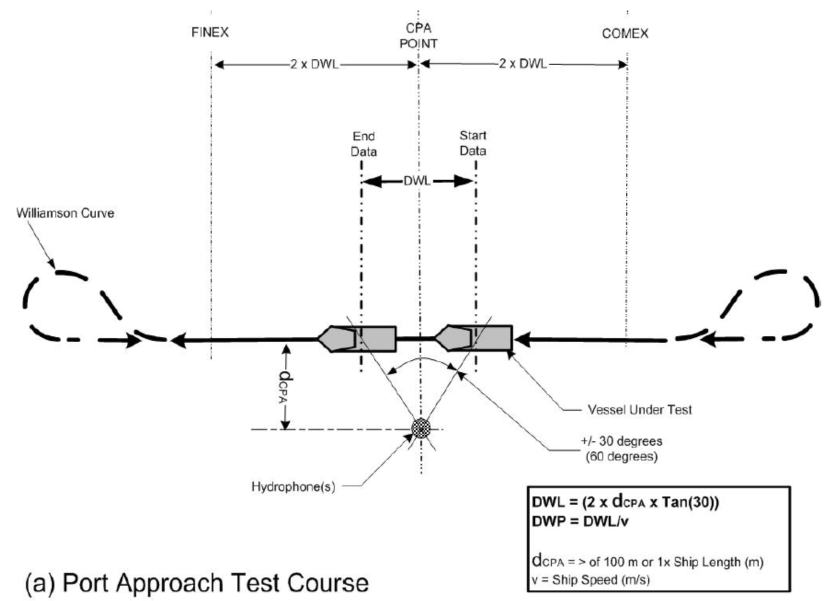


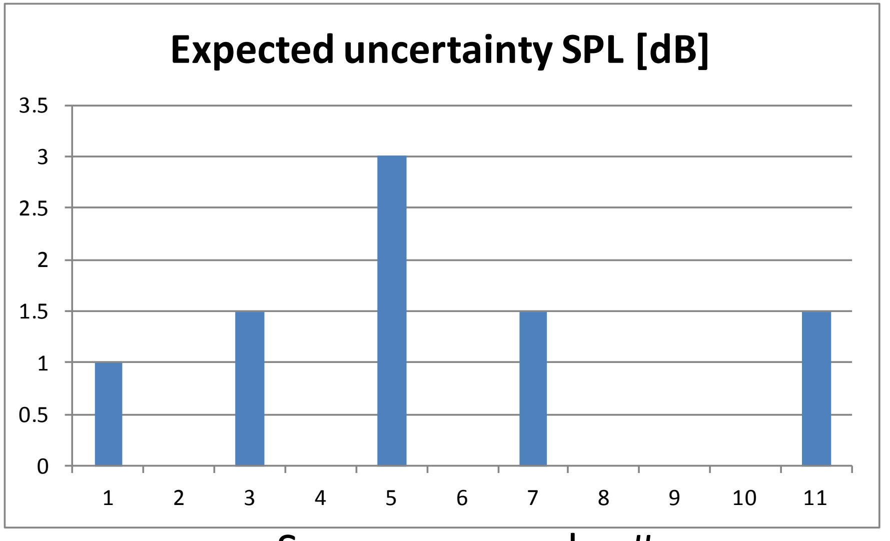
Figure 1 – Grades A and B hydrophone geometry

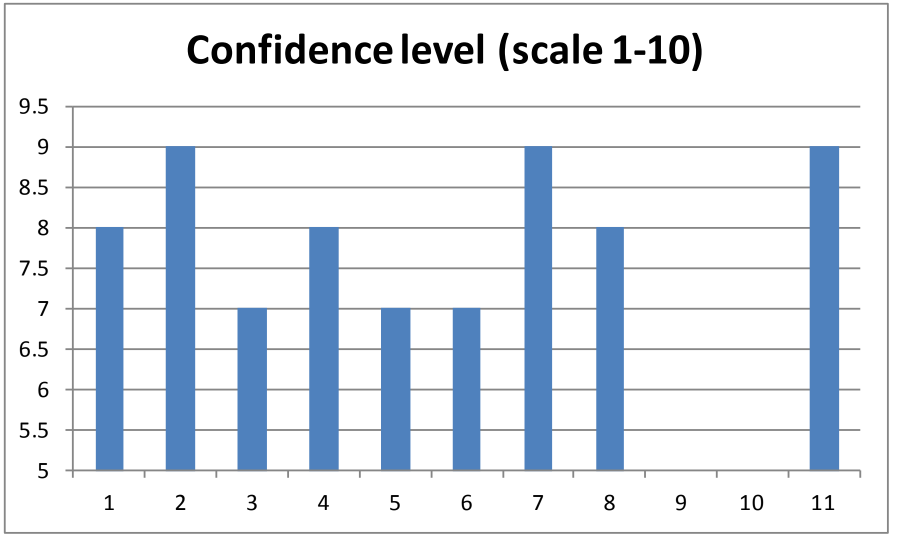


(a) Port Approach Test Course

FS survey – 4. Data

- Measured full scale Sound Pressure Levels





Survey responder #

Grade name	Precision method	Engineering method	Survey method
Achievable measurement uncertainty	1,5 dB	3,0 dB	4,0 dB
Measurement repeatability	± 1,0 dB	± 2,0 dB	± 3,0 dB

