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WIND PROPULSION AND UNDERWATER RADIATED NOISES MITIGATION

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SUMMARY

From various scientific studies, we know that vessels' Underwater Radiated Noises (URN) have significant negative impacts on marine life. As the worldwide maritime traffic increased over decades, oceans are getting noisier. Since a few years, part of the shipping industry is working to mitigate URN, and most maritime organizations are preparing future rules to protect marine life from noises. URN emitted by vessels mainly come from propeller cavitation and machinery equipment. Studies show a clear reduction of URN with ship speed decrease as propulsion power is reduced.
Wind propulsion is the most silent means to propel a vessel. Its contribution to ship propulsion is an opportunity to reduce URN to acceptable levels for marine life, but it implies ship speed reduction. The question is therefore "What would be the maximum achievable speed, combining wind and conventional propulsion, keeping the URN to an acceptable level for the marine life?"

UNITS
All values are given using the International System of Units.

ABBREVIATIONS

ANL	Ambient Noise Level
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
DT	Detection Threshold
OSS	Optimum Ship Speed
RPM	Round per Minute
SL	Source Level
TL	Transmission Loss
TWA	True Wind Angle
TWS	True Wind Speed
URN	Underwater Radiated Noises
WASP	Wind Assisted Ship Propulsion

1. INTRODUCTION

"Imagine you live in a dark place, and you must rely on your hearing the same way you would rely on your vision. And that space is loud and getting louder. It's certain to cause you stress." This statement from CLEAR SEAS Centre for Responsible Marine Shipping (Canada) clearly illustrates the issue of growing URN levels in the oceans and their impacts on marine life.

While several global entities like the EU are continuously working on measures to reduce URN emitted by ships, there is no state today currently imposing legally binding requirements. But they will certainly come someday.

As the shipping industry is working on URN mitigation measures for the existing fleet and newbuilding, wind propulsion is an additional opportunity to reduce noises along with other benefits.

To quantify the benefits of wind propulsion for URN mitigation and marine life protection, this article presents the following aspects:

- Sources and levels of URN emitted by vessels, and the effect of ship speed
- Sensitivity of marine mammals to URN depending on the level and frequency band
- Principles of Wind Assisted Ship Propulsion (WASP)
- An example of URN mitigation on a WASP cargo vessel.

2. URN MITIGATION INITIATIVES

The below main initiatives regarding URN mitigation show how active this topic is at a worldwide level. Many other initiatives exist in this field (national and regional).

2.1 IMO SDC 8: LATEST UPDATES

In a bid to address the issue, the IMO Sub-Committee on Ship Design and Construction (SDC 8, January 2022), began its work to review the 2014 "Guidelines for the reduction of URN from commercial shipping" (MEPC.1/Circ.833). Given the complexities associated with ship designs, the guidelines focus on primary sources of URN, namely on propellers, hull design, onboard machinery, and various operational and maintenance recommendations

2.2 PIAQUO PROJECT

The European project AQUA laid the ground for the PIAQUO Project, an initiative led by EU gathering several international partners, aiming at reducing the acoustic impact of maritime traffic and adapting it in real time to the ecosystems.

2.3 THE ZERO POLLUTION ACTION PLAN

In the frame of COP 15 (Montreal, December 2022), the EU is taking action today to better protect marine life from URN. The new limits mean that no more than 20% of a given marine area should be exposed to continuous URN over a year. These URN pollution limits are part of the Zero Pollution Action Plan and are the first of this kind at global level.
These threshold values have been developed under the Commission's Marine Strategy Framework Directive.

2.4 CLASSIFICATION SOCIETIES' NOTATION

Seven classification societies have implemented voluntary class notations for ships related to URN limitations, motivated by environmental concerns. For other reasons, research and cruise vessels were the first type of vessels to obtain these notations. However, a tanker has been awarded the DNV's Silent-E class notation (DNV GL 2017) in 2021 being the first cargo vessel to do so for environmental motivations.

3. URN EMITTED BY VESSELS – EFFECT OF SPEED REDUCTION

3.1 SOURCES AND LEVELS OF URN EMITTED BY VESSELS

URN emitted by conventionally propelled vessels mainly come from propellers cavitation, hull appendages and machinery equipment.

The design of propulsion machinery and associated propellers usually leads to propeller cavitation at nominal speed. Cavitation is the formation and collapse of vapor-filled cavities in water due to low pressure in the fluid (vortices) and/or on the blade or appendage surface (bubble or sheet cavitation). This phenomenon creates significant underwater noise over a wide frequency range. Propeller cavitation appears above a certain propeller rotational speed (RPM) and ship speed (called cavitation inception speed) specific to each propeller and ship design. Avoiding or limiting cavitation is of interest for certain types of ship. For example, navy ships propulsion aims at acoustic discretion while research vessels need low URN for their acoustic equipment. Cruise vessels target passengers' comfort with low noise levels.
The cavitation of propellers mainly depends on the blade hydrodynamic loading. As the blade rotational speed increases, the internal side blade load increases while the external side pressure decreases until it reaches local pressures below which water vaporises. Cavitation may be mitigated by the combined use of low tip speed (low rpm/high pitch), larger blade area ratio, uniform inflow (hull design), optimized blade loading, and reduced tip loading. Cavitation may also be reduced if the blade loading is reduced at a given ship speed using an additional mean of propulsion (wind for example as we will see further).

Hull appendages, when properly designed, produce low levels of URN, and rarely cavitation.

Machinery equipment transmit noises and vibrations to the hull through the room air and their structural supports. The hull then radiates this noise in the sea water. The noisiest machinery equipment are:
- Propulsion diesel engines (low, medium or high speed)
- Diesel Generators

Rotating machines and electrical motors may also contribute to URN at a lower level.

From report [2], the following noise levels, measured at 6 m depth, are given with respect to vessel sizes:
- Gross Tonnage from 500 to 50 000 UMS: 160 to 180 dB (typically general cargos)
- Gross Tonnage from 50 000 to 100 000 UMS: 170 to 200 dB (typically large tankers)

In terms of frequency band, the URN emitted by ships cover a wide range from 10 Hz to above 10 kHz depending on the type of vessel and speed. The major part of the world ocean shipping fleet is constituted by tankers, bulk carriers and containerships. They are therefore the major contributors to oceans URN levels. Report [5] shows that peak mean sound levels appear between 30 and 100 Hz for these vessels with levels ranging between 170 and 190 dB re 1 µPa m depending on the model (source at 6 m below sea level).

