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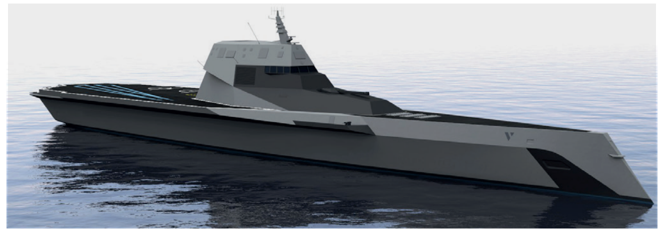
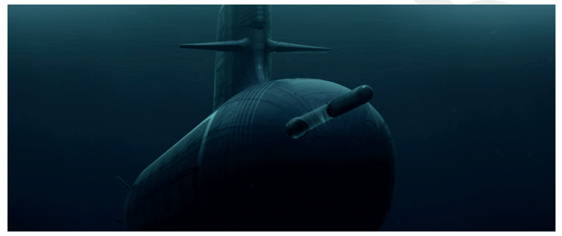
RESEARCH

SCIENCE FOR NAVAL INNOVATION

NAVAL GROUP

POWER AT SEA

CONTENTS


EDITO

PREPARING FOR THE FUTURE
WITH TECHNOLOGICAL RESEARCH

I am very proud to present this third issue of our magazine RESEARCH, *science for naval innovation*. The purpose of this publication is to illustrate our technological research mission and international vocation, as well as Naval Group's passion for the sea.

Our naval defence research activities are paving the way for the future. They contribute to finding the ideas liable to lead to future innovations and transforming them into technologies with strong added value for our customers. They also allow the development of a range of tools for achieving productivity gains or improving difficult working conditions. Above all, Naval Group research is part of a tradition of scientific and technical excellence which has been built up by our predecessors over nearly four centuries.

The world is changing fast and Naval Group activities are becoming increasingly international. In this context, the challenges we face are numerous:

- The first is to **take full advantage of the cutting-edge work being carried out in the French and international scientific ecosystems**. Innovation can no longer be carried out alone: it is now global. Accelerating our outreach to the outside world will enable us to keep up with the increasingly rapid pace of innovation. In recent years, we have thus set up numerous scientific cooperation agreements with industrial or academic partners, clusters, IRTs or public institutions, and we aim to continue this approach, in line with our technological roadmaps;
- The second is to **develop our scientific expertise**. In order to support innovation in increasingly sophisticated fields, we must give ourselves the human resources needed to make the appropriate choices – whether technical or strategic – at the right time. Cooperating with the world of research enables us to maintain or acquire the fundamental skills we need, while being able to call on a network of very high-level expert partners;
- The third is to **support our development internationally**. Innovation no longer has borders and the search for partners must also look outwards, seeking the best around the world. The global openness of R&D is also a key factor in the success of the international outreach of Naval Group, thus supporting its commercial export growth.

Collaborative research is thus at the heart of our activity and some of the work presented in this issue are remarkable examples of this. I believe that these examples are particularly significant because, more than ever, we will in the future have to rely on our present and future partners in order to take up the new naval defence challenges.

These include the utilisation of functional materials, the implementation of artificial intelligence algorithms or blockchain-based techniques, the integration of connected objects or drones, big data processing, increased on-board energy capacity and the optimisation of smart grids, reinforced cyber-security, the integration of quantum communications, the development of services built around on-board data centres, innovative processes – such as additive manufacturing – the use of digital twins, the transformation of our industrial tool toward a 4.0 factory, etc.

Meeting these challenges implies mastery of various techniques, but I feel that it is also important to point out that this will require a parallel focus on the cognitive sciences, in order to anticipate and facilitate their assimilation by the future operators. This point will become particularly critical once the human/machine balance is disrupted by the integration of increasingly sophisticated decision-making algorithms.

I could not close this introduction without specifying that the work presented in the following pages, as well as all the other research carried out within Naval Group, also serves to support all the professions which provide remarkable expertise on behalf of our product developments. It is the achievement of all the scientific players in the group, some of whom are spotlighted in this issue.

I hope you enjoy reading this issue.

Vincent Geiger
Director of Naval Research.

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COLLABORATIVE RESEARCH

GREATER INNOVATION THROUGH COOPERATION

Innovation – and more specifically open innovation – lies at the heart of Naval Group's concerns, as it aims to offer its customers high-performance, affordable products. In order to meet this R&D challenge, international cooperation has become crucial in seeking out new ideas and boosting reactivity. This principle means that new technologies can be introduced faster – thus staying a step ahead of the field.

Although Naval Group enjoys a reputation built around its industrial achievements, it is less well-known that its technological progress also lies upon a solid scientific base. Naval Group's research projects are carried out at Naval Research, the technological research center, located on three sites in France: Nantes (Loire-Atlantique), Ollioules (Var) and Cherbourg (Manche). This entity comprises 150 researchers and engineers. It can draw on the services of four centers of excellence: the CESMAN (Naval Structures and Materials Expertise Center), the CEMIS (Information Control and Signatures Expertise Center), the CEMEP (On-board Energy and Power Control and Expertise Center) and Sirehna, originally a spin-off from École Centrale de Nantes and which is now a wholly-owned subsidiary of Naval Group specialising in hydrodynamics.

This foundation is made all the more robust by the fact that it is outwards-looking. To enhance its innovation capabilities, Naval Group thus builds on knowledge and resources from research teams at the cutting edge of the French and international scientific ecosystems. To do this, the group is firmly committed to different forms of collaboration in upstream research, referred to as Science and Technology (S&T). "*Cooperation is a major challenge for any industrial firm, because the pace of innovation cycles is increasing*" remarks François Duthoit, Head of collaboration in the Engineering Department. "*In many technological fields, the world of research is conducting work which could eventually be adapted to naval systems*" explains Vincent Geiger, Director of Naval Research. If a new concept looks promising, it is first taken to the prototype stage. Its integration into the production engineering and the group's products only begins after its innovative value is confirmed.

PROJECTS CARRIED OUT WITH THE BEST RESEARCH CENTERS

Naval Research is a stakeholder in research laboratories bringing together academic and industrial partners around themes of common interest. Thus, the Joint Laboratory of Marine Technology, created in 2016, combines École Centrale de Nantes, the University of Nantes and Naval Group. What are its ambitions? To work on key technologies such as naval hydrodynamics, numerical simulation and additive manufacturing (see the box on the hollow propeller blade demonstrator). For its part, the Gustave Zédé laboratory brings together Naval Group and ENSTA Bretagne for experimental research and modelling work relating to materials performance (strength, durability, stability). "*Innovation is the business of tomorrow: it transforms ideas into real added value. The hollow blades produced by the Joint Laboratory of Marine Technology are a concrete example of collaboration helping*

to significantly speed up applications" explains Vincent Geiger.
In the same spirit, but using different means, Naval Group has also initiated joint projects with French technological research institutes (IRT) such as Jules Verne (Nantes) in robotics, augmented reality, simulation and modelling; M2P (Metz) for materials, metallurgy and processes; and SystemX (Saclay) in the fields of agile industry and numerical engineering. Another illustration of this dynamic collaborative approach: six academic chairs, created in partnership with schools or universities, allow participation in teaching and research on subjects such as acoustic signature simulation, cyber-security or the place of humans in ship building.

AN ANNUAL MEETING DEVOTED TO SCIENCE & TECHNOLOGY

Last but not least, Naval Research is actively involved in various competitiveness clusters, including the Pôle Mer Méditerranée and the Pôle Mer Bretagne Atlantique, because they are ideal locations to grow innovation projects between partners (industry, SMEs, universities, research centers). Naval Group also shares innovation roadmaps with equipment and system manufacturers. This enables each party to speed up and optimise its R&D, while focusing on what stands a real chance of becoming an innovation and thus being integrated into products and systems.
Since 2018, a day-long event bringing together Naval Group's S&T teams is held every autumn. It is an opportunity to share their progress, whether in the field of technological concepts or scientific tools, to reflect upon scientific issues and to discuss future innovations with high added value. After a first in-house edition, subsidiaries and partners are now invited to present their very latest results and share their S&T prospects with a view to anticipating and preparing for the future.

CENTERS OF EXCELLENCE IN TECHNOCAMPUSES ABROAD

Innovation knows no borders. The movement initiated in France is also being extended internationally by means of a proven approach: the creation of cooperative agreements on chosen projects and, when they have grown sufficiently, consolidation by a framework agreement or Memorandum of Understanding (MoU). In some, the approach leads to the creation of a local center of excellence. There are in fact two types of cooperation. On the one hand, those designed to progress S&T roadmaps or interact with renowned experts in Naval Group's fields, in which case the country is of little importance. On the other, those which also participate in the group's internationalisation efforts. The partner countries are then chosen according to business opportunities, whether established or to be developed, and in order to enable the group to play a role in the local naval defence ecosystem. *"This enables long-term relationships to be created with local organisations and decision-makers"* points out François Outhoit.

Naval Group has thus created a research laboratory in Chile, the MERIC (Marine Energy Research and Innovation Center), now managed by its subsidary Naval Energies. Similarly, the decision was taken to create a Naval Group Center of Excellence (CoE) in Australia, to manage the numerous cooperations which have been launched and to become eligible for cooperative funding arrangements and research tax credits. This CoE will be situated within a technocampus, a cooperative structure shared with about fifteen industrial and academic partners. Two other CoE are currently being created, one in Singapore, the other in Belgium. This will stimulate innovation opportunities within the Naval Group teams involved in research and innovation.

