#4

RESEARCH

SCIENCE FOR
NAVAL INNOVATION

NAVAL GROUP

POWER AT SEA

CONTENTS

FORE-WORD

STAYING ON COURSE
FOR FASTER INNOVATION

In her speech to the armed forces at the start of 2022, the former Minister for the Armed Forces presented the main focuses of the defence policy, with a message to all: **prepare to deal with the conflicts of the future, especially by anticipating and adapting our capabilities for action**. This means, in her own words, *"remaining at the cutting edge of future technologies, with ambitious, large-capacity projects, a strong European industrial and technological base and an enhanced capability to innovate."*

Innovation is at the heart of Naval Group's strategy. We must be able to meet the challenges set out in the Military programming law by overcoming technical barriers and contributing to research activities at the highest level. Our innovation work covers every stage of a ship's life cycle, from its design then construction right through to its maintenance and deconstruction. A single ambition drives our teams: contributing to the availability and operational superiority of naval forces.

The 5th edition of *Naval Innovation Days*, in October 2021 shed light on our strategic issues and the challenges to address. **Naval Group is currently working on several fronts to capture the most innovative ideas**: controlling complexity - essential for collaborative naval combat - stealth, energetic performance and more... Our teams are fully engaged in the functional and physical integration of drones in our naval force - one of the main challenges here being controlled decision-making autonomy. They also dedicate their time to developing algorithms to support tactical manoeuvres for submarines, ship performance thanks to composite solutions, energy optimisation and the hybridisation of energy-propulsion architectures, as well as cybersecurity.

Naval Group is convinced that research remains vital in preparing for the future. We must make quicker progress on key academic subjects related to our technical and industrial issues. While we are keeping up the pace of our work on long-term subjects such as materials science, our experts and researchers are also keen to integrate rapid current developments in Artificial Intelligence, and prepare for emerging subjects such as quantum technologies. This work contributes to the innovation not just of today, but of the future too, and represents the backbone of our ambitions: **keeping a step ahead in the naval industry and standing out from the competition; guaranteeing technological and operational superiority to our customers, in all oceans; and improving competitiveness, a condition for our leadership on an international level**. Naval Group's global innovation strategy is set around six unifying focuses: Invulnerable Ship, Smart Ship, Smart Naval Force (collaborative air combat), Smart Availability (maintaining operational superiority in combat), Blue Ship (the autonomy, eco-design and energetic performance of ships) and Smart Industry (the naval industry of the future).

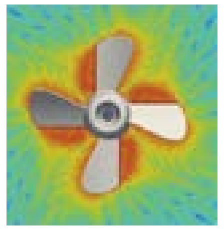
Research and Innovation requires cutting-edge expertise, provided by Naval Group's scientific community in the first instance. It meets the strictest academic standards and strengthens our international influence thanks to its publications and participations in scientific conferences. An increasing number of PhD students working on CIFRE theses are joining our teams and contributing as such to the dynamic nature of our research.

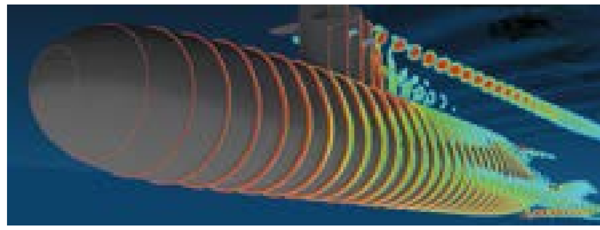
The quality of our research also depends on the scientific partnerships that we create, both in France and abroad, with a view to *Open Innovation*. Agreements for cooperation have been drawn up for research with the academic world and large public centres, as well as Co-innovation agreements with industrial companies, and the development of centres of excellence for R&D abroad.

Our Scientific Council also supports the group's approach to innovation by providing its opinion on our scientific focuses; leading working groups on highly innovative subjects; actively contributing to the acknowledgement of in-house scientific competencies; connecting us with scientific networks, as well as organising the scientific "La Pérouse" prize.

Our research work allows us to anticipate upcoming technological breakthroughs and to prepare for the future. It moves forward in line with the needs of our customers. So let's stay on course, not only by using our in-house talents, but also by calling on active support from our academic and industrial partners.

Pierre Éric Pommellet,
Naval Group Chairman & CEO





EDITO

CELEBRATING 10 YEARS OF SERVICE FOR THE GROUP'S INNOVATION STRATEGY

Naval Research, Naval Group's Technological research centre (CRT) turns 10 this year! For the past 10 years, we have been watching the **CRT teams work on a daily basis around complementary activities of expertise, scientific and technological research**, all aimed at providing support to naval programs.

Scientific and technological support represents a major challenge for Naval Group. It enables us to remain at the forefront in the fields of sovereign assets or those specific to naval defence, and even head for further development. **In preparing the controlled integration of tomorrow's innovations, this backing allows Naval Group to rise to numerous challenges**: building ships that are capable of remaining longer at sea and proving their superiority at all times - such as in terms of information - when engaging with threats; as well as designing and building more competitive ships.

In order to meet these challenges, we must **identify and acquire the key scientific capabilities that allow us to prepare the appropriate technological answers**. This work notably consists in transposing to the world of naval defence the scientific and technological developments currently led by civil industries with huge investments. There are numerous challenges for us in the field of applied sciences and the nine areas of S&T (Science & Technology) that are led by the CRT:

- **Advanced numerical methods**: better apprehending the complex aspects of reality using new numerical environments to better represent it, enabling us to better plan ahead;
- **Humans & Systems**: modelling the operator, understanding collective and individual reactions and adapting our systems to them in a dynamic manner; managing a user -centric design;
- **Digital systems**: designing updatable digital architectures and infrastructures that can be adapted at low cost; preparing tools to manage the increasing complexity inherent to digitalisation;
- **Data processing**: managing the key technology for creating artificial intelligence that will set us apart: decision-making and behavioural autonomy, high-level scheduling, crew - human collaboration and joint decision-making, etc.;
- **Energy**: increasing energetic efficiency, autonomy and density; meeting the needs of directed-energy weapons.
- **Eco-design and the environment**: improving our knowledge of the carbon and environmental footprint of our ships; ensuring our ships' ability to resist to the dramatic climate changes predicted;
- **Materials & Structures**: increasing our productivity both in manufacturing and maintenance, reducing the frequency and severity of damage (fatigue, corrosion, fouling, etc.), knowing the ship's condition in real time, developing functionalised materials to provide new added values;
- **Wave-material interactions**: improving predictive tools for signatures and threat assessment, creating new materials for stealth and the integration of antennae;
- **Fluid mechanics**: predicting and controlling turbulence and physically complex flows, better interpreting hydrodynamic loads for sizing structures, improving our prediction of hydrodynamic signatures.

Ten years after the creation of its CRT, **Naval Group can rise to these challenges using the multiple strong points it has developed**: a robust scientific program, scientific and technical skills as well as high-level laboratories, recognition of its scientific expertise; an affirmed attractiveness; a high-level multi-discipline Scientific Council and prominent academic and industrial partnerships, both open and collaborative, led in the spirit of co-innovation through research.

This new edition of our RESEARCH magazine illustrates this dynamic by offering you a glimpse of our recent successes and our projects to come. We hope you enjoy your reading, getting a closer look at our scientific and technological work, and meeting the women and men behind making it a success on a daily basis.

Vincent Geiger
Scientific Director at Naval Group,
Director of Naval Research.

Naval Group (DCNS at the time) created the Research entity in 2010 to better organise the activities dedicated to research and expertise, as well as introduce new initiatives. Alain Bovis, the entity's first Director of Research and now Vice-President of the Academie de la Marine, looks back over the context at the time and the initial observations made. *"The late 2000s saw the beginning of some major programs, such as the Barracuda (nuclear attack submarines), which called for a renewal of our technological bases. This meant re-establishing our R&T with two objectives in mind: obtaining the highest-performance design tools and investing, in order to build up a catalogue of tried and tested technologies... Innovation without these resources is simply not possible! We took advantage of this turning point to combine our in-house assets that were spread back then between three different centres: CESMAN and Sirehna in Nantes, and CEMIS in Toulon. So Naval Research was born, offering a consistent and complementary set of services, with a dedicated budget and the possibility to look for new projects and partners."*

01

COLLABORATIVE RESEARCH

JOINT LABORATORIES: COOPERATING IN THE FIELD OF ACADEMIC RESEARCH TO PAVE THE WAY FOR THE FUTURE

For a long time, research projects were conducted in-house at Naval Group. International competition and growing expectations in terms of excellence and innovation have brought about changes. To encourage innovation, the industrial group thus decided to develop an ecosystem of skills and technological resources with academic research, the most successful form of which is joint laboratories. Better yet, a team dedicated to these partnerships was formed, led by Florence de Launet, Head of Naval Group Research and Innovation Cooperation with French and international academic bodies.

According to Frédéric Meslin, Development Manager at Centrale Nantes engineering school, *"the Naval Research structure is a driving force for Naval Group's innovation and has succeeded in unifying partnerships with public research"*. Florence de Launet confirms: *"This structure has allowed us to work on projects with low technological readiness levels to acquire both scientific knowledge and strategic expertise with a specific industrial objective and to move forward in an Open Innovation logic."*

Joint research with leading public bodies is indeed a major strategic tool for driving and boosting the group's innovation, ensuring its international scientific reputation and providing it with leverage to obtain extra funding to add to Naval Group's investments. Naval Group appointed Florence de Launet in 2018 to coordinate these partnerships. *"Such partnerships have existed for some time, but they needed some form of structure"*, she explains. *"Our objective was to further our knowledge of research ecosystems, funding windows and procedures for working with academic teams: theses, research chairs, Basic Ordering Agreements or joint laboratories."*

PARTNERSHIPS DEDICATED TO NAVAL GROUP'S CHALLENGES

Naval Group has thus brought about a real cultural change, allowing partnerships with the academic ecosystem to become an opportunity for all research work in science and technology. This included engaging in joint laboratories to build research programs that specifically address the company's needs. *"Because of their bilateral nature and shared governance, joint laboratories are a versatile structure for collaboration"*, describes Florence de Launet. *"It is a very mature form of collaboration, based on the mutual understanding of each other's issues and on the pooling of human, financial and material resources. It is all about the co-construction of a research project, not about the provision of a mere service."*

What makes a joint laboratory so unique is that it is a joint venture between an academic entity and an industrial company. A joint collaboration has many advantages, including the possibility of using the school's technological platforms - for instance the swell and hull tank at Centrale Nantes - to test large elements. *"A joint laboratory, which is generally created on the basis of an existing and solid collaboration, provides the basis for a broader partnership"*, says Elisabeth Crépon, member of the Naval Group Scientific Council and Director of ENSTA Paris. *"It provides access to skills from the school beyond those involved in the initial partnership and allows a wide variety of TRLs* to be embraced within the projects."* It opens the door to interdisciplinary programs that can provide a comprehensive scientific response to industrial challenges.

ENTERING THE EXPORT MARKET AND SECURING INTELLECTUAL PROPERTY

"*More generally, the joint laboratory is an opportunity for Naval Group to collaborate with the partners of its own academic partners, especially internationally*", points out Armel de la Bourdonnaye, who is also a member of the Naval Group Scientific Council and Director of INSA Haut-de-France. "*This allows the industrialist to engage in 'scientific diplomacy' and to approach the export market more easily.*" Another significant advantage of a joint laboratory is that the contract signed by both parties allows intellectual and industrial property issues to be considered upstream. This is very reassuring because everything is secured prior to the bilateral agreement. "*The joint laboratory also promotes Naval Group's expertise to engineering students, whether they are doing a master's degree, a thesis or post-doc research. A great way to encourage future careers!*" Finally, a joint laboratory provides an opportunity for schools to better understand the full range of the company's needs.

The first joint laboratory partnerships were established with ENSTA Bretagne and Centrale Nantes, bringing to fruition long-standing collaborations. "*The Gustave Zédé laboratory (refer to box) was born in 2015, after ten years of joint research*", recalls Yann Doutreleau, Scientific Director at ENSTA Bretagne. "*Our mutual trust and desire to work together were already very strong.*" The academic and industrial researchers are more than just partners. "*They are actual 'colleagues' who are eager to build projects together over the long term,*" emphasises Frédéric Meslin. "*They are very much involved and are used to responding together to calls for tender from European programs.*" And to actually win them, as was the case with the RAMSSES program, which resulted in a world first to which ENSTA Bretagne also contributed by carrying out tests.

A JOINT LABORATORY APPROACH THAT IS SET TO CONTINUE

Both these structures have since then renewed their contracts for a period of five years. "*We are considering extending our laboratories' scope of research in line with our engagements to Naval Group's international programs*", continues Florence de Launet. And that's not all, as new joint laboratories are to be set up, imagining new technologies for the ships of the future. "*Numerous discussions are underway with future leading academic partners, such as Sorbonne University, the French National Centre for Scientific Research (CNRS), the French Research Institute for Exploitation of the Sea (IFREMER) or Defence schools (for instance Saint-Cyr Coëtquidan or ENSTA Paris), in fields as diverse as quantum physics, eco-design, drones, electromagnetic discretion, underwater acoustics and even social and human sciences. Our collaboration in research is not over yet!*"

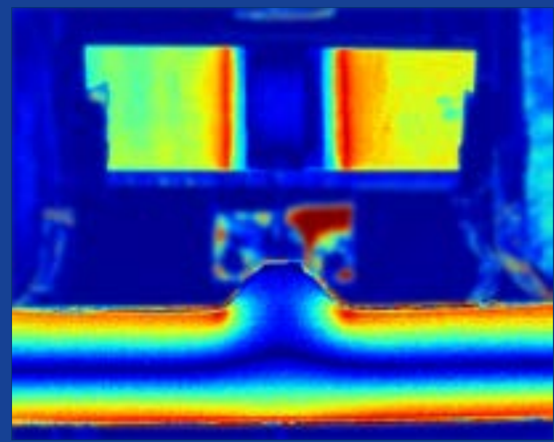
"

"We see this as a medium-and long-term investment, which will give us the opportunity to steer the scientific program, to have access to upstream academic research and to participate in the recruitment of talented young people who will drive our innovation"

Florence de Launet

SELF-HEATING CHAIR: MEASURING THE TEMPERATURE OF WELDED JOINTS AND PREDICTING THEIR LIFESPAN

What was originally only an idea was materialised in a thesis between Naval Group and ENSTA Bretagne at the Gustave Zédé joint laboratory in 2017. "*Loic Carteron's thesis work developed a self-heating method for characterising the initiation and propagation of cracks in welded joints in a very short time*", explains Florent Bridier, Research Engineer at CESMAN** and Head of the Gustave Zédé laboratory for Naval Group. "*Previously, a test campaign lasted several weeks and required dozens of samples; with this new method, one day of testing and two specimens are now sufficient!*" The self-heating characterisation method represents such an opportunity for predicting the lifespan of naval structures that it motivated the creation of the 'Self-Heating' chair in 2021 with the financial support of the French National Research Agency (ARN). This chair, also involving ENSMA in Poitiers on the academic side and Safran on the industrial side, should boost collaborative research on self-heating and consolidate test methodologies from academic work for future industrial applications. "*Between now and 2025, we will be working on implementing self-heating on various metallic or composite materials*, concludes Florent Bridier. *The chair is now in place, with eight PhD. students and four post-doctoral researchers sharing their research activities between ENSTA Bretagne, ENSMA, Safran et Naval Group.*"



Example of thermo-elastic coupled measure on a welded joint
The experimental device developed within the research framework of the Self-Heating chair allows for quantifying the wear characteristics of a structural element, by coupling a fatigue test and thermal behaviour data, acquired with a thermal camera. The figure gives an example of a thermo-elastic coupled measure for a welded joint for a naval application (top view and side view).

A HOLLOW BLADE IN ADDITIVE MANUFACTURING, A WORLD FIRST

"*Let's examine the example of naval hydrodynamics*", continues Jean-Jacques Maisonneuve, Head of the Scientific Field for Fluid Mechanics at Naval Group "*Together we developed a digital model of wave behaviour.*" The value of this research is considerable: predicting movements better and anticipating the ship's control in order to improve its stabilisation and reinforce the safety of operations such as helicopter landing, even in heavy seas. Until now, such operations were only possible under moderate sea conditions. Tomorrow, they will be possible under stronger and more challenging sea conditions!

Research in additive manufacturing has also proved successful. "*Three years were enough to achieve a world first: from printing a large-scale solid propeller blade, which we did in 2017, to manufacturing a hollow blade in additive manufacturing using the WAAM process** (Wire Arc Additive Manufacturing) in 2019*", explains enthusiastically Guillaume Rückert, Senior Expert in Metallic Materials Manufacturing at the CESMAN. "*Being part of a joint laboratory allows us to go beyond this achievement and to improve processes of increasingly complex parts.*" Since 2019, JLMT partners have optimised metal deposition parameters with new materials, including different titanium alloys. They have also worked on alternatives to the WAAM process and modelled the manufacturing phase to predict the behaviour of a part. "*Today, we have mastered the technology and have fitted a 2.5 metre wide propeller made of five hollow blades onto the mine countermeasures warship Andromède, which set sail at the start of 2022*", concludes Guillaume Rückert.

JLMT JOINT LABORATORY: CONFIRMING A HISTORIC PARTNERSHIP WITH CENTRALE NANTES

The Joint Laboratory of Marine Technology (JLMT) was co-created by Centrale Nantes and Naval Group in 2016 under the leadership of Guillaume Rückert - Senior Expert in Metallic Materials Manufacturing at the CESMAN - and Jean-Jacques Maisonneuve - Head of the Scientific Field for Fluid Mechanics at Naval Group and Expert at Sirehna, a subsidiary dedicated to the control of the dynamic behaviour of naval platforms. *"Our involvement with École Centrale was only natural, as it is one of the few institutions in France to be interested in naval hydrodynamics. Our relationship was historically strong."* What is the objective? To share innovation capacities, equipment and test facilities, and rapidly launch operational research on three specific subjects: naval hydrodynamics, additive manufacturing and multi-physics. And, the results are remarkable, with concrete applications.

A world premier: a hollow propeller blade produced by additive manufacturing
In the framework of the RAMSSES H2020 European project, Naval Group and Ecole Centrale de Nantes have developed a prototype of a hollow propeller blade obtained by additive manufacturing. This innovation fosters both operational and industrial gains, and bears the ambition of enhancing the energetical efficiency of the process and mitigate the environmental impact of propulsors.

SIX JOINT LABORATORIES

Already six joint laboratories for Naval Group! The first two - Gustave Zédé and JLMT - have produced decisive results with an international impact. Renewed in 2019 and 2020, they have received significant research intensity to continue their work. In the meantime, four new joint laboratories have been set up, led by the Florence de Launet's team.

- The **Gustave Zédé Laboratory**, created in 2015 in collaboration with ENSTA Bretagne, working on the operational integrity of materials and assemblies for naval structures.
- The **Joint Laboratory in Marine Technology** (JLMT), created in April 2016 in collaboration with Centrale Nantes, working on the additive manufacturing of large parts by wire deposition, on free surface issues in naval hydrodynamics and on modelling materials, naval structures and the quantification of uncertainties.
- The **Joint Laboratory for Innovation in Artificial Intelligence** (LC2IA), created in September 2017 with ENSTA Paris, working on artificial intelligence, system engineering for the design of critical autonomous systems as well as information management and decision-making support.
- The **Underwater Information Processing Laboratory** (LTISM), created in December 2017 with Toulon University, working on the processing of underwater information.
- The **Intelligent Naval On-board Systems** (SENI), created in November 2019 with ENSTA Bretagne, working on the design and development of on-board systems, especially in the field of autonomous marine robotics and artificial intelligence.
- The **INRIA Ambition 2023 Laboratory**, created in December 2019 with INRIA, working on artificial intelligence applied to cybersecurity and signal processing.