3.2 URN MITIGATION BY MACHINERY AND PROPULSION DESIGN

Modern ship with propeller propulsion can reduce significantly the URN levels by propulsion design. This can be done by optimizing the propeller for reduced cavitation by increasing the blade area ratio for example which involves a small loss in efficiency. It can also be achieved by reducing the propeller tip speed through RPM reduction which is made possible by low-speed electric propulsion motors. This implies typically a higher machinery weight and cost compared to mechanical transmissions. Il can also be achieved by improving the ship wake into the propeller, typically by going to twin shafts, or even better choosing thrusters or pods (more expensive).

Machinery equipment airborne and structure borne noises (and vibrations) can be reduced by resilient mountings and isolation of enclosures. Electrical propulsion achieves some of these objectives by allowing resilient mounting of the diesel generators.
It shall be noted that resilient mountings on main propulsion engines are adapted to 4-stroke medium to high-speed diesel engines, but not to heavy 2-stroke engines low speed engines (major part of the fleet) due to their weight.

These considerations have led to the propulsion architecture of cruise vessels for example, which have very strict requirements for noise and vibration onboard, thus implying low URN. These ships may obtain URN class notations at speeds exceeding 15 knots. This is similar for research vessels to avoid interferences with acoustic equipment.

Retrofit of existing vessels with the above design features may bring a noise reduction in the range of 6 to 8 dB in low and high frequency bands respectively [2] which is not negligeable. But retrofit costs are usually too high for cargo vessels.

3.3 URN MITIGATION BY VESSEL SPEED REDUCTION

Hydroacoustic studies show that URN levels increase exponentially with vessel speed. In view of the predominant source of URN from propellers' cavitation and the significant cost of retrofit, ship speed reduction (along with propeller rotational speed reduction) is still the most efficient measure.

Report [2] gives the result of a speed reduction experiment in large areas close to Vancouver harbour. The vessels were asked to slow down to 11 knots and the noise reduction was measured between 6 to 12 dB for tankers/bulkers and containers vessels respectively. These reductions look rather small in % but are significant for marine life since a 3 dB reduction is equivalent to divide the perceived noise level by a factor of 2. Hence 6 dB and 12 dB correspond to a noise power level reduction factor of 4 and 16 respectively.

Report [3] presents the results of URN measurements emitted by a total of 29 commercial ships transiting in the Santa Barbara Channel, southern California coast. A graph (see Figure 1) was derived showing the relationship between the ship speed and broadband source level for various types of vessels of which fastest container ships (20-22 kts) emit noise levels around 184-188 dB whereas the slowest chemical product tankers (11-12 kts) emit noise levels around 176-178 dB.

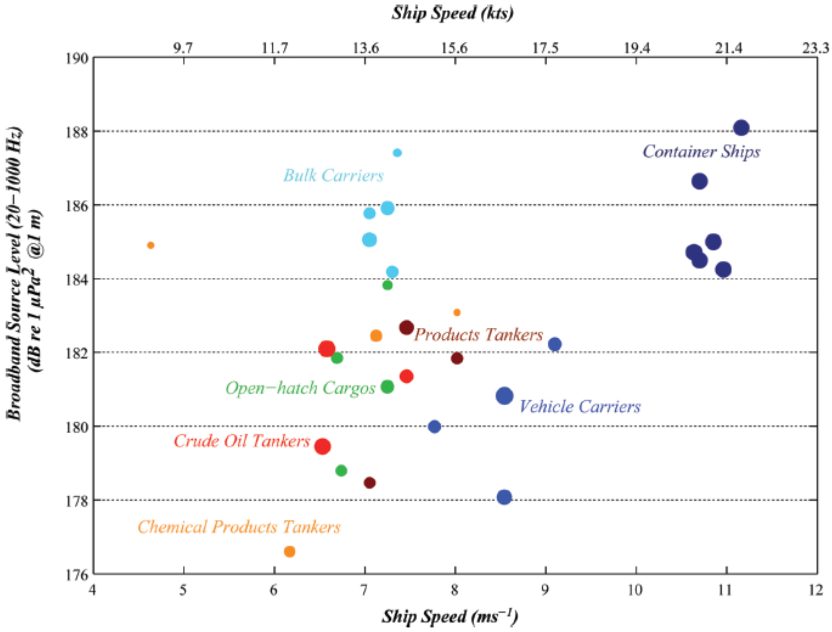

Figure 1 – Broadband Source levels for various types of vessel vs ship speed[3]

Ship energy consumption analysis can identify the most efficient ship speed (minimum consumption for a given distance travelled) which is typically much lower than the design ship speed. Ship speed limitation (debated in IMO committees without decision yet) brings, on top of URN reduction, the following main advantages:

- Fuel consumption reduction
- CO2 emission reduction
- Pollutants and particles emission reduction
- Increased contribution of wind propulsion for WASP vessels

Note regarding electric propulsion on batteries: this configuration concerns few vessels in the world and used for small distances. Speed reduction is anyhow required to reduce URN.

3.4 PROPAGATION LOSS FACTORS IN THE SEA

It is important to estimate or take assumptions on URN propagation losses to assess the impact of ship noises on the marine life.
Several factors influence the URN propagation losses between the source and the receiver:

- URN levels and frequencies at the source
- Depth of the source (below sea surface)
- Water depth and type of seabed (as the noises are reflected on the seabed)
- Sea water characteristics (temperature and salinity) in various layers
- Distance of the receiver from the source

This large number of parameters makes it complex to assess accurately the noise level received at a certain point of the ocean. Unless live in-situ measurements are available, modelisation is required and usually involves certain simplifications to estimate the propagation losses.

The URN source is close to the propeller depth, bottom of hull depth, or draft (usually set at 6 m below the sea surface).