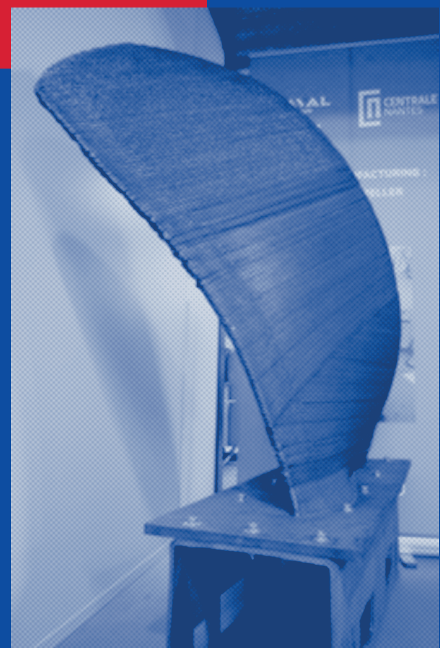
Every year, the "S&T Days" bring together the scientific community of Naval Group

PRINTING THE PROPELLERS OF TOMORROW: A STORY OF COLLABORATIVE INNOVATION

In early 2019, Naval Group and École Centrale de Nantes announced an unprecedented achievement: printing of the first hollow propeller blade demonstrator using metallic additive manufacturing. The two partners are working on the design of propeller demonstrators to improve the operational capabilities of ships. This approach is carried out within the framework of the European H2020 RAMSSES project. It is funded by the European Commission and devoted to reducing the environmental impact of civil shipping.

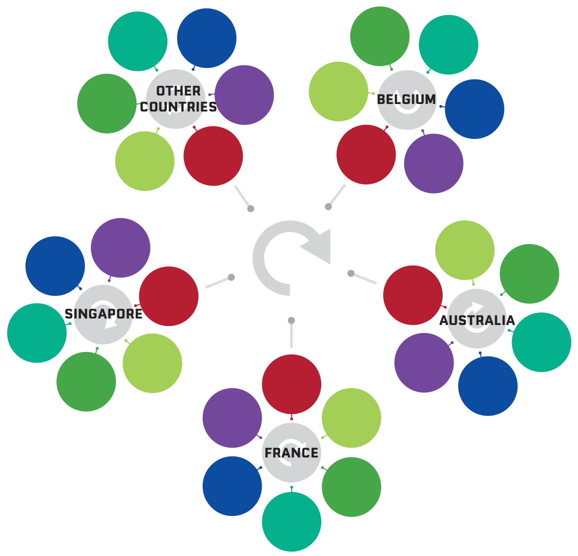
This 1/3 scale stainless steel hollow propeller demonstrator is representative of a container ship propeller and required less than a hundred hours of printing for a mass of about 300 kg. This is a genuine technical achievement enabling more than 40% weight savings compared to the conventional process. Naval Group and Sirehna were able to draw on the expertise of École Centrale de Nantes in trajectory generation and additive manufacturing. For its part, Sirehna oversaw the design of the blade, to improve its energy efficiency and reduce the environmental impact of the propellers.

As recalled by Patrice Vinot, Head of the propeller work package for the RAMSSES project at Naval Group, *"even though additive manufacturing is increasingly present throughout the industry, the programming and design of complex parts such as ship propeller blades is a very real challenge for our teams and those of our partners. The potential of the process, as shown by this new case study, suggests unparalleled performances for the propellers of tomorrow. It is by taking part in projects such as RAMSSES and coordinating our network of academic and industrial partners that we will succeed in ensuring the long-term adoption of 3D printing by the shipyards"*.



The hollow blade demonstrator developed by Naval Group and École Centrale de Nantes, is produced using 3D printing

FOSTERING INTERATIONAL COLLABORATIVE RESEARCH



Naval Group has for a long time been forging ties with various entities in France contributing to its open innovation policy. The strategy of collaborative research internationalisation consists in developing a similar ecosystem in each of the countries in which Naval Group undertakes an industrial partnership.

A PRIZE TO SUPPORT PROJECTS FROM NAVAL GROUP STAFF

The "La Pérouse prize" was created in 2018 to reward the originality and vitality of the staff at Naval Group, by encouraging them to propose promising and audacious research projects. The jury, chaired by Sophie Bretesché, Vice-Chair of the Naval Group Scientific Council, awarded the prize to the data scientist Fabien Chaillan in 2018, for his project on automatic recognition in a big data context for naval defence. The 2019 prize went to Estelle Chauveau, research engineer, and Maxime Debert, senior software architect, for their project on underwater vehicle evasion route optimisation. The prize winners receive a research grant of 6 to 12 months to develop their project within Naval Group, in collaboration with a top-level laboratory in France or abroad.

The winners of the 2019 La Pérouse prize, surrounded by members of the jury and Hervé Guillou, CEO of Naval Group (right)

AN INTERNATIONAL AND MULTI-DISCIPLINARY SCIENTIFIC COUNCIL

The Scientific Council of Naval Group is a consultative body consisting of thirteen scientific personalities of five different nationalities. Its role is to give opinions on the scientific policy and technical strategy of Naval Group. *"The aim is to take us off beaten tracks and direct our innovative capability towards disruptions that will make a difference"* emphasises François Duthoit. The members are not and do not claim to be scientific specialists in the group's disciplines: their role is to assist the group with identifying potential breakthroughs and disruptive technologies and with taking them on-board. They are all recognised experts in their own fields (history, aeronautics, sociology, renewable energies, innovation, economics, philosophy, etc.) and most of them are members of other scientific councils, although few are specialists in the Group's activities. *"It is precisely this variety of backgrounds that interests Naval Group"* François Duthoit confirms.

"We are organised into thematic working groups which submit their reports after a few months of work and discussions" explains Joël Bertrand, Research director at CNRS*, who chairs this Council. *"We can thus shed light on Naval Group's decisions with respect to the technological and human aspects that will prevail tomorrow… and even beyond, because some of the projects are for the very long term"*. This projection into the future is also a major aspect mentioned by Sophie Bretesché, Professor of sociology of organisations at the IMT (Institut Mines-Télécom) Atlantique, and Vice-Chair of the Council: *"Any major technological innovation in a ship creates changes in the organisation of the personnel, first of all in manufacturing and then in day-to-day use. The different viewpoints of the members of the Council enable each potential technological disruption to be seen from different perspectives and therefore analysed comprehensively and in a very concrete manner"*.

The members of the Naval Group Scientific Council:

- Joël Bertrand, Research director at CNRS, France
- Sophie Bretesché, Assistant academic director, IMT Atlantique, France
- Elisabeth Crépon, Head of ENSTA ParisTech, France
- Armel de La Bourdonnaye, Chancellor of the Academy of Poitiers, France
- Jean-Luc Fihey, Professor at École des Technologies Supérieures de Montreal, Canada
- Hubert Girault, Professor at École Polytechnique Fédérale de Lausanne, Switzerland
- Saadi Lahlou, Professor at the London School of Economics and Political Science, United Kingdom
- Thierry Massard, Adviser to the high commissioner, the Alternative Energies and Atomic Energy Commission, France
- Jean-François Minster, Member of Académie des Technologies, France
- Maria Nadia Postorino, Professor at the Mediterranean University of Reggio Calabria, Italy
- Jean-Marie Tarascon, Professor at Collège de France, France
- Olivier Rey, Research director at CNRS, France
- Dominique Vernay, Member of Académie des Technologies, France

*CNRS (Centre national de la recherche scientifique): National Center for Scientific Research.

"S&T LIES AT THE HEART OF OUR OVERALL INNOVATION STRATEGY"

Naval Group relies on its technological innovation activity to meet the expectations of its customers. This activity comprises two aspects. S&T (Science and Technology), on the one hand, places emphasis on upstream research. R&D (Research and Development), on the other hand, focuses more on existing products, processes and services, or those yet to be invented. How do these components interact? What is the added value? Analysis with Éric Papin, Technical Director of Naval Group and Vincent Geiger, Director of Naval Research.

What are the goals of Naval Group's overall innovation strategy?

Éric Papin: The aim is to allow French and foreign navies to gain combat superiority in terms of information management, engagement capability and availability at sea. Naval Group needs also boosting its ability to compete in an increasingly competitive market. Our technological strategic plan is thus broken down into major innovation challenges, with differing timescales: the development of new products, processes or services in the short term; contribution to new technologies in the medium term; and for the more distant future, assessment of the major trends in the naval field for the 2050 time-frame and the development of air-sea systems over that period.

How can these ambitions be given tangible form?

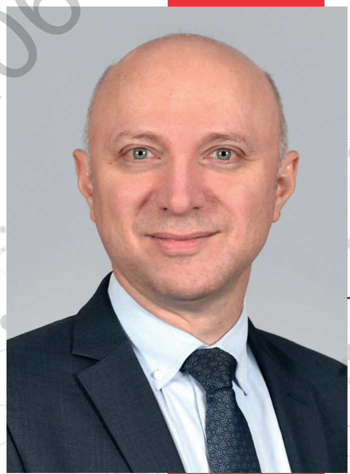
Éric Papin: We group them under six leading projects: "Smart Naval Force", the aim of which is to develop the operational capabilities of ships working collaboratively with each other and with drones, aircraft, etc.; "Invulnerable Ship", which aims to improve the stealth of ships, their engagement capability and their ability to withstand maritime or military attacks; "Smart Energy", focused on the electrification of systems and more sparing and efficient use of energy resources; "Smart Availability", devoted to improving availability at sea (robustness, predictive maintenance, remote assistance, etc.); "Smart Ship", which aims to develop digital, connected ships and finally, "Smart Industry", the aim of which is to facilitate the work of the design offices, workshops and shipyards in building these increasingly complex ships, managing their configuration and guaranteeing their cybersecurity
Each of these leading projects comprises fifty or so scientific and technological roadmaps, with an upstream research component (S&T) and an innovation-oriented component (R&D). Each project resulting from these roadmaps is linked to a precise time-scale and entrusted to a manager. This approach gives us an accurate view of how ongoing and future projects interconnect and complement each other. For example, artificial intelligence is growing rapidly: it is at the heart of numerous projects and concerns several of these leading projects.

"The Naval Group technological strategic plan is broken down into major innovation challenges, with differing timescales."