* TRL: Technology Readiness Level.
** The CESMAN (Centre of expertise for naval equipment and structures) is a Naval Group Research and Development unit.

NAVAL GROUP - CNRS PARTNERSHIP: SEEING FURTHER, SEEING THE BIGGER PICTURE

In signing a framework agreement with the French National Centre for Scientific Research (CNRS) - one of the leading research organisations in the world - Naval Group is taking a long-term view of its collaborative innovation strategy, while also gaining access to new scientific expertise and to an international network of excellence. The two partners, who already have three joint laboratories, have also collaborated on one-off projects and are now stepping up a gear.

The framework agreement signed between Naval Group and the CNRS at the start of 2021 lays out future collaborations legally and in terms of resources and intellectual property on patents, etc. Everything has become much simpler, as it is no longer necessary to renegotiate for every new joint project.

ALREADY 60 R&D CONTRACTS AND THREE JOINT LABORATORIES

This partnership has further extended Naval Group and CNRS mutual understanding and trust which has been nurtured over the past few years through some 60 R&D contracts and the creation of three joint laboratories between 2015 and 2019 (refer to the article on joint laboratories). "*Naval Group's way of thinking out its projects over a 30-year period fits in perfectly with the long timeframe of scientific research*", believes Jean-Luc Moullet, CNRS Executive Vice President in charge of innovation.
Vincent Geiger, Naval Group Scientific Director, emphasises the scope and scale of the CNRS's activities: "*It gives us an international insight into laboratories of excellence, scientific themes that are on the rise and the breakthroughs to come. And it opens doors to international collaborative programs such as 'Create' in Singapore.*"

STAYING AHEAD OF THE GAME ON CERTAIN ISSUES...

The two partners spent two days sharing their science and technology roadmaps as well as defining priorities within the very broad scientific scope of interest to naval defence. "*We took our work a step further, mobilising our best experts and raising some real issues*", highlights Jean-Luc Moullet. A Research and Innovation Committee was then created to further this pooling of resources.
Naval Group intends to tailor its level of engagement to suit each topic. "*On topics such as underwater detection, the human factor, corrosion or material fatigue, we are at the international state of the art and we intend to remain so*", explains Vincent Geiger. "*That is why, for instance, the CNRS created the Gustave Zédé Laboratory, which has been working on the operational integrity of materials and naval structures.*"

... KEEPING AN ACTIVE WATCH ON OTHERS

Naval Group will set the bar lower on other topics, but nevertheless keeping a very active watch. "*The best of the world's R&D in artificial intelligence, in particular, is conducted by other entities. The CNRS - as well as INRIA with whom we have also developed a strategic partnership - can help us take ownership of key-topics and adapt them to naval defence.*"
Transferring research findings to industry has been a fully-fledged mission of the CNRS since a 1982 decree. "*We do not conduct any applied research*", explains Jean-Luc Moullet. "*We provide scientific answers to industrial issues, to help our partners innovate and strengthen their markets. Naval Group provides us with rich and varied issues, which can mobilise almost all of our disciplines*". Researchers in mathematics, physics, digital sciences, energy, humanities and social sciences in particular are often at the forefront. A much-needed effort in the service of national defence.

"Naval Group's way of thinking out its projects over a 30-year period fits in perfectly with the long timeframe of scientific research"

Jean-Luc Moulet, CNRS Executive Vice President in charge of innovation

02

NAVAL GROUP'S SCIENTIFIC CHALLENGES

70 IT connection points on a second-generation submarine, 800 on a third-generation ship planned for 2030: digital technology, omnipresent but seriously affected by obsolescence, is changing the way ships are designed.

SUBMARINE DESIGN GETS TO GRIPS WITH THE DIGITAL REVOLUTION

Often considered as the most complex industrial systems in the world, submarine are now becoming increasingly digitised. Decisive elements of the ship's performance, the digitised functions are highly interdependent and are subject to rapid obsolescence. How can engineers and architects adapt their design methods to tackle these new challenges? The question is crucial for the naval defence sector.

Why is a submarine so difficult to design? Firstly, very few submarines are built, and each generation significantly differs from the previous one. Secondly, a submarine is not only powered by a mini nuclear power plant, but is also equipped with a sophisticated weapons system and is the home of some hundred people for several months. Thirdly, it contains over a million components (compared to ten thousand in a commercial plane, for instance), who all have a vital effect on the ship's weight, balance and acoustic stealth – to mention just a few…

IT CONNECTIONS MULTIPLIED BY TEN!

"Up until now, the baseline design process has used traditional systems engineering methods to manage all of these various aspects simultaneously", explains Pierre Dallot, Scientific Advisor at Naval Group Research. *"This implies a detailed definition, before manufacture, of the components that will be integrated into each function. This approach is, however, not adapted to digital systems, which include numerous unknown elements, rapidly become obsolescent and are highly interdependent."*
This problem is even more crucial as these digital systems manage vital functions: the propulsion with nuclear reactor, the submarine's stability, its diving, navigation and combat management… Each of these functions are now becoming ubiquitous : *"We had 70 IT connections points on our second generation of ships and there will be 800 for the future generation!"* And most importantly, they will allow us to cut costs drastically. *"In the 1990's, the American Navy doubled the sensitivity of their sonar over a period of just a few years by optimising their software"*, explains Christophe Baixas, Head of the Scientific Field 'Digital Systems ' at Naval Group. *"The role of software will become a key driver for the performance of our future ships."*

FIRST STEPS IN THE ORGANISATION OF THE IP AND CLOUD PROTOCOL

The next question is, how to integrate equipment that will become obsolete in two to three years into the design of a submarine whose construction spreads over a period of ten years? What will be considered as state of the art in a decade's time, in terms of network architecture, artificial intelligence or cybersecurity? *"Traditional system engineering is still useful for elements with long life cycles, the hull being the most extreme example"*, Pierre Dallot comments. *"We must, however, learn to think differently about digital systems: to imagine solutions that are easy to adapt, to manage uncertainty rather than specifications, to forecast rather than predict."* In other words, to plan for a cultural revolution !

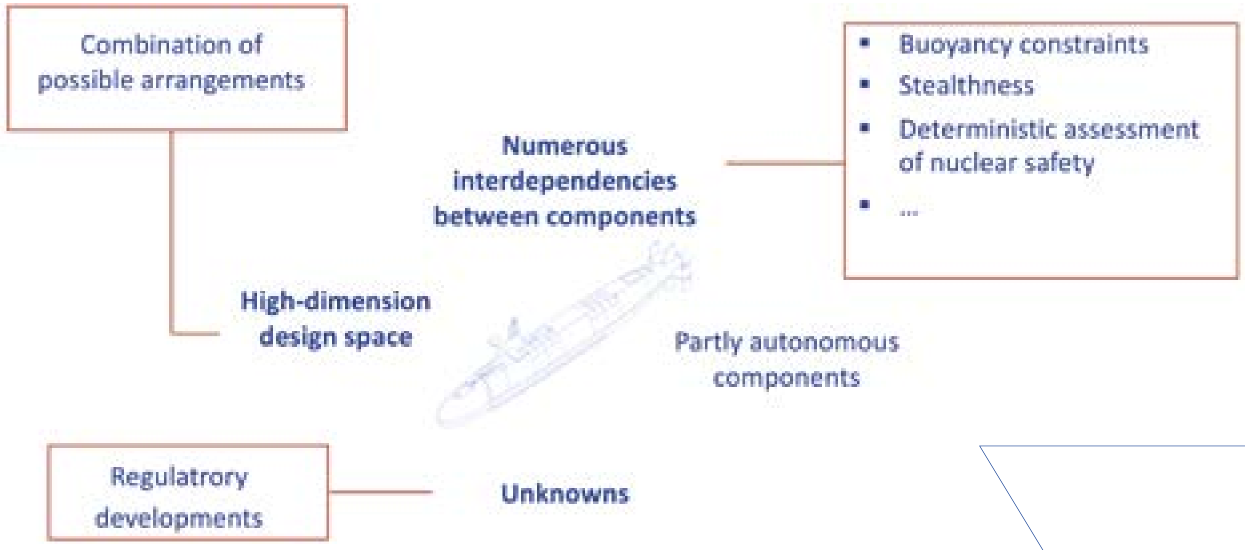
Fortunately, the digital world has already begun to manage its proliferation. Infrastructures and networks have been standardised by means of an IP protocol. As for Clouds, they offer a flexible solution for allocating resources (data, computation means, networks) to needs, and subsequent changes are therefore made easier. *"We will lean on these pillars"*, confirms Christophe Baixas, *"because they give us adaptability on three levels: changes that can be managed by software modifications, proactive obsolescence management, continuous improvement of computing power and services."*

PLAN FOR CAPABILITIES TO BE CAPABLE OF CHANGE!

The key concept of this approach is in planning for what is called "capabilities". In other words, one must think of technical characteristics for the submarine that will facilitate the continuous integration of innovation and emerging technology... without interfering with other systems. This is the price to pay for grasping and taking advantage of emerging technologies, such as artificial intelligence, or countering new threats rapidly. "*The customer will define the main objectives to be met, but these will naturally change over time. We will create the IT architectures that can be quickly adapted to these objectives.*"
There is however no such thing as a unique design method, available to coordinate such a level of flexibility. "*The idea is to seek inspiration in civil industry, where competition and the versatility of its customers are constraining factors*", Pierre Dallot points out. As for Christophe Baixas, he has studied an American approach known as "Enterprise Complexity", which was the key focus of the DoD's (American Department of Defense) IT modernisation project. "*It includes a technical part, with flexible and adaptable complexity management tools such as the Cloud, and an equally important human part. 'Conway's law' points to the isomorphism between an architecture and the organisation that designs it. Design teams must therefore be reconfigurable to adapt to constantly changing needs.*"

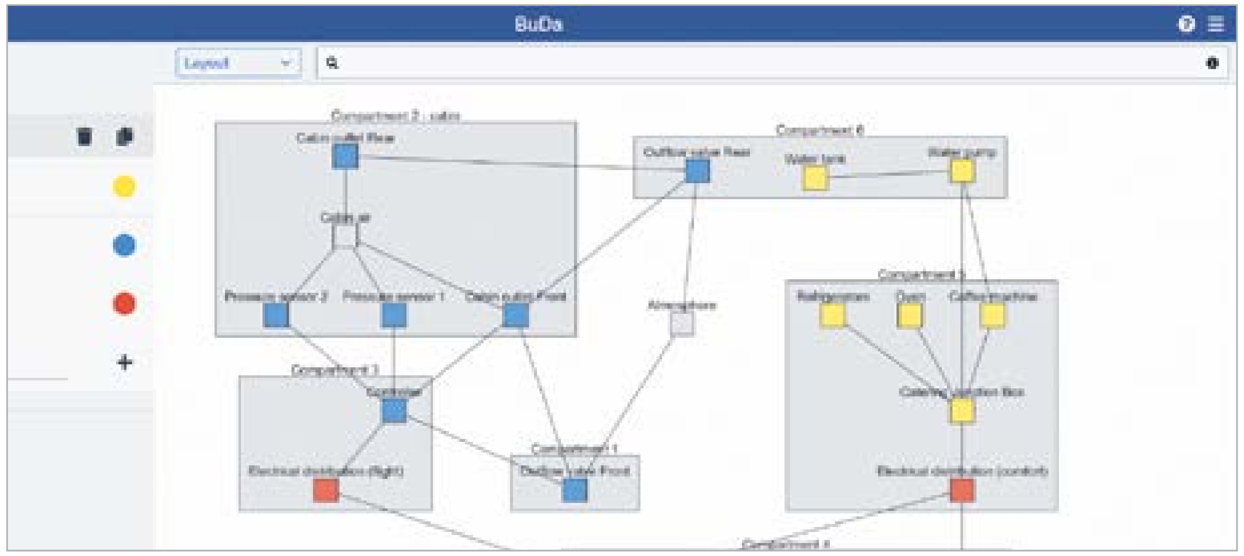
THE CHALLENGE OF OBTAINING CUSTOMER ACCEPTANCE REGARDING SCALABILITY

Enterprise Complexity has a considerable impact on the architectures developed, the way of working, business models, customer relations and more. It is a radical move away from hierarchy-driven organisations. Teams taking their own decisions and deciding on their capacity to learn are essential in order to rapidly adapt a complex system to the circumstances and challenges at play. A product's design and its use create a *continuum*, as the changes made follow the product throughout its life cycle.
Customers must however also adhere to this new model as a ship specified down to the finest detail cannot be scalable. "*We are working with other parties in the Defence sector on a 'document of conviction' that explains this approach to our specifiers*", reveals Pierre Dallot. In late 2021, Naval Group and a number of other compagnies responded to a call for tenders from the European Defence Fund. It concerns a multi-mission digital surface ship, that can be operated by various EU countries, and where IT architecture is of the utmost importance. "*If we are awarded the contract, we will be able to perform full-scale tests on this new design model*", Christophe Baixis highlights.



ENRICHING SAFETY ANALYSES THROUGH SIMPLICITY

Although this revolution requires time, practices are changing fast due to more targeted progress. One example is Alan Guegan, in charge of developing design-aid tools at Sirehna (Naval Group subsidiary), who has come up with a new way of visualising data for safety analyses: "*When experts examine a ship's fluid, electric and IT networks, they review thousands of components connected via kilometres of cables and piping. The representation graphs are loaded with no particular hierarchy, and the task becomes complex: it's just like on a map of France where all the roads you can see, from the motorways right down to the byways, would be the same size and colour.*"
Contrary to this principle, the prototype developed by Alan Guegan, called BuDa, aims at simplicity: a single line to represent two objects that interact, whether there are one or thirty physical connections between them. Certain 'high level' errors can be detected in this way: a secured system connected to another that is not secure, a switching loop that does not respect a design rule, an object essential to a function but which is not connected, etc. "*This tool does not replace safety analyses but improves them by giving a much broader view, and offering multiple angles of observation.*" In 2020, BuDa was one of the two projects chosen for Naval Group's first Intrapreneurial program. This recognises the growing presence of complexity-related challenges in the naval defence sector.



> "A complicated system contains numerous components. In a submarine, these components are interdependent, which is an indication of its complexity"
>
> *Pierre Dallot*

On this picture representing the systems on board a commercial aeroplane, BuDa highlights the undesirable coexistence (compartment no.6) between the coexistence of the coffee machine and its water supply with a safety-related piece of equipment, the pressure regulator valve in the cabin. This configuration has given rise to an actual case of negative pressure during a flight: the water reservoir started to leak and prevented the valve from working correctly.

ARTIFICIAL INTELLIGENCE, A FUTURE GAME CHANGER FOR NAVAL DEFENCE

Anticipating, predicting, preventing, securing, optimising, accelerating, managing, detecting, locating, monitoring, protecting, cross-referencing information, sorting images, automating tasks, assisting navigation, etc. Artificial Intelligence is of great importance to National Defence, and 100 million euros have therefore been devoted to research in this field. To take advantage of this technological shift, Naval Group has been involved in various projects for several years now.

In April 2019, the French Minister of Armed Forces Florence Parly stated in her speech at the DATAIA Convergence Institute in Saclay that she *"intends to make Artificial Intelligence a priority in our national defence. [...] This technology] shall allow us to better understand and predict threats, to act faster and with greater precision and certainty."*

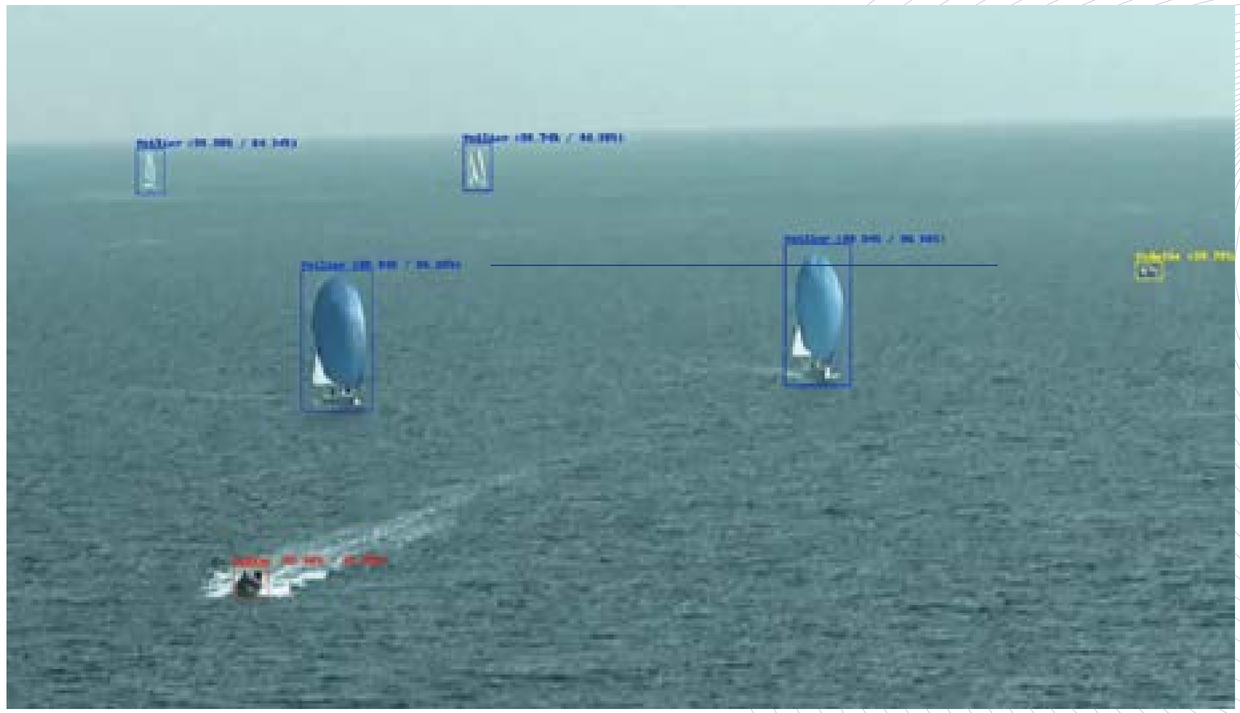
MAJOR INVOLVEMENT IN AI

In 2019, Artificial Intelligence (AI) was already a topic of interest for Naval Group. The company is even involved in several large-scale programs, such as the confiance.ai challenge launched in 2021, intended for *"securing, certifying and enhancing the reliability of systems based on artificial intelligence"*. *"In concrete terms, the projects are structured according to the degree of maturity of the work, depending on whether it is in the R&D phase or ready for industrial development"*, explains Jean-Michel Tran, Technical Director in charge of Artificial Intelligence. *"This research is very demanding, not only because we are working on critical systems and because the ships must remain undetectable, but also because the marine environment is complex and not very communicative. There is no room for error!"*

> "Our goal is to our goal is to propose IA-based tools to valuate data, such as information related to submarines, frigates, services, etc., which are available and scattered in various entities within Naval Group"
>
> *Vincent Martin*

DETECTING ET CLASSIFYING TO ASSIST OPERATORS AND NAVIGATION

Naval Group's AI research activities are primarily aimed at providing solutions to its customers. *"The applications developed by our team mainly involve assistance to operators and navigation"*, explains Quentin Oliveau, Head of Data Science at CEMIS*. *"Our goal is to detect ships at sea and classify them, using machine learning."* This "supervised" learning technique is based on the pre-labelling of the data. *"Imagine a ship equipped with a camera, taking pictures of the sea. The labelling stage consists in drawing a rectangle around each ship present on the pictures. We then train an algorithm to predict the position of rectangle outlining the ships on new pictures, by prompting it to mimic what it has seen on this 'labelled' data."*
The same principle applies to the classification of these pictures, aiming to recognise the ship, not just spot it: is it an inflatable boat, a sailing boat, a jet ski or a rowboat? The algorithm is able to predict the type of ship, provided it has labelled each recorded image as being an inflatable boat or other. The difficulty lies in the time necessary to acquire this data initially, but the leap in performance provided by high-quality labelling is so substantial with machine learning methods that it is clearly worth the effort. In addition to picture recognition, the algorithms developed at Naval Group are also used to identify underwater noises. Others are intended to optimise the energy consumption of ships or to plan their trajectories.



IA technologies may be used in order to detect the presence of ships in a given area and to produce a classification of the detected boats.

MAKING THE MOST OF INTERNAL DATA WITH ALGORITHMS

AI is also used to improve certain Naval Group processes, such as those related to purchasing, calls for tender and maintenance. *"Our databases are full of feedback"*, asserts Vincent Martin, Data Scientist at CEMIS. *"Our mission consists in offering AI-based tools to add value to this information, which has been scattered all over the place, within various Naval Group entities: submarines, frigates, services, etc."* Information from operating data, drawings, reports, contracts, etc., are stored in various databases. But the question is how to retrieve such heterogeneous information, exploit it and make it useful?
There are several steps to answering this question. The first step is to identify on which server or database the information is located. They are then collected and centralised at COSIN**, a 500 sq. meter Data Centre located in Toulon which has been housing extensive Naval Group data since 2017. *"We process this heterogeneous information using algorithms, and provide users with search and analysis capabilities"*, explains Vincent Martin. And how do we do that? Take T-REX for instance. It is a search and analysis engine for non-conformity sheets, used by 300 Naval Group employees. Manual labelling of data was "mission impossible" due to the hundreds of thousands of reports currently in the search engine (and 300 new non-conformity sheets daily), which is why AI is so useful. One algorithm will extract the text from documents*** and try to understand its meaning, beyond the vocabulary used, in order to label the information, for example according to whether it is public, confidential or classified. Another algorithm will categorise non-conformities based on text recognition, according to the type of problem (welding, maintenance, contract, etc.), just like Google News is capable of placing an article about a tennis match in the Sports category.
During the learning phase, the system is given examples of well-organised recordings to learn how to categorise new recordings. During the inference phase, the algorithm is then capable of classifying new records, even if they are written differently from those encountered in the learning phase. This is possible because the models used "encode" the meaning of the information rather than just the words. Therefore, two words or sentences that are written with a different vocabulary but are semantically close will be close in the representation space created.

*The CEMIS (Centre of Excellence for Information Human factors and Signature Management) is a Naval Group Research and Development unit.
** Operational Digitally Integrated Support Centre.
*** This is known as "Optical Character Recognition", the transformation of an image within a computer file into a separate text file.

THE CHALLENGES OF ARTIFICIAL INTELLIGENCE IN DEFENCE

The fact that this research is conducted by naval defence brings additional challenges compared to civilian applications. Obviously, there are requirements for cybersecurity and data access authorisations. But they are not the only ones. The fact that it is impossible to use external information - that relates to meteorology for example - or the very particular language and acronyms used in the French navy, also creates specific difficulties. It is therefore necessary to adapt the algorithms to the specificities of a terminology that does not exist anywhere else. The tools must also work in conjunction with a dense human crew, especially in submarines, to distinguish one voice from another and from ambient sounds. But that is not all. *"While we do have a lot of data, we still have less data than in the civilian sector: in the military sector, there is no series effect and therefore no operating history"*, reminds us Vincent Martin. *For instance, in the French navy, there is only one aircraft carrier, the Charles de Gaulle."*
The next step for AI at Naval Group will be to apply it to combat systems that drive weapons. France intends to use AI in a defensive mode. The algorithms will be used to select the forces to be deployed and the effective weapon to respond to a given attack, after having clearly identified the threat. *"Again, this will be an aid to decision-making,"*, concludes Jean-Michel Tran, *"because France refuses to entrust a lethal decision to a machine that would act autonomously and beyond human control."*

A NEURAL NETWORK TO PREVENT MEMORY LOSS

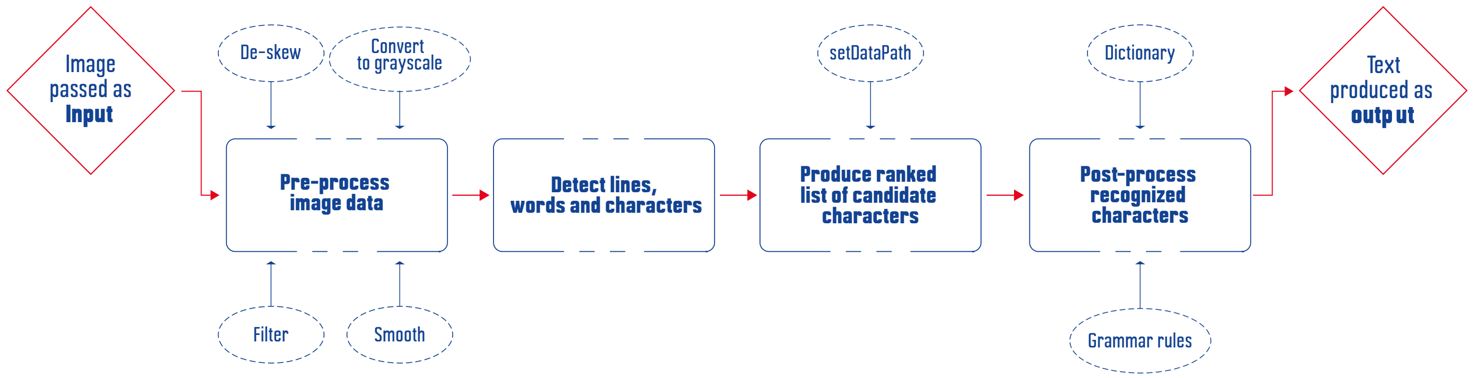
On land, computer memory is not a problem, but on board a ship, *"storage capacity is limited"*, explains Quentin Ferdinand, PhD student at ENSTA Bretagne preparing a CIFRE thesis at Naval Group. *"However, for AI to be able to recognise a boat, it needs to be capable of 'generalising'. An inflatable boat does not necessarily look like another inflatable boat, but it does share some common characteristics. It is therefore necessary to have a very extensive collection of different images labelled 'inflatable boat'. The more we have, the better the learning capacity of the algorithm."*
In this regard, Quentin Ferdinand is working on Deep Continual Learning algorithms to improve their performance. *"This emerging discipline requires the storage of data acquired over time. This is where the problem lies: on a ship, due to lack of storage capacity, some old images have to be deleted to make room for newly acquired data. And the algorithms may come to forget them."* To solve this problem, Quentin Ferdinand uses a neural network, placed between the input data (photos of boats) and the output data (recognition of an inflatable boat, for example). This network is capable of learning, based on numerical operations, and of scaling up the way neurons transmit information to continuously learn as new data is acquired. *"I'm testing the storage of very small amounts of data: 2,000 images, no more than the memory of a smartphone"*, summarises the PhD student. *"This is the best way to solve the problem at its root."*

WHEN AI SOLVES ISSUES AND NON-CONFORMITIES

Jérémy Trione, Data Scientist at COSIN, confirms: *"Contrary to what is implied in science fiction, AI will not replace humans! Quite the opposite, it is intended to help them."* For him, algorithms are first and foremost about providing solutions. The example of the use of fire electric pumps (EPI) on the Charles-de-Gaulle is in this sense revealing. The question was whether the management of this equipment met the needs of the carrier. *"The technical specialist, who had noticed failures, provided us with the operating history. Based on this data, and in less time than is necessary to determine it, we conducted a study that defined the pressure threshold not to be exceeded by the ship's 17 EPIs, in order to maintain an optimal level of operation. Better still, we were able to determine that the problem was mechanical, not human."*
Another benefit of AI is its ability to solve non-conformities. The aim was to reduce the time spent processing the non-conformity sheets in the database. Some can remain open for months, during the different solving stages (reported, validated, corrected, applied). *"AI allows for automatic access to feedback on whether someone has encountered this non-conformity and how they have resolved it, to apply the same method. It saves a huge amount of time and quality."*

FROM THE LAB BENCH TO INDUSTRIAL AI

AI is not just an R&D objective at Naval Group. Of course, it is intended to be used on naval ships and on a daily basis. However, switching from the laboratory to the project is not as straightforward as it might seem. "*To do so*", says Quentin Oliveau, "*we deliver algorithms that we have designed in R&D to our industrial teams. They then define the network interfaces so that all the algorithms can communicate with each other, specify the protocols and hardware constraints. They determine the amount of memory needed, or the electricity consumption. In other words: a series of operations to make sure that everything works, which is called 'algorithm porting'*.
Industrial demonstrators have been tested on "asymmetric" threats warfare applications, a subject of major interest for the French navy. In this context, they are integrated into a processing chain allowing to evaluate how dangerous a ship is. On the same principle, Naval Group has developed a system for a customer in the oil industry that detects ships approaching an offshore natural gas storage platform off the coast of Mozambique, to anticipate collision risks or potential threats. "*In this project, called Coral South, our challenge is to detect very small objects on the horizon, which are no larger than a few pixels, blurred by the sun's reflection on the waves.*"



MASSIVE IN-HOUSE DATA MANAGEMENT

Even when the aim is not to supply products to customers, but to develop solutions for in-house projects, the industrialisation of algorithms is unavoidable. "*We are in charge of the continuous automation of data flows*", explains Christophe Minutolo, Data Engineer at COSIN. "*The researchers design an algorithm in Python, which allows them to quickly validate its operation and perform tests on their computers, but not to automate the program.*" To industrialise it, Christophe Minutolo rewrites the codes in Java, for example, to manage large volumes of data, while running the AI in parallel with several COSIN machines using Spark programming interfaces. "*If you sort a deck of tarot cards, you will need 10 minutes to do it. If you split the cards between three people, you will need three times less time. That is the principle of parallelisation in Big Data.*" This has resulted in a rise in the number of files processed from 200 per hour to 6,000 per hour, with the capacity to process files of several GB! In concrete terms, the processing of 29,902 documents, amounting to 508 GB, "ingestion"* and the OCR took only 12 hours. "*This means that in half a day, we can manage volumes of data that used to take several weeks to process. Such a major achievement for Naval Group's processes!*"

+

Optical Character Recognition (OCR) allows a computer system to recognise the text in an image. This task, which is simple for humans, is less so for a machine that only «sees» pixels, which are sometimes noisy and of different sizes and fonts. The algorithms used for this task generally proceed as follows:

- **Pre-processing the image** to standardise it, denoise it, emphasise shape outlines...
- **Line, word and character detection.** Depending on the quality of the image, the text is not always positioned perfectly horizontally and words and lines are not always clearly separated.
- **Character recognition.** The method may involve several algorithms, for example to determine the most likely word according to the context. This is particularly useful when the characters are similar, such as the number 0 and the letter O.
- **Production of the output text.**

*Data ingestion refers to the process of collecting data from different sources and centralising it on a destination site, where it is ready to be analysed and used.

03

THEY DO SCIENCE AT NAVAL GROUP

A PH.D. STUDENT TELLS ALL

MY THESIS WAS A GREAT OPPORTUNITY TO EXPLORE NEW HORIZONS IN NUMERICAL SCIENCES

Damien MAVALEIX-MARCHESSOUX

After graduating as an engineer at ENSTA Paris, Damien Mavaleix-Marchessoux joined Naval Group's teams to pursue a CIFRE thesis in applied mathematics under the guidance of two university tutors – Stéphanie Chaillat and Marc Bonnet from ENSTA Paris – and of an industrial tutor – Bruno Leblé from Naval Group in Nantes. A way for this maths enthusiast to reconcile theoretical investigation and R&D leading to concrete applications.

What led you to do a thesis after graduating in engineering?

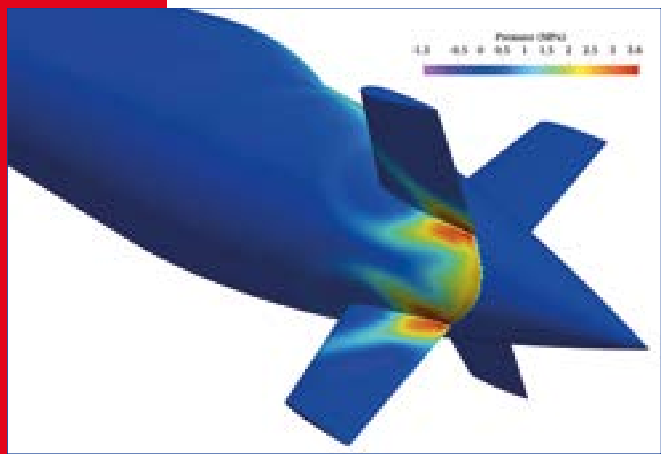
Initially, I wanted to become a maths teacher. But during my final year at ENSTA, where I was majoring in science, I attended a lecture given by an engineer. And that's what changed my mind! I took this course of study, especially because it contributes to transforming new theoretical knowledge into technologies for the general public. This aspect has always been a great source of motivation for me.
When I was in my third year of engineering school, I was considering getting a Ph.D. abroad. But one of my teachers, Stéphanie Chaillat, offered me the chance to work on a CIFRE thesis subject with Naval Group.
I found the research subject – wave propagation in fluids and structures – fascinating, and I saw an opportunity to combine physics and applied mathematics, while meeting the real needs of a specific project and opening up prospects in R&D within Naval Group. I am also pleased that my calculations, which have military applications, can be applied to civilian subjects too, such as the study of earthquakes. Finally, it perfectly meets my desire to participate in innovation by adding theoretical skills.

How do you feel about this first professional experience combining industrial and academic activities?

The concept of CIFRE thesis, on this subject in particular, matches exactly my initial ambition of contributing to theory-driven innovative sciences. Moreover, I feel like I am participating in the innovation process from one end to the other: first, I started with the theoretical basis, the mathematical equations that govern the physical phenomena; then I developed a model, involving highly motivating optimisation stages that required that I simplify a very complex problem without distorting it; and finally, I went on to implement the procedures I had designed by means of numerical computation.

More generally, besides the research subject, what encouraged you to join Naval Group?

The two tutors guiding me throughout my thesis are renowned academics in the field of innovation combining applied mathematics and wave propagation. I knew that with the POEMS* laboratory, I would benefit from high-level theoretical support on this subject; and integrating an upstream R&D project at CESMAN**, within a prestigious company such as Naval Group… It was a proposal I simply could not refuse, and certainly not given such an interesting and enriching thesis subject!
And, I don't regret this decision! Throughout my thesis, I also received training in high-performance computation and "profiling", which is a very useful method for optimising calculations and making the most of supercomputers. By the time I defended my thesis in December 2020, I had gained a solid background in a numerical simulation. I then joined Naval Group's teams, which is a privilege for a young engineer like me, given the variety of career opportunities this company offers. I now work at the CEMIS*** to address the problem of tracking objects (ships, drones, etc.) moving around ships or submarines. The knowledge I acquired in applied mathematics and modelling of physical phenomena thanks to my Ph.D researches is of great value for understanding these fields, which are new to me, and for developing new innovations.



Example of computation on a ship facing an underwater explosion
The simulation, carried out using the method developed by Damien Mavaleix-Marchessoux, is used to determine the level of pressure exerted on the stationary object a few milliseconds after a shock wave has impinged the submarine. The quality of the computation is illustrated by the smooth wave front that spreads over the zone. it is checked that the "causality" of the wave is respected, and well-known physical phenomena are observed, such as multi-reflections at the rear of the submarine, when the wave meets the rudder gear. The geometry studied corresponds to that of a BB2 submarine ship (*as presented in the following reference: B. Overpelt, B. Nienhuis et B. Anderson, Free running manoeuvring model tests on a modern generic SSK class submarine BB2, Pacific International Maritime Conference, Sydney, Australia, 2015*).

MY RESEARCH IN A FEW WORDS

My thesis involved modelling fluid-structure coupling caused by a far-field underwater explosion. It required modelling a submarine (which is a deformable structure) and studying the impact of a shock wave propagating through the water onto its hull. So, I focused on how the wave is transmitted to the structure. My goal was to design an efficient procedure, that is as general as possible, so that it can be extended to other situations and even, for example, to the impact of earthquakes on buildings.

There are several input parameters: first, the description of the submarine by a numerical mesh that details its geometry as well as the characteristics of the explosion, including its position in relation to the ship and its intensity. Then, the simulations are performed by separating two aspects: on the one hand, solving the interaction between the shock wave that propagates in the fluid and a supposedly rigid and immobile submarine; and, on the other hand, considering deformation and the response of the submarine structure. More precisely, we couple the equations describing the shock wave propagation to those describing the deformation of the ship structure, by imposing a continuity of velocities and pressure on the surface of the ship, between water and hull, using so-called "continuity equations". Most of the effort in my research consisted in proposing an algorithm which significantly reduces computation time.

The model we used is of course a simplification of reality. It is based on two major assumptions. The first is that the presence of the submarine does not affect the explosion. This is true when it happens a hundred meters or so away from the ship. The second is that the shock wave is temporally separated from the oscillating bubble of hot gases also generated by the explosion. The evolution of this gas bubble is much slower than that of the shock wave: the time scales are respectively in seconds or milliseconds. The bubble moves slowly while periodically "inflating-deflating" and can be extremely destructive if the period of its oscillations corresponds to the submarine's own frequency. Beyond my thesis, the next step would be to study the transition between the two problems: the interaction between the submarine and the shock wave on the one hand, and the submarine's response to the stress of the gas bubble on the other hand.

Underwater explosion in the vicinity of a submarine (an artist's representation)

* The POEMS laboratory (Wave Propagation: Mathematical Study and Simulation) is a joint entity of ENSTA Paris, CNRS and INRIA.
** The CESMAN (Centre of expertise for naval equipment and structures) is a Naval Group Research and Development unit.
*** The CEMIS (Centre of Excellence for Information Human factors and Signature Management) is a Naval Group Research and Development unit.

TAKE THE WORD OF AN EXPERT

MATHEMATICAL AND NUMERICAL METHODS ARE CONSTANTLY EVOLVING

Cédric LEBLOND

After initially pursuing an academic career, Cédric Leblond joined Naval Group in 2012. What does his job involve? As the Head of Naval Group Scientific Field "Advanced Numerical Methods", he contributes to the development of numerical simulation tools and leads R&D partnerships to further develop them.

Tell us about your career before joining Naval Group?