Shallow water depths increase the sound reflections which usually increase the sound levels close to sea surface. Reversely, deep waters will better absorb noises as they lead to less reflections.
On the other hand, in deep waters, low frequency energy (<100 Hz) may travel over tens of kilometres, which is why ship noise has the potential to mask the marine mammals' communication far away from the source [1].

Hard seabed like rock increases the sound reflections whereas sedimentary seabed partially absorbs noises. The shape of the seabed also influences the propagation pattern which is another source of complexity.

Sea water temperature and salinity have an impact on the sound celerity. When the water column is constituted by multiple layers with different characteristics, the boundaries are acting like reflection surfaces. For example, a hot layer of several meters near the sea surface (typically during summer) will trap the noises which will enhance URN in the top layer. Marine mammals living in this layer will obviously suffer from this phenomenon.

We can therefore conclude that the URN level at the source alone is not the only indicator for the impact on marine life.

Based on marine traffic statistics across the oceans, and using URN propagation models with various input parameters and assumptions, it is possible to derive sound maps. EU-funded projects generated numerous sound maps (BIAS, AQUO, SONIC, JOMOPANS and JONAS) based on predictions of sound pressure levels to show how noisy are the oceans, especially along the maritime routes.

4. MARINE LIFE AND URN FREQUENCIES AND LEVELS

4.1 MARINE MAMMALS' SENSITIVITY TO URN

This article does not aim at giving all aspects of marine life sensitivity to human activities. It only refers to study results focusing on the impact of URN emitted by vessels on certain specifies of marine mammals (which may cover the sensitivity of other species).
The marine mammals' frequency band of communication is commonly used as the band within which they are likely to be disturbed. However other frequency bands emitted by vessels may also be detrimental to them on other aspects.
Studies are usually comparing these communication frequency bands to those emitted by vessels to evaluate the potential impact on marine life.

Report [5] presents the vessels URN frequency broadbands depending on the source (propeller or machinery) versus marine mammals' communication frequency broadbands. Figure 2 shows an example of such comparison.

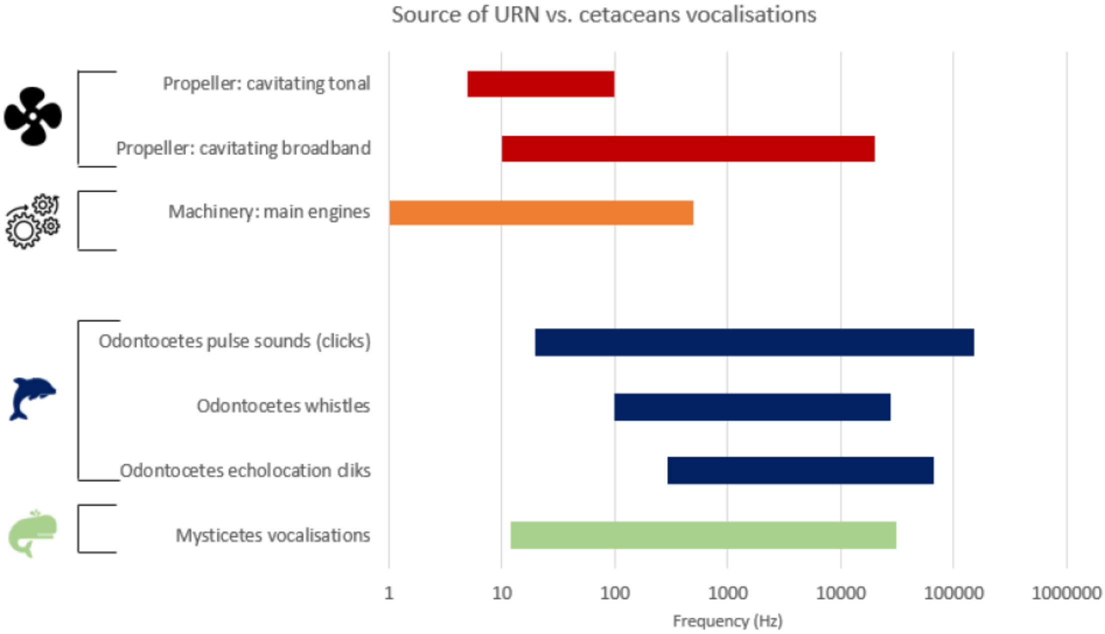

Figure 2 - Frequency range of shipping noise and different types of vocalisations produced by cetaceans. The frequency ranges are based on the minimum and maximum value of frequency found in literature for the different types of vocalisations (red colour = high contribution / orange colour = medium contribution)[5]

It is clear that the propeller cavitation frequency range covers all species communication frequency ranges. We know from previous sections that peak sound levels from bulker, tanker and container ships occur between 30 and 100 Hz which band interferes at least with Ondontocetes clicks and Mysticetes vocalisations.

From [5], we understand that shipping noises potentially have the following impacts on these cetaceans (depending on the sound levels):

- Changes in vocal behaviour
- Changes in diving and swimming patterns
- Reduction in the communication range
- Foraging behaviour
- Physiological responses

Temporary or permanent hearing damages are unlikely from URN emitted by vessels.

Regarding fishes, we also learn from [5] that their communication frequency broadband ranges from 30 to 5000 Hz, also overlapping with shipping noises. There are also evidences of negative impacts from shipping noises on invertebrates (behavioural, morphological and physiological changes).

4.2 NOTIONS OF AMBIENT NOISE AND COMMUNICATION DISTANCE

An Ambient Noise Level (ANL) including shipping traffic can be defined by the Wenz statistical level curves [8].
In the case of marine mammals, in a certain ANL, two individuals (or groups) may communicate up to a certain distance. If the ANL is high, the two individuals need to be close to communicate and if the ANL is low, the two individuals may be remote to communicate.
The first reaction of marine mammals when the ANL increases is to raise their source level (SL) gradually up to a certain physiological limit [1].

In the example of Figure 3, the maximum communication distance for frequencies around 100 Hz, in a Wenz type of ANL of 78 dB, is reached at R= 40 km. It represents the maximal range up to which the passive sonar equation is satisfied: SL–TL–ANL ≥ DT with DT (Detection Threshold) = 10 dB.