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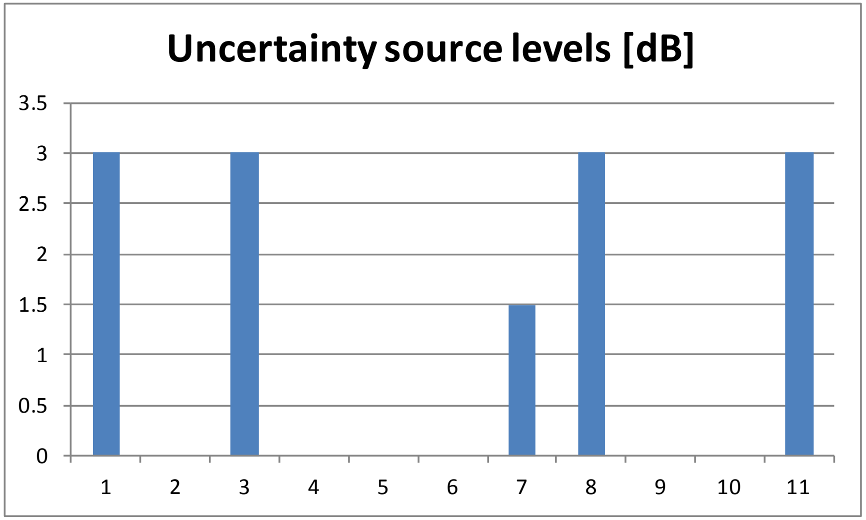
FS survey – 5. Corrections

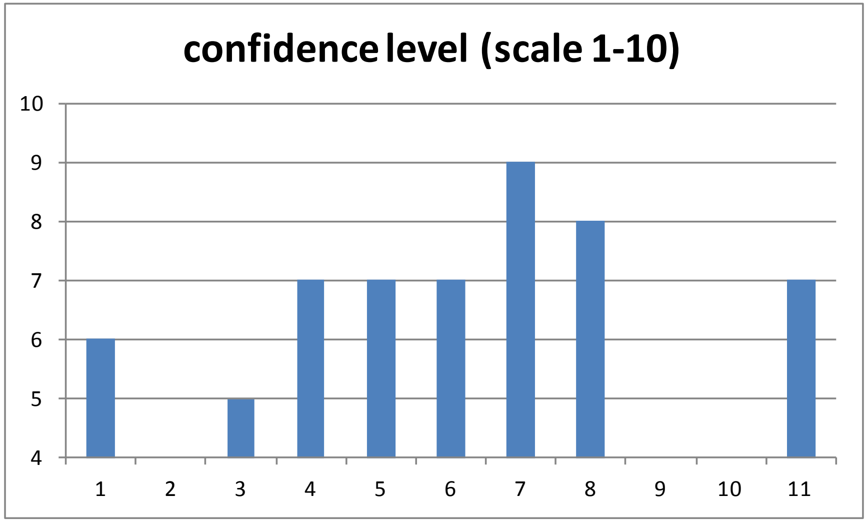
- Corrections to obtain source levels
  - Ambient noise (60%)
  - Propagation loss:
    - $20*\log_{10}(R)$ correction (80%)
    - Free surface (Lloyd mirror) correction (30%, but depends)
    - Use environmental parameters (20%)
    - Measurement (30%)

No standard available for shallow water !