Éric Papin, Technical Director of Naval Group

HUMAN & SYSTEM: A NEW FIELD OF INVESTIGATION FOR AI

As Vincent Geiger explains, "*Artificial Intelligence will boost the capabilities of tomorrow's ships, in terms of usability or even maintainability. So that AI can reach these goals and help crews in their various missions and tasks, it must be designed taking into account of the characteristics of the user ('Human Factors', or HF). The HF issues relating to AI are focused on utility, usability and acceptability, such as the distribution of functions between Human and System, the choice of levels of autonomy, situational awareness aids, confidence in the automation results, etc. In addition, the data resulting from HF studies may also draw on AI for monitoring the cognitive status of the operator and the adaptive human-machine interfaces for example. Finally, HF studies can also provide AI with valuable information about the simulation and/or an understanding of how the operator works. The ties between these two domains are thus increasingly close and require joint S&T studies. The future 'hybrid teams' will consist of humans and autonomous systems helping to improve on-board comfort and crew and ship performance. It then becomes necessary to develop technical solutions fostering these new forms of collaboration between the digital entities and the crews.*"



Éric PAPIN

Vincent GEIGER

What are the benefits of upstream research for an industrial group such as Naval Group?

Vincent Geiger: Our S&T activity is preparing for the future! Far upstream in the process, it consists in identifying solutions, processes, methods and means, which offer high value-added innovation potential for our customers, both in-house and external. S&T also contributes to continuously improving the overall technical knowledge relating to the naval sector, whether in terms of optimising products, enhancing expertise in construction processes or reducing the arduousness of the work in production. The S&T activity complements R&D even though its process is completely different – in terms of investment level, risk-taking, time-scale, types of skills, type of collaboration ecosystem, confidentiality constraints, funding sources, etc. We are now focusing on the overall interconnection of R&D and S&T subjects and relationships and to do this, we are deploying an appropriate governance.

Éric Papin: Our goal today is to link S&T to R&D and to our leading projects. This is a crucial step in structuring, in which Vincent Geiger, as Director of Naval Research, plays a key role along with the support of scientific managers. Together, they will be defining a vision for S&T, consistent with that of our leading projects.

NUMERICAL SIMULATION OF WELDING: A RESEARCH PROGRAMME WITH NUMEROUS APPLICATIONS

From 2014 to 2018, Naval Group carried out collaborative work involving in-house experts and academic partners, including Bretagne Sud University. To what end? To apply numerical methods to model physical phenomena in order to predict and mitigate the thermal, mechanical and metallurgical consequences of welding.

"It would be an illusion to confirm and even to prove that a perfect weld has been obtained if, during the course of the work, the metal has been altered to such an extent that it loses the main qualities being sought."

In 1894, Jean Jules Laffitte, the inventor of the welding plate, was already well aware of the complexity of a process, on which knowledge and practices have considerably progressed for more than 100 years, in all industrial sectors.

At Naval Group, the welding activity attracts exceptional technical talent and know-how on all the manufacturing and through-life maintenance sites. Welding requires extreme attention to detail and it is furthermore a multi-physical operation incorporating thermal, hydraulic, metallurgical and mechanical processes. *"A submarine represents about a million parts and several kilometres of welds"* explains Florent Bridier, engineer at the Naval Group research centre in Nantes. *"Even if the group has expertise in various welding techniques, via numerous qualification procedures, the impact of welding on the mechanical and thermal behaviour of the assembled parts remains a subject on which continued work is needed."*

A VIRTUAL WELDING TOOL TO BE DEVELOPED

In 2014, Naval Group suggested to this materials scientist that a new area of research be initiated around the numerical simulation of welding. The purpose was to model physical phenomena in order to predict and mitigate the thermal, mechanical and metallurgical consequences of welding. In short, to develop a virtual welding tool to address the needs of various teams within Naval Group, from design office to shipyard, regarding welding techniques.

The first months of work were devoted to identifying the problems encountered, both by the engineers in charge of designing some parts and by the production teams in charge of welding them, or those devoted to through-life support of ships and submarines. When should a vacuum chamber be opened after an electron beam welding operation, without weakening titanium parts? Can machining of openings in hull sections be finalised before being welded? How to optimise the design of a ship element so as to limit the stresses induced during welding? *"The problems submitted to me can vary widely. There are concrete or simple cases to which an answer may be given in a few days, as well as complex questions which are more likely to require research studies or expert assessment"* observes Florent Bridier. *"So numerical simulation may require more development work and time before performing a first calculation."*

PREDICTING, ESTIMATING AND LOCATING RESIDUAL DEFORMATION

During a welding operation, the metal parts to be assembled undergo a significant rise in temperature. Welding involves melting matter at the interface between these parts. One of the consequences is that the microstructure of the material around the weld bead is liable to be modified. Crystalline rearrangements (or "phase changes") occur, entailing a change in the physical properties of the material. Furthermore, a double mechanical effect takes place when the weld cools, because it then pulls on the material. First of all, the structure deforms, just like a sheet of paper to which a bead of glue is applied. *"Numerical simulation of welding can predict these residual deformations, locate them and estimate them quantitatively"* explains Florent Bridier.

The deformation of a welded part can reach several tens of millimetres and the consequences are more than just aesthetic. Because this reduces the mechanical strength of the parts, industry is seeking to reduce it by means of various heat and mechanical treatments. This work to "straighten" parts after welding takes time and leads to extra costs. *"One of the goals of simulation is to be able, with the on-site welding specialists, to validate solutions which will minimise the residual deformations associated with this process"* continues Florent Bridier. *"Controlling these deformations means reducing the time spent on straightening the welded structure."*

"One of the challenges of numerical simulation of welding is to validate, with the experts of this process, technical solutions which will improve its quality."

Florent Bridier, materials science expert

A TRADE-OFF BETWEEN PRECISION AND COMPUTING TIME

Welding leads to a second mechanical effect: heat, shrinkage, phase changes will generate residual stresses in the welded part. *"The stiffened panels of surface ships, the hull sections of submarines, or the internal structures of nuclear propulsion reactors are all subjected to high loads and the residual stresses after welding add-up to theses service stresses. Predicting the residual stresses via simulation can help to guide or even optimise how mechanically welded parts are manufactured or designed. Minimising the residual stresses associated with welding could possibly permit a higher service loading to be authorised"*. From 2014 to 2018, a collaborative research program involving different Naval Group teams was thus set up on the subject of numerical simulation of welding. *"Various research projects, performed in collaboration with Naval Group experts within the technical network called 'Implementation of metal materials' and with its academic partners, such as Bretagne Sud University, contributed to expanding the applications of numerical simulation of welding"* states Florent Bridier. Do we want to accurately represent the coupling between all the thermal, mechanical and metallurgical phenomena with a long response time? Or, on the contrary, are we looking to identify trends, thus making it possible to model a large number of welding operations? (see interview of Christophe Le Pellec). Depending on the problem at hand and the industrial context, a trade-off between the precision of calculation and the computing resources for a simulation needs to be found. The working group thus developed three numerical methods liable to meet the needs of the shipyards and the design offices (see box on computing methods). On-site, the welding specialists have been able to assess the relevance and reliability of simulation by correlating the numerical results with measurements on welded mock-ups.

THREE QUESTIONS FOR CHRISTOPHE LE PELLEC, ENGINEER AND WELDING COORDINATOR, LORIENT SITE, NAVAL GROUP

In 2014-2016, you carried out an R&D project in collaboration with Naval Research teams on numerical simulation of welding. What were you looking for?

We started from an observation: the hull panel straightening phases did not totally eliminate the deformations produced by the welding operations and this prejudiced the perceived quality of our ships. When a ship is delivered to a customer, the visual impact is important. Our company image is at stake. We were therefore looking for technical solutions to minimise the residual deformations as much as possible. We more particularly wished to test a difference sequence for the welding operations. To evaluate the effects of this, we used numerical simulation.

What were the conclusions of this study?

Numerical simulation of welding first of all confirmed that it was a good idea to change the order of the welding operations on our panels. Each panel consists of assembled plates and a grid of stiffeners. Instead of fitting the entire grid of stiffeners and then weld it, we proposed first of all to tension the panel, then apply the first set of stiffeners, weld and then fit the second, perpendicular set of stiffeners. Simulation provided quantitative proof that this second method reduced deformations, thus confirming our observations in the shipyard. Numerical simulation of welding also confirmed that it was preferable to weld the first set simultaneously on either side of the stiffener, using an automatic welding carriage, a technique that had not previously been used at Naval Group Lorient.

New prospects for collaboration?

After recent collaboration in welding the stiffeners themselves, we have just launched a new area of research with the teams at Naval Research, this time on flanged welding. Here, we are looking at the assembly phase for the parts making up the hull. During welding, can we limit deformation by mechanically constraining these parts? In short, what happens if we prevent the structure of a ship from moving during assembly of the hull? We are hoping that welding simulation will indicate the level of residual stresses generated in the rings. An excessive level could lead to problems of cracking, something that we naturally wish to avoid. Numerical simulation of welding is a cheaper alternative to certain tests on mock-ups or actual parts and also helps us save valuable time.

CONFIRMING INTUITION

They are without doubt the most complex technical objects currently being designed. The third-generation nuclear ballistic missile submarines – or SNLE 3G – scheduled for launch by 2032, have been occupying hundreds of engineers at Naval Group for several months. On the Indret site, they are designing the large components of the future on-board nuclear propulsion reactor. This precise part of the detailed preliminary project relies on data obtained with numerical simulation of welding. *"In the design phase, we proposed thinner sidewalls of the channel heads of the reactor internal structures, in order to reduce the residual welding-induced mechanical stresses in the front plate"* remarks Maxime Schwartz, in charge of the design of reactor internal structures. *"It was an engineer's hunch. The welding simulation carried out over a few weeks at Naval Research, confirmed our intuition. This computation conducted well upstream enabled us to optimise the design."*

FROM RESEARCH TO TRANSFER OF SKILLS

"Whether or not coupled with this on-site experimental approach, simulation is above all a means of rationalising and assessing our practices" highlights Maxime Schwartz, engineer in charge of the design of the reactor ships for the future third-generation ballistic missile submarines (SNLE-3G). He works at Nantes-Indret, a site specialising in propulsion, and designs elements to be installed in the nuclear power plant carried on-board submarines. *"Do we create a single bulk part or several parts to be welded together? What should the thickness be? And the geometry? These are all questions to be answered, given that we design our nuclear power plants for forty years of service"* explains Maxime Schwartz. This design aspect also draws on progress made in numerical simulation (see box "Confirming intuition").