After graduating from ENSEIRB-MATMECA in Bordeaux with a degree in mathematical modelling and engineering and a master's degree in applied mathematics, I began a CIFRE thesis in 2004 at Naval Group - then called DCNS - on the design of submerged structures that can be subject to underwater explosions.
In 2008, I started my career as a Research Engineer at the French National Centre for Scientific Research (CNRS) in La Rochelle. I mainly worked on "model reduction techniques" and their application to real-time flow control and to air quality, and put my skills in the field of hydrodynamics into practice on four different applied mathematics projects.
Then, in 2012, I joined Naval Group as a Research Engineer in mathematical modelling and numerical simulation at the time when the company's technological research centre Research was created. I then started working in the development of advanced numerical methods. I provide technical expertise in various fields such as fluid and structural mechanics, acoustics and data analysis. I also coordinate research projects in applied mathematics and advanced numerical methods.

What are the concrete applications of mathematics at Naval Group?

Naval Group designs ships that have high levels of requirements; in terms of resistance to severe loads, seakeeping, hydrodynamic behaviour, structure lifetime, or acoustic, noise and vibration, etc. Demonstrating these performances through numerical simulations requires modeling complex physical phenomena. In the naval industry, applied mathematics is used in many simulations, such as in the interaction between ship structures and surrounding fluid. To that end, we have to describe the processes involved and their relationships, which is done by means of mathematical models. Then, we have to solve the equations that make up these models. Mathematics also contribute to transforming equations and adapting them for further processing with computer-based techniques. The challenge is to solve very complex models mathematically and numerically, by reducing the computational time and ressources. Ideally, for an industrial application, each computation must be carried out in a maximum of one week and on standard computers, without using supercomputers.
My main area of expertise is 'model reduction', a way of formulating mathematical problems that allows for fast computations and that nevertheless capture the complexity of physics. These approaches can then be used to compute numerous data, which may be further used to ground probabilistic approaches.
I also work on more theoretical subjects, such as the reformulation of Green's functions, which is present in many models that are useful to Naval Group (acoustics, mechanics, etc.).

To sum up, the aim of our research is to develop efficient simulation techniques, to improve their performance, particularly in terms of computational resources, while ensuring their accuracy. We systematically qualify the degree of confidence of our results, in order to determine the precise margins of error. This allows us to both refine our mathematical methods appropriately and guarantee our customers that our design methods are reliable.
R&D on these subjects is carried out in-house but also through research partnerships with academic teams and other industrialists, notably via CIFRE theses. These collaborations help us to develop innovative computation methods, which each partner then adapts to their own trade – as we have been doing with EDF R&D for five years.

NUMERICAL TOOLS, AN IMPORTANT AREA OF RESEARCH FOR CESMAN

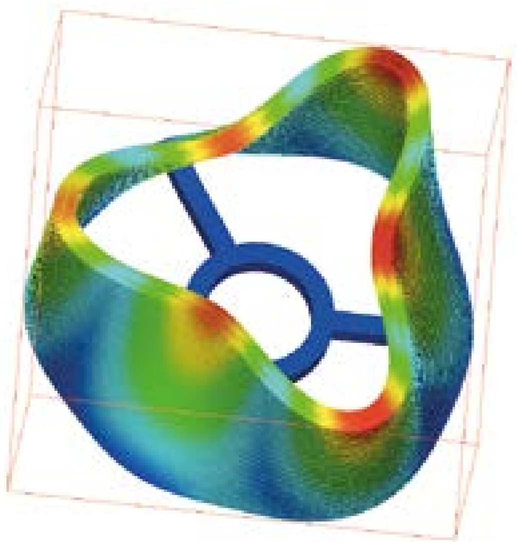
The CESMAN (Centre of expertise for naval equipment and structures) brings together, within Naval Group Research, skills in the characterisation of materials and structures. For cross-functional studies, based on complex physical phenomena, ten research engineers working in the S3M department (Simulations and Methods for Mechanics and Materials) optimise mathematical and numerical simulations. Their objective is to demonstrate and reinforce the performance of ships, both in their resistance to shocks and in their acoustic discretion for example. The CESMAN provides both support for Naval Group teams, who need expertise on materials or structural designs, and significant upstream R&D work.

Can you tell us more about your current research?

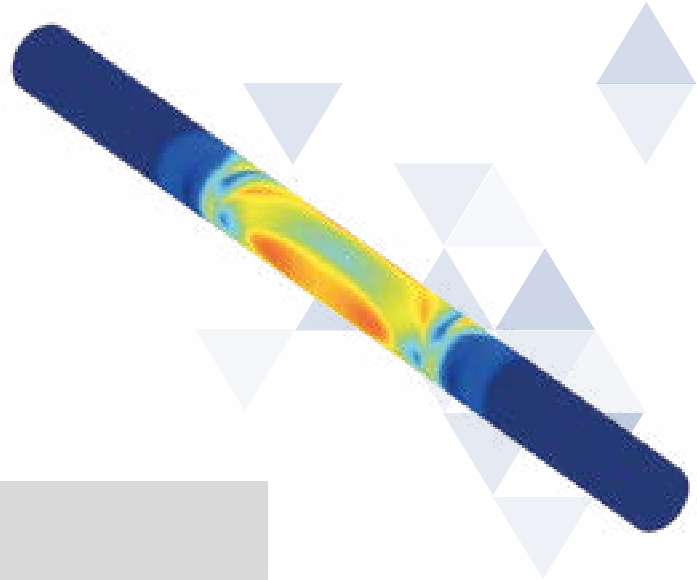
We are always on the lookout for academic advances in mathematics and numerical sciences, to apply emerging methods as quickly and efficiently as possible to Naval Group's specific issues. Since 2021, we have been working on hybrid modelling with measured data in order to integrate them into the tools used at Naval Group. Ultimately, the challenge is to achieve real-time monitoring of ship structures. To achieve this goal, we combine numerical models with real-time measured data. This is a real numerical challenge, which can only be met with very recent mathematical methods. We also seek to integrate artificial intelligence techniques into our mathematical modelling. Apart from the scale models and measurement data, this third element is indeed essential to differentiate normal behaviour from abnormal behaviours and to provide some missing data.

We are also working to improve turbulence-related mathematical models since, in fluid mechanics, industrialists do not yet have access to modelling turbulence around a moving ship. And here too, artificial intelligence could be useful, providing the mathematical equations and models of data inaccessible by numerical simulation. This hybridisation between models and data offers interesting prospects for solving the complex problems that engineers and designers may face.

Model reduction and innovative computation
"Model reduction" techniques allow for instance to perform real-time mechanical computation – here applied to the vibratory study of a thruster – on numerical devices as simple as a digital tablet.



"Multi-physic" numerical models
This simulation renders the dynamic behaviour of a propulsion nozzle, whose vibrations are dampened by a specific device. The computation estimating the noise radiated by this structure is based on a "multi-physic" mathematical model, which describes the mechanical and acoustic behaviour of metallic and viscoelastic materials, as well as the influence of the surrounding fluid on the structural vibrations.



Modelling adapted to various uses
This computation illustrates the state of stress in a submerged hull undergoing the effects of a pressure wave that is generated by an underwater explosion. It is derived from analytical modelling, i.e. based directly on a mathematical model whose solution is set out in an explicit equation, which can be calculated quickly.

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SCIENTIFIC COUNCIL

JOËL BERTRAND,
PRESIDENT OF NAVAL GROUP'S SCIENTIFIC COUNCIL: «A GOOD WAY TO GET THINGS MOVING!»

"You are here to dream up the impossible... and challenge us!". When Naval Group's former CEO Hervé Guillou created the Scientific Council in 2016, he set out the objective for its 13 members to achieve. They are researchers from various disciplines: energy, materials and process engineering but also sociology, philosophy, science of management and more. *"They express their own ideas, whatever organisation they come from"*, explains Joël Bertrand, Emeritus Research Director in Science at the CNRS* and President of the Council since 2016.

The Scientific Council provides its point of view on the subjects submitted to it, giving its opinion, for example, on the group's strategy concerning batteries. The members work around a table but also out in the field: visits have already been organised to the submarine construction shipyard in Cherbourg, and to Toulon during maintenance on the aircraft carrier *Charles de Gaulle*.
The Council can also look at any subject of its choice, whether current or upcoming, such as submariner's well-being or the future of unmanned defence vessels. *"We are not here to assess work but to help direct it"*, specifies Joël Bertrand. *Our role also includes identifying reputable foreign universities, in particular when they are carrying out research in the field of defence and may open doors for Naval Group."*

CONTRIBUTING TO THINKING AROUND QUANTUM TECHNOLOGIES

Members of the Scientific Council participate in working groups to address certain areas in phase with the challenges and issues facing Naval Group. These reflections and analyses generally lead to a report setting out conclusions on the subject and its level of maturity within the company and giving recommendations in terms of developing skills, partnerships, etc. The manner in which the quantum report (see box) was worked on was a little different. *"We were called on to analyse the report and its conclusions, correlating them with our own knowledge on the subject and the current situation: the launch of our national quantum program"*, explains Dominique Vernay, member of the Academie des technologies and former Technical Director at the Thales group.
"In our view, this very well-researched and detailed report provides a clear enough position of Naval Group as a technology user - quantum in this case – that is continuous developing and openly questioning scientific subjects", adds Brigitte Plateau, professor at the school of higher education Grenoble INP and delegate for European alliance strategies. In the opinion of these two members of the Scientific Council, the group's most important investment should, above all, be in skills. There is a need for experts covering enough subjects to understand how exactly these quantum technologies can be used in confronting Naval Group's issues.

"The subject of quantum only really emerged in 2020 with the Technical and Innovation department's decision to create a working group, led by the Naval Innovation Hub", explains Romain Kukla, Quantum strategy lead. *"We interviewed representatives from companies, start-ups and research laboratories to find out more about managing innovation, how it is used and the preliminary feedback obtained. The subsequent report led to a specific mission that I managed with a dedicated budget: prioritising the report's recommendations, looking at them in more depth and starting experimental work.*
"We have tested one application in particular which optimises a submarine's trajectory by modelling it with a quantum formula. The Scientific Council considers that further work on sensors should be a priority focus. The purchase of three quantum sensors will enable us to test the technology under real conditions on the Charles de Gaulle aircraft carrier", he concludes.

A LABEL TO IDENTIFY AND ACKNOWLEDGE SCIENTIFIC COMPETENCIES

In 2022, Naval Group called on the members of the Scientific Council to sit on the steering committee that appoints experts and senior experts. The objective is to give some of these expert profiles backing with the creation of a scientific label. Thierry Massard, former Scientific Director at the CEA, and Jean-Luc Fihey, Director for the promotion of R&D at ETS (Ecole de technologie supérieure) in Montreal.**

Thierry Massard: *To meet our S&T challenges, Naval Group needs to develop its relationships with the academic world, relying on employees that are able to build these bridges or reinforce them. Jean-Luc Fihey and myself have reflected on the criteria that would allow us to assess the scientific interest over and above the technical expertise itself: PhD, HDR (accreditation to direct researches), publications in scientific journals of the three highest ranks, participation in conferences, etc. We have been working with the HR department and Vincent Geiger, Scientific Director at Naval Group , to set out the typology for this label on the basis of an existing critical analysis.*

Jean-Luc Fihey: *This skills mapping is essential. Science is evolving at an increasing speed, which means that experts must both keep up with this progress and be capable of contributing to breakthrough innovation. Naval Group is already carrying out high-quality research and there is still room for improvement. The «La Pérouse» prize (see box) also works towards the same worthy objective: encouraging the development of ambitious projects with a long-term perspective by freeing up Naval Group's creative energy.*

THE LA PÉROUSE PRIZE :
EXPLORING NEW SCIENTIFIC FOCUSES

"Five years ago, we suggested the creation of a scientific prize centred on innovation and research", explains Sophie Bretesché, professor of sociology at IMT Atlantique engineering school and member of the Scientific Council. *"The idea is to encourage Naval Group employees to explore new areas of science that may be of use to the company in terms of our products and services. The Jury makes its selection on the basis of written projects submitted and exchanges with their project leader. We want to promote an interdisciplinary approach and taking risks, as innovation is a collaborative process full of unknowns!"* The prize winners receive funding for the exploratory phase of their project and the jury assesses the benefits brought to the company over the longer term. In 2021 for example, the 2020 prize winners, Cédric Leblond and Emilien Billaudeau, developed a method for monitoring structures in real time, based on the analysis of measurement data and advance mathematical models.

04

FLUID MECHANICS

ULTRA-POWERFUL MODELS TO OPTIMISE SUBMARINE PROPULSION

Thanks to the development of numerical simulation, engineers are now capable of defining the performance of heat exchangers - which are essential components in submarine propulsion systems - more rapidly and at minimal cost. And they are also dreaming up new concepts! An initial collaboration between the site of Indret and Nantes Université leads to the development of an innovative modelling tool that combines 1D and 3D, as well as four theses and several scientific publications.

This discovery was somewhat coïncidental... In 2011, Vincent Mélot, a Design and Research Engineer at the Naval Group site of Indret, discovers the promising results of some scientific research on modelling heat exchangers in some scientific publications. "*We were looking to develop modelling tools in order to adjust the sizing of equipment, and there it was, a real path to finding the solution*", he recalls.

Composed of thousands of tubes integrated into a shell, heat exchangers are one of the most important but also cumbersome components on a ship. In terms of nuclear propulsion, they transfer heat between various circuits on board. The steam generator converts energy produced by the nuclear reactor into steam, which the turbine then uses to rotate the submarine's propeller. The condenser then cools this steam when it comes into contact with the seawater system.

BOOSTING THERMAL PERFORMANCE TO LIGHTEN THE LOAD

Calculating a heat exchanger's thermo-hydraulic characteristics is a critical element of the specifications for manufacturers in order to reach the level of performance required for propulsion on our ships. And this is where numerical simulation is a real asset! The teams in Indret were eager to draw on the expertise of their long-term local partner, LTeN* at Polytech'Nantes, who specialises in analysing heat transfers. Their objective was to develop a tool capable of modelling the physical characteristics required.

There is a considerable number of arrangement constraints on board a submarine. "*The power of exchanges at play in the heat exchangers is huge, and the devices used are increasingly compact*", explains Vincent Mélot. And what is the end goal? To make ships lighter, reduce the cost of equipment and facilitate operations for the crews in charge of maintenance operations. Increasing the size of heat exchangers is therefore not an option. "*In a nuclear power plant, a few more pipes running along the floor are enough to increase the thermal power of equipment*", says Bruno Auvity, Researcher at the LTeN. However, in a submarine's compact environment, each equipment item is sized to the absolute minimum required to cover the given need.

A 1D/3D COUPLING TO DESCRIBE HEAT TRANSFERS

There were two CIFRE theses identified: one by Clément Bonneau from 2014 to 2017, and the other by Loïck Kalioudjoglou between 2016 and 2019. They enabled the first bricks of a calculation model to be defined – ones that were capable of characterising thermal and hydraulic performances for condensers and steam generators respectively, in fine detail. *"With the content of both theses and help from the fluid calculation team in Indret, we developed an extremely powerful 1D-3D coupling modelling tool. It is quicker and more accurate, and we now use it on a daily basis in our design phases"*, explains Vincent Mélot.
This model is partly based upon the coupling of two approaches: 1D modelling, which gives a large-scale description of a simple flow into a tube when the fluid flows in one direction only, and CFD** calculations to model the flow outside tubes, based on numerical methods solving the Navier-Stokes equation – one which describes the three-dimensional movements of fluids on smaller scales. However, the calculation time necessary for modelling complex flows in 3D – such as the fluid that passes through several thousand tubes – can be very time-consuming.
The other basis of this model is the use of a porous media equivalent to the tubes, obtained by integrating source terms for head loss and heat transfers into the Navier-Stokes equation. To describe heat transfers in the exchangers in further detail, it is essential to combine these approaches, which is the reason behind the development of this 1D/3D hybrid modelling. *"This project has allowed us to develop our ability to perform large calculations while maintaining the same level of accuracy."*

A DIGITAL TWIN TO SIMULATE THE ENERGY-PROPULSION LOOP

"We were then able to offer a certain number of innovative solutions to reduce thermal and hydraulic losses and improve the thermal power density of equipment", adds Bruno Auvity. For example, we can expel air pockets trapped in the condensers. Indeed, air can infiltrate the system as the condenser is empty, in other words, with a pressure lower than atmospheric pressure. As air is an incondensable gas, it has a significant effect on heat transfers and, therefore, steam condensation. In search for solutions, quick, accurate numerical simulations can prove decisive in modifying the geometry to capture this air.
And a third thesis by Claire Dubot between 2018 and 2022, allowed the model for even shorter calculation times to be validated. Work on a fourth thesis on the development of a numerical twin will begin in Autumn 2022. It should provide detailed simulations for the complete energy-propulsion loop.

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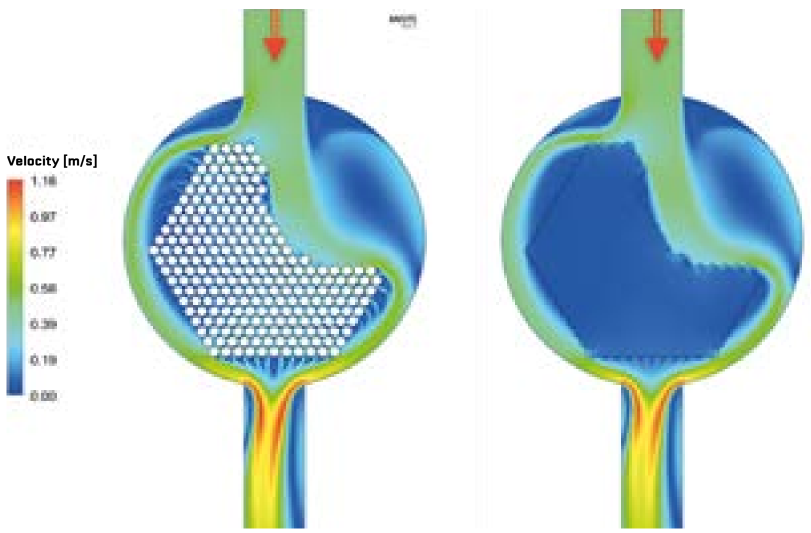
"This project has allowed us to develop our ability to perform large calculations while maintaining the same level of accuracy"

Vincent Mélot



Fluid flow outside of a tube (velocity range) in a heat exchanger
On the left, a simulation where the tubes are taken into account, and on the right, the result of the numerical model developed.

OPTIMISING THE SURFACE OF EXCHANGE AND PREVENTING RISKS OF CLOGGING

As key equipment for generating electrical and mechanical energy, and therefore maintaining life on board, the condensers are large components whose precise sizing is essential in the ship's design. The two condensers are part of what is known as the driving unit module and located below the turbine. They are both three metres high and wide, and four metres long. But these equipment items are also expensive and highly exposed. *"The simulation tool developed on the site of Indret will allow us to use various surface exchanges and materials in order to optimise the size of a component and predict clogging margins for the equipment"*, explains Pierre Berg, Technical Director for propulsion equipment at Naval Group.
The challenge in designing the submarine's driving unit is to fit the complete system into the area allocated to the equipment. Predicting the performance of a condenser or exchanger is therefore of utmost importance to ensure that the equipment meets requirements right from the design studies phase and that risks can be removed as soon as possible. The numerical simulation tool also allows experimentation with new exchanger and condenser architectures by limiting long and costly test phases.

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* LeTN - Thermal science and energy laboratory.
** CFD (Computational Fluid Dynamics) refers to the computer-aided calculation techniques that allow simulation of fluid flows.

BETTER UNDERSTANDING THE TURBULENCE PHENOMENA FOR IMPROVED ACOUSTIC DISCRETION

For the first time ever at Naval Group, a model was used to "rapidly" simulate and under various conditions, the turbulence of hydrodynamic flows near the hull, which causes acoustic radiation and fatigue on ships. The technological barrier was lifted between 2017 and 2019, thanks to the work undertaken with Nantes University, Centrale Nantes and La Rochelle University on the ASTRID "Modulo π" project. Funded by the French Defence Procurement Agency (DGA) and led by Cédric Leblond - an Engineer in Modelling at CESMAN - the work has allowed the combination of Sirehna-operated LES (Large Eddy Simulations) simulation tools and model reduction methods.

In order to improve the lifespan and acoustic discretion of ships, designers are investigating a combination of geometries and innovative composite materials. What is their purpose? To minimise appendage weight and their vibration, while optimising hydrodynamic performance. But this is no simple task. "*We have very little if any feedback on the seakeeping of innovative configurations*", explains Cédric Leblond, Modelling Engineer at CESMAN*. Furthermore, operational situations cover a wide range of flows and no numerical model is presently capable of "rapidly" computing the effects of turbulent flows on structures under all these conditions. Well, until now.

A TURBULENT BOUNDARY LAYER THAT IS HARD TO MODEL

The main difficulty is to account for complex physical phenomena, which are not easy to represent in fluid mechanics: turbulence, and in particular "flow separations" in the turbulent boundary layer, close to the hull. At the bow of the ship, the flow is said to be "laminar": it is made up of layers of fluid that slide over one another. But the flow along the hull soon becomes turbulent, mixing vortices of various sizes and energies. "*Between the laminar and turbulent regimes, there is a highly sheared fluid layer that generates hydrodynamic instabilities and vortices and whose evolution remains somewhat unknown.*" That is what we call the "turbulent boundary layer".
In the case of a curved profile, such as for a hull appendage or a propeller blade, a pressure gradient is added to the shear, making the turbulent boundary layer singular, i.e. unstable. The induced vortices are then so significant that they generate detached vortices. "*These are the ones that cause a problem because they are difficult to simulate. The area where they occur depends on the speed or angle of incidence of the profile*", explains Cédric Leblond. "*Computations may also predict different areas of occurrence depending on the models and discretisation methods used...*"

FASTER COMPUTATION OF HYDRODYNAMIC LOADING

What is the solution? Taking into account uncertainties in models. Between January 2017 and December 2019, CESMAN and Sirehna engineers, along with teams from the Laboratory of Engineering Sciences for the Environment (LaSIE) - a joint research unit between La Rochelle University and the CNRS - and the Research Institute in Civil and Mechanical Engineering (GeM) - a joint research unit between Nantes University, Centrale Nantes and the CNRS - set out to develop a faster computation method for hydrodynamic loading.
This method takes into account the variability of the parameters by allowing the uncertainty to be propagated in the computation. This means that a large number of possible values for these parameters can be included at a lower cost. The research was carried out on a case study: a twenty-centimetre NACA airfoil. "*In this project, we have developed an approach which is widely used in the field of aeronautics and automobiles (the'weak fluid-structure coupling technique' relevant to aerodynamics) - but which is totally innovative in the naval field because hydrodynamics requires a 'strong fluid-structure coupling technique. This approach made it possible to partially overcome this limitation*", continues Cédric Leblond.

SIMULATING FLOWS WITH THE LES METHOD

The challenge was to rapidly obtain the fine computation results associated with all possible flows around the selected NACA airfoil. Regarding this complex subject, it was vital to take a careful, controlled and concerted approach at every stage of development. The first step was to create a database with a detailed characterisation of the flow. For several weeks, the Sirehna teams ran their powerful computers and simulated different hydrodynamic loading cases with a high fidelity LES method (see box) at different flow speeds (up to 20 knots) and for different pitching angles of the airfoil. In order to produce an even larger database, the LaSIE team then used this initial data to set up a reduced-order model capable of producing a result in just a few minutes. Extensive data production work was then carried out in La Rochelle leading to the development of a meta-model that reproduces the pressure of the turbulent fluid on the wall and operates in a fraction of a second.

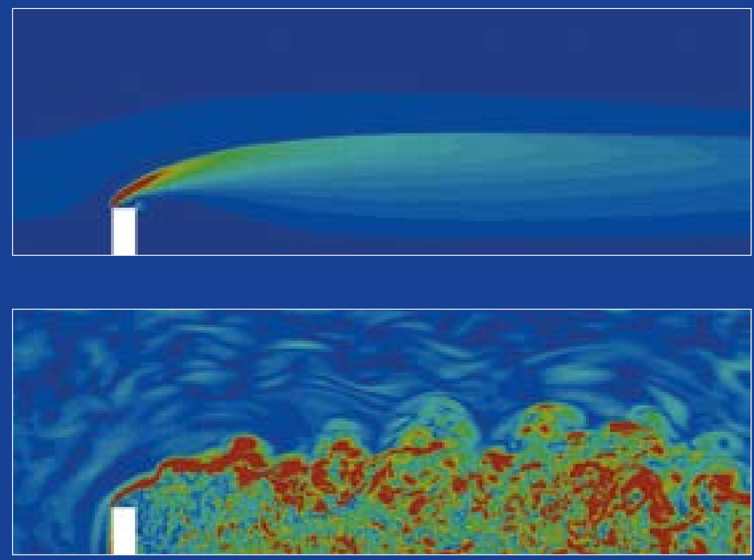
This meta-model was developed by the GeM team, using artificial intelligence methods, to provide a tool for the rapid computation of hydrodynamic loads. This tool was finally passed on to the CESMAN, which then carried out the vibro-acoustic computations. In analysing the results, the engineers were surprised by some of their findings (see box). "*This innovative methodology, combining mathematical modelling and physical data analysis, opens the way for further work and extends the analysis to more realistic structures than a NACA airfoil, anti-roll keels for instance. Performing LES computations on these structures, which can reach several metres in length, will require greater computing power, and the use of supercomputers such as those found at the French Alternative Energies and Atomic Energy Commission (CEA)*", concludes Cédric Leblond.

OBTAINING A "HIGH FIDELITY" DATABASE WITH NUMERICAL SIMULATIONS

Two methods can be used to study the flow of a turbulent fluid using numerical simulations, knowing that this random three-dimensional phenomenon is so difficult to grasp.

- The RANS (Reynolds Averaged Navier-Stokes) method is a simple and cost-effective technique that is designed to rapidly obtain an average solution of the fluctuations of the pressure and velocity fields in the flow. This method is generally used to determine "global" values, such as hydrodynamic forces on an airfoil.
- The LES (Large Eddy Simulations) method is used to resolve turbulence by means of a very precise spatial and temporal discretisation. The turbulence scales smaller than the mesh size are then filtered and modelled, while the large scales, containing most of the flow energy, are fully resolved.

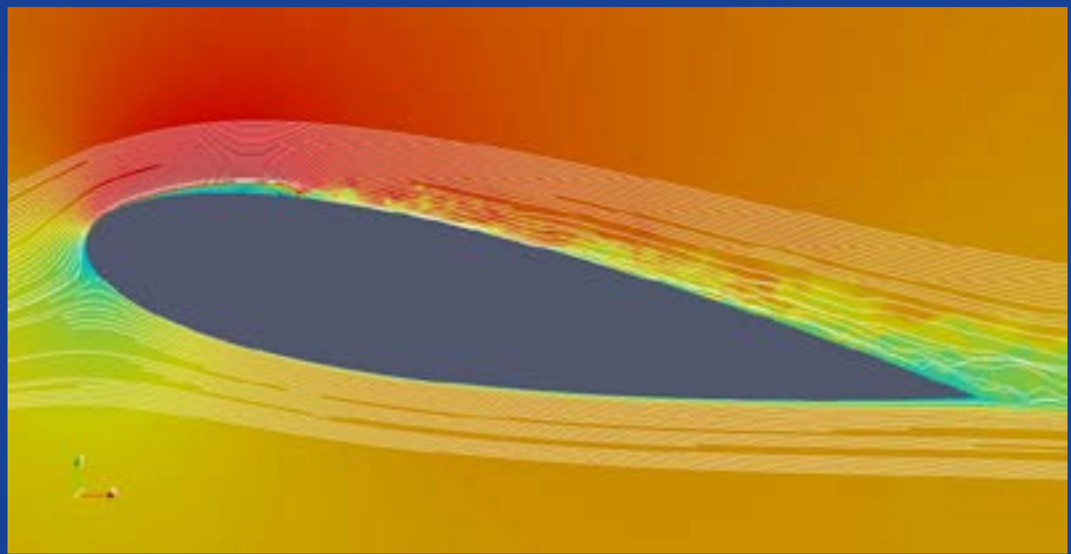
"*We applied the latter method in the Modulo π project*", explains Luc Bordier, Engineer at Sirehna. "*Our team had to produce 'high-fidelity' computations for flows around a given experimental appendage.*" First, the team created a mesh of the fluid containing several tens of millions of cells. Then they carried out the actual simulations, which required substantial computing resources (thousands of cores for hundreds of hours of computation). "*And so, for the first time, we obtained a database characterising turbulence in a dozen configurations defined by different speeds and bank angles of the airfoil*", adds his colleague Jean-Charles Poirier.

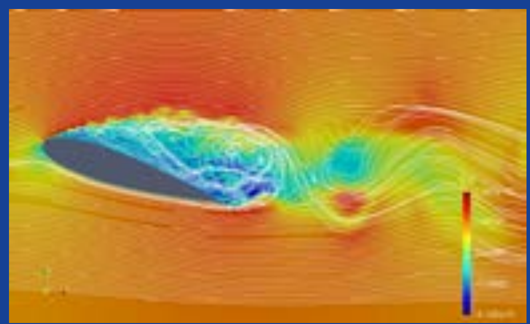


Example of CFD simulations past an obstacle
The figures highlight the difference between the RANS method (top) and the LES method (bottom) on a similar configuration. The LES computation, which is more accurate than the RANS computation in its description of turbulent scales, requires greater computing and data storage resources. It provides access to "local and instantaneous" information, whereas the RANS computation provides more "global and averaged" data.

WHEN LES SIMULATIONS REVEAL UNEXPECTED PHENOMENA

The richness of the physics solved by the LES simulations has provided new, rather counter-intuitive information, giving engineers a glimpse of new fields of analysis. "*Not only have we observed all the expected phenomena around the NACA appendage but we have gone beyond that*", says Cédric Leblond enthusiastically. "*We were able to follow the instant evolution of the flow: from the stable laminar stage to the formation of laminar/turbulent transition waves which precede the commencement of the fully turbulent phenomenon.*" And then, surprise. The results showed that "extreme" situations for an airfoil – with the highest speed and steepest pitching angle – were not necessarily the most useful for sizing this ship structure. "*The most important vibration and stress levels were observed for intermediate configurations - for example six- or eight-degree bank angles - and for detached vortices, that have been generated, not from the leading edge to the trailing edge, but over only part of the airfoil.*"

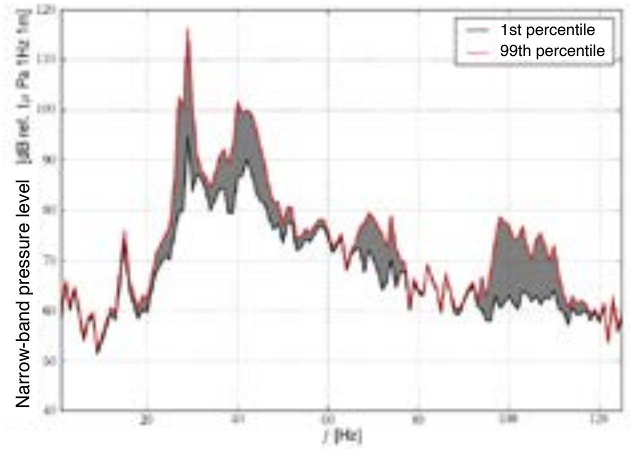




Turbulent flow computations closer to physics
Examples of LES computations performed on the Reynolds High Number NACA airfoil, with angles of incidence of 10° (top) and 18° (bottom): these simulations capture complex physical phenomena.

"GETTING TO GRIPS WITH INDUSTRIAL REALITY"

Cyrille Alléry - LaSIE Researcher at La Rochelle University - is pleased to say: "*The collaboration on the Modulo π project has been very productive and has resulted in several publications*". Members of the team knew each other well before the project started as they had already worked together previously. "*As researchers, we are used to working on academic research applications. I think it is important to tackle the real world, as it can give us a real feel for the industrial reality and further our research.*" For Mathilde Chevreuil, GeM Researcher at Nantes University, the extrapolation work conducted for the project allowed her to further develop machine learning techniques. "*I obtained some very satisfying results, covering unexplored areas, which have enabled CESMAN engineers to carry out computations for applications of interest to Naval Group. It is not something that can be quantified straight away, but I know that new mathematical and numerical developments will find their use in a future research project.*"



Taking into account uncertainties in the computations
Example of computations of the random radiated pressure spectrum, generated by the vibration of an airfoil excited by a turbulent flow, taking into account the propagation of uncertainties of the material parameters.

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* CESMAN (Centre of expertise for naval equipment and structures) is a Naval Group Research and Development unit.

MODELLING SWELL AND ITS IMPACTS TO BETTER DESIGN OUR STRUCTURES

For the very first time, the teams at Sirehna have succeeded in modelling and computing the probability of critical hydrodynamic loads occurring on appendages. This work was carried out as part of the Astrid «Apphy» project between 2018 and 2021 and involved Naval Group Lorient, ENSTA Bretagne, Ifremer and Bureau Veritas. They aim to design the structure and equipment of our ships as accurately as possible.

Five tonnes of seawater per square metre… This is the pressure that a hull appendage must be able to withstand under extreme conditions. This figure – incorporated into the regulations in the 2000s – contributes, along with other fixed values, to determining the thickness of materials that make up the hull, the frame, the stabilising fins, and more globally, the ship's overall structure. "*These fixed values are essential*", explains Sébastien Le Niliot, Head of the Structures computation department at Naval Group in Lorient. "*If they are under-estimated, they can generate damage and expensive repairs. This leads to a re-evaluation of regulations in the aim of reinforcing crew safety and extending a ship's lifetime.*" Without any accurate and concrete impact models on which to base work, these fixed values have been reviewed and increased.
Have these values been over-estimated? And if so, by how much? "*We are currently looking to anticipate the various situations in which the ship is likely to be damaged and, using this knowledge, to think about the best compromise possible between weight and robustness in the design phases in order to improve sea-keeping performances.*" This is also one of the major stakes for certification societies, such as Bureau Veritas, who have been developing probabilistic computation methods over the last twenty years in order to adjust its regulations. Reducing the design margins – and therefore the ship's overall weight – by reducing the volume of equipment, for example, would help to optimise propulsion. Or increasing the number of personnel or equipment on board with an equivalent level of propulsion.

A SET OF AMPLITUDE WAVES AND VARIABLE FREQUENCIES

However, swell is a random (or "stochastic") phenomena and very difficult to model. Conditions at sea change rapidly from one day to the next and from one moment to another. Some waves – frequent and of low amplitude – will have a limited impact on the ship but will nevertheless fatigue the structure over the long term. Others, rarer but more violent, will create impacts, with increased pressure and stress on the hull and its appendages, affecting the entire ship and producing a negative effect on seakeeping. This phenomenon can even cause certain elements of the ship to crack or break. "*Swell comprises a set of wave amplitudes and variable frequencies, dependant on external parameters such as the distance to land or the wind, which is, in itself, stochastic*", explains Jean-Jacques Maisonneuve, expert in fluid mechanics modelling at Sirehna.
Whereas the sea state remains relatively constant over a scale of several hours, a ship can encounter very different sea states, depending on the geographical areas it passes through and the surrounding weather conditions. In total, it is estimated that a ship encounters some 50 million waves of extremely varied profiles over its 30 to 40 years life span. These navigation conditions are impossible to reproduce in a test tank or using a series of deterministic calculations. So just one solution remains: modelling the effects of swell by representing it as a random variable and using statistical calculation methods to determine the ship's behaviour. "*To explain this in another way, we needed to combine the random response of the ship in each sea state with the probability of encountering each of those sea states*", summarises Jean-Jacques Maisonneuve.

> *"To explain this in another way, we needed to combine the random response of the ship in each sea state with the probability of encountering each of those sea states"*
>
> *Jean-Jacques Maisonneuve*

RAMPING UP SKILLS TO MODEL LOAD CONDITIONS

It is for this reason that the Apphy* project came about, with support from the ANR (French national research agency). In order to best adjust hydrodynamic loads to the needs of ships, Jean-Jacques Maisonneuve and his colleague Jean-Charles Poirier decided to associate probabilistic data to their CFD** 3D numerical computations, which are accurate but very expensive in terms of computation time. Engineers called on several entities, ENSTA Bretagne, Ifremer and Bureau Veritas, drawing on their recognised expertise in the discipline to develop probabilistic analytical methods. This research firstly allowed them to model multiple cases of hydrodynamic loads, rapidly and at minimum computational cost, using advanced mathematical models under controlled conditions. They were then able to create curves showing the probability of occurrence of these loads.

Based on this work, the engineers at Sirehna were able to identify the events shown as the most limiting for the structure according to the ship's operating conditions, meaning its speed, incidence compared to the swell and sea state. This enabled them to concentrate the use of their CFD simulations on the areas of interest. A lengthy and costly analysis – based on the breakdown into millions of volume-based components that has enabled the calculation of the pressures and stresses exercised by the fluid in these extreme situations. And lastly, Ifremer used its tanks located in Brest to carry out two test campaigns (in June 2020 and June 2021) on cases of hydrodynamic impact which validated the approach.

PUSH FOR A CHANGE IN REGULATIONS TO LIGHTEN THE STRUCTURE

"*We have tested a number of configurations for the angles of impact and entry into water, beginning with a simple academic case, a triangle, up to more complex industrial configurations, such as a NACA fin profile and a 'spray rail', which is the appendage located at the front of a ship to break the oncoming waves*", explains Jean-Charles Poirier enthusiastically. Without currently having obtained an operational tool, the ANR project has been the opportunity for Naval Group teams to develop their skills on modelling hydrodynamic impacts and to qualify this method using a combined probabilistic/CFD method. "*We now possess a tool box with various statistical models that can be rolled out on a number of cases of application*", concludes Jean-Jacques Maisonneuve. "*The development of a probabilistic approach - provided this work is continued in the coming years - would require the definition of an acceptance threshold for the level of stress and occurrence, as well as a requalification of the design processes. This is the dialogue that we are now looking to establish, both internally and with certification societies.*" With our project partner Bureau Veritas, for example. "*The probabilistic approach is a valuable research tool for refining empirical data and updating regulation*", points out Quentin Derbanne, Head of research in hydrodynamics and structures Bureau Veritas Marine Off-shore. It enables us to obtain statistics on a ship's structural behaviour and to ensure that the risks of plasticizing, cracking or buckling – three degradation mechanisms for structures – remain below a pre-defined level of acceptance. "*A probabilistic approach requires a large number of calculations and is impossible to use in a design loop. It can, however, be used to prove that the deterministic rules set using a limited number of cases, are enough to guarantee an acceptable sizing with better-managed design margins.*"

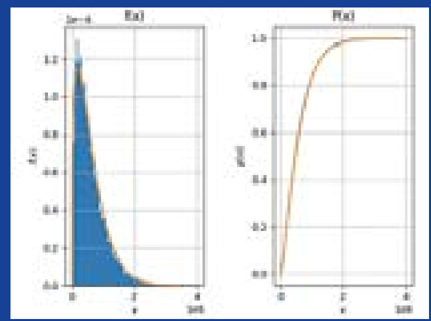
OUR LONG-TERM GOAL: PREDICTING THE LEVEL OF STRESS IN STEELS

Ifremer researcher Alain Tassin believes that this collaboration was the chance to better understand the real design conditions for ships and the industrial applicability of ongoing fundamental research work. As for Nicolas Jacques from ENSTA Bretagne, the analytical models he has developed go beyond the results of experiments and take the sea environment and its variability into account. And the researcher isn't going to stop there! "*Ideally, we need a tool capable of determining the risks of breakage on hull appendages with various sea states*", he explains. "*We mainly looked at extreme hydrodynamic loads in this project, for example the probability that the fin undergoes a level of stress above that of its ultimate strength. If we were to apply these developments to the most common cases, we would be closer to predicting the levels of stress in steel, and therefore, other risks of structural and equipment failure, such as fatigue.*" To produce even more accurate designs.

> "The probabilistic approach is a valuable research tool for refining empirical data and updating regulation"
>
> *Quentin Derbanne, Head of research in hydrodynamics and structures Bureau Veritas Marine Off-shore*

PROBABILISTIC METHODS: ESSENTIAL FOR MODELLING SWELL

Simulating all the various sea conditions is impossible: there are millions of wave profiles and they all have different probabilities of occurrence. However, if swell is modelled as a "*stochastic Gaussian process*" – assuming that all the conditions can be described using Gaussian curves that specify the random breakdown of occurrences and wave amplitudes –, it is then possible to obtain probabilities for impact stress using analytical impact models based on fluid mechanics equations (Navier-Stokes equations) modified according to the approximations that enable their calculation, at the expense of possibly altering the accuracy of results.
In practice, these models are almost exact in terms of their simple geometrical shapes, in 2D or with a small angle of incidence. Other methods, such as CFD calculations, can process a wider range of problems, but require longer calculation times. "*One of the methods used during this project was to use a restricted number of carefully chosen CFD calculations to create a simpler mathematical model – a 'meta-model' – of the impact conditions, yet sufficiently robust to correctly account for other CFD calculations. This meta model could then be used in a probabilistic and statistical approach for the hydrodynamic loads generated and their effects*", explains Jean-Charles Poirier.

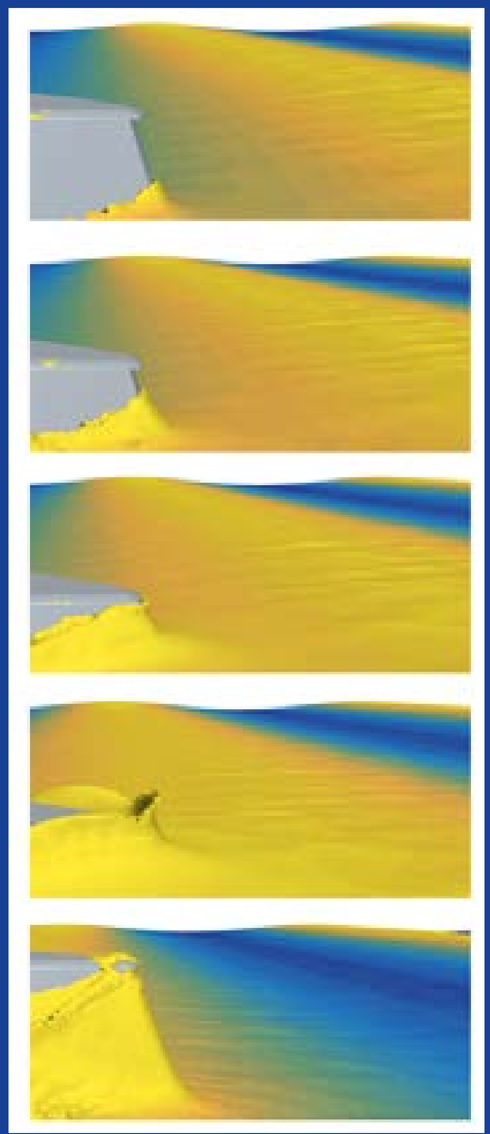


Example of a statistic model
This figure represents the "short-term" distribution (for a given sea state) of impact stresses on a spray-rail, where "x" represents the stress (in Newtons) and "f(x)" the probability factor for this figure. P(x) is the corresponding distribution function: its value for stress x shows the probability that the stresses encountered on this sea state do not go over the stress x, an important fact in dimensioning the spray-rail!

* Probabilistic Approach to assess hydrodynamic loads for sizing ship appendages in swell.
** CFD (Computational Fluid Dynamics) are the computer-based computation techniques which enable the simulation of fluid flows.

CFD AND ANALYTICAL -A COMBINED APPROACH TO INCREASE EFFICIENCY

A CFD model is grounded on a tight meshing of the volume studied, with several million cells integrated into an ultrathin 3D description, and has no geometrical limitations. However, it still remains an expensive method in terms of time and computation powers, in spite of the constant evolution of computer performances. A single simulation using the CFD method can take between ten hours or so up to several days, whereas only a few seconds or minutes are necessary for an analytical approach. Specialists working on the Appy project have therefore developed an approach combining both approaches, which rapidly generates thousands of data, identifies the most relevant then integrates them into the overall CFD model.



Example of a CFD numerical simulation
This computation of swell impact on the spray-rail is based on an ultrathin three-dimensional model. It allows a detailed description of the physical phenomena and calls on a large amount of IT resources.

TWO TEST CAMPAIGNS TO VALIDATE THE MODEL

Two test campaigns were carried out over a three-week period in June 2020 and June 2021. They tested a reduced-scale fin in the swell tanks at the Oceanographic centre in Brest. The first took place in calm, flat water, with an imposed speed and waves at various angles of incidence. The second was carried out using a fixed fin at an imposed angle of incidence for waves, but with irregular sea states. *"The idea was to carry out experiments in order to validate the analytical and numerical hydrodynamic models developed by our partners"*, points out Alan Tassin. The most complex aspect was to model what is known as "separation events" that arise when air cavities form on the fin as it enters the water. These happen either on the leading edge – the rounded section at the front – or on the trailing edge - at the sharp section on the back. *"This work was a real challenge but helped us to further our knowledge on the subject. We had never worked on an asymmetric body before, such as the geometry requested by Naval Group."*

Both test campaigns on the impact of regular waves on a fin took place at IFREMER, and produced data that was useful in validating hydrodynamic models.

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05

WAVE/MATERIAL INTERACTIONS

"What sets Naval Group apart is its novel approach to medium-frequency vibro-acoustics based on realistic and complex ship geometries"

Valentin Meyer

VIBRO-ACOUSTIC MODELLING, UP CLOSE TO THE ACTUAL STRUCTURE OF SUBMARINES

Obtaining an accurate simulation of the noise generated by various external or internal noise and vibration sources requires taking into account the actual complex structure of a submarine. This is the aim of Naval Group's research in vibro-acoustic modelling, which has been carried out in collaboration with the Laboratory of Vibration and Acoustics (LVA) at INSA Lyon and has resulted in major advances in the "mid-frequency" range.

Submarines must minimise the noise they emit, especially those caused by vibrations from internal stresses on board the ship for example (such as engines). In order to optimise vibro-acoustic performance on extended frequency ranges and identify potential noise sources early on, Naval Group engineers model the physical phenomena at play, right from the design phase. With added novelty: major advances in the "medium frequency" range, for which no suitable industrial tool has yet been developed.

REDUCING NOISE GENERATED BY VIBRATIONS, AN ABSOLUTE NECESSITY

The acoustic requirements of a submarine are of three kinds. The first one is the ship's discretion to passive sonars that listen to the sea using hydrophones. Ideally, to remain undetectable, an operating submarine should not emit any acoustic signal greater than that of the ambient noise of the sea. The second one is its stealth when confronted to active sonars, i.e. when its hull is subject to external acoustic stimulation. This is closely linked with its capacity to minimise the waves emitted to its environment. The third requirement is related to the submarine's detection performance: it should be able to use its passive sonar without being disturbed by the noise made by its own vibrations. Indeed, the performance of the sonar antenna installed in a submarine's hull depends on the signal-to-noise ratio which is all the better when the noise is low. However, the noise sources closest to sonar are the internal excitations in the hull (clean noise) and turbulence generated by the ship's movement.

"*It is absolutely vital for a submarine to be discrete, both actively and passively, in all frequency ranges. It is important to keep an eye on the low- and medium-frequency signatures as early as the design phase*", sums up Valentin Meyer, Engineer in Vibro-Acoustic Modelling at Naval Group's CEMIS*. Mastering the signature before manufacturing therefore requires mathematical and numerical simulations of the submarine's hull and its acoustic behaviour, over the entire frequency range, typically from a few hertz to several tens of kilohertz.

COMPUTATION TIMES, LOCKING SIMULATIONS AT MEDIUM FREQUENCIES

"High-frequency" simulations - i.e. those greater than a few hundred Hertz - are based on the computation of the vibratory and acoustic energies involved, without having to consider the hull's exact geometry. "Low-frequency" simulations - i.e. those lower that a few Hertz - use numerical computations with the "finite element method", where the hull is modelled with a mesh containing a reasonable number of elements (which drives the computational effort). The vibro-acoustic response of the submarine can then be computed from its own vibration frequencies, which are quite distinct from one another.

But, for "medium frequencies" - those between a few dozens and a few hundreds of Hertz - simulation is considered satisfying if more and partially-overlapping natural frequencies of vibration are represented, which requires a much finer mesh of the hull surface. The hull's local vibrations are modified in particular by the presence of internal structures such as stiffeners or bulkheads, and it is necessary to take them into account in order to model the physical phenomena involved and obtain precise results. The numerical or analytical methods usually used are not adapted to these complex geometries. However, the resolution on a very fine meshing of a surface of thousands of square meters would require very long computation time.

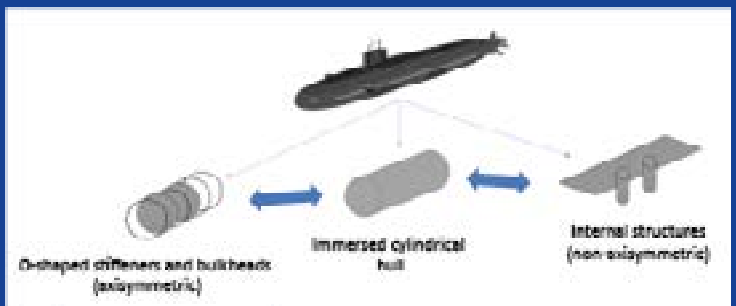
THE KEY: BREAKING DOWN INTO SUB-SYSTEMS

"What sets Naval Group apart is its novel approach to medium-frequency vibro-acoustics based on realistic and complex ship geometries", explains Valentin Meyer. *"Our work, conducted with researchers from INSA Lyon, considers the submarine's physical system as the sum of sub-systems. The submarine is envisaged as a cylindrical hull coupled with the surrounding water, which allows for an analytical resolution at medium frequencies. Various structural elements are then added to this hull, which can each be processed as finite elements, in a very precise way, before integrating them into the global computation."* This means it is possible to realistically account for the presence and locations of stiffeners, bulkheads and various internal elements of the submarine that may contribute to its vibro-acoustic response. *"We have studied this new approach with Naval Group in order to develop mathematical functions - in this case the so-called 'Condensed Transfer Functions' (CTF) - that are adapted to each sub-system"*, explains Laurent Maxit, Researcher in Mechanics and Vibro-acoustics at the LVA laboratory in INSA Lyon. *"They allow the characterisation of the vibratory behaviour of each sub-system at their interface with the hull. They can be computed from a model which is specific to each sub-system. For example, an analytical model for the hull in the water and a finite element model for structures inside the hull can be used."*

Once the condensed transfer functions have been computed for the different sub-systems, they can be assembled to predict the vibro-acoustic response of the submarine to different excitations - such as turbulence in the water, internal noise or acoustic waves from an active sonar. Simulations based on this approach can thus reveal the spatial irregularities in the vibro-acoustic response at different points on the hull and in its environment, in computation times of around a few hours, compatible with an industrial application.

THE SUB-STRUCTURING APPROACH, A REALISTIC HYBRID COMPUTATION METHOD

The "sub-structuring" approach consists in describing the structural elements of a submarine separately and providing solutions for each of them, using the computation method best suited to each element (as illustrated in the figure below). This allows complex structures to be modelled and their vibro-acoustic response to be simulated quickly and accurately.

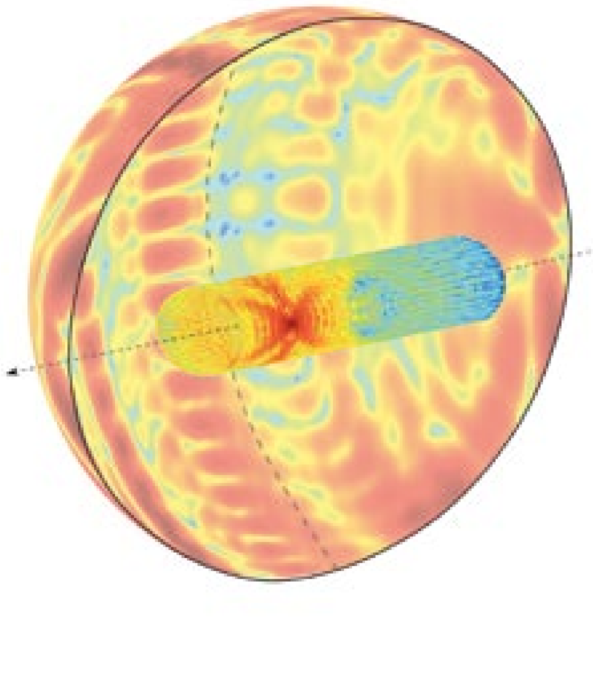


Sub-structure modelling
In recent developments, the sub-structuring of a submarine's geometry also includes the presence of a partial acoustic coating on the hull. This refined approach, based on "subtractive" vibro-acoustic modelling (rCTF method), was the subject of Florent Dumortier's CIFRE thesis.

EVER IMPROVING MODELLING

"In order to further improve our simulations, we have recently refined this 'sub-structuring' approach to submarine geometry to take into account the presence of acoustic coating on the hull", continues Valentin Meyer. This particular study was the subject of Florent Dumortier's CIFRE thesis, still in collaboration with the LVA laboratory. What is its purpose? To take into account that the surface of a hull may be clad with acoustic insulation that minimises the noise radiated from the hull (masking material) or absorbs waves from an active sonar (anechoic material). The effect of coating materials has already been extensively studied, as has been the vibro-acoustic signature of cylindrical hulls coated with them. But these studies are faced with a more complex reality: the hull is not always fully coated. If a hull is partially coated or coated with different types of materials, it is no longer said to be "axisymmetrical", meaning that the semi-analytical methods generally used in this case no longer apply. However, it is essential to model finely and obtain results in reasonable computation times for real configurations, which are often different from a simple cylindrical hull with a single vibro-acoustic characteristic throughout its structure.

Florent Dumortier's thesis, which was co-supervised by Valentin Meyer and Laurent Maxit - has drawn on the results from the collaboration between INSA Lyon and Naval Group on the CFT method to develop a different approach to vibro-acoustic modelling (referred to as the "reverse Condensed Transfer Functions" or rCTF). This method models a partially-coated hull from a fully-coated hull model where a portion of the hull coating is removed and replaced by water. This approach can be integrated into the sub-structuring approach and ultimately lead to precise computational solutions that can be used in naval engineering.



Accurate "medium-frequency" vibro-acoustic computation
A totally submerged submarine is subjected to a continuous vibration of 1 kHz in frequency. The blue-red colour scale on the cylinder is proportional to the intensity of the vibration resulting from this vibratory excitation (targeted on the dark red dot, in the left part of the cylinder). The simulation of the pressure radiated by the cylinder - represented here on a half-sphere - takes into account the presence of several dozens of stiffeners, arranged in their actual position in the modelling of the structure. Taking into account the geometric specificities of the submarine results in a marked irregularity of the vibro-acoustic response according to the position on its hull and its environment.

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* CEMIS (Centre of Excellence for Information Human factors and Signature Management)

UNDERSTAND, PREDICT AND LIMIT NOISE OF FLOW AROUND A SUBMARINE

Naval Group research engineers have recently made great progress on modelling and simulating flow-induced noise by going into more detail on assumptions for models and their mathematical resolution. And what are the results of this research, carried out in collaboration with experts in physics and numerical methods? A simulation tool capable of computing the noise caused by turbulence from flows over complex industrial geometries.

The flow of water around a moving submarine affects hydrodynamic performance (manoeuvrability, seakeeping, etc.). It can also be the source of noises that add to the ship's acoustic signature and which may also have an effect on its acoustic listening systems (sonar). Naval Group is carrying out intensive research work on how to simulate flow-induced noises so as to predict their consequences and minimise their effects. Experts at CEMIS* have recently made new contributions in the field, thanks to joint research work with academic teams, specialists in fluid mechanics and mathematical and numerical methods.