FS survey – 5. Corrections

- Predicting source levels from sound pressure levels

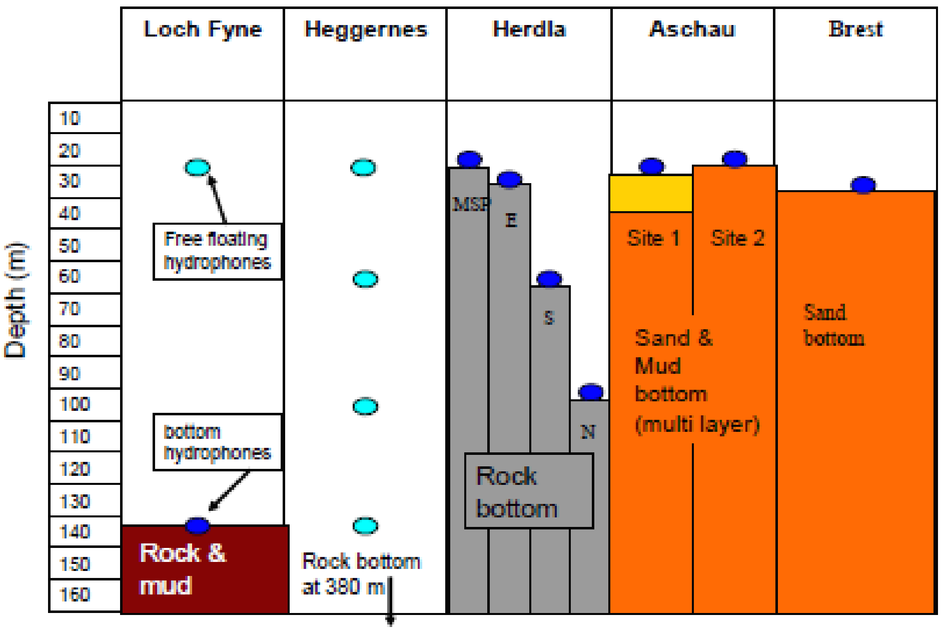




- Note of caution: uncertainty levels will increase due to variability of cavitation, sea state, ship condition, …

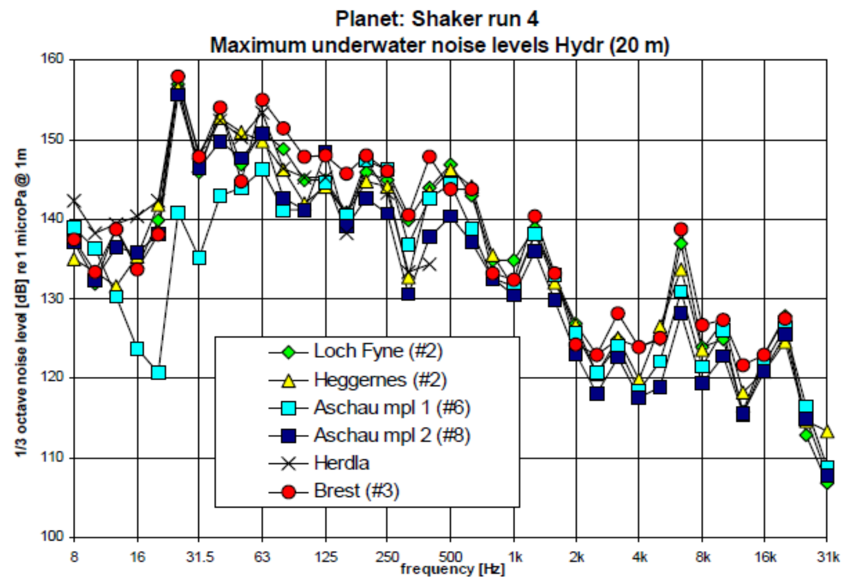
RIMPASSE trials with 2 ships

Hasenpflug et al, UDT 2012



Variability SPL, shaker runs

Comparison (*)	f < 100 Hz	f > 100 Hz
Deep water (free hydr)	~2 dB	~2 dB
Shallow water (bottom hydr.)	~5-7 dB (*)	~5-7 dB



* Aschau: known problem at low frequencies

Uncertainties FS

- Data acquisition and processing
- Correction for propagation losses
  - Shallow water increases uncertainty
- Repeatability of ship signature itself
  - Lack of data in public domain

- *Remark: distinction between contribution of different noise sources can be difficult*