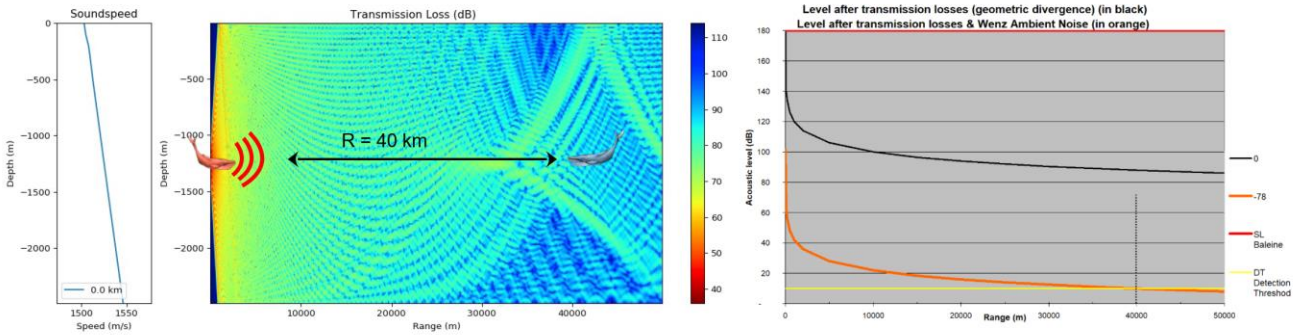

Figure 3 – Illustration of communication distance limit between 2 marine mammals at 100 Hz with:
Water depth =2500 m, ANL= 78 dB (Wenz Traffic2), SLwhale =180 dB, Whale depth =1250 m
Model used to calculate TL between the source and the receiver separated by a range R:
Left: Parabolic model. Right: TL= 20 Log_{10} (R) (Semantic-TS)

When a motor vessel comes close to any of the two individuals, the URN emitted by the vessel reaching the individual (after propagation losses) may come above or below the ANL. If the received vessel noise level is higher than the ANL, then it reduces the maximum communication distance, thus disturbing the animals' social life. This effect will be evaluated in the example presented at §6.

5. CONTRIBUTION OF WIND PROPULSION

5.1 BENEFITS OF WIND PROPULSION

URN emitted by 100% wind-propelled ships are expected to be below the natural underwater noise levels with careful machinery design. The major sources of URN on sailing ships are the following:
- Hull hydrodynamic noises which are very low for marine life
- Power generation and other machinery equipment noises which can be isolated
- Transient noises such as bow thrusters and anchor mooring noises

As shown in report [4], wind propulsion has been the subject of more attention recently, targeting to reduce shipping carbon footprint and air pollution, as well as fuel consumption as it is an important source of OPEX saving.
Modern wind propulsion concepts require fewer crew than in the past, using automation and electrical or hydraulic motorization in the rigging.

But even nowadays, targeting a high percentage of wind contribution involves lower ship speeds and lower reliability of Estimated Time of Arrival (ETA). Therefore, most wind propulsion concepts are considered as a WASP systems and try to find the best compromise between wind contribution and speed.

There is a large variety of modern wind propulsion concepts (main ones presented in [4]) which are usually mixed with conventional propeller propulsion. The optimum percentage of the mix between wind and conventional propeller propulsion mainly relies on the ship program, the selected wind propulsion technology and the size of the wind propulsion system.

The wind propulsive power depends on [4]:

- the true wind speed (TWS)
- the ship speed
- the angle between the true wind and the ship heading (TWA)
- the surface area of the propulsion system exposed to the wind
- the lift and drag coefficients provided by the selected technology

5.2 WIND THRUST CONTRIBUTION VERSUS SPEED

The typical relation between required propulsive thrust and ship speed is exponential and specific to each ship design and loading. The reason for having an exponential increase of the propulsive thrust is due to a hydrodynamic relationship between ship's drag (or resistance) and speed, specific to each vessel (several ship's parameters involved). At low speed, the relation of resistance to speed (V) is approximately to V^2 and it increases to V^3 at higher speeds. Typically, an increase of about 20% of the ship speed will increase its propulsive power demand by more than 50% [4].

On a sailing ship which does not use its propeller propulsion (100% wind propulsion), polar diagrams are commonly produced by Velocity Prediction Program (VPP) to show the sailing performances which combine the sail system and hull performances. The polar diagram is used to forecast the ship speed for given TWS and TWA. Typically, for a given TWS, the maximum ship speed is obtained for TWA varying from around 135° to 45° (angles with respect to ship heading).

As the ship speed increases, the AWS increases as well and the AWA decreases. The wind thrust and ship speed increase in a virtuous circle up to a certain equilibrium speed. For vessels with poor sailing abilities (high resistance and/or small sail system) using only wind propulsion (like cargo sail ships), this phenomenon is however minor.

As seen on most polar diagrams, for TWA varying from about 45° (TWA limit) to 0° (head wind), the ship speed drops rapidly down to 0. What determines the point where the wind thrust starts to decrease is the AWA limit. This limit is specific to each rigging and wind propulsion technology. An AWA limit around 35° is typical, smaller values being possible.

When combining conventional and wind propulsion, the ship speed may be selected by the captain, adjusting the propeller propulsion to the required level (RPM) depending on the complementary wind thrust. The driving parameters for wind thrust contribution are the AWS and AWA.

Above a certain ship speed, the AWA limit is reached and the wind thrust starts to decrease drastically as the AWA reduces towards ship axis (0 deg). This principle is applicable to most WASP systems. The ship speed limit associated to AWA limit (wind thrust start of decrease) is specific to each wind propulsion concept and vessel but it is clear that sail systems capable of producing thrust close hauled (high lift to drag ratio) will be more beneficial in terms of average wind power contribution.

Above a higher ship speed limit, the rigging starts to generate more drag than thrust: it is therefore bringing a negative contribution.