At the Nantes research centre, the time has come for skills transfer. After five years of R&D, a rather short period of time for such a complex issue, welding numerical simulation is today being deployed around a new roadmap. The goal will eventually be to qualify the personnel who will be handling the numerical tool on Naval Group sites. *"The implementation of welding numerical simulation by the teams at Indret, Lorient, Cherbourg, Ruelle, Brest and Toulon requires the drafting of professional guidelines, with general and practical on-site training sessions"* states Florent Bridier.

In parallel with the programme already launched for welding, another one is opening up with the development of additive manufacturing. A new way of manufacturing, possibly more economical in terms of material and time. *"For large sized parts, Naval Group is looking at an additive manufacturing technique which is comparable to welding, involving hundreds, even thousands of welding passes"* explains Florent Bridier. To support the development of these techniques, a research programme is already under way to allow the simulation of the multi-physical effects of additive manufacturing.

COMPUTING METHODS: FROM LOCAL TO GLOBAL

Numerical simulation of welding must adapt to industrial applications. When the aim is to repair a ship in service, the teams need an answer in just a few hours. For upstream design of parts, a longer calculation of several days or even weeks is acceptable. This is why three computing methods were used and evaluated at the Naval Group research centre in Nantes.

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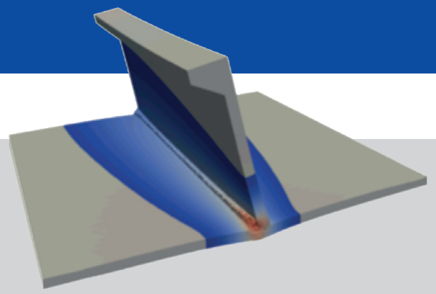
1

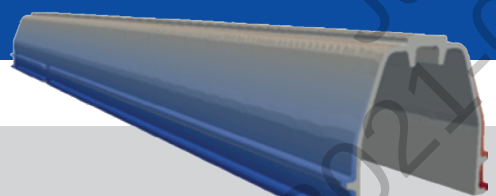
The first, which consumes large amounts of computing time, takes account of all the components of the physical problem, covering the various thermal, mechanical and metallurgical couplings. The behaviour of the material can thus be predicted, notably the residual deformations and stresses, on just a few centimetres of weld bead. *"The physical problem is a complex one: to model the phenomena in detail, one must restrict oneself to an extremely local scale"* explains Florent Bridier.



Calculation of the deformation of a fillet weld joint during welding is obtained with the so-called "transient thermo-mechanical modelling": simulation can, for example, predict the temperature field in the joint (values between 20°C in blue and 2500°C in red).

2

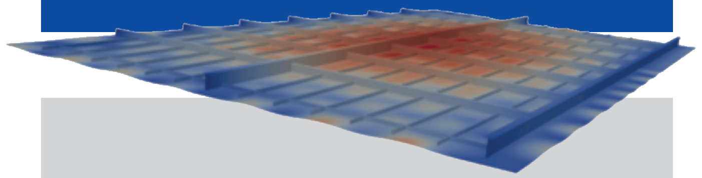
The second method, known as "local-global" is designed for long parts, with few welds. Its principle is based on a local calculation (previous method), which is then projected over the entire length of the part, *"by assuming that the irreversible deformations resulting from welding simulated over a few tens of centimetres are representative of what happens over the entire length."*



For this large welded structure, the computation uses the so-called "local-global" method and can in particular estimate the displacement field (values between -20 mm in blue and +20 mm in red).

3

A third method is used for parts requiring a lot of welds, such as a surface ship deck with numerous stiffeners. This technique, referred to as the "inherent strain method", is built around the use of a database, generated either numerically or on experimental mock-ups in the shipyard, and gathering information on shrinkages induced by welding. The latter are then applied by finite elements to each weld bead. The resulting elastic linear calculation predicts the final deformation of the part in a very short period of time.



The so-called "inherent strain method" can be used to perform computations on more complex parts, such as this portion of a surface ship deck, where several tens of welds are modelled. The computation for example gives access to the out-of-plane displacement that is in the direction perpendicular to the deck (values between 0 mm in blue and 50 mm in red).

02

THEY DO SCIENCE AT NAVAL GROUP

A PH.D. STUDENT TELLS ALL

I HAD THE CHANCE TO DO MY THESIS IN A UNIQUE CONTEXT, WITH UNIQUE EXPERIMENTAL MEANS

Émeline ARNAUD

After completing her engineering diploma at ENSTA Bretagne, Émeline Arnaud joined Naval Group to pursue her Ph.D. thesis in materials science, under the dual supervision of a university tutor – Damien Halm, from ENSMA Poitiers – and an industrial tutor, Julien Beaudet from Naval Group in Nantes. She looks back at a rewarding experience which she could not have imagined at the start of her studies.

How did you find yourself doing a thesis after obtaining your engineer's diploma?

I took a year off after my second year of studies, during which I joined a research laboratory at Southampton University in Great Britain. This experience was fascinating for me and I discovered new ways of working. After obtaining my naval architecture engineering diploma, I could indeed have started my career straight away.
It so happened that Naval Group, an industrial player well known to the students at ENSTA Bretagne*, was offering this research program which appealed to me with the combination of experimentation and numerical aspects. I wanted to delve deeper into understanding complex physical mechanisms and my experience in Southampton had given me a taste for research.

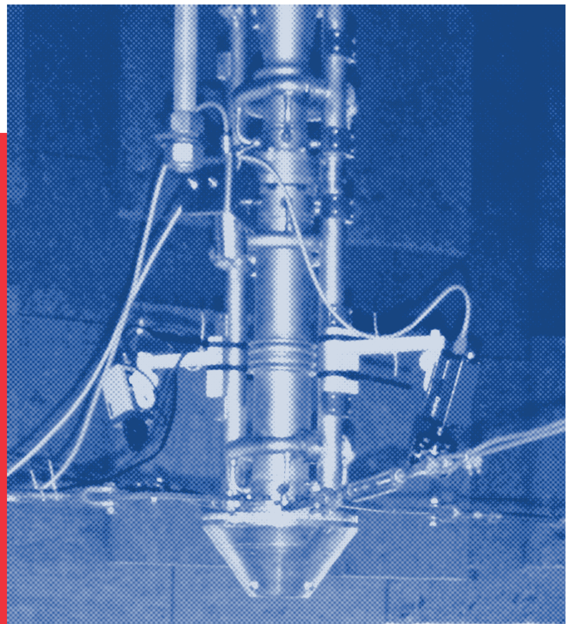
Over and above the research aspect, why did you join Naval Group?

I could not miss this opportunity to access exceptional test facilities, further my studies, and carry out scientific work with tutors who I immediately took to during our initial interviews! I already knew that I didn't want to pursue an academic career, but this project, partly funded by ANRT* through the CIFRE* programme, was led under dual supervision: that of Julien Beaudet, from the Naval Group research centre in Nantes and that of Damien Halm, from a university research laboratory at ENSMA* in Poitiers. This enabled me to maintain contact with industry while developing my knowledge of the materials used in naval construction.

* ENSTA Bretagne (École nationale supérieure de techniques avancées de Bretagne): Brittany National School for Advanced Techniques.
** ENSMA (École nationale supérieure de mécanique et d'aérotechnique) : National Mechanical and Aerotechnical School.
*** ANRT (Association nationale de la recherche et de la technologie) : National Association for Research and Technology.
**** In France, the so-called "CIFRE programme" supports Ph.D. students to pursue doctoral studies within industrial compagnies, in collaboration with universities.

Looking back, now that you have defended your thesis, would you do the same again?

Without hesitation, yes! Professionally, this thesis has taught me a lot in terms of scientific rigorousness and putting results into perspective. It has incited me to ask the right questions and I've met some wonderful people, on both a human and scientific level! I did the right thing in grasping this opportunity to work for three years in a unique context, with rare experimental facilities. I was trusted and allowed to explore my own avenues. Working in this way, interacting with numerous supervisors and technicians, in two different contexts, was highly beneficial for me. My results will also be of practical interest to Naval Group, which had real industrial expectations with regard to the materials I studied, in order to validate solutions ready to be used in real applications. That also is a source of satisfaction.



The MARTEL test bench (aero-acoustic research and technology facility for launcher environments) is a unique experimental facility in Europe. It was developed by the Centre National d'Études Spatiales for the design work on Ariane launchers and can be used in the "ablation" configuration for the purposes of our study. The combustion of liquid oxygen and hydrogen is able to achieve heat flows with a temperature of close to 1900°C at a velocity of about Mach 3. The heat protection plates are directly exposed below the torch and sensors monitor the degradation for a given exposure time.

MY RESEARCH IN A FEW WORDS...

Ablative thermal protection systems are commonly used in the aerospace industry. They are generally made of composite materials which isolate elements subject to severe aerothermal flows, while themselves degrading.

One of the challenges is to more clearly understand the influence of the composition (matrix, reinforcement and porosity) of these materials on their thermal behaviour and their ablation resistance. I therefore experimentally tested sixty or so different materials and then supplemented this study by developing a numerical model.

The experimental characterisation explored the behaviour of the materials at three different scales:

- the thermochemical behaviour was characterised by thermogravimetric analysis (TGA), thermomechanical analysis (TMA) and differential scanning calorimetry (DSC);
- the thermal behaviour was evaluated using a bench fitted with an oxy-acetylene torch;
- the resistance of the materials to a severe aerothermal jet was tested on the MARTEL test bench, equipped with a mini-booster for testing samples several tens of centimetres wide and studying the combined thermal and aerodynamic impact.