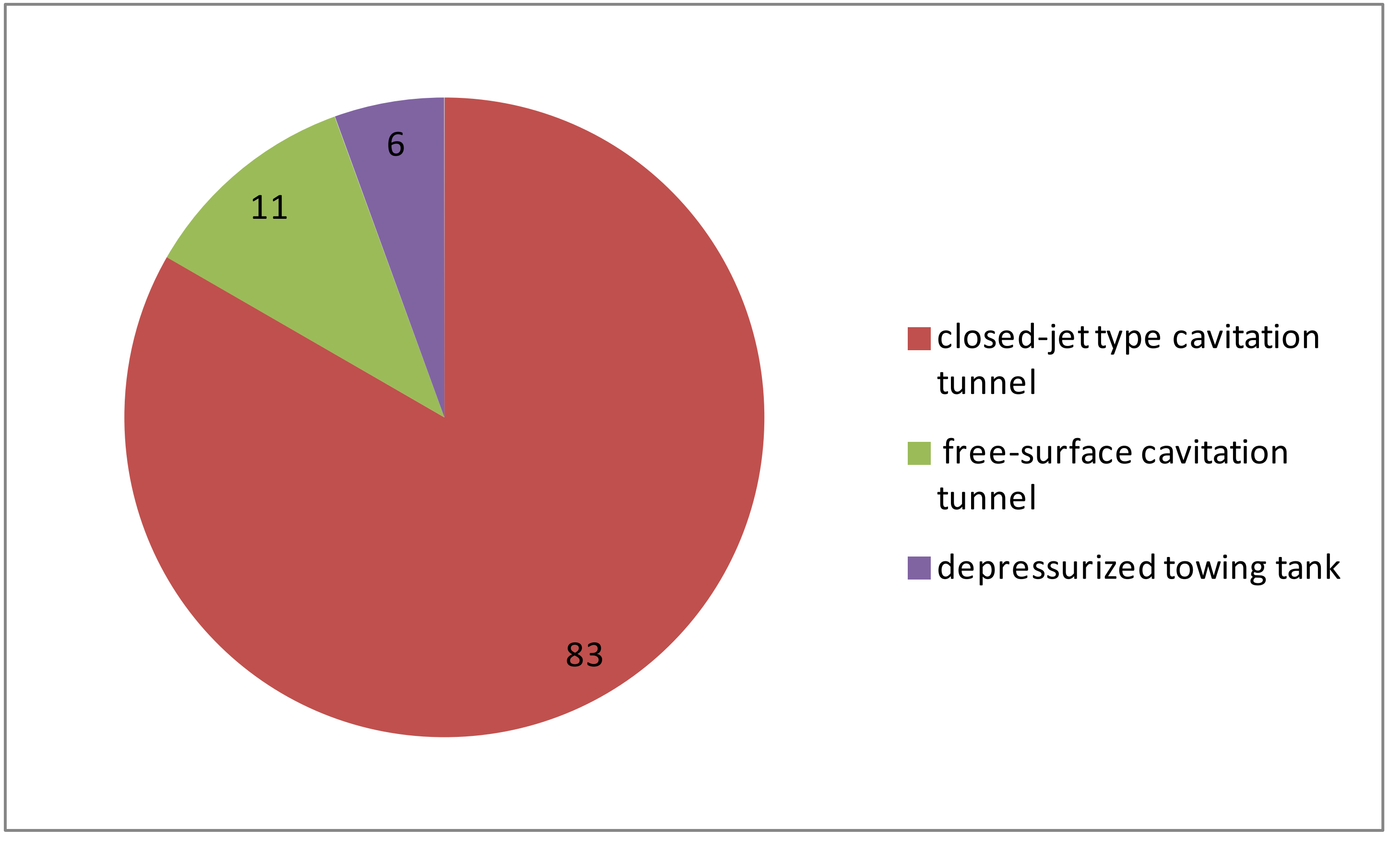
Guidelines model scale measurements (7.5-02-01-05)

- Purpose: ensure consistent and reliable noise measurements in model scale facilities
- Extension to guidelines on hull pressure measurements
- Contents, also in survey:
  - Measurements
    - Test set-up / Test-conditions / Instrumentation /
    - Background noise / acquisition and processing /
    - Other items: air content / nuclei / blockage
  - MS – FS scaling methods
  - Review parameters
  - Uncertainty and validation

Survey Model Scale noise measurements

- Results not in draft proceedings, available at registration desk
- 18 organizations responded (12 countries)
  - China: CSSRC, SSRI
  - Germany: HSVA
  - Italy: INSEAN, U. Genua
  - Iran: U. Sharif
  - Japan: MHI, JMUC, MEGURO
  - Korea: KRISO, HHI
  - Netherlands: MARIN
  - Norway: MARINTEK
  - Russia: KRYLOV
  - Sweden: SSPA, Rolls-Royce
  - Turkey: Istanbul TU
  - USA: NSWC/CD