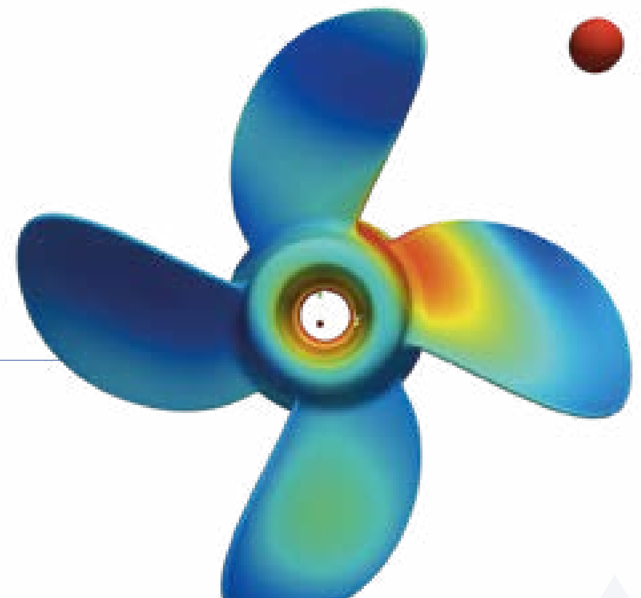
CHALLENGE FOR A SUBMARINE: REMAINING DISCREET DESPITE ITS MOVEMENT

A perturbation of fluid generates eddies of varying sizes and energies: in fluid mechanics, the process is known as "turbulence". These eddies are generally invisible to the naked eye but can nevertheless have major acoustic effects. They can create loud noises when they cause the ship's platform (hull, appendage, superstructures) or propeller blades to vibrate, or otherwise diffract around the ship's specific geometrical features, such as the propeller. "*A submarine's acoustic signature, to be kept as low as possible for highly strategic reasons, is influenced by a number of mechanisms. We have in particular studied eddies created by the ship's movements, or those of the propeller blades, as these are the main sources of fluctuations in water pressure. These pressure fluctuations are the source of a direct sound that can be amplified by the hull's features, as well as an indirect noise, generated by hull vibrations or even the propulsor*", explains Gilles Serre, Fluid mechanics modelling engineer at CEMIS.
The flow of water around a submarine or propeller creates a "turbulent boundary layer" in which the speed of fluid varies progressively from the speed at which the ship moves – or the propeller blades rotate – to zero (far from these structures). "*The thickness of a boundary layer increases between the nose and aft of the submarine for a hull of around a hundred metres, and can reach several dozen centimetres at the aft*", specifies Gilles Serre. "*The boundary layer creates eddies with various life spans and sizes, creating excitation whose frequencies cover a wide range, up to several dozens of kilo Hz. Propeller blades have a smaller boundary layer of around a centimetre depending on the rotation regimes, but this is enough to cause variations in pressure and, therefore, noise.*"

> "We have in particular studied eddies created by the ship's movements, or those of the propeller blades, as these are the main sources of fluctuations in water pressure"
>
> *Gilles Serre*

MODEL AND COMPUTE THE EFFECT OF TURBULENCE

To determine the noise generated by turbulence preliminary requires modelling of the physical processes within the turbulent flows. And the goal? To describe the change in time and space of the eddies, and so the way in which they exchange energy with the acoustic modes. A space-time representation of the hydro-acoustic and vibroacoustic excitation sources of structures (submarine hull, propeller blade) in contact with the flow is thus obtained. The stake is then to describe how these sources will "radiate", in other words how the noise generated by flows and vibrations will propagate through the water.
The difficulty for engineers is modelling these very complex phenomena in the most accurate and efficient way possible. This means using a computer to numerically compute them, without the computation times becoming too long, in order to envisage industrial applications. The mathematical models used are based on the so-called "Lighthill equation", which is derived from the equations for fluid mechanics (Navier-Stokes). It is used to describe the sources from which fluctuations in pressure arise, which then create noise. This approach helps to formulate the problem in a simple manner and obtain a relation used to calculate the level of noise and its position, according to the excitation frequency and its distance to the source. However, the application of this "integral equations" method to naval structures (complex shapes submerged in water) is not without serious problems: in particular, this method requires the use of a mathematical function, a specific "Green's function" which is difficult to construct for complex geometries.



Example of a Green's function computation with an integral method
The Green's function is used to identify the sources of noise responsible for the hydro-acoustic radiation of a structure (the propeller in this case), excited by the eddies in the surrounding flows. Its computation is illustrated here by the identification of the contributions of propeller vibrations to an acoustic measurement that would be taken at the red point, for a given frequency. This result is also an intermediate step which is necessary for computing – using the Lighthill equation – the hydro-acoustic radiation caused by the diffraction of eddies at the edge of the blades.

INNOVATE TO REDUCE COMPUTATION TIMES

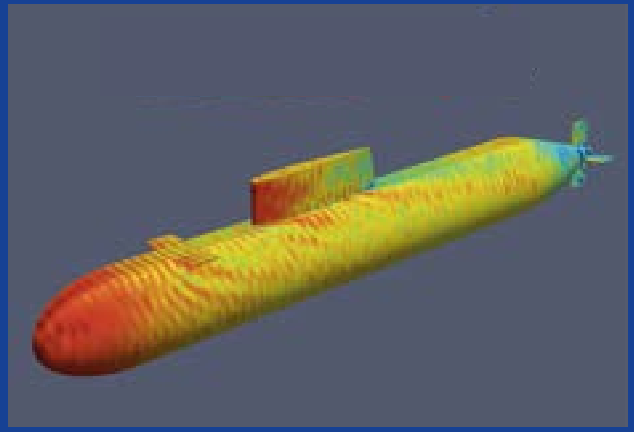
The development of an integral equation method responding to the specific nature of flow noises subsequently took place in collaboration with several researchers from ENSTA Paris. Benjamin Cotté, senior lecturer at the Industrial application laboratory (IMSIA) in ENSTA's Mechanical department, and a specialist in modelling vibratory sources; Jean-François Mercier, Director of research at the POEMS laboratory, joined to Inria, which centres its research on the mathematical and numerical properties of Green's functions and the method of integral equations; and Stéphanie Chaillat, also a researcher at the POEMS laboratory. *"This research was carried out as part of Nicolas Trafny's PhD, for whom Jean-François Mercier and I were tutors, and in partnership with Naval Group"*, explains Benjamin Cotté. *"It posed several academic problems. We needed to elaborate a method of modelling that was suitable for the specific and complex geometries of the structures concerned, all of which are totally submerged in water. This situation had been little studied until that time, for acoustic problems, with the integral equation method"*. *"These two specificities led us to using an 'analytical' formulation of the Green's functions as well as integral equations, for as long as possible before going on to the next phase which is numerical resolution of the problem"*, adds Jean-François Mercier. *"We aimed, in particular, to reduce computation times, something of real need for industrial applications. Our colleague Stéphanie Chaillat, a specialist in numerical resolution of integral equations, helped us enormously with our research."*

WORKING TOWARDS A DESIGN TOOL FOR PRODUCTION ENGINEERS

After three years of research conducted as part of Nicolas Trafny's thesis (see box), Naval Group now possesses new analytical and numerical tools capable of computing a spectre of noise intensities in the frequency ranges of interest, using the boundary layer parameters. The latter can be the result of experimental measures or simulations. This represents real progress in the modelling and simulations that will, over the long term, allow engineers to optimise the design and performance of ships.
"The method that has been developed now allows us to define the 'level of noise', meaning the maximum intensity of noise and the areas or elements of the submarine responsible for generating it, concluded Gilles Serre. *We are continuing work to characterise the directions in which noises are most intense, and hope to then take more detailed parameters into account, such as the temperature gradients in water which have a heavy impact on the underwater propagation of sound. The results obtained so far are very encouraging and we now have an in-house tool that surpasses the performance of any existing off-the-shelf product. We are currently working to improve these numerical tools to render them more ergonomic for Naval Group production engineers, as well as continue to increase their maturity so that the computations can be spread to a larger number of industrial applications."*

A PREDICTIVE MODEL FOR COMPLEX GEOMETRIES

The thesis work conducted by Nicolas Trafny has enabled significant progress to be made in estimating the noise of marine propellers and ship appendages. Knowledge of industrial challenges, modelling of physical phenomena, applied mathematics and numerical development are the obstacles to be lifted in order to simulate the noise made by flows, known as a multidisciplinary approach.
Over the last three years, one of which he spent at ENSTA Paris, Nicolas Trafny concentrated on situations in which all submarines – even the most discreet – could betray themselves due to their hydrodynamic noise characteristics at various sound frequencies. *"When the turbulent boundary layer develops along the surface of the submarine and the blades of its propeller, it can amplify the phenomena of diffraction. The energy associated with the turbulence is then converted into sound waves. This conversion can be very efficient, especially when near to geometric shapes"*, specifies Nicolas Trafny. *"I developed a new approach based on an acoustic analogy, which allows a complex-shaped obstacle, such as a submarine, to be taken into account. Over and above the existing methods, all limited to simple shapes such as spheres, cylinders or infinite plates, my thesis work allowed me to create a predictive model to use with a complex geometry"*. Nicolas Trafny presented his thesis in November 2021 and went on to join the acoustic team at CEMIS.



The work conducted by Nicolas Trafny has allowed simulation of two mechanisms responsible for radiated noise, depending on the observer's position. The image shows the areas responsible for emitting vibro-acoustic sound as seen by the same observer positioned in front of the submarine.

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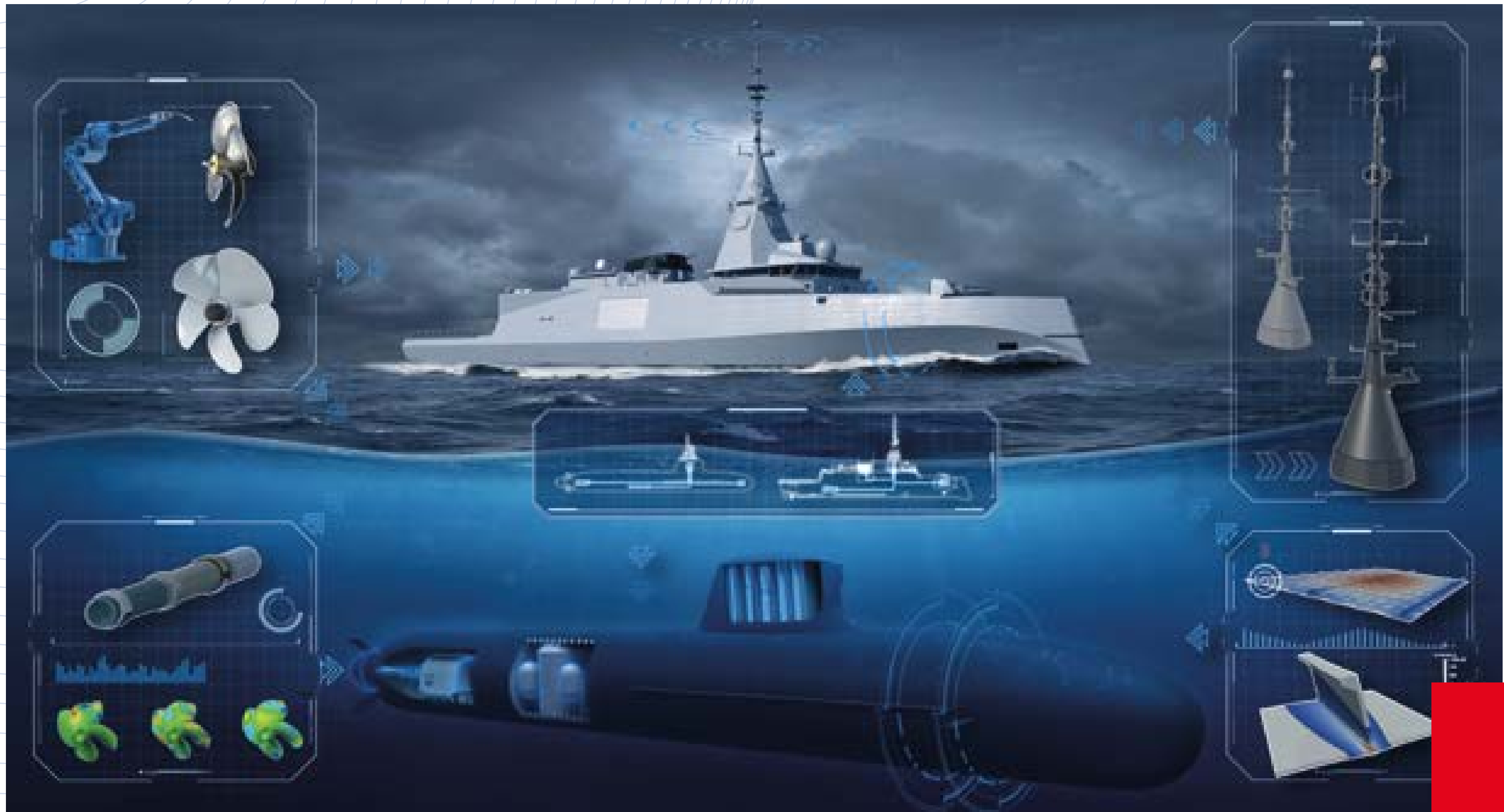
*CEMIS (Centre d'Expertise de Maîtrise de l'Information et des Signatures) is an R&D unit within Naval Group.

06

MATERIALS AND STRUCTURES



THE COMPOSITE PROPELLER AN INNOVATION MAKING ITS WAY FORWARD

Why should a submarine or surface ship's propeller be made of metal? Naval Group has taken a proactive approach to the issue since 2016 and has been working on composite-material designs, which it believes offer a lighter and stronger solution. The main priority is to equip warships with this new technology, but its low cost is an advantage that may lead to its use in the civilian sector.

Research work aimed at designing a composite propeller for naval ships began by challenging established knowledge. For example, worries of breakage, even though certain materials are extremely resistant. Or the belief that such a critical equipment item could not do without the reassuring solidity of metal. However, Naval Group was convinced of the properties of composite, and created the Hélico project in 2015 - a program fully financed with shareholder's equity.

TWO SMES IN THE WEST OF FRANCE AS PROJECT ASSOCIATES

"The Hélico project included a thesis on modelling fluid/structure coupling and a study carried out by our subsidiary Sirehna on propeller performance simulation and calculation tools", explains Frédérique Le Lay, a specialist in composite materials. *"Then in 2016, we signed up to a RAPID* project along with the French Defence Procurement Agency (DGA) and two SMEs based in the west of France. Its aim was to design, manufacture and test a demonstrator."* RAPID innovation projects focus on so-called "dual-use" technologies, and their potential use in both the civil and the military sectors. This potential access to huge new markets was of particular interest to the two SMEs, Méca (a design office in the region of Nantes) and Loiretech (a manufacturer for complex industrial parts). Controlling cost and maintenance were, of course, key elements in the project. And on the naval defence side, reducing propeller performance was obviously out of the question!

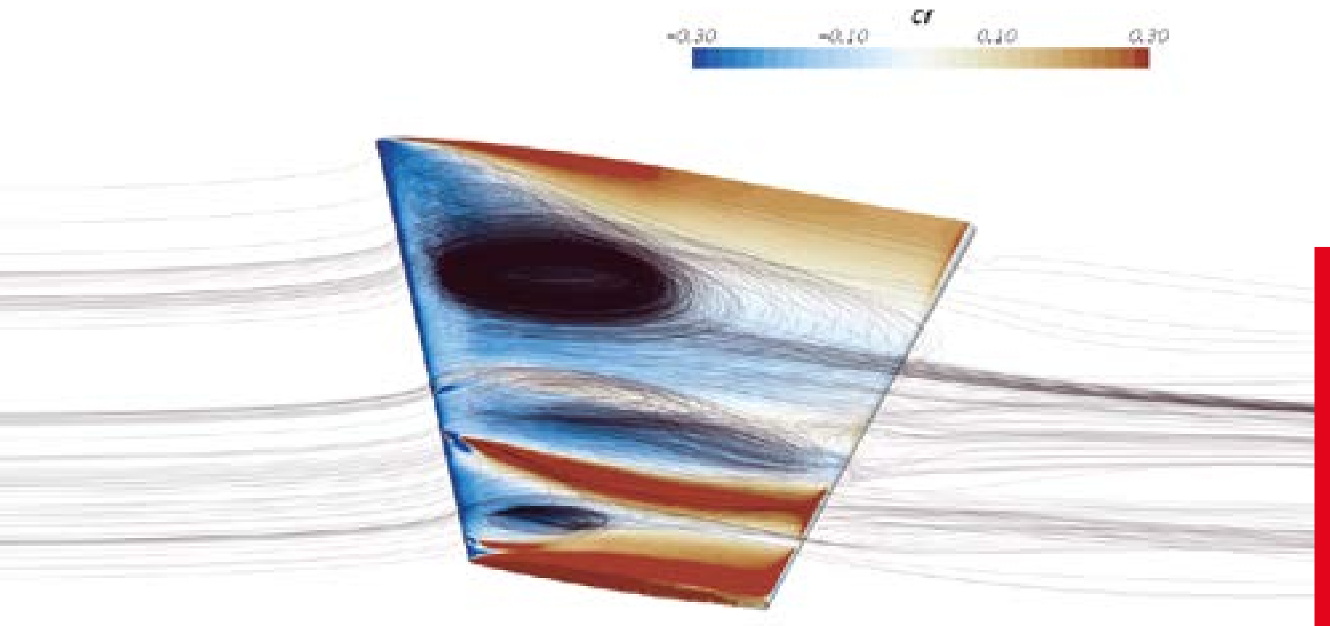
"We have come a long way since", Frédérique Le Lay adds. *"Only a few civilian ships had been fitted with composite propellers at the time, with a high production costs and weaknesses in the leading and trailing edge connection. In the event of an impact, these propellers could delaminate or even break."*

A BLADE THAT IS DEFORMED BY WATER PRESSURE

Researchers first looked at modelling and simulating the use of this future propeller. The thesis conducted by Centrale Nantes aimed in particular to understand the behaviour of composite propellers in fluid flows. This is an extremely complicated problem to examine. *"A blade has a trapezoidal shape; it is not flat but curved and slightly twisted"*, points out Antoine Ducoin, teacher-researcher at Centrale Nantes. *"Water pressure deforms it and water flow generates high-frequency vibrations. And this flow can also be separated from the blade along the trailing edge, thus reducing the efficiency of propulsion."*
The duration of this thesis was not enough to model all these phenomena. In addition to this, the vibratory aspect was put to one side in order to look at blade deformation in more detail. Laetitia Pernod, PhD student at Naval Group to whom this work was assigned, studied the absence of rupture risks. *"These results converged with full-scale tests that we had conducted at the École Navale"*, continues Antoine Ducoin. *"We then engineered the composite by inserting optical fibres into its folds to measure the level of deformation. A first!"*

WHEN DEFORMATIONS BECOME A VIRTUE

The work performed by Naval Group's subsidiary Sirehna aimed to be more application-based. It coupled computation codes on composites, the hydrodynamics and mechanics, in order to define the propulsion performance of the propeller. *"It's a very light part which rotates at great speed"*, explains Pol Muller, Head of studies at Sirehna. *"These blades can be deformed up to a few percent, whereas deformation on metallic blades is counted in thousandths or tens of thousandths."* Our team was also able to prove there was no risk of breakage. However, they were confronted with a number of problems, and in particular how to accurately model a composite blade made up of 10 to 30 different and non-homogeneous layers. They verified a phenomenon widely covered in the scientific literature: on a well-designed blade, deformations are a virtue - meaning that they benefit to propulsion and at several operating regimes. Metallic blades, however, are more rigid and so can only be used under an optimal regime. *"We have succeeded in developing a computation chain that allows us to rapidly simulate and test dozens of blade profiles for design needs"*, reveals Pol Muller. *"I could even define the ideal hydrodynamic shape when the blade is deformed, and the tool worked out the shape the blade should have when it is not rotating."*



How can composite blades be solidly fixed onto a metallic hub? Answer: with a solid system using eight slot bolts per blade

FIXING COMPOSITE BLADES ONTO METAL: A REAL TECHNICAL CHALLENGE

This possibility had not been explored during full-scale tests using the twin-motor vessel Le Palais: the composite blade had to be identical to its metal twin so as to avoid destabilising the ship. However, the contract for these tests signed in March 2016 with the ship's owner – a company called Navix - energised and boosted the creation of our Rapid project, baptised FabHéli. *"We had two years to size and design a blade that was unprecedented, meaning it was not covered by any reference standards"*, confides Samuel Durand, at the Méca design office. It was fortunate that Loiretech had started working on composite blades for tidal turbines two years earlier. Even if this type of blade rotates at a slower speed and is not used for propulsion, we were able to draw on this experience for our own work.
The main design difficulty for Méca was deciding how to attach the five blades to the hub of the drive shaft. *"The couples were tens of times higher than those of tidal turbines. In addition to this, the removable blades that we had opted for posed problems with loosening, clearance and fatigue. After conducting comparative studies, we chose a fastening system using eight slot bolts per blade."*

Computation of fluid/structure interactions via "co-simulation"
A computation methodology adapted to deformable hydrofoils was drawn up thanks to the thesis by Laetitia Pernod. It is based on using two numerical tools to model flow characteristics and the mechanical state of a composite profile. The coupled computation requires finely-tuned numerical adjustments in order to show precisely the physical aspects at play, and provide baseline data for validating the simplified approaches to fluid/structure coupling.

BLADES OF THE RIGHT SHAPE, WITHOUT MACHINING

The final link in the project, Loiretech, was in charge of manufacturing the five blades for the prototype propeller to be used on the Le Palais. The company had not retained the two most common processes used for composites - prepreg and vacuum infusion – for cost reasons. The choice made was Resin Transfer Molding (RTM), often used in the fields of automobiles and aeronautics, that allows for the manufacturing of parts in a single block. However, some large-scale adaptations were necessary.

"*Our blades are 40 mm thick, against a maximum of 6 mm for car bodywork*", specifies Franck Bourcier, Marketing and Innovation Director at Loiretech. "*Otherwise, RTM does not create perfect shapes; machining is required, which leaves bare fibres and can cause capillarity in the marine environment. We have also taken particular care in designing the preform, as well as the density and length of carbon fibres, in order to create the final blades rapidly. They were validated by Naval Group and passed tests in Lorient successfully.*"

COMPOSITE BLADES, A SUBJECT ALWAYS IN THE SPOTLIGHT

But why didn't this test result in the fitting of composite propellers to defence ships yet? Because changing the material used for such a critical part is time-consuming for it requires studies, testing and validation. The adventure continues! Since the end of FabHéli in 2018, Centrale Nantes has ramped up its skills in the field of using composites with fibre optics. It has also improved its fluid/structure interactions within several Naval Group projects. "*This subject is still very relevant*", considers Antoine Ducoin. Méca has also been associated with some of these projects.

Sirehna now possesses a computation chain that can be used with its design work. Bureau Veritas worked with the FabHéli project to create the basis of an approach to certifying composite propellers. And lastly, Méca and Loiretech have been working on the European project Copropel since mid-2022, coordinated by a Greek university. The aim of this project is developing and testing larger composite propellers (up to 2 metres compared to 1.10 m for FabHéli) over several months and on various civilian vessels, including container ships. "*We especially hope to validate the 15% economy in fuel and the attenuation of radiated noise*", reveals Franck Bourcier. These assets would also increase chances of gaining our first naval defence contracts.

WHY USE A COMPOSITE PROPELLER?

- **It halves the propeller's weight** in comparison to its metallic equivalent.
- **It reduces the overall weight of the propulsion system and saves up to 15 % on fuel** in relation to a metallic propeller. This aspect could not be validated within the framework of the Hélico and FabHéli projects, but it will be validated during the European Copropel project, which began in June 2022.
- **It reduces production costs** in mass series production, which will help to absorb the initial investment made for manufacturing the moulds.
- **It simplifies maintenance**: a well-established network already exists, specialised in the repair of composites in the naval sector. In the event of severe damage on removable blades, a simple replacement of the blade is needed.
- **It attenuates the acoustic, magnetic and electrical signatures** of the propeller. This aspect is interesting for naval defence ships (minehunters for example), oceanographic exploration vessels and fishing boats, whose noise is recognised by certain types of fish. Once again, the anticipated benefits must be validated by the Copropel project.

"We especially hope to validate the 15% economy in fuel and the attenuation of radiated noise"

Franck Bourcier, Marketing and Innovation Director at Loiretech

The composite propeller manufactured by Loiretech, tested on a passenger ship.

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HOW CAN WE DESIGN "GREENER" DEFENCE SHIPS?

Although they are not subject to civil fleet regulations, defence ships are still expected to generate less waste, consume less energy, impact marine biotopes as little as possible and become easier to recycle at the end of their life cycle. Eco-design has become one of Naval Group's main goals and has inspired numerous research projects.

At the end of 2021, the countries bordering the Mediterranean Sea agreed to make it an Emission Control Area (ECA) as of 2025. The decision went rather unnoticed, but says a lot about the growing environmental requirements at sea. From Gibraltar to the Suez Canal gateway, civilian ships will be required to use very-low sulphur fuel oil (0.1%, compared with 0.5% previously). The aim is to reduce emissions of pollutants and fine particles.

INTERNATIONAL REGULATIONS, CUSTOMER SPECIFICATIONS: THE PRESSURE IS ON!

Before being established in the Mediterranean Sea, ECAs had been so in the Baltic and North Seas, in parts of the Caribbean and along the coasts of the United States and Canada. But with the Mediterranean Sea and its 2.5 million sq. kilometres, this approach is being taken to another level. "*And this is part of a wider trend*", adds Gaëlle Rousseau, Eco-designer Manager at Naval Group. "*International maritime regulations are setting increasingly stringent standards for hull paint, ship waste and discharges, end-of-life recycling, etc.*"
Technically speaking, these regulations do not apply to naval defence. But we can hardly ignore these regulations or consider that this exception will last. Especially as the French Defence Procurement Agency and a number of Naval Group's foreign customers are also starting to introduce environmental requirements in their specifications. All this requires a great deal of thought before ships are built.

"With more than 50 studies per year on the topic, our research activities include an environmental component"

Joëlle Gutierrez

FIFTY TO SEVENTY ENVIRONMENTAL STUDIES A YEAR

"*These subjects are not new to us*", points out Joëlle Gutierrez, Technical Director in the field of the Environment and Eco-design. "*For the past several years, 20% of our research activities have included an environmental component, which represents 50 to 70 studies per year. We are working towards reducing the impact of our ships in various areas: managing our waste, reducing the weight of our structures, assessing bio-based materials and greener solutions for combating fouling* or corrosion, etc. But engaging in eco-design, as Naval Group chose to do at the end of 2021, is taking things to the next level.*"
Indeed, eco-design involves quantifying all the environmental impacts of a ship - from its construction to its deconstruction - in order to be able to confront different options in terms of materials, assembly techniques, engines, etc., and determine which one will be the "greenest".

OUR NUMBER ONE PRIORITY: OUR SHIPS' CARBON FOOTPRINT

"*Quantifying these impacts is a research topic in its own right*", declares Gaëlle Rousseau. "*The diesel oil consumption-greenhouse gas production-global warming chain is at the heart of our concerns. We also want to develop a sustainable and shared model for measuring carbon footprints, that can apply to our ships. We have taken three measures in-house, but they are not comparable to those of civilian fleets and their regular routes: our missions are by nature unpredictable and extremely versatile.*"
Naval Group therefore launched a two-year collaborative project on carbon footprint modelling with the Arts et Métiers Institute of Chambery and École Nationale Supérieure Maritime (ENSEM), which specialises in ship energy transition and optimisation. "*We want to establish typical consumption and usage profiles*", explains Dominique Follut, its Research Director. "*But the challenge is knowing where to put the cursor. The same profile cannot be applied to a patrol boat and an aircraft carrier. Nor can individual profiles be made, as they would be too complex to model. The ideal solution would be to come up with large families of profiles, which are generic enough to include several ships and yet precise enough for each one to be optimised.*"

A ship may be conceived in order to be easily dismantled, thus allowing to re-use some recycled parts, but this has to be anticipated at the early designed stages...

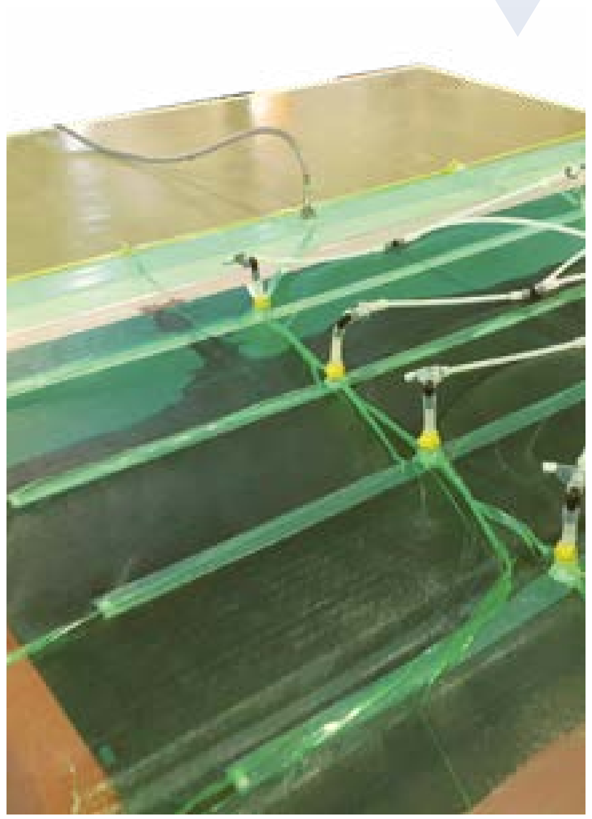
CONCILIATE MILITARY CONSTRAINTS WITH ECO-DESIGN

What exactly can be optimised? Propulsion, of course, with potential prospects for using any of the new fuels that ENSM is studying: hydrogen, bioethanol, biogas, ammonia, etc. But also, other aspects, such as choosing the right materials or facilitating the ship's deconstruction at the end of its life cycle, in order to recover and reuse certain parts. Dominique Follut however insists on one constraint: "*We are talking about naval defence! Eco-design criteria must not penalise operational performance and our readiness to carry out missions around the world. We have to rule out any virtuous fuels that cannot be found in most ports, or ecological systems that are too complex to repair. The scientific approach is best combined with a good dose of realism.*"
Carbon footprint modelling has another virtue: it feeds into Life Cycle Analyses (LCA). In addition to greenhouse gases, they take into account all environmental impacts: consumption of raw materials, transportation, pollutant discharges into water and air, waste generated, etc.

> "We wish to develop a joined and lasting modelling methodology of the carbon footprint of ships, which may be transposable to military applications"
>
> *Gaëlle Rousseau*

COMPOSITE MATERIALS: AT LEAST HALF THE WEIGHT OF STEEL...

These whole-ship approaches go hand in hand with more targeted research. For instance, research into composite materials, which are expected to replace steel and metal alloys in certain components, such as the superstructures of surface ships. "*They are half the weight for the same strength*", justifies Émilien Billaudeau, Composite Material Engineer. *"And if the weight of ships decreases, their consumption and emissions will also decrease. We could even consider reducing the size of the propulsion systems."*
Naval Group has used composite materials on its ships for the past 60 years, on submarine decks and bridges for instance. However, major technical barriers in terms of assembly and fire resistance have so far restricted their use in large structures on surface ships. These barriers should soon be lifted, as demonstrated by the 2017-2021 European Ramsses project. Naval Group notably took part in the validation of steel/composite superstructures whose mechanical strength, fire resistance, multi-material interfaces and durability were characterised.

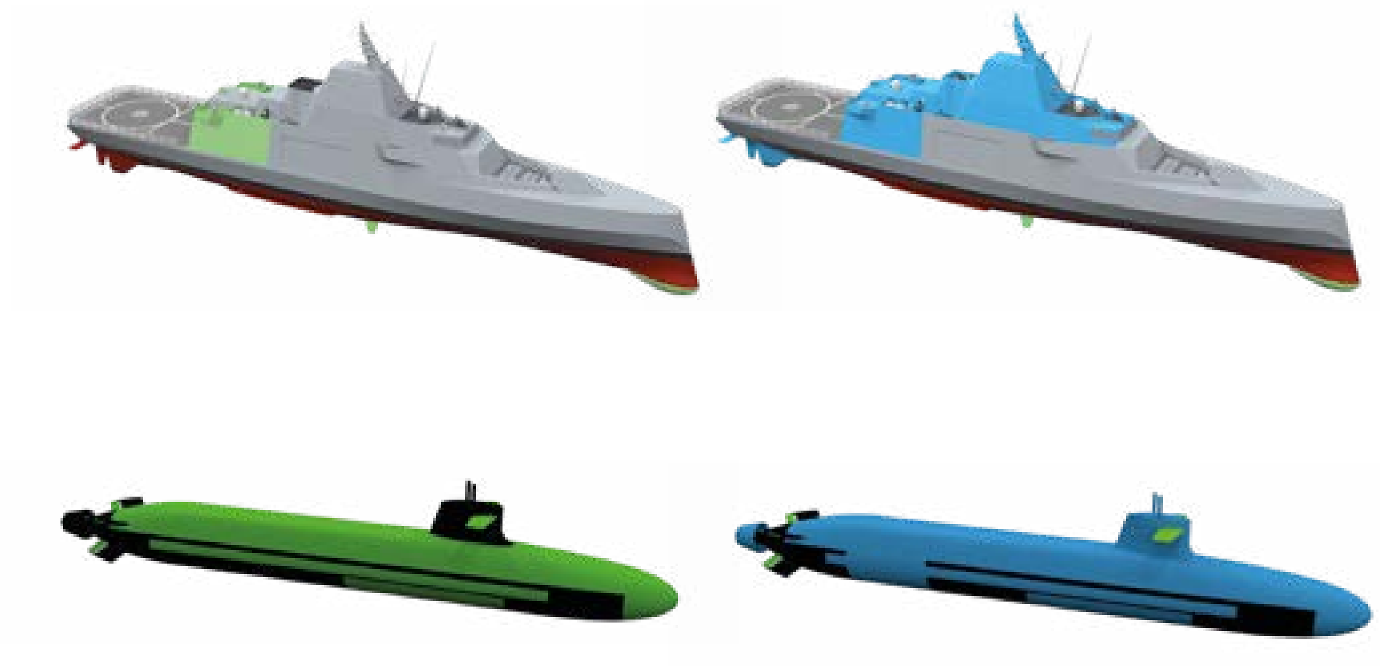


Production of a composite material for ship superstructures by infusion process for the European project Ramsses, in which Naval Group took part between 2017 and 2021.

... BUT WEIGHT IS NOT THE ONLY RELEVANT CRITERIA

"*Our ships are to incorporate more and more composites and we have decided to establish a roadmap for these materials*", confirms Gaëlle Rousseau. "*Since weight is not the only relevant criterion, we carry out LCAs in order to identify and compare their impacts on the environment.*" Out of the twenty or so composite references used by Naval Group, only the most commonly used will be the subject of these LCAs. "*We are mainly focused on their manufacturing process, which may require more or less energy, and on whether they are bio-based or not*", describes Robin Sauter, Environmental Design Manager Some incorporate flax fibres, bamboo or basalt, which is indeed a good point. But these elements are always combined with some kind of petroleum-based resin, meaning end-of-life recycling is not that obvious.
As for choosing the process, it is driven by environmental and architectural constraints, but also by the stresses that the part is subjected to and its criticality: "*A submarine mast, for example, withstands both the hydrodynamic drag force and the heavy seas*", explains Émilien Billaudeau. "*It is designed with a high level of performance, which will require the use of carbon-fibre composites if we are to adopt composite masts in the future.*" Doing all we can for the environment, but without sacrificing the ship's performance; this is the tricky equation posed by the transition to eco-design.

Although they are not yet widely used on today's ships, composites are expected to replace metal in numerous submarine and surface ship structures.



Composite structures present onboard

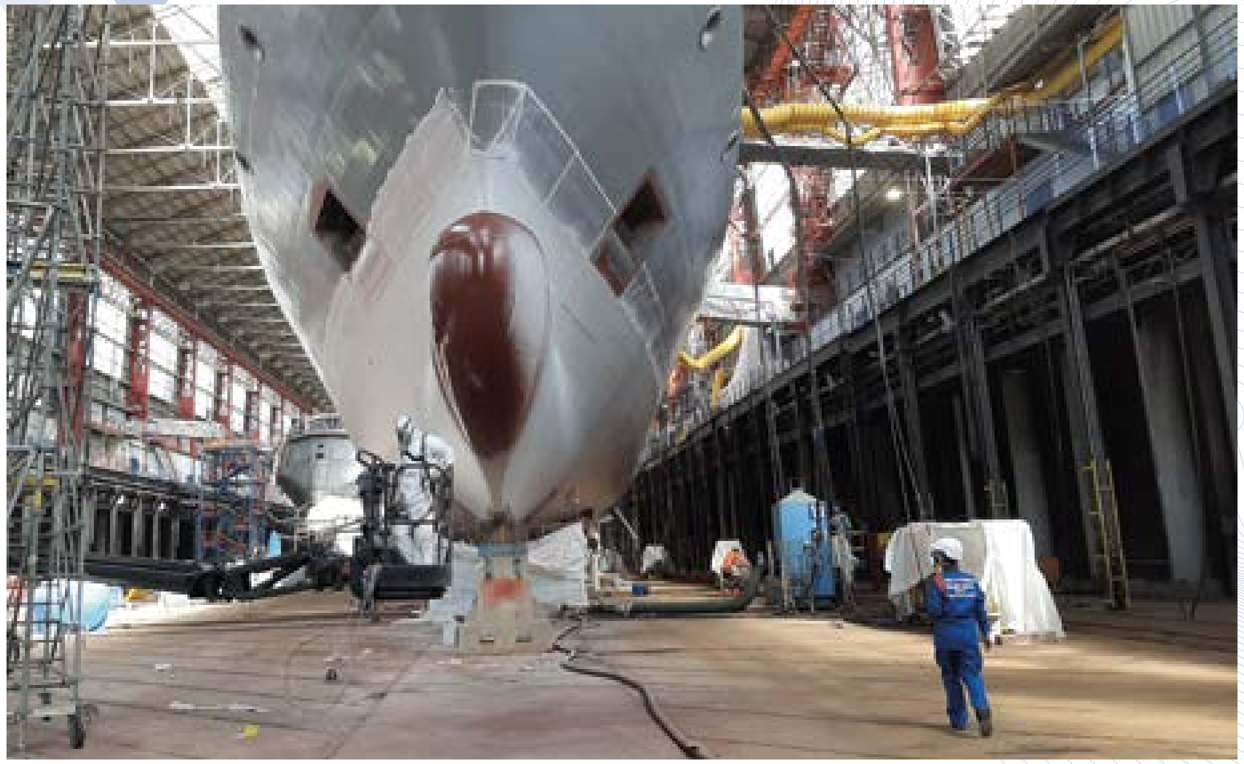
Composite structures in development

* 'Fouling' refers to the accumulation of marine microorganisms on ship hulls.

AN ENVIRONMENTAL ANALYSIS FOR EACH SHIP BY 2023

LCAs are an input data for environmental analyses, whose purpose is to list all the environmental impacts of a ship, including in the event of a failure. *"For example, it could be an oil leak on board or a puncture in the gas oil tank"*, explains Robin Sauter. "We consider the likelihood of such events, their severity and potential extent, and then reach an overall score."
By the end of 2023, most of the ships built by Naval Group or under design will have undergone an environmental analysis, which implies a high level of mobilisation in-house. *"We want to raise awareness among our colleagues and encourage some of our customers to anticipate, to strive for performance that goes beyond the regulations in force"*, explains Gaëlle Rousseau.

This flax-based composite is produced by Naval Group in Lorient.



The paint on ships, which protects them from corrosion and fouling, is in constant contact with the marine environment. This is why Naval Group is looking at new, "greener" formulations.

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