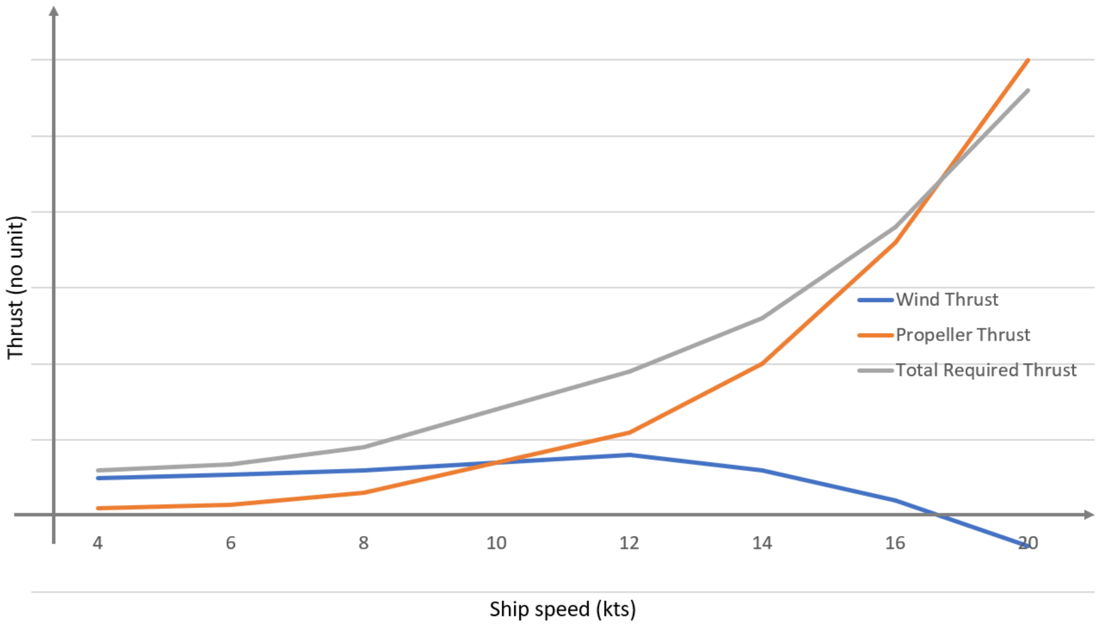

Figure 4 – Typical wind thrust contribution for TWS of 15 knots and TWA of 60 deg (XP Sea)

The typical graph of Figure 4 represents the situation on a hypothetical WASP ship using specific wind conditions with TWS of 15 knots and TWA of 60 deg as an example.
An AWA limit of 35° is assumed in this example (angle below which wind thrust starts to decrease).
The ship speed associated to the AWA limit is around 12 knots. We may call this speed the "Optimum ship speed" (OSS) although it does not mean that it is the best speed for other criteria.

As the ship speed increases to the OSS, the AWS also increases up to about 23 knots. This drives the wind thrust up to its maximum at the OSS. Above the OSS, the wind thrust starts to decrease which requires increasing further the contribution of the propeller propulsion.

Above a certain ship speed (18 knots in this example), the AWA drops down below another limit (27 deg in this example) where the WASP system is expected to generate more drag than thrust, therefore a negative contribution.

5.3 OPTIMUM SHIP SPEED FOR ACCEPTABLE URN LEVELS

As it is clear that 100% wind propulsion at slow speed gives the lowest URN levels, and 100% conventional propulsion at maximum speed is the worst case for URN emission, the question is:
"What would be the maximum speed achievable combining wind and conventional propulsion at which the URN would be acceptable for marine life?"

The answer to that question is quite complex as it depends on the following main parameters:

- Vessel characteristics including hull dimensions, displacement, machinery and propulsion design
- Sail system characteristics
- Environmental conditions at any time (wind speed, wind direction, sea state, routing, etc.).
- URN propagation loss factors as seen previously
- URN levels and frequencies acceptable for the marine life (specific to each group of species).

Assuming hypothetical values or design options, we can focus on the relation between propeller RPM, ship speed, wind contribution and URN levels.

5.4 EXPECTED PROPELLER RPM AND URN REDUCTION

To quantify the contribution of wind propulsion to the URN reduction, we may compare the two following situations for the a OSS ship speed of 12 knots as shown in Figure 4:

- Case A: 100% conventional propeller propulsion
- Case B: Mix between 60% conventional and 40% wind propulsion

In Case A, a propeller RPM_A is set with blades fully loaded for the given speed.

In Case B, a propeller RPM_B ($< RPM_A$) is set with blades less loaded.

At RPM_A corresponds URN_A where cavitation may occur
At RPM_B corresponds $URN_B < URN_A$. where cavitation is expected to be minimum or nil.

We are therefore looking at an estimate of the URN reduction = $URN_A - URN_B$.

When we look to the URN levels emitted by vessels at different RPM, they are associated to different vessel speeds, which means that in all cases, the propeller is fully loaded for the required speed in an equilibrium between thrust and drag.

Let us consider the case of a vessel under conventional propulsion only at a certain RPM0 and Speed0 associated to URN0. If we add wind propulsion to conventional propulsion keeping the same RPM0, the vessel will accelerate to Speed1, however the propeller loading will drop somehow which will reduce the cavitation and therefore the URN level to URN1<URN0. Keeping the wind propulsion contribution and same wind conditions, if we reduce the RPM from RPM1 to RPM2 and slow down the vessel back to Speed0, the cavitation will further be reduced and the URN level will further drop down to URN2<URN1<URN0. As a result, URN2 level potentially includes no cavitation, other sources of noises (machinery) being predominant.

6. EXAMPLE OF URN MITIGATION IMPACT BASED ON A CARGO VESSEL FITTED WITH WASP

6.1 METHODOLOGY

As stated previously, cargo vessels (bunkers, tankers and containerships) constitute the vast majority of ocean shipping traffic. These vessels are usually not designed with a machinery and propulsion for low URN levels (like navy, research and cruise vessels). URN reduction on these vessels through WASP retrofit and appropriate propulsion management would therefore bring a significant benefit to marine life worldwide.

The methodology considers the example of a cargo vessel defined in report [7]. Although this cargo vessel is not fitted with a WASP system, the purpose is to compare the two cases (A and B) as described in §5.3 assuming that the cargo vessel could be fitted with an appropriate WASP without changing other characteristics. The WASP system is not defined but should be compatible with the assumed performances.

Report [7] defines relations between RPM, ship speed and URN.
Then for each URN frequencies and levels A and B, site and environmental assumptions are taken to estimate the propagation losses. An assumption is taken on the ANL including shipping traffic (ANLshipping).

Ultimately, a comparison is made between the two cases to determine the impact of wind propulsion on the maximum communication distance between two individuals (or groups). The reasoning is that starting from a maximum communication range of 40 km (see Figure 3), two individuals separated from that distance should come closer by R_A in Case A and by R_B in Case B in order to communicate. R_A and R_B are therefore the minimum required gathering distance to be achieved by one individual (or a group) to communicate with another due to the presence of a vessel.

6.2 CARGO VESSEL CHARACTERISTICS, URN FREQUENCIES AND LEVELS

The cargo vessel characteristics in below tables and figures are extracted from [7].

Vessel name:	M/V OVERSEAS HARRIETTE
Date of construction	1977
Deadweight:	25 515 tons
Length overall	172.9 m
Beam:	22.8 m
Draft full load:	10.2 m
Draft ballasted:	7.9 m (condition of measurements)
Maximum speed:	15.9 kts (full load)
Associated rpm:	145 rpm
Propeller diameter:	4.9 m
Number of blades:	4
Engine type:	Direct-drive, two-stroke diesel (Hitachi/Babcock & Wilcox 6K67GF, 6 cylinders)
Engine power:	11 200 HP (low speed engine)
Diesel generator:	5 cylinders (Hitachi/B&W)

Table 1 – M/V Harriette characteristics[7]

Propeller rotational speed (rpm)	**Ship speed (knots)**	**Keel aspect wideband source level (*) (dB re: 1 mPa at 1 m)**
68	8	178
86	10	180
105	12	184
122	14	190
140	16	192

(*) Peak values

Table 2 - Relation between Engine speed, ship speed and wideband source levels[7]

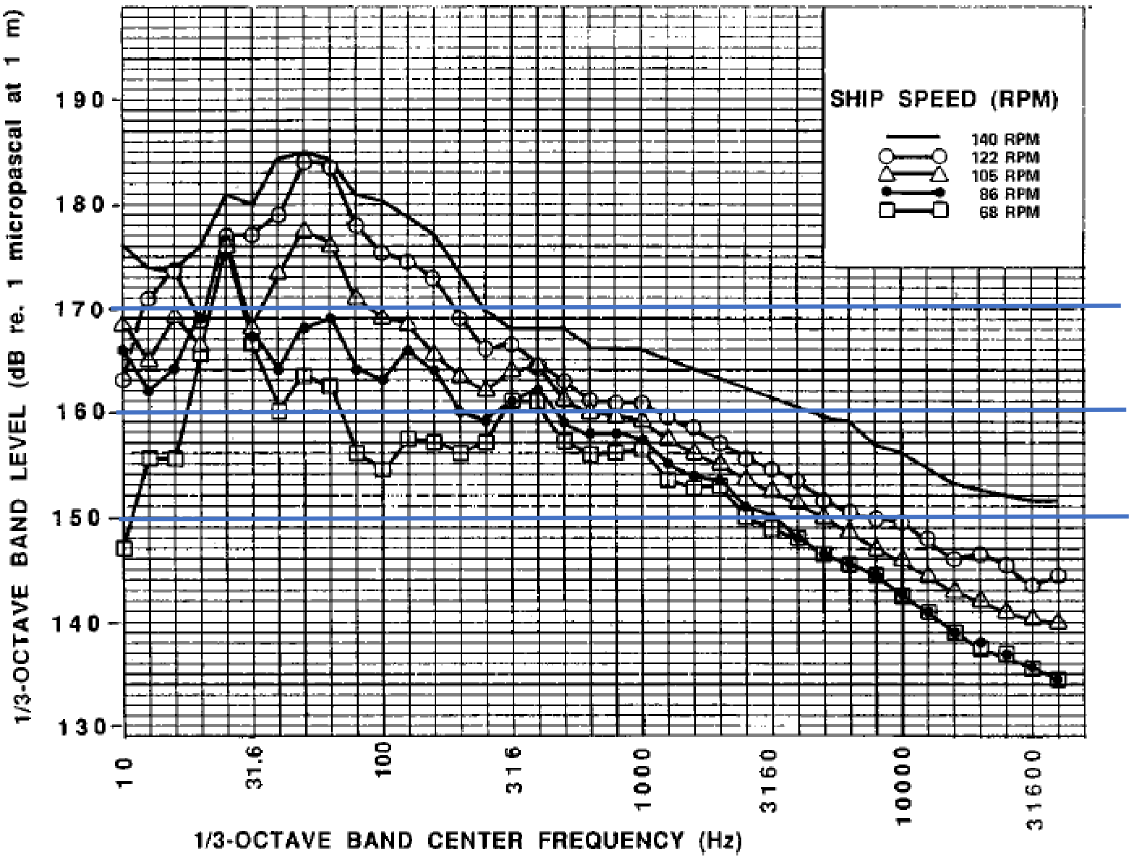

Figure 5 – Keel-aspect third-octave bandwidth spectra of the vessel at various speeds[7]

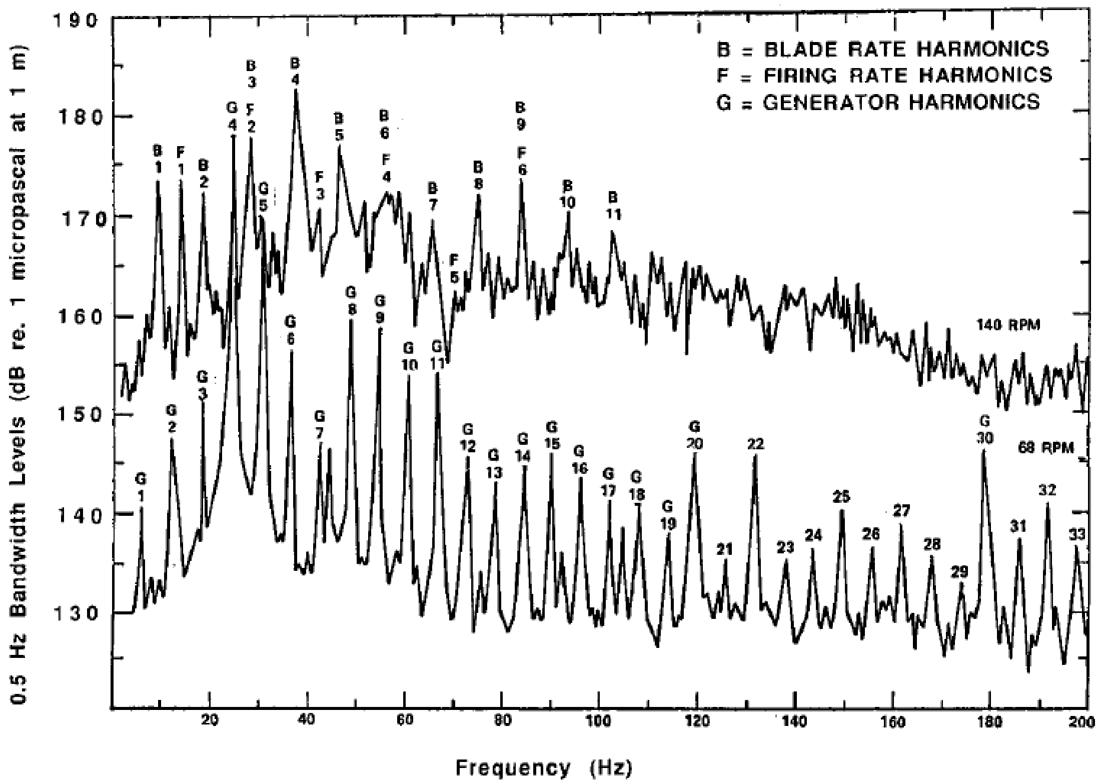

Figure 6 – Keel-aspect narrow-band spectra of the vessel in 0.5 Hz bands at low speed (68 rpm) and maximum speed (140 rpm)[7]

B = Blade rate harmonics are related to cavitation
F = Firing rate harmonics are related to the propulsion engine noise
G = Generator rate harmonics are related to diesel generator noise

6.3 STUDIED CASES

Following the methodology described in §6.1, Table 3 presents cases A and B to be compared. The URN levels are maximum values of specified broadband ranges taken from Figure 5. It is to be noted that they are in line with the measured values presented in §3.2 and [2] [3].

Parameter	**CASE A 100% Conventional Propulsion**	**CASE B 60% Conventional 40% Wind**	**Difference**
Ship speed (knots)	12.0	12.0	
Thrust form conventional propulsion	100%	60%	
Thrust form wind propulsion	0%	40%	
Propeller rotational speed (rpm)	105	68	-37
URN maximum levels	Values in dB from Figure 5 except (*)		(dB)
10 – 31.6 Hz	178	165 (*)	-13
31.6 Hz – 100 Hz	179	165 (*)	-14
100 Hz – 316 Hz	170	161	-9
316 Hz – 1000 Hz	164	161	-3
> 1000 Hz	159	156	-3

Table 3 - Studied cases (XP Sea)

CASE B uses the following wind conditions (same as in Figure 4):

- TWS = 15 knots / TWA = 60 deg
- AWS = 23 knts / AWA = 35 deg

(*) As stated in [7], it is understood that propeller cavitation is significant above a speed of 10 knots (86 rpm), which means that at 68 rpm, maximum URN levels are emitted by diesel generators (G) as shown in Figure 6. The URN peak levels for 68 rpm between 20 Hz and 40 Hz appear to go above 165 dB. This is not a realistic situation on modern cargo ships as resilient mountings and insulation in the machinery is common nowadays. This means that all URN emitted by diesel generators (G) should be below 165 dB at any frequency band. We therefore consider this value as a maximum in CASE B at 68 rpm.

For the evaluation of the impact on marine mammals, we will focus on frequencies around 100 Hz for which the reduction is from URN_A=169 dB to $URN_{B=}$155 dB, therefore -14 dB (see Figure 5).

In this example we may first give an equivalence in terms of noise contribution per vessel between Case A and Case B. Based on a logarithmic relation between noise levels and the number of emitting sources, in this example, with an offset of 14 dB, we may say that the URN_A emitted by one vessel is equivalent to 25 vessels emitting at URN_B ($10^{\frac{14}{10}} \cong 25$). This result is coherent with the findings of report [9].

6.4 ILLUSTRATING THE IMPACT OF ADDITIONAL NOISE ON COMMUNICATION DISTANCE

In our illustrative example of Figure 3, below the ANLtraffic, the marine mammals may communicate to a maximum distance of 40 km. When a vessel sails near a receiving whale, it generates a source URN which propagates to the receiving whale. Close to the vessel, the local ANL is louder than the ANLtraffic. The local ANL decreases as it propagates and starts equalizing the ANLtraffic at a certain distance. Beyond this distance, we may consider that its contribution is "drowned" in the statistical noise.

In Figure 7 the first graph compares the propagation losses between Case A (orange curve) and Case B (green curve) crossing the ANLtraffic (yellow line at 78 dB). The orange and green curves cross the yellow line at 36 km and 8 km respectively.
The second graph shows the same information in terms of minimum gathering distance R_A and R_B. The two whales are considered distant from 40 km and need to gather by R_A = 36 km and R_B = 8 km to be able to communicate.

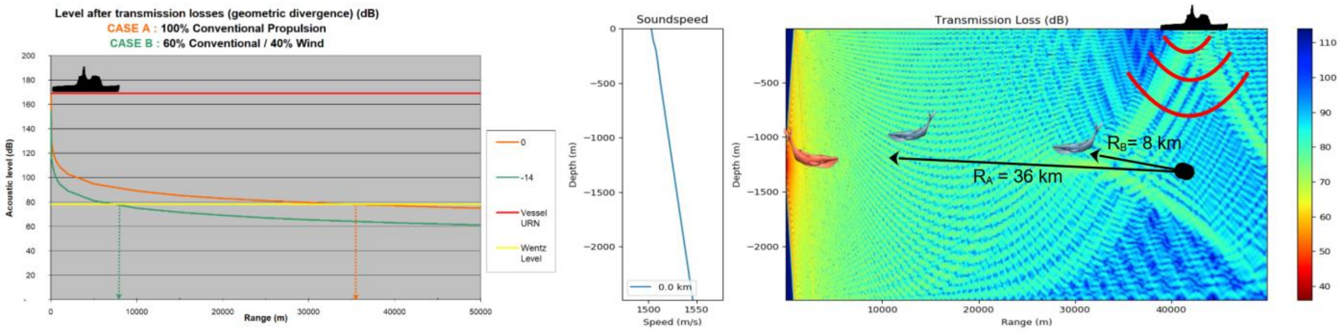

Figure 7 – Gathering distance R_A (orange) and R_B (green) required to be achieved by marine mammals to communicate (Semantic-TS)

6.5 MACRO ESTIMATING THE IMPACT OF ADDITIONAL NOISE ON COMMUNICATION DISTANCE

To generalise the benefit of wind propulsion in terms of maximum communication range (R) between marine mammals, we start from a reference state without maritime traffic. Then we express the reduction of R as a function of the noise disturbance from a vessel.

We define:

- R_{ref} as the reference range, maximum communication range in an environment without maritime traffic (ANL_{ref}), satisfying the passive sonar equation:
  $SL - TL(R_{ref}) - ANL_{ref} + DT = 0$
- R as the maximum communication range in the disturbed ANL due to a vessel coming across the area: $SL - TL(R) - ANL + DT = 0$
- $\Delta_{ANL} = ANL \quad - ANL_{ref} > 0$ is therefore the disturbance of the noise, view as a strictly positive anomaly, when a ship is passing through

Then $SL - TL(R_{ref}) - ANL_{ref} + DT = SL - TL(R) - ANL + DT$

implies TL(R) –TL(R_{ref}) = -Δ_{ANL}

Assuming, as an order of magnitude, a classical model for the transmission losses: TL(R) = A.$\log_{10}$(R)

Then we find: $\log_{10}\left(\frac{\mathrm{R}}{\mathrm{Rref}}\right) = -\frac{\Delta_{ANL}}{A}$ or $\frac{R}{Rref} = 100\ x\ 10^{-\Delta ANL/A}$ expressed in % of communication range reduction depending on the ANL degradation.

The following Figure 8 illustrates this relation and shows how fast the communication range is reduced with the increase ANL degradation.

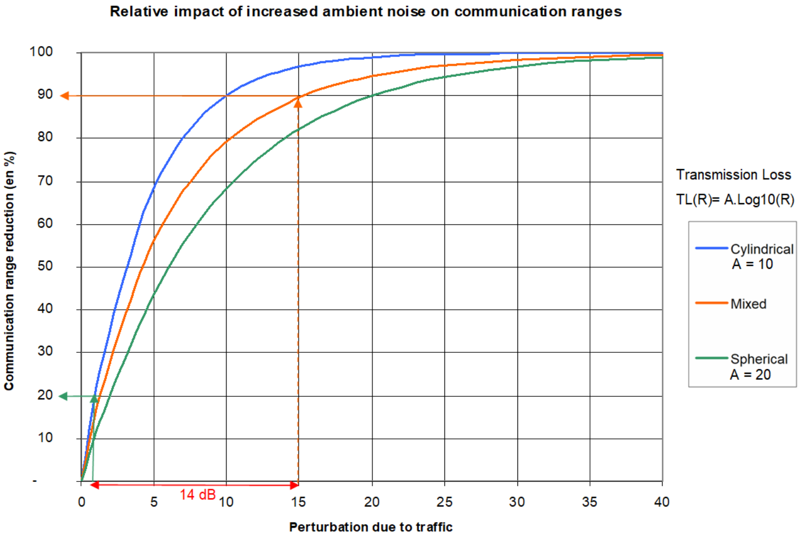

Figure 8 – Loss of marine mammals' communication range vs ALN degradation due to shipping traffic(Semantic-TS)

In Case A, Δ_{ANL}= $15.3\ dB$, the communication range reduction is of 90% (36 km versus 40km)
In Case B, Δ_{ANL}= $1.3\ dB$, it drops down to 20% (8 km) which is a considerable saving

7. CONCLUSIONS

The above results show that the benefit of wind propulsion contribution to conventional propulsion can be very significant with regards to URN levels reduction and marine life preservation.

Many parameters influence the results. Parametric data of URN measurements, as a function of speed, RPM and ratio of conventional vs wind propulsion are currently critically lacking to be able to carry out a serious impact study. However, the presented example shows that a WASP cargo vessel bringing a wind contribution of 40% on the propulsion (Case B) will reduce significantly the disturbance of marine mammals' communication while keeping the same speed as with 100% conventional propulsion (Case A). In this example, the communication range between two individuals is decreased by 90% for Case A and by 20% for Case B compared to a reference ambient noise level.

The benefit is expected to be greater with stronger winds or broad reach point of sail, and reversely smaller with lighter winds or close reach point of sail.

Reducing URN levels to an acceptable level for marine life means setting WASP vessels' speed to an optimal balance between wind and conventional propulsion. This good practice should be applied especially when the vessel enters areas where URN sensitive marine species are present. This requires real time on-board monitoring of marine species position and, ideally, a software displaying live URN levels and maximum allowable URN levels depending on the distance to sensitive species.

It should also be highlighted that collisions between ships and marine mammals represent a significant source of decline in the species (difficult to distinguish from other sources). This risk and severity of such collisions are drastically lowered by reducing ships' speed.

All these benefits are obviously cumulated with carbon footprint reduction and fuel savings.

A recent order in France for two 220 m long sailing cruise vessels shows the way: project name “Silenseas”.

Following this analysis, one can foresee that future regulations will push towards a reduction in vessel speeds and the use of wind propulsion in order to reduce fuel consumption, carbon footprint, and URN of shipping, all at the same time.

8. ACKNOWLEDGEMENTS

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