MS survey – 1. Facility



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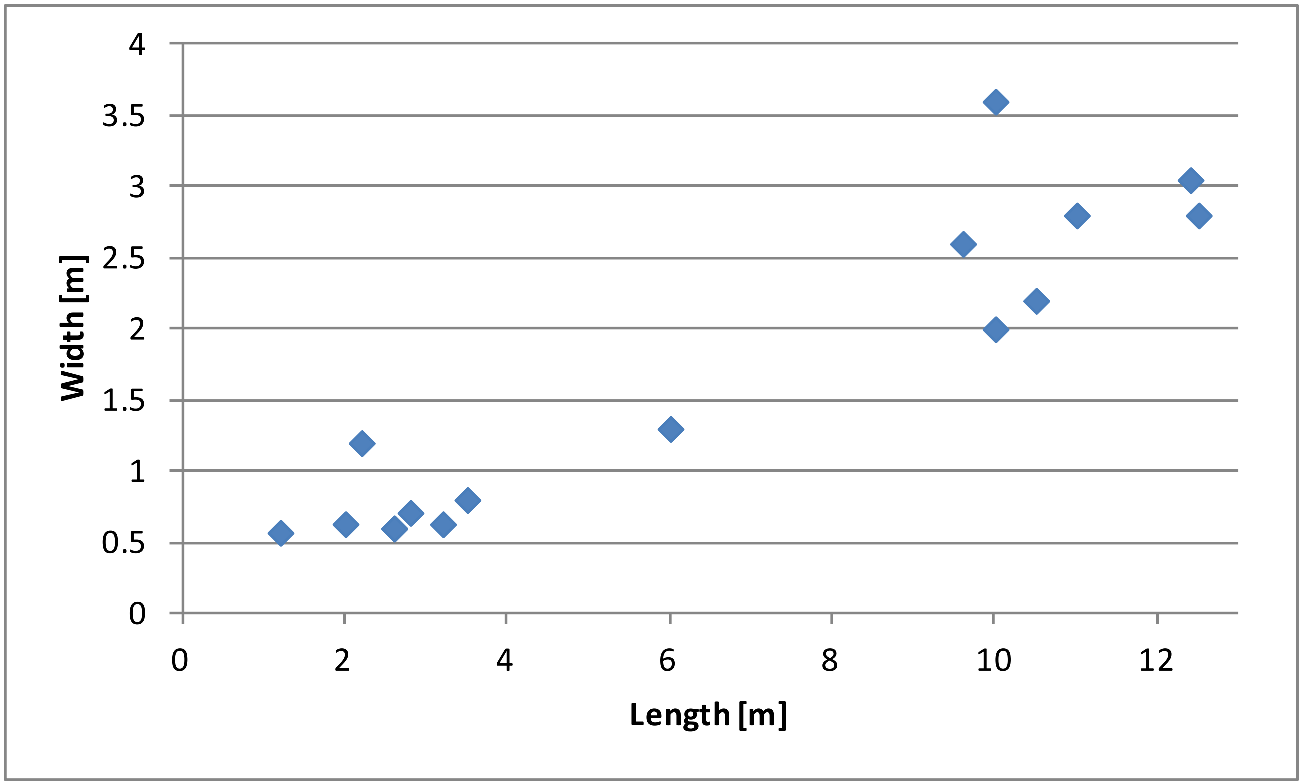
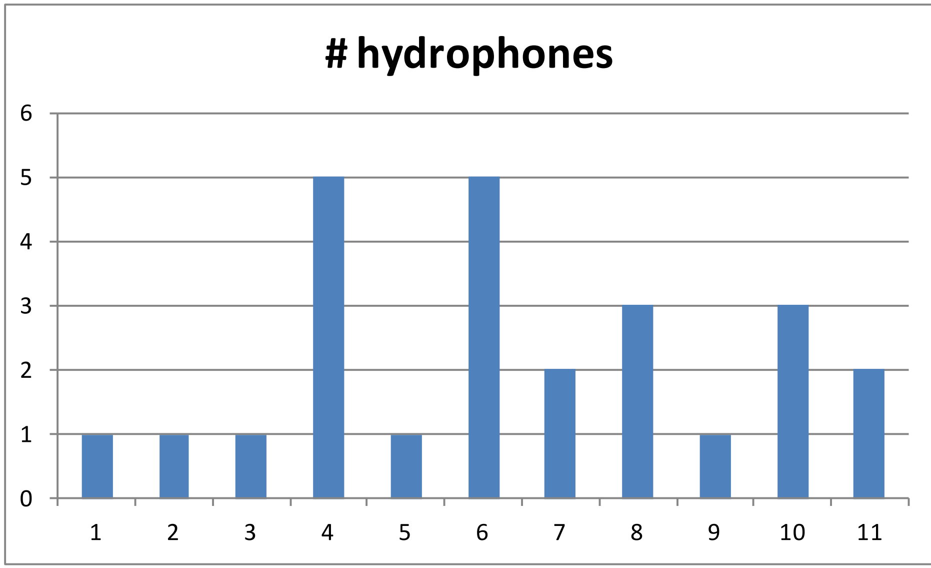
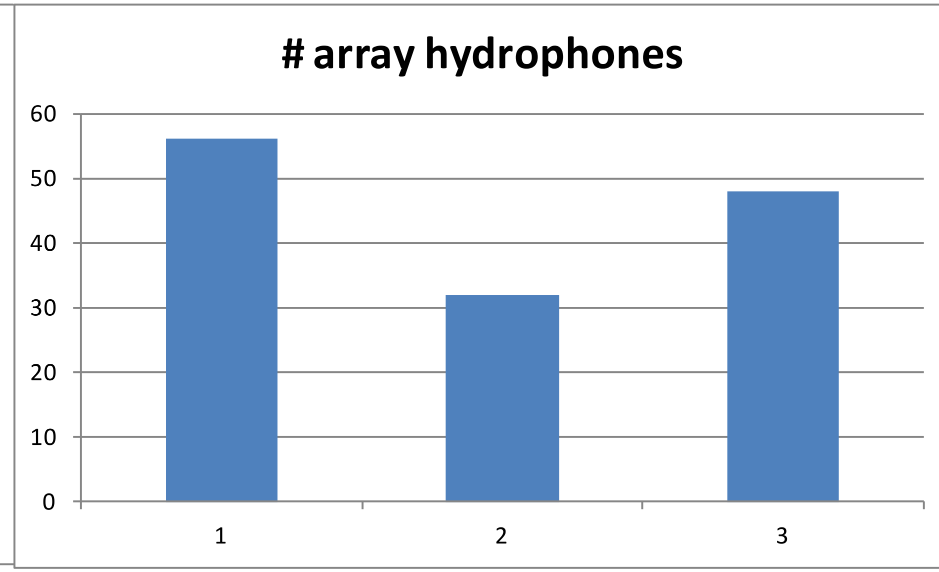
MS survey – 1. Facility