With these tests and the specific engineer's numerical model that I developed to simulate ablation, I was able to reveal the links between the thermophysical properties and ablation resistance of a composite material and then propose degradation scenarios for each of the materials.

TAKE THE WORD OF AN EXPERT

THE TECHNOLOGICAL BUILDING BLOCKS LINKED TO ENERGY AND POWER CONVERSION ARE UNDERGOING PROFOUND CHANGES

Arezki BOUZOURÈNE

After starting out as a technical analysis expert, Arezki Bouzourène joined Naval Group in 2017. What is his role? Creating the Expertise and Management Centre for ship on-board energies and power (CEMEP), a field that is undergoing profound changes.

Tell us about your career before joining Naval Group

After a Ph.D. in electrical engineering, with a specialization in power electronics, I began my career in field expert analysis work. My role was to identify and analyse the causes of printed circuit boards failures during production. I then took part in R&D studies to develop new concepts for electric vehicles at the equipment manufacturer Valeo. I continued my career at the Thales group, where I held several positions and technical responsibilities – product manager, technical leader, technologist, technical coordinator for transverse projects, expert. In 2013, my position as group technical expert enabled me to work outside aeronautical applications, notably on Thales Underwater Systems products, intended for naval defence. In 2017, I joined Naval Group to develop a new expertise and technological research department at Naval Research, the CEMEP (see box). This department provides a response to a real need for skills, both to provide technical support for the teams involved in the ongoing programmes, as well as for research into advanced technologies and their integration into future generations of ships.

Could you describe the role of energy management in the naval field?

In today's ships, the energies used for propulsion are electrical, thermal and mechanical, requiring complex management of the various power streams. The new trend is for increasingly widespread electrification, thus simplifying the ship's energy architecture. This leads to flexible and optimised management, facilitating the integration of new sources and new consumers. Energy control via optimised management will help guarantee that the ship performs its missions, while offering superiority at sea.

What are the current prospects?

The technological building blocks for energy and power conversion are undergoing profound changes. Among the technologies identified as promising, yet disruptive for applications such as conventional submarines, solid electrolyte lithium batteries would have several advantages. They are non-flammable. Their charge density is five times that of a conventional lithium-ion battery, and they recharge faster. There are still a number of obstacles to be overcome before using this technology, which is currently at the R&D stage. However, its emergence onto the energy storage market could take place as early as 2025, thanks to the large-scale development investments made by the world's manufacturers. The CEMEP is supporting the management and integration of such emerging technologies. It relies on an intelligence watch and forward-looking studies of developments in power electronics, protection and management systems. It thus provides a strategic view of the increasing pace of change in battery systems, as compared with ship developments for which the time frame is far longer. This approach aims to adapt cutting-edge technologies to the naval field, through a process of incremental integration and opens the door to optimised use of energy sources and the development of smart grids.

THE CEMEP: INTEGRATING THE ENERGIES OF TOMORROW

The Expertise and Management Centre for ship on-board energies and power (CEMEP) was created in 2018. This new department at Naval Research focuses specifically on technologies linked to energy and the corresponding electronics, as well as on the simulation of electrical architectures adopting these new technologies. The CEMEP thus expands the fields of competence of the Naval Group's Technological & Innovation Direction (DIT), with a number of complementary roles:

- **IDENTIFYING** and evaluating emerging technologies to study the consequences of their integration into the electrical architectures of existing or future Naval Group products
- **PROVIDING** the project teams with technical and expert support
- **DEMONSTRATING** through prototyping, the performance of disruptive technologies for ships already designed or future ships
- **MONITORING** technological developments and drafting technological roadmaps

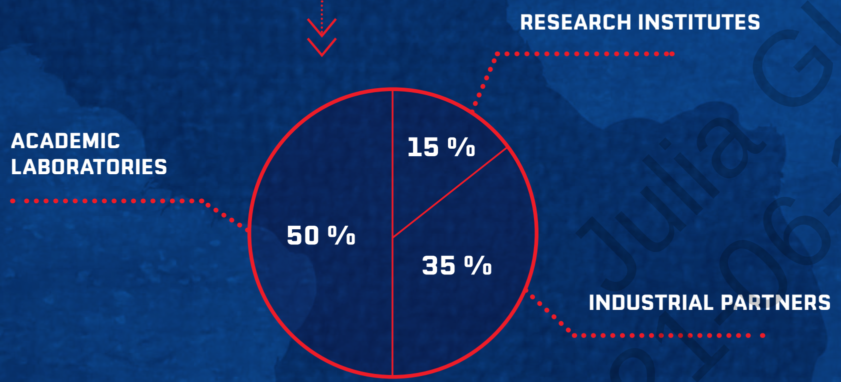
SCIENCE & TECHNOLOGY (S&T)

KEY-FIGURES

- **10** JOINT LABORATORIES AND UNIVERSITY CHAIRS
- **40** PATENTS/YEAR
- **117** PATENT FAMILY
- **50** PUBLICATIONS IN SCIENTIFIC JOURNALS AND COMMUNICATIONS IN CONFERENCES
- **30** PH.D. STUDENTS/YEAR

COLLABORATIVE PROJECTS

- **60** IN FRANCE
- **10** IN EUROPE
- **15** WORLDWIDE



SCIENTIFIC FIELDS

The S&T (Science & Technology) themes are organised into eight fields. *"If we are to be understood by our academic partners in France and abroad, it is important to present our activities transversely and scientifically"* explains Pierre Dallot, S&T manager. This approach has another advantage: *"It enables us to better anticipate the development of technologies which will add value to the next generations of ships."*

1. GLOBAL NUMERICAL MODELS
2. HUMANS AND SYSTEMS
3. NUMERICAL SYSTEMS
4. DATA PROCESSING
5. ENERGY
6. MATERIALS AND STRUCTURES
7. WAVES/MATTER INTERACTIONS
8. FLUID MECHANICS

TOWARD AN INTERNATIONAL SCIENTIFIC OUTREACH

FORMS OF COOPERATION

- LOCAL DEVELOPMENT OF NAVAL GROUP RESEARCH
- BILATERAL COLLABORATIVE RESEARCH STUDIES
- PARTICIPATION IN MULTILATERAL COOPERATION PROGRAMS
- MEMBERSHIP OF LOCAL INSTITUTIONS FOR COLLABORATIVE RESEARCH
- STAFF EXCHANGE
- INVOLVEMENT IN LOCAL EDUCATIONAL AND TRAINING PROGRAMS
- INVOLVEMENT IN FRENCH EDUCATIONAL AND TRAINING PROGRAMS SUPPORTED BY NAVAL GROUP

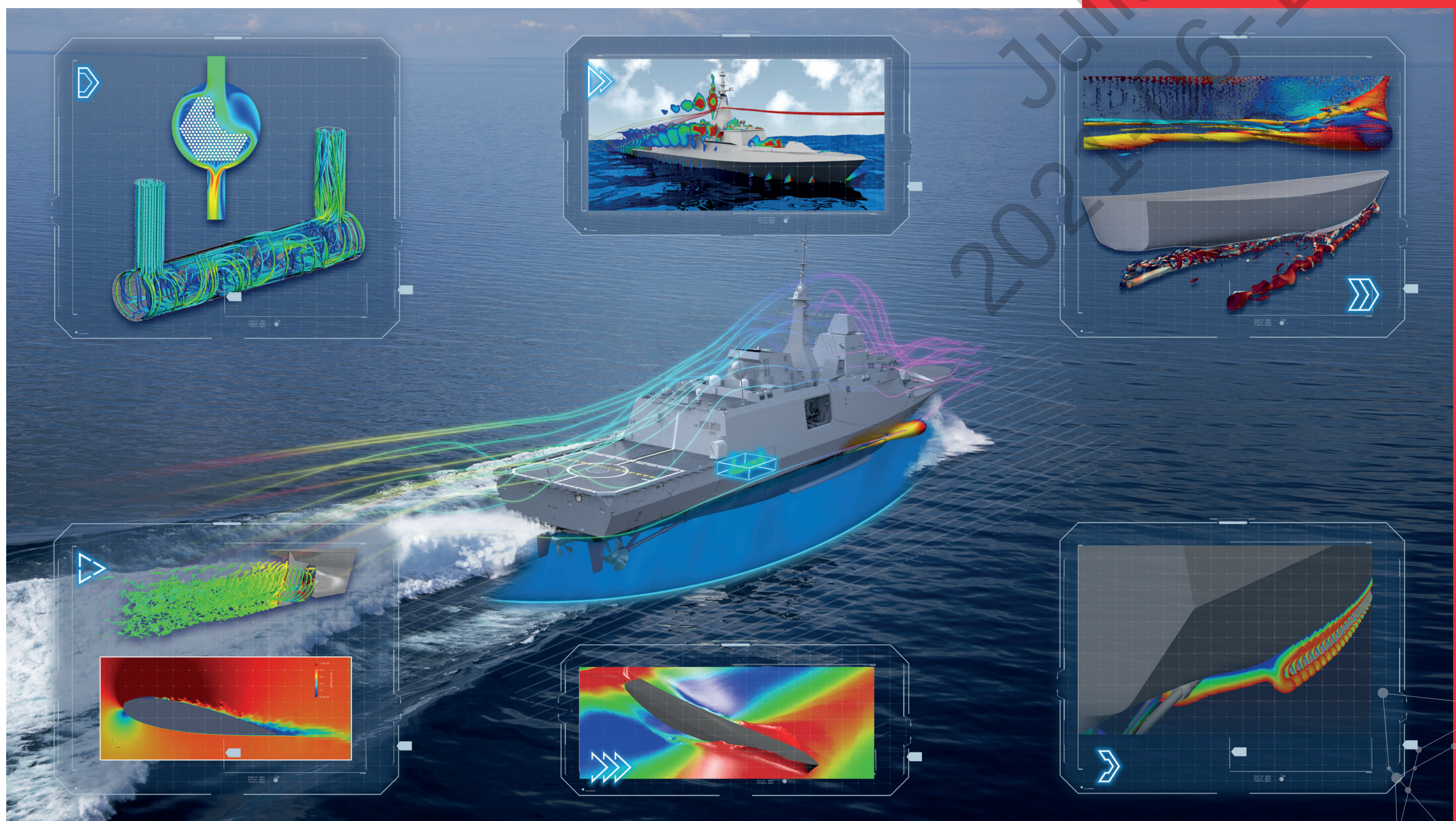
"Innovation lies at the heart of Naval Group's development strategy and international cooperation is an essential lever in innovation" explain Béatrice Adam and Florence de Launet, Heads of partnerships. The group is thus involved in various forms of cooperation, such as joint research projects – to initiate or reinforce academic collaboration – or the creation of research laboratories abroad – to draw on the fields of excellence in the country.

CENTRES OF EXCELLENCE ABROAD

At the beginning of 2020, Naval Group will have a Centre of Excellence in Australia – before others which will be opening in Singapore, Belgium and India. This Australian centre, which will be located on a technocampus called OzCean, brings together 16 local partners: nine universities, three Australian states and key-player companies. On this same technocampus, Naval Group is developing another project, in cooperation with CNRS and three Adelaide universities: *"This new research centre will carry the prestigious title of a CNRS International Research Laboratory"* states François Duthoit, Head of collaborations at the Technological & Innovation Direction. *"OzCean will be a structure dedicated to cooperation; other partners will join it, such as the ETIs or the Australian Ministry of Defence"*. The programme of research projects includes: AI, drones, human factors, factory of the future and materials science.

03

FLUID MECHANICS



MODELLING PRESSURE FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS

Reducing the empirical aspect of turbulent hydrodynamic loading calculations (commonly referred to as "vibro-acoustics"): this is the ambition of the researchers at Naval Group and the University of Aix-Marseille, who have designed a model suitable for a wide variety of situations. This model combines versatility and precision, while keeping down computational costs.

The phenomenon of flow turbulence can be encountered in nature, in numerous industrial processes and in naval hydrodynamics. Turbulent flows can induce vibrations of hulls or hull appendages.

When turbulence develops, vortices of different scales are produced by the fluid shear which takes place close to the wall. These cause the pressure fluctuations responsible for vibrations, which then become potential sources of ship acoustic indiscretions...

CALCULATING TURBULENT PRESSURE SPECTRA

In order to quantify these vibration levels, engineers and researchers need to know the "turbulent pressure spectra" which characterise the hydrodynamic loading. They have empirical models at their disposal. These spectra are easily calculated but nonetheless remain limited to simple configurations which are sometimes remote from the reality of the ships and the conditions they encounter at sea.

In order to obtain more precise data, it is theoretically possible to calculate the pressure spectra using fluid mechanics equations – the so-called "Navier Stokes equations" – by means of various methods. "Direct Numerical Simulation" (or DNS) consists in calculating all the turbulence scales and their interactions: this is a method that requires important computational resources and is at present limited to simple problems. "Large Eddy Simulations" (or LES) consist in calculating only the most significant turbulent structures in the flow. These methods produce a large quantity of data, although processing them to calculate spectra remains complex. "Reynolds Averaged Navier-Stokes" (or RANS) simulations are based on a local and statistical description of turbulence that reproduces the values taken by fluid pressure and/or velocity over a period of time. They use turbulence models and are currently the most efficient for complex geometries.

AN ANISOTROPIC MODEL

Naval Group engineers have chosen to develop an intermediate numerical approach to the turbulent spectrum, which combines RANS calculations and data obtained from DNS simulations. They thus developed a model capable of predicting the turbulent pressure loading in a wide variety of situations, and at low computing cost. *"The aim is to reduce the empirical part of evaluating the turbulent pressure spectra used in industry, while broadening their scope of application to curved structures"* explains Cédric Leblond, fluid mechanics expert.
This model was developed under a collaboration with the M2P2 (Mechanics, Modelling and Clean Processes) laboratory at the University of Aix-Marseille, thanks to work of Myriam Slama during her Ph.D. researches with Naval Group. The proposed "anisotropic model" calculates the pressure spectrum

> "Processing data from high resolution flow simulations enabled us to calculate turbulent pressure spectrum with greater accuracy."
>
> *Cédric Leblond, fluid mechanics expert*

A TURBULENT PRESSURE SPECTRUM MODEL

In order to calculate vibrations of hulls or hull appendages excited by turbulent flows, the engineers and researchers at Naval Group use "turbulent pressure spectra" which represent the fluctuations of hydrodynamic loading. A new spectrum model is based on the following equation:

$$\frac{1}{\rho^2}p(\xi,t)p(\eta,t+\tau)$$

$$= -\int_\Omega\int_\Omega\left(4\frac{\partial U_i}{\partial x_j}(x)\frac{\partial V_k}{\partial y_l}(y)\overline{u_i(x,t)v_l(y,t+\tau)}\frac{\partial G}{\partial x_i}(\xi,x)\frac{\partial G}{\partial y_k}(\eta,y)\right.$$

$$\left.+\,2\overline{u_i(x,t)v_k(y,t+\tau)}\cdot\overline{u_j(x,t)v_l(y,t+\tau)}\frac{\partial^2 G}{\partial x_i\partial x_j}(\xi,x)\frac{\partial^2 G}{\partial y_k\partial y_l}(\eta,y)\right)dx$$

It shows that the spectrum can be calculated using three types of data:

- the first, in red, are the so-called "Reynolds stresses". They represent the overall physical characteristics of the turbulent flow and they are obtained using RANS simulation;
- the second, in green, are exact. They describe how the fluid propagates the pressure from one point of the flow to another;
- the third, in blue, are the estimated averages describing the "turbulent velocity correlation". They represent how the flow varies in the turbulent boundary layer and model the fluid velocity fluctuations over time and in space. The research carried out at Naval Group concerned a new method of calculating them. "*The parameters of the model are calibrated on published DNS calculation results*" explains Cédric Leblond. "*This approach enables us to significantly improve the precision of our simulations.*"

for a turbulent boundary layer at high Reynolds numbers, and for non-nil pressure gradient flows: it is thus more general than the models used hitherto at Naval Group.

This work, aimed at producing applications, thus addresses two constraints: firstly, the methodology proposed must be appropriate for use in a design office; next, the calculation results must be obtained in no more than a few days – rather than in several months as would be the case with LES simulations. *"Developing a technique with a reasonable computing time for the engineers was an integral part of this thesis"* states Cédric Leblond.

REDUCING COMPUTATIONAL TIMES

The research carried out met this requirement while investigating three directions. The first, theoretical, was able to propose a new space-time correlation model for turbulent velocities. Referred to as "Kriging-based Elliptic Extended Anisotropic Model (KEEAM)", it is an extension of a model available in the scientific literature. Its advantage: to enable these correlations to be evaluated in all regions of the turbulent boundary layer, whereas the initial model is only valid for the outer part of the boundary layer. *"Myriam Slama proposed turbulent velocity correlation models, which she calibrated using data produced by DNS simulations published by researchers"* adds Cédric Leblond. *"It is the processing of these data which enabled us to design more reliable models."*

The second direction of the work is algorithmic. It consisted in developing a numerical method that is as fast as possible, by means of various methods – such as a technique for re-sampling the computational grids, combined with an estimator of the simulation error.

For Cédric Leblond, *"the combination of all these algorithms enabled us to shorten the computational costs needed to resolve the model we used in the simulations. The latter is based on the Poisson equation, derived from the Navier-Stokes equation for turbulent pressure, and a large part of the work done by Myriam concerned these algorithm developments."*

ANOTHER BRICK IN THE COMPUTING WALL

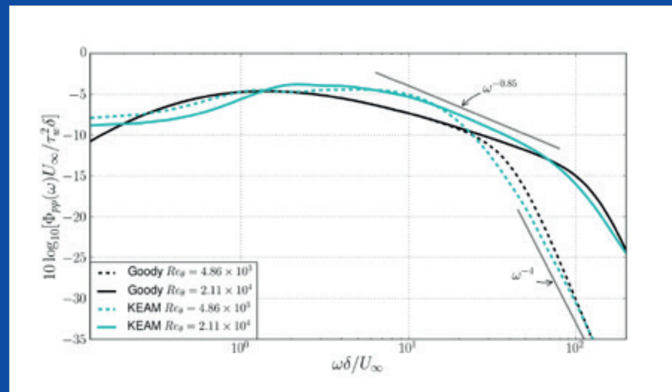
The third direction of this research is IT: the aim is to develop an upgradable software based on the previous theoretical and algorithmic developments and usable by engineers and experts at Naval Group. *"End-to-end development of a computer code now allows us to perform simulations for real configurations of hydrodynamic flows. The code we developed was the 'brick' that had so far been missing in our numerical toolbox."*

The proposed model in fact enables Naval Group's engineers to calculate more precise velocity correlation coefficients. The main benefit is greater precision along the entire computational chain, up to the definition of turbulent wall pressures. The latter will be of use for "vibro-acoustic" calculations which could then be performed by Naval Group's experts for a variety of applications, contributing to improve the prediction of acoustic signatures and to investigate solutions to reduce them.

NAVAL GROUP'S KEEAM MODEL

The figure below represents the turbulent pressure spectra corresponding to two simple configurations (a flow of water on a flat wall at two different velocities). The values are represented in conventional form, well-known to experts in the field. The spectra calculated with the method developed by Naval Group are represented by green lines; the spectra determined with an empirical model, by black lines.

The figure shows that the two types of spectra are very close, thus validating the new method. It can be used by the engineers to calculate pressure spectra for real configurations, whereas the empirical spectra are only valid in specific situations.



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HOW TO SIMULATE FLUID FLOWS? THE KEY ROLE OF CFD

Naval Group engineers use numerical methods to study the behaviour of ships and submarines. What is at stake? Increased performance, increased safety of certain operations and increased competitiveness. There are many calculation methods with a variety of uses, as illustrated by a few examples analysed by hydrodynamics experts.

Launching torpedoes is one of the most important missions of a submarine. Ensuring safe launches and determining the launching domain require trials at sea, which often prove to be costly and complex to conduct. The numerical approach offers an interesting alternative, which Naval Group engineers and researchers have already been using for a decade.
These new numerical methods thus help predict the behaviour of submarine weapons and evaluate the best operational window for torpedo launches. In addition to this use, simulations help determine various aspects of a ship's hydrodynamic performance, such as dynamic stability, the radius of gyration and the trim control of a submarine.
Fabian Pécot, modelling engineer (fluid mechanics at Sirehna), Thierry Taillefet, modelling expert (fluid mechanics at Naval Group Ruelle) and Alain Nédellec, hydrodynamics expert (Naval Group Lorient) tell us about the numerical methods used – methods based on a computational fluid mechanics (CFD) code and its advanced meshing functions.

What fluid mechanics simulation methodologies are used by Naval Group?

Thierry Taillefet: They vary widely and depend on the situations concerned! For example, we are developing various methodologies to help evaluate the hydrodynamic performances of devices launched from submarines, such as tactical weapons, decoys and drones. We choose the methodology to be used according to the ejection mode considered or the phase of the ejection that we want to describe. The choice also depends on the precision required or the computational resources available for the project.
Some methodologies are based on overall physical models, such as those of ship manoeuvrability. They can for example be used to calculate the trajectory of torpedoes after launch. Others use CFD techniques, which consist in solving the fluid flow equations by dividing the spatial domain of interest into a mesh of small juxtaposed volumes. This approach, which is very close to physics, is one of the most accurate. It does however demand long modelling time and substantial computational resources.

Fabian Pécot: To simulate torpedoes launched by swim-out, we use the functions offered by CFD computer codes, which include the so-called "chimera" method. These employ the overlap of two computational grids, which exchange information in order to simulate the progress – inside a submarine launch tube – of a torpedo propelled by its two counter-rotating propellers.

> "Numerical simulations are validated by comparing their results with data obtained from experiments with mock-ups."
>
> *Alain Nédélec, hydrodynamic expert*

Alain Nédellec: The development and maintenance of such software entails considerable work, which it would be impossible for Naval Group to finance and amortise. We therefore use off-the-shelf computer codes to solve fluid mechanics equations – the so-called "Navier-Stokes equations" – for "medium Reynolds number" situations. In other words, the software simulates the flow of a fluid around an object moving through it and utilises modelling of the turbulence developing along the walls.
For each type of computation, our work is to define the various parameters to be used in the simulations. These include the mesh quality, the boundary conditions (for example representing the hull of the ship), the turbulence modelling and the behaviour of the device under the influence of the forces exerted by the fluid.

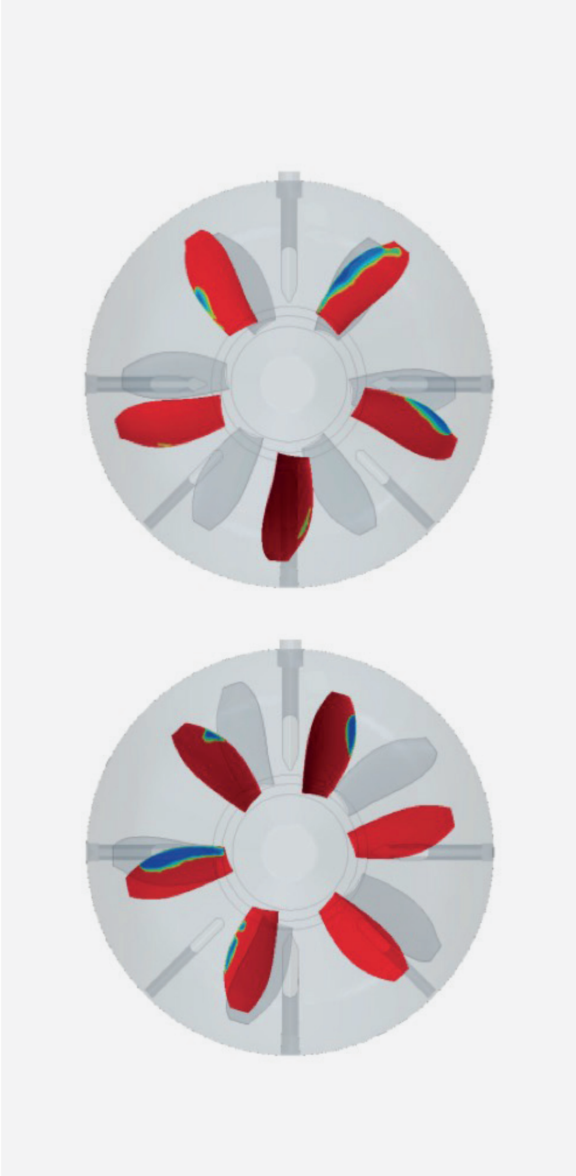
How are these methodologies validated?

FP and TT: When launching underwater weapons for example, we carried out sea trials with a drone strongly resembling a torpedo. This drone was launched with swim-out from a launch tube opening into free space. We studied two tube diameters and two launch speeds. For these four configurations, various measurements were taken: propeller rotation speeds, drone acceleration and pressures along and at the end of the tube during each launch. We then used the rotation speeds, obtained during the tests, as inputs for the simulations and compared the other parameters measured with those calculated by our models.

AN: Simulation validation is essential if we are to be able to trust the calculations! We draw on numerous cases and to do this, Naval Group uses measurements obtained during tests performed on mock-ups but also at sea on certain surface ships or submarines. These data are compared with the results of calculations made in the same conditions. Comparison of a variety of physical parameters enables us to validate the pertinence of the simulations conducted by our engineers. They also enable us to better control the uncertainties inevitably present in both calculations and tests.

SIMULATING HYDRODYNAMIC WITH CFD

Naval Group engineers use CFD to understand more clearly the hydrodynamics of underwater vehicles such as drones. The calculations presented here enable the risk of the onset of cavitation to be estimated. The parameter represented is the volume fraction of vapour on the outer surfaces of the drone's upstream and downstream propeller blades (the values vary from 0% in red to 100% in blue). The blue zones show the locations where cavitation is liable to occur.



For example, what physical phenomena are considered in the weapon launch simulations – and why are they important in your calculations?

TT and FP: The simulations aim to represent the main physical phenomena observed during torpedo launches. They are basically the interaction between the movement of the torpedo and the flow of the fluid – we speak of "fluid-structure interaction" – the influence of the confinement of the thruster in the launch tube and cavitation. Modelling fluid-structure interaction is necessary because the dynamics of the water and the torpedo are closely coupled. This interaction between the blades of the two counter-rotating propellers and the walls of the tube lead to a reduction in propulsion performance, owing to the confinement in the tube: the aim is to quantify this precisely.
Cavitation corresponds to the phenomenon of "cold" vaporisation of the liquid water under the effect of a local reduction in pressure. This phenomenon manifests itself on the outer surface of the blades of a propeller downstream of the leading edge, by the formation of a cloud of bubbles and/or a pocket of vapour covering all or part of the profile. Cavitation is prejudicial because it impairs the propulsion performance of propellers; we are therefore seeking to prevent its onset, which for example depends on the conditions of immersion and the velocity of the fluid flow.

How are these phenomena taken into account when evaluating the best operational launch window for a torpedo?

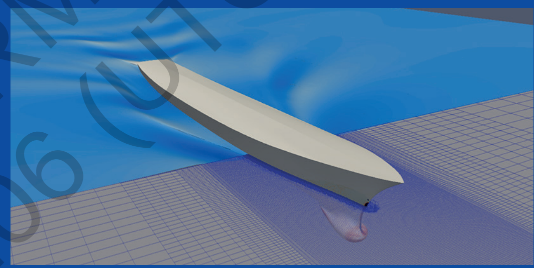
TT and FP: To influence the ejection and swim-out performance, one of the means at our disposal is to ensure that the torpedo launch tube is of sufficient diameter. This choice, made at design stage of the submarine and weapon launch tube, is partly based on our calculations. These also enable us to determine the minimum launch depth, for example to minimise the risks of the onset of cavitation.

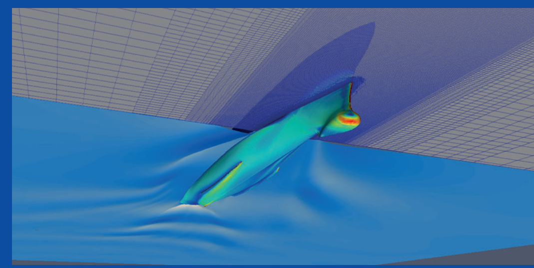
What are the challenges of CFD simulations?

AN: For centuries, a ship had to be built so that sea trials could be carried out in order to assess its behaviour. As of the 19th century, naval engineers developed mock-up test methods to address certain design questions, such as calculating the propulsion power needed to reach a given speed or evaluating manoeuvrability and seakeeping performance. Although very useful, these tests demand considerable resources… without forgetting the fact that building a mock-up takes time!
International competition in the naval sector is becoming stiffer year after year, so Naval Group is looking to bring down the duration and cost of its hydrodynamic studies. CFD is thus a good means of reducing the volume of mock-up tests and thus boosting competitiveness.

WHAT IS CFD ?

CFD, standing for "Computational Fluid Dynamics", is a means of using a computer to approximately resolve the famous "Navier-Stokes equations" which model fluid mechanics. Except for a few simple cases, one does not know how to analytically calculate a solution to theses equations. The numerical approach is needed to understand real cases, such as aircraft flight or ship hydrodynamics.
To do this, the volume of the fluid – typically air or water – surrounding the ship is split into a large number of small elements, constituting a "mesh" (or a "grid"). The flow conditions are imposed at the boundary of this numerical domain, while the flow characteristics (pressure, velocity, density, etc.) are calculated there at all points of the grid by means of a computer program.
This then solves the fluid mechanics equations and provides a numerical solution after a computational time ranging from a few hours to several days, depending on the size of the problem and the available computational resources.





Computation mesh and result of CFD simulation for the flow around a hull. The simulation for example helps to predict the seakeeping of ships and to evaluate certain aspects of nautical performance.

FP and TT: For the ejection of submarine weapons, numerical simulations have a two-fold benefit. On the one hand, they can calculate the operational launch domain of a submarine weapon and, on the other hand, they enable design studies to be carried out in the opposite direction – that is verifying that the ejection performance of a weapon is compatible with the desired launch requirements.

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USING PHYSICS AND MATHEMATICS TO PREDICT SEA STATES

Designing systems to control motions of platforms at sea: this is one of the objectives of a Sirehna/Naval Group team. There is no shortage of potential applications, such as stabilising a frigate for a helicopter landing or controlling marine energy recovery systems. Obtaining models to predict sea states is a key aspect in the development of control systems.

Life on-board a ship is not all plain sailing. Some operations cannot be carried out in heavy seas, for example with steep wave slopes. Can this be overcome? Naval Group engineers are attempting to push back this limit. They are thus developing control systems capable of predicting waves and ship motion, about ten seconds in advance, so that they have the time to control them.

"This type of control is not yet deployed on-board: current systems measure the motion of a ship at a given time and seek to reduce it by means of mechanical systems, in reaction to this motion" explains Jean-Jacques Maisonneuve, expert in hydrodynamics at Sirehna. *"The aim is to move away from systems in which we simply counteract observed motions, towards systems which enable us to anticipate and control them better. Anticipating ship motions would enable us to conduct a certain number of operations in complete safety, in sea states that are as heavy as possible. We are thus looking to develop a system characterising the incident wave field in advance."*

"We are developing a model for the prediction of sea-states which combines accuracy and speed of execution."

Jean-Jacques Maisonneuve, hydrodynamic expert

ACCESSING THE DETERMINISTIC PROPERTIES OF THE SWELL

This research is the subject of a Ph.D. thesis by Nicolas Desmars, at the LHEEA* laboratory at École Centrale de Nantes, which is collaborating with Sirehna/Naval Group as part of the Centrale Nantes/Naval Group Joint Laboratory for Maritime Technology, and an ASTRID project PREDEMONAV, funded by the ANR* and DGA*. *"This project aims to achieve real-time, deterministic prediction of motions of a ship, based on measurement of the swell to which it is subjected"* explains Nicolas Desmars.

Developing such a system requires that three key operations be carried out with precision: the first consists in accurately measuring the elevations of the surface of the water around the ship, which gives the free surface dynamics; the second aims to predict the waves at the location the boat will be in within the next 10 to 20 seconds. As for the third operation, it consists in calculating the ship's response to the predicted conditions. The work done by Nicolas Desmars focuses on the second step: it aims at building mathematical models capable of predicting the wave dynamics. Various models may be used to meet that goal.

PREDICTION LIMITS IN HEAVY SEAS

Linear-type models offer extremely fast calculation, compatible with the real-time constraint. What are their limits? They are not sufficient for describing swell propagation in real conditions. *"We are looking to precisely identify the amplitudes and phases of the wave field at a given location and time"* explains Jean-Jacques Maisonneuve. *"The estimation of their phases is crucial and linear models, which give good results in moderate swell conditions, prove to be incapable of providing reliable predictions in rough seas conditions…"*

Non-linear models would in this case be better candidates: they are closer to reality and propagate the swell with all of its wave components and their physical characteristics. They represent two types of non-linearities: "geometrical" non-linearities, which allow a more precise representation of the dynamics of the waves when the peaks are sharper or the troughs flatter; "spectral" non-linearities, which take account of variations in the propagation speed of the waves with respect to their amplitude.

A MATHEMATICAL FORMULATION OF THE LEVEL OF THE WAVES

As Jean-Jacques Maisonneuve reminds us, *"this type of model nonetheless requires considerable computing resources and – at least for the time being – cannot be used to develop the 'real time' systems we wish to deploy on-board. Our aim is therefore to design an intermediate method, offering both more precision than the linear models and more flexibility than the non-linear models currently in use."*

The model, named "Choppy", takes account of the primary non-linear effects in the evolution of waves over the target prediction time-frame (a few tens of seconds). The modelling, based on a so-called "Lagrangian" representation of flows, leads to an analytical formulation of the free surface dynamics, which lends itself easily to computation. *"This enables us to carry out the measurements assimilation step in a straightforward manner"* adds Nicolas Desmars. *"The formulation we use also explicitly takes into account the wave dynamics, which allows prediction of the sea state at a later moment without having to resort to a time-integration numerical scheme, which is more costly in terms of computational resources. Our model thus allows the prediction of wave propagation over time more precisely and almost as rapidly as a linear model."*

* LHEEA (Laboratoire de recherche en Hydrodynamique, Énergétique et Environnement Atmosphérique): Hydrodynamics, Energy and Atmospheric Environment research Laboratory.
** ANR (Agence nationale de recherche): French National Research Agency.
*** DGA (Délégation Générale pour l'Armement): French Defense Procurement Agency.
**** In France, the so-called "CIFRE programme" supports Ph.D. students to pursue doctoral studies within industrial compagnies, in collaboration with universities.

USING SYNTHETIC OPTICAL MEASUREMENTS

Surface elevation data are required by the algorithm so that it can make these predictions. Measurement instruments such as LIDAR (optical remote detection) will be used on board ships to obtain them. During the algorithm development phase, the researchers do not however have access to real measurements.They then opt for another approach, as explained by Nicolas Desmars: *"In order to develop our algorithms, we used synthetic data which are representative of the optical measurements taken with a LIDAR. They were created on a computer using a numerical wave model, which accurately describes the spatio-temporal evolution of the ocean's surface."*

This model, named "High-Order Spectral" (or HOS), can be used to develop the swell prediction algorithm. It has another advantage: is allows for the calibration of the quality of the prediction, by understanding the influence of the algorithm's parameters on its performance and determining the quantity of information needed by the calculation method. *"There is considerable spatial heterogeneity in the optical measurements and this poses difficulties while processing the data. We nonetheless demonstrated that with our method, they can be overcome. We already revealed the benefits of representing certain non-linear effects, which become important as the prediction time-frame increases or when the sea is rough and the waves steep."*

Future research will enable the team to validate the method and experimentally quantify its performance, thanks to the measurement results obtained in the wave tank facility at École Centrale de Nantes. *"To do so, we used sensors to acquire data in the same way as a LIDAR and I am currently working on analysing them"* concludes Nicolas Desmars.

WAVES IN NUMERICAL MODELLING

The reconstruction algorithm consists in supplying a wave numerical model with optical measurements, whether obtained at sea or simulated on a computer. The quality of the sea state prediction depends on the precision of the reconstruction: minimising the "reconstruction error" is thus one of the key-issues of the project.

The optical measurements generate a mesh of points with an extremely heterogeneous spatial distribution. The density of these measurement points decreases with the distance from the sensor (fixed on the ship) and, at low angle of incidence, the wave front masks the measurements of the points located behind it. Therefore, the positions of the measurement points remain unknown. *"The reconstruction method must be applicable without having to rely on a specific form of measurement mesh"* explains Nicolas Desmars.

The assimilation technique used therefore consists in specifying the parameters of the wave model which minimise the reconstruction error: *"This is a relatively conventional mathematical problem that can be solved with efficient algorithms based on an iterative method. The solution obtained after convergence supplies parameters for the 'Choppy' model, which we will then use to propagate the sea state for the prediction."*

Ship measuring the surface elevation ahead of its trajectory

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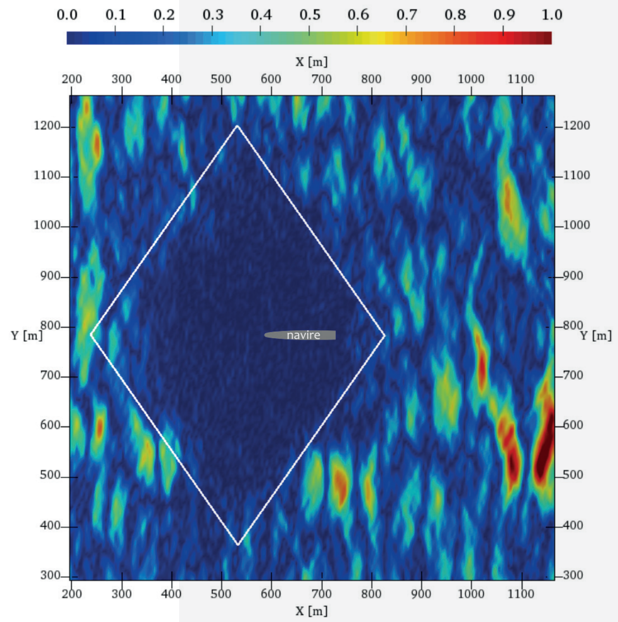


MINIMISING THE RECONSTRUCTION ERROR

The field of observation around the ship covers a diamond of about 600 metres by 800 metres. In this zone, the sea state reconstruction error has been minimised (in blue, nil error, in red, close to 100%). The information linked to each incident wave for the ship propagates at its own speed and is not the same for all the waves. Therefore, over time, the information measured for each wave is dispersed in space and the prediction zone shrinks. *"We therefore have to choose the zone in which the measurements are taken, so that the prediction zone corresponds to the ship's trajectory within the prediction time-frame."*

04

MATERIALS AND STRUCTURES

> "With the so-called 'self-heating' method, we expect to bring down the testing time to two days and divides its cost by ten."
>
> *Julien Beaudet, research engineer in materials*

TOWARDS FASTER AND CHEAPER FATIGUE CHARACTERