UDT 2019 – Improving submarine array integration for operational performance

Abstract — In underwater warfare the passive SONAR system is the main sensor of the submarine, thus its performance is usually considered as a key requirement. However, the performance does not depend only on the SONAR system but is also closely linked to how the design of the submarine integrates the SONAR arrays and to the quality of the submarine itself. In this document, we will discuss different aspects of the integration of SONAR arrays into the submarine that can improve operational performance of a submarine with a focus on its two main SONAR arrays, the bow and the flank array. To highlight key points of this analysis simulations have been performed on two models of medium size (2000t) conventional submarines (SSK) with distinct array integration and results are presented.

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1 Introduction

On modern submarines, the main SONAR arrays to detect surface or underwater threats are the bow array, the flank arrays and the towed array. If the towed array performance relies on its technology, the bow array and flank array operational intrinsic performance strongly depend upon the quality of their integration to the submarine. Indeed, their integration can influence detection performance with the main following impacts:

- Disturbing signal received by the array
- Increasing array self-noise
- Disturbing acoustic classification and identification of a threat
- Creating “ghost” detection

It is the submarine designer’s responsibility along with the SONAR manufacturer, thanks to a strong teamwork, to optimize the integration of these arrays in order to maximize their performance.

To illustrate key points of SONAR integration, two SSK submarines with about the same displacement and same length but with different hydrodynamic shapes and SONAR array integration have been compared.

2 Submarines models studied

2.1 Type A submarine

The first submarine considered in this paper will be referred as “**Type A**” and has the following characteristics:

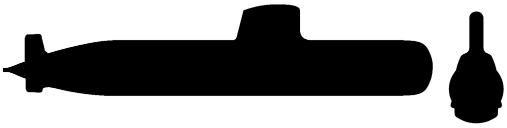


Fig. 1. Type A submarine

Its bow array is a cylindrical array, positioned in the upper part of the bow (above torpedo tubes) and the flank arrays, are mounted under fairings (GRP dome/fairings).

2.2 Type B submarine

The second submarine considered here will be referred as “**Type B**”. It has the following characteristics:

Fig. 2. Type B submarine

Its bow array is also cylindrical and about the same size as the one of “**Type A**”. But on this submarine, the array is positioned in the lower part of the bow (under torpedo tubes).

Its flank arrays are planar thin flank arrays, flush mounted with hydrodynamics fairings in front and behind the array’s acoustic part.

3 Bow array integration

3.1 Overview

Thanks to its wide frequency bandwidth and large bearing coverage, the bow array plays a major role in the knowledge of the acoustic situation around the ship.

However, in order to maximize detection performance this array must be fitted properly into a submarine.

For medium size SSK the bow cavity cannot be dedicated solely to the array and is usually shared with other equipment. The positioning of the bow array has a strong impact on the whole architecture of the submarine and on the SONAR detection performance. From SONAR point of view, the followings points shall be considered:

- Optimize array positioning and reduce array sensitivity to ambient noise
- Maximize array bearing and elevation coverage
- Minimize impact of self-noise on the array

These points are developed in the chapters hereunder.

3.2 Optimizing array position based on ambient noise consideration

As presented in the overview, on a medium size SSK, the bow cavity hosts a lot of equipment including torpedo tubes and the bow array, but these are the ones which have the strongest impact on the architecture of the submarine. Considering only these two major elements, then two types of configurations are be possible: one with the bow array above torpedo tubes and the other one with the array below the tubes.

Considering SONAR performance, the bow array fitted below torpedo tubes shall be preferred because it reduces array sensitivity to ambient noise.

Indeed positioning the bow array in the lower part of the bow cavity, the array is protected from the ambient surface noise of the waves coming from above and takes all benefits of the anisotropy of ambient noise.

Surface noise is often strongly non isotropic. According to the sound velocity profile, the energy coming from the surface is detected at positive elevation angles from short to medium range through a direct path, whereas the energy coming from negative angles comes from bottom reflection or refraction of noise at longer range, as illustrated in the figure hereunder.

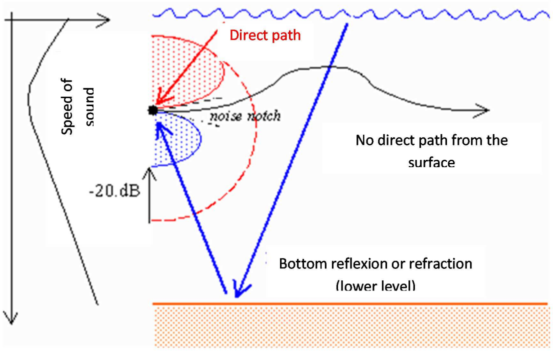


Fig. 3. Surface noise structure

Within bow array frequency bandwidth, we can notice that there is more noise coming from the surface than from the seabed.

By positioning the array in the lower part of the bow a significant gain up to 10 dB over the surface noise (considering an omnidirectional sensor) can be expected.

In this case, the optimization of the array installation could offer significant improvement in terms of surface noise rejection, as illustrated in the figure hereunder (Fig. 4), thanks to the masking of the surface noise on the array hydrophones.

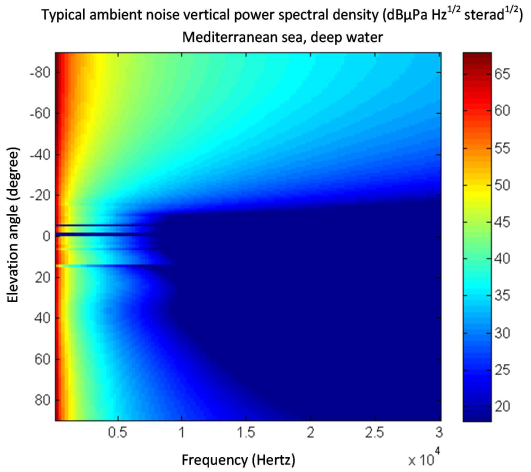


Fig. 4. Typical ambient noise vertical power spectral density

3.3 Maximizing bearing and elevation coverage

Maximizing the coverage of the bow array both in terms of bearing and elevation is essential because, the bow array remains the main sensor of the submarine to cover the frequencies above 5 kHz.

For bearing coverage, a back baffle area cannot be avoided, even by deporting the array under or above the hull (such as on 1950s submarine design – see Fig. 5). With this configuration, the self-noise would be much higher reducing drastically detection performance with submarine increasing speed.

Fig. 5. Flore submarine

To obtain the widest bearing coverage, the array should be integrated as forward as possible into the bow cavity and the acoustic window should be extended backward.

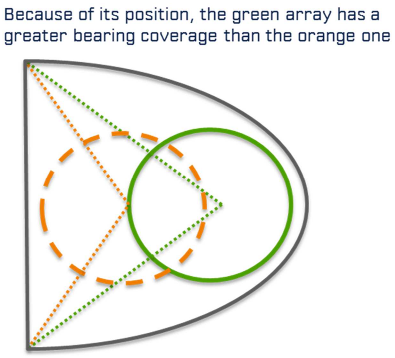


Fig. 6. Impact of array positioning on the bearing coverage

The forward array positioning also benefits elevation coverage. If architecture constraints allow it, this coverage can be greater than +40° and -40° (elevation) allowing the array to detect most of sound rays propagating into the sea (even for surfacing phase). To get that aperture towards the rear of the submarine, the acoustic window should be vertically extended so that the submarine bow structure do not mask sound coming from the rear (above or under).

Fig. 7. Scorpene® submarine

By positioning the bow array in the lower part of the bow cavity, surface noise rejection is obtained and bottom reflected beams detection capability is achieved at the expense of lower positive elevation coverage. However higher positive elevation coverage is usually not required (even for surfacing phase) as it leads to short detection ranges even at maximum depth of the submarine.

3.4 Minimizing the impact of self-noise on the bow array

Due to their relatively high listening frequency bandwidth and to the submarine's low vibration level, the two main components of self-noise on bow array are usually flow noise and electromagnetic perturbations.

Flow noise is linked to the overall shape and submarine speed. Flow noise will drive the optimum detection speed, which is considered as the maximum speed at which ambient noise remains higher than self-noise. For the same ambient noise, a submarine with lower self-noise will be able to operate at higher speed than another one, giving it a great advantage.

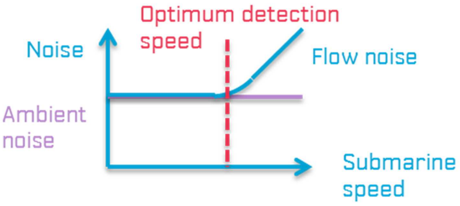


Fig. 8. Optimum detection speed definition

3.4.1 Minimizing flow noise

Flow noise received by the array is directly linked to the shape of the submarine and to array position in the bow cavity. The hydrodynamic shape of the submarine is a submarine designer responsibility because it has a strong impact on other main performance aspects of the submarine such has radiated noise, maximum speed, autonomy.

Flow noise is an uncorrelated source of noise and so is not reduced by specific array beamforming such as adaptive beamforming. Two ways are used to limit impact of flow noise:

- optimize the submarine hydrodynamic shape
- optimize the array position in the cavity

The acoustic excitation generated by a water flow can be described by its pressure auto-spectrum. Different models can be found in the literature. The most commonly used are Corcos, Goody and Chase [1]. These models allow comparing hydrodynamic self-noise level of different configurations (hydrodynamic shape and array positioning).

Hereunder we present some simulation results of the acoustic excitation of the bow array on Type A and B submarines using Chase auto-spectrum model 1987

$$S_{pp}(\omega)=2.\rho^2U_t^4.\omega^{-1}.h.(2.\pi/3.C_m.\alpha^{-3}.(1+\mu^2.\alpha^2)+\pi.C_T.\alpha^{-1}.(1+\alpha^{-2})) \qquad (1)$$

With

$\alpha=(1+U_c/(b.\omega.\delta)^2)^{1/2}$
$h.C_m=0.466$
$h.C_m=0.014$
$b=0.75$

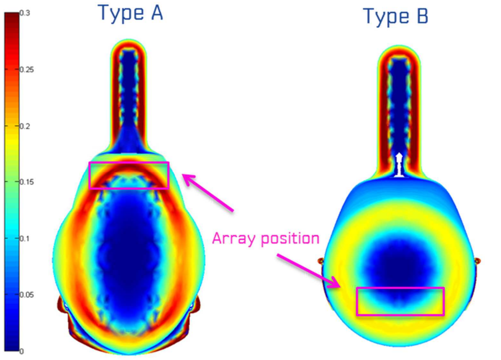


Fig. 9. Acoustic excitation level at 8 kHz and 12 knots for Type A (left) and Type B submarine (right)

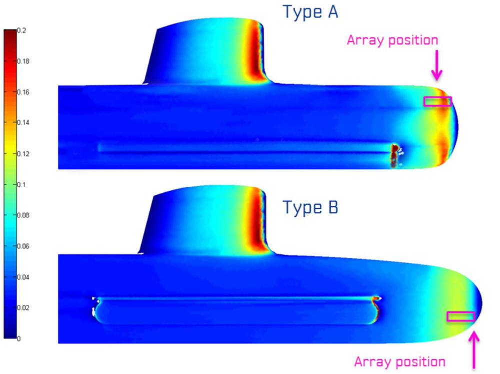


Fig. 10. Acoustic excitation level at 3 kHz and 8 knots for Type A (top) and Type B submarine (bottom)

Fig. 9 and Fig. 10 show that submarine Type A has poor hydrodynamic shape and moreover its bow array is located where the hydro-acoustic excitation is at a maximum. On the other hand, Type B submarine has a smooth hydrodynamic shape and the bow array is located in a quieter area in term of flow noise level. Considering the integrated noise level over the acoustic window, Type A submarine has a noise level at least 3dB higher than Type B, for every speed and in the whole frequency bandwidth of the bow array.

More complex simulations can be performed to optimize the array positioning and the design of the SONAR cavity. Usually for submarine programs, dedicated design cycles are performed between submarine designer and SONAR manufacturer to optimize the integration of the bow array:

- submarine designer defines submarine shape, array position and cavity size
- submarine designer computes hydrodynamic parameters around the submarine and the average self-noise level in the cavity
- SONAR manufacturer computes self-noise after SONAR processing (at beamforming level, array gain,…) using hydrodynamic simulation provided by submarine designer.
- SONAR manufacturer and submarine designer team analyze results and optimize bow array design and integration.

This optimization also takes into account the experience (especially at sea measurements) of both SONAR manufacturer and submarine designer on previous submarine class.

Following recent development [1], it is now possible to take into account complex and spatially growing turbulent flow coupled to the vibroacoustic response of an array (module & phase) enclosed behind an elastic dome. This new method shows the SONAR response after beamforming and therefore a coupled optimization between SONAR Manufacturer and Submarine designer can take place in order to design the shape of the dome, the cavity coating, the array geometry and its location within the SONAR cavity.

This development uses a spatial and stochastic methodology to model the flow inhomogeneity and its statistics. Below is an example of hydroacoustic noise simulation on a generic elastic dome including a cylindrical array One can notice the noise reduction in the 0° bearing and the impact of the cavity rear wall type (reflecting vs absorbing).

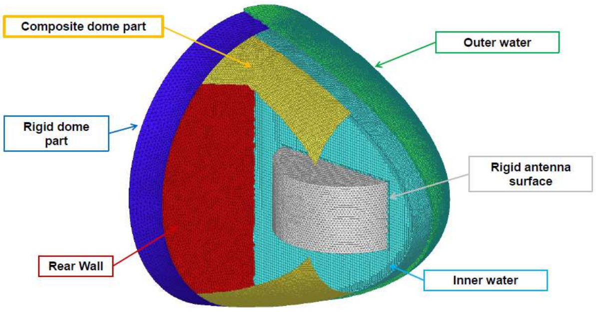


Fig. 11. Generic Bow SONAR cavity geometry

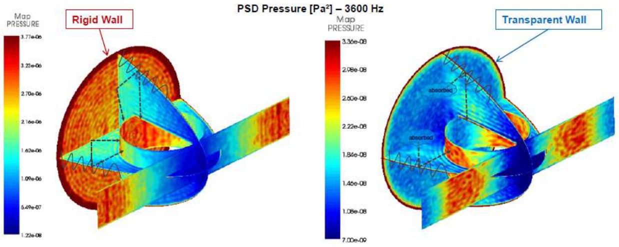


Fig. 12. Example of Bow SONAR Pressure PSD

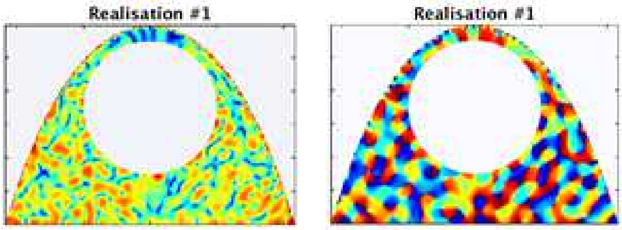


Fig. 13. Example of one stochastic noise realization (left: module; right: phase)

3.4.2 Electromagnetic compatibility

Electromagnetic compatibility was a major issue when SONAR arrays were analogue. Now, with digitalization close to the sensors, the phenomenon has been reduced but still remains. This signal pollution has a strong impact on detection performance when trying to identify a threat. Indeed, when the acoustic signal is polluted by electromagnetic phenomena, many frequency lines appear on analysis display and they make operators identification work harder and slower. Reducing the impact of electromagnetic interference on the SONAR is a job for both SONAR manufacturer and submarine designer.

At SONAR manufacturer level, specific actions are taken to suppress electromagnetic noise coupling or data transmission loss. Acoustic channels are shielded and use symmetric differential structure to minimize electrical noise pick-up between sensors and amplification and digitization stage. The data transmission between SONAR antenna and inboard cabinets is then quite immune to CEM because of the use of a digital link.

To reduce electromagnetic pollution, the submarine designer works on the routing of array cables to ensure that they do not pass close to strong electromagnetic generators such as electrical convertors, motor and that array cable harnesses are separated from other cable harnesses especially from ones carrying electrical power. Given that most electromagnetic field generators are located inside the hull, a good way to reduce the risks is to route array cable outside the pressure hull and to position pressure hull penetrator as close as possible to the SONAR cabinets.

To go even further in reducing electromagnetic noise, the use of optical fiber transmission is a solution. To reach full performance of this new kind of transmission, SONAR manufacturer and submarine designer work together to adjust array signal needs to transmission line features (cable and pressure hull penetrator).

All the technical solutions presented here for reducing electromagnetic noise are applicable to both CA and FA arrays

4 Flank array integration

4.1 Overview

For the last two decades flank arrays have been widespread on most submarines and their performance has been considerably improved (wider sizes, higher number of hydrophones, larger frequency bandwidths). As they are mounted onto the submarine hull, these arrays are very close to submarine noise sources and their integration has a major impact on their performance.

To secure or improve detection performance this array must be fitted properly on the submarine hull.

Depending on the array technology, integrating a flank array can have a strong impact on the architecture and the performance of the submarine depending on their technology (increase of drag and so reducing endurance). SONAR detection performance is strongly influenced by how this integration is done. From SONAR point of view, the followings points shall be considered:

- Optimize array positioning and reduce array sensitivity to ambient noise
- Minimize impact of self-noise on the array

These points are developed in the chapters hereunder.

4.2 Optimizing array position based on ambient noise considerations

As for the bow array (see section 3.2), the same considerations are applied to flank array integration in order to optimize it towards environment features.

A negative elevation tilting of the array between 15° and 25° (of course depending on submarine constraints) is chosen to reduce array sensitivity to ambient noise.

In this condition, the optimization of the flank array installation could offer significant improvement in terms of surface noise rejection, as illustrated in the figures hereunder.

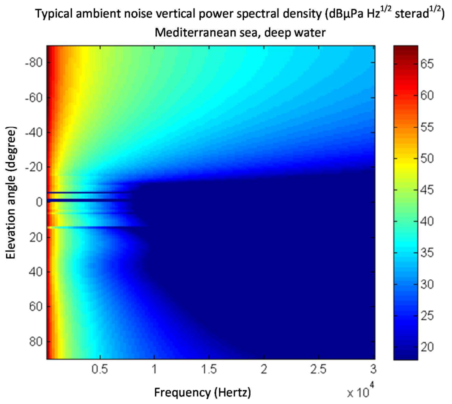


Fig. 14. Typical ambient noise vertical power spectral density

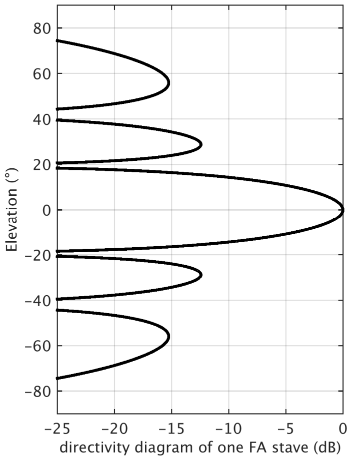


Fig. 15. Typical directivity diagram of one FA stave at its Shannon spatial frequency

Flank arrays have far less restrictions on their dimensions than the bow array, thus the shape can be also adjusted to optimize its performance thanks to the elevation directivity.

4.3 Minimizing impact of self-noise on the flank array

Due to their bigger size, flank arrays address a lower frequency range than the bow array. Thus the main self-noise components of the flank arrays are different from the bow array and are usually the following:

- Mechanical noise component at lower frequencies (from 200 Hz to about 1 000 Hz).
- Flow noise component above 1 000 Hz

4.3.1 Mechanical noise

Mechanical noise perceived by the flank array comes from the sources located inside the hull such as submarine engines, pumps, and other auxiliaries. The practice of masking materials between the array and the hull is one solution to reduce that noise.

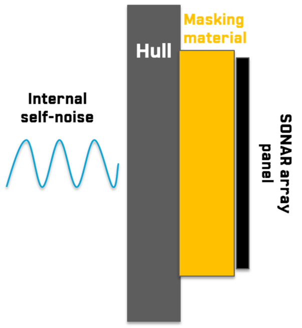


Fig. 16. Illustration of SONAR array mounted on backing material to reduce internal self-noise

But as mechanical noise is a very low frequency noise, it requires a very thick layer of material, which has a strong impact on a submarine: drag increase, buoyancy control. Indeed, as shown in the figure hereunder (Fig. 17) at low frequency the pressure field radiated by a stiffened cylindrical hull (representative of the pressure hull of the submarine) excited by a mechanical source (punctual force) is far more widespread than the flank array and its backing material.

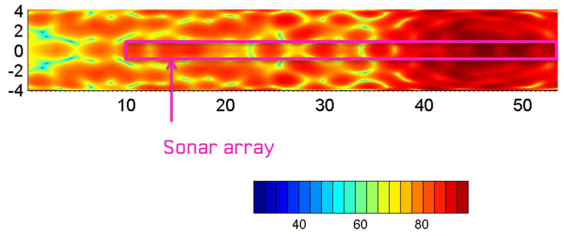


Fig. 17. Maps of nearfield (1 m) pressure field (dB ref µPa) on a stiffened cylindrical hull (55 stiffeners), excited by a punctual force at 600 Hz.

As shown on Fig. 17, despite masking material, array sensors will still perceive a strong pressure field coming from above and under the array, thus increasing self-noise.

To effectively reduce the effect of such sources on the array the SONAR manufacturer and submarine designer will adjust flank array shape and position to reduce their sensitivity to internal noise sources. Indeed main mechanical noise sources are located at the aft of the submarine (engine and propulsions system). The array performance is driven by its surface area. Keeping that identical, it is possible to make the array a shorter length (but taller), and so flank arrays can be better positioned to avoid the aft part of the hull as illustrated on the figure hereunder Fig. 18):

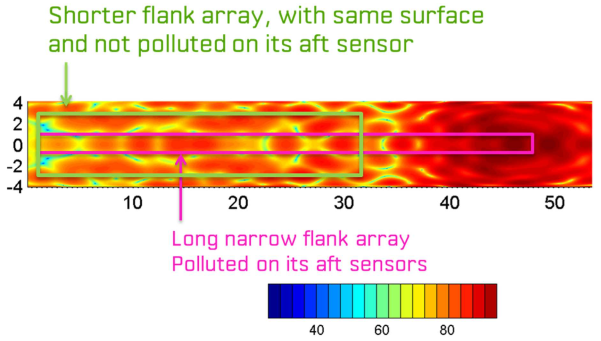
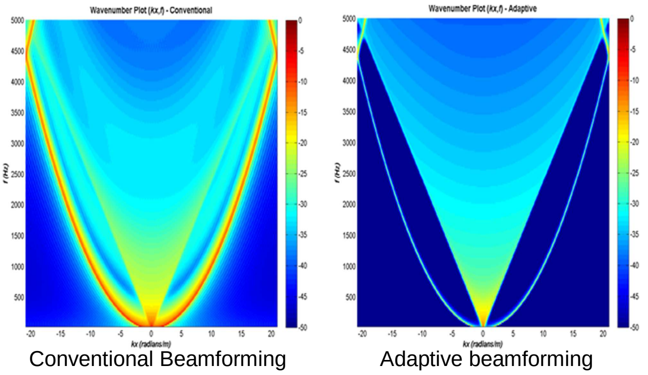


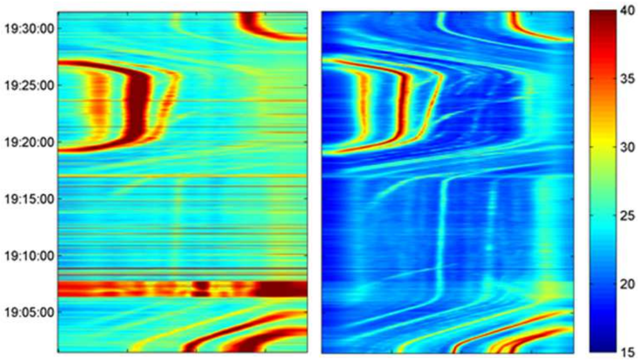
Fig. 18. Maps of nearfield (1 m) pressure field (dB ref µPa) on a stiffened cylindrical hull (55 stiffeners) representative of the pressure hull of a submarine, excited by a punctual force at 600 Hz. And with two different flank arrays shapes and positioning.

The global detection performance of the flank array is obtained by the combination of the array performance, its optimized integration to the submarine and the SONAR processing capabilities with advanced adaptive beamforming which is known to reduce correlated noise such as mechanical noise as shown on the figures hereunder (Fig. 19 and Fig. 20).



Conventional Beamforming Adaptive beamforming

Fig. 19. Flank array k-Omega plots (bearing vs frequency)



Conventional Beamforming Adaptive Beamforming

Fig. 20. Typical flank array broadband waterfalls (bearing vs time)

Having taller flank arrays also increases the effect of adaptive beamforming to reduce mechanical noise.

4.3.2 Flow noise

The first flank arrays were designed for low frequency detection, with digitalization and the evolution of processing capability, their frequency bandwidth has been considerably increased and they now reach mid frequency band (about 5 kHz) and even 10 kHz for upcoming development. Due to this frequency increase, flank arrays are impacted by hydrodynamic self-noise component above 1 kHz. To preserve the high performance of the array in the upper bandwidth and as no advanced SONAR processing (such as adaptive beamforming) has a reduction effect on hydrodynamic component of self-noise, the SONAR manufacturer and submarine designer must take great care of hydrodynamic aspects of the flank array installation on the ship.

A strong collaborative work shall be done by SONAR manufacturer to define array technology with the least impact on submarine hydrodynamics and by the submarine designer to provide the best fairings to avoid self-noise generation on the array. Optimizing hydrodynamics of the flank array will also benefit the submarine speed, endurance and radiated noise.

Hereunder Type A and Type B submarines flow noise excitation caused by the flank arrays and their fairings are compared. Type A has thick flank arrays mounted under large fairings while Type B has flush mounted thin planar flank array, with adjusted fairings front and back to smoothen the incoming flow.

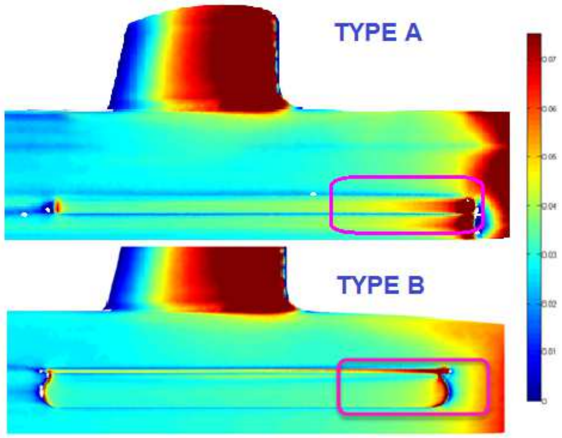


Fig. 21. Acoustic excitation level at 3 kHz and 8 knots for Type A (top) and Type B submarine (bottom). Magenta square shows the difference between thick flank arrays with angular form and thin planar flank array with smooth hydrodynamic fairings.

While Type B submarine has smooth hydrodynamic shapes, Type A has angular fairings and forms close to the array. These angular forms will generate vortices (as shown on figure Fig. 22 hereunder) which will increase self-noise even more.

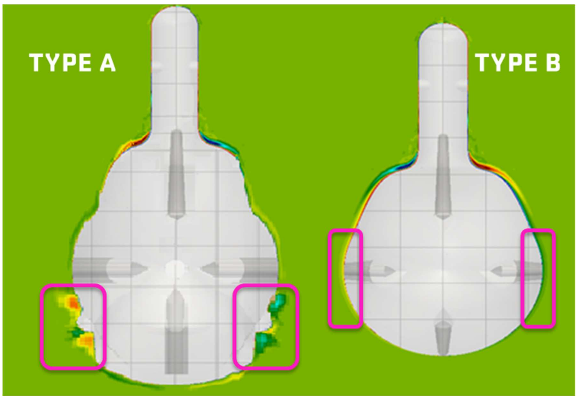


Fig. 22. Maps of vorticity on Type A submarine (left) and Type B submarine (right) showing the generation of vortex on Type A submarine by its angular form of flank arrays.

Giving an overall level estimation of the self-noise on Type A vs Type B would be difficult, especially due to the difficulty in computing the vortex noise component but according to Thales and Naval Group experience, it lies between 3 and 6 dB.

4 Conclusions

Submarine SONAR performance depends on the design of the acoustic arrays, their associated processing and the quality of the array integration to the submarine. Only strong collaborative work between SONAR manufacturer and submarine designer can lead to the best underwater detection performance. This paper has studied the influence of array integration on SONAR performance for the two main arrays of a submarine the bow array and the flank arrays. Beyond the necessity to implement the most advanced signal processing technics such as adaptive processing, the main recommendations regarding physical integration to optimize detection have been given.

These recommendations are summarized here for the bow array:

- The best array location is in the lower part of the bow to protect it from surface noise and optimize negative elevation sound rays detection.
- The shape of the bow and the exact position of the array in this shape shall be optimized taken into account hydrodynamic component of self-noise.

And for the flank arrays:

- The array position shall be chosen in relation with array shape in order to avoid the noisiest parts of the submarine (usually the aft part of the pressure hull).
- At equal surface area (and so array gain), higher flank arrays get higher benefits from adaptive beamforming.
- The hydrodynamic of the flank arrays and their fairings shall be studied by SONAR manufacturer and submarine designer to limit the impact of the array on ship performance and to reduce array self-noise. Angular shapes shall be avoided because they generate vortex which is an important source of noise.
- Thin flush mounted planar flank arrays present all the benefits listed above.

References

[1] M. Berton, Modélisation de la réponse vibro-acoustique d’une structure excitée par une couche limite turbulente en présence d’un gradient de pression statique, PhD thesis, INSA Lyon, 2014

Author/Speaker Biographies

Edouard HONORE has held the position of underwater detection specialist at Naval Group for 8 years during which he has specialized in SONAR array integration to submarine and surface ship.

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