- Size cavitation tunnels



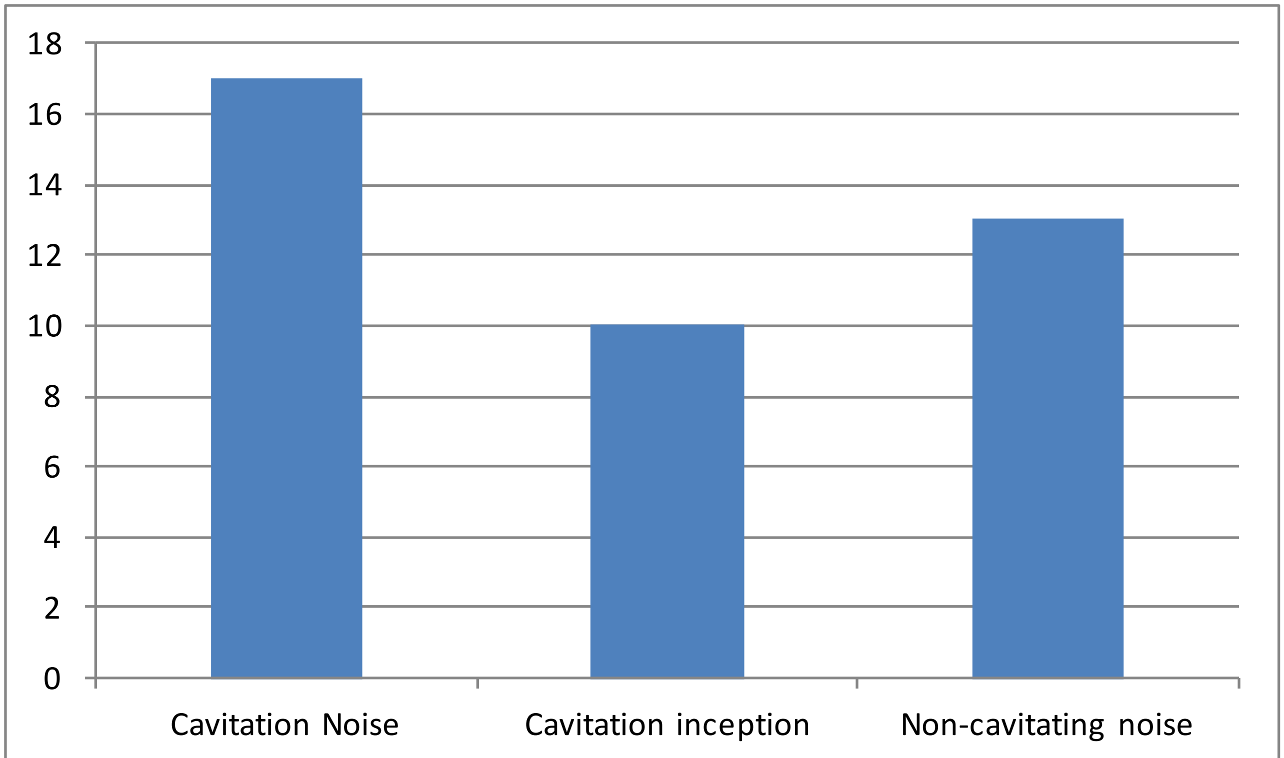
MS survey – 3. Hydrophones





MS survey – 4. Test conditions

- Purpose noise measurement



Guidelines MS

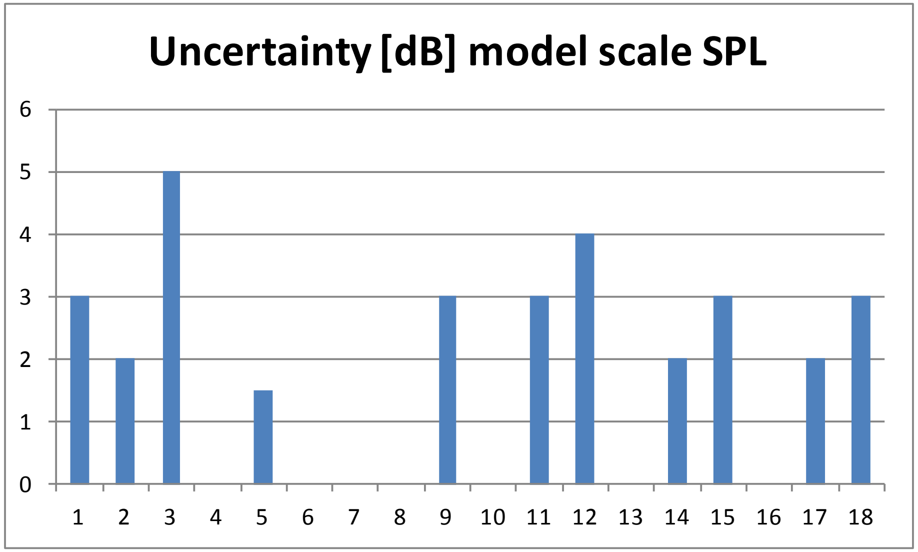
Critical items MS measurements

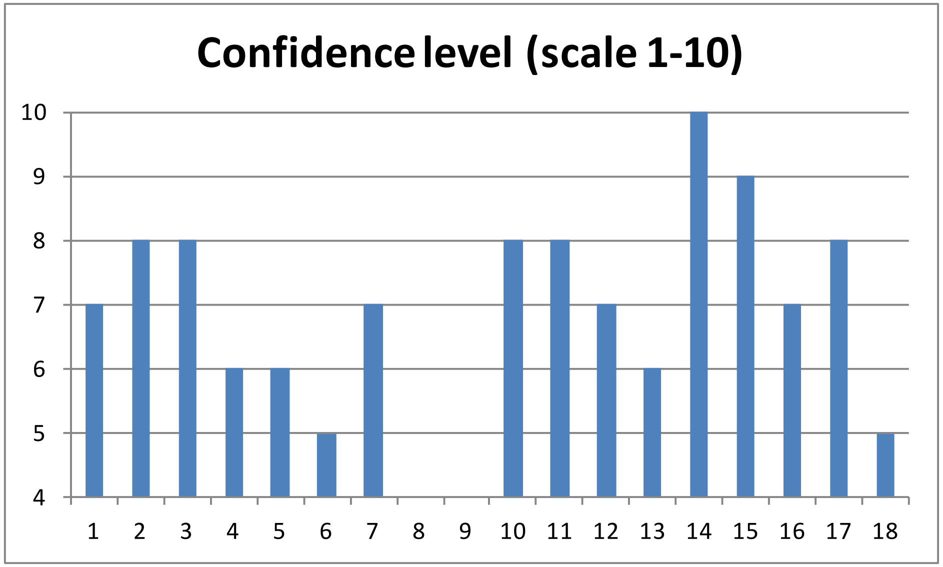
- Ship wake field
- Cavitation control (nuclei, air content, roughness)
- Hydrophone position
- Influence wall reflections on measured noise
- Influence air content on sound transmission
- Background noise levels (facility, driving train, …)
- Distance normalization

-> Need for benchmarking case

MS survey – 4. Test conditions

- Model scale sound pressure levels



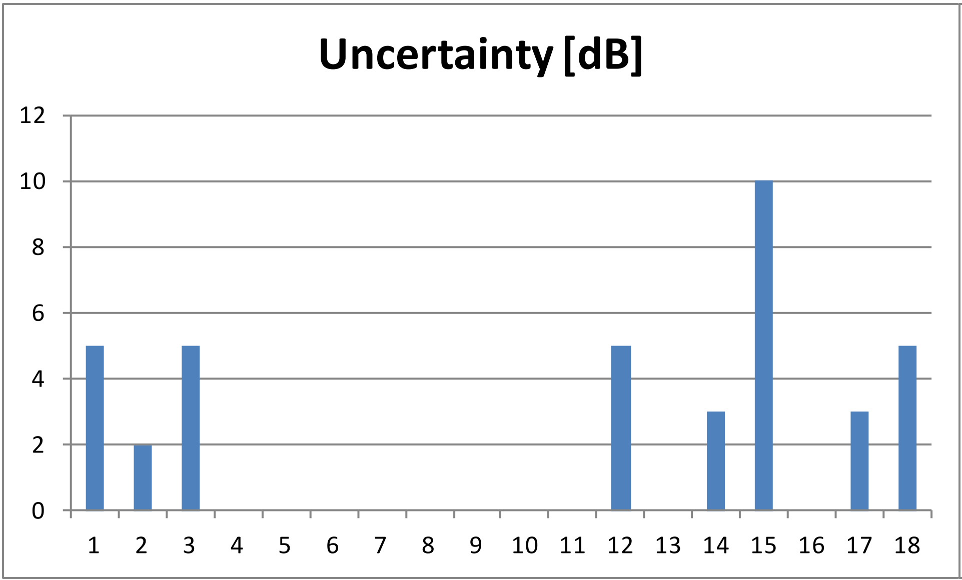


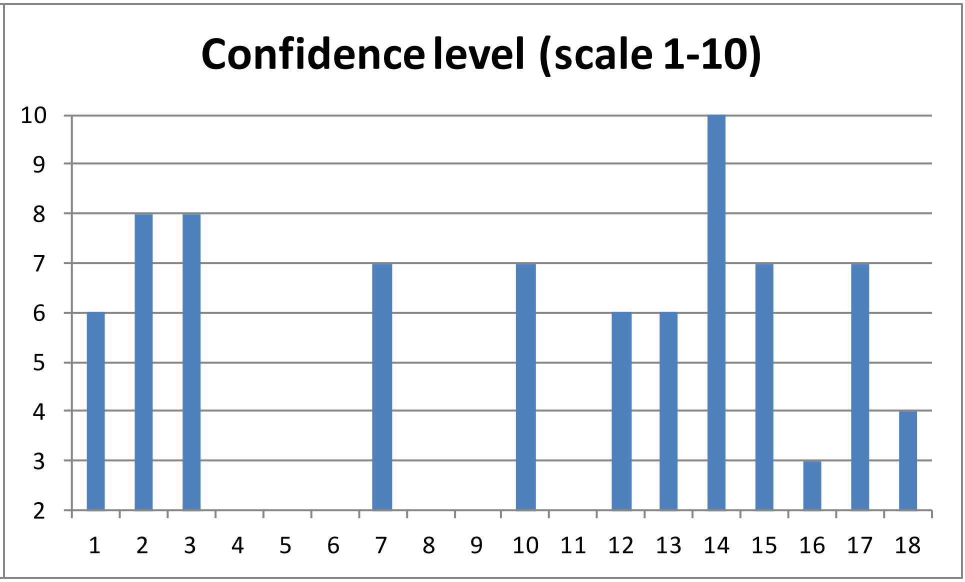
MS -> FS noise scaling

- ITTC ’78 scaling formula’s for <u>developed</u> cavitation noise still in use
  - but varying exponents are used
- Scaling for tip vortex cavitation noise issue
  - Delayed inception at MS poses problems
- Lack of sufficient FS data for validation
  - EU FP7 projects AQUO and SONIC will provide more data for commercial vessels

MS survey – 5. Scaling

Predicting Full Scale Cavitation noise from Model Scale tests





Conclusions

- Shipping noise is getting more attention due to impact on marine environment
- Various noise sources reviewed, machinery and cavitation noise typically dominant
- Prediction of cavitation noise difficult
  - Advanced numerical capabilities in development
  - Model scale measurements need more information on uncertainty, accuracy and scaling
- Regulation
  - No legislation available but is expected in the future (EU GES)
  - Noise limits specified by ICES and DNV Silent Class
- Guidelines
  - ISO standard for full scale deep water noise measurements is acceptable
- Model scale noise measurements
  - Based on survey, more work needs to be done

Recommendations

- Adopt guidelines 7.5-02-01-05 and 7.5-04-04-01
- Develop procedure for model scale noise measurements
- Establish communication with ISO working groups on full scale standards
- Update overview of regulations and standards
- Review noise prediction methods
- Review uncertainties
- Define benchmarking case for numerical prediction methods and model scale noise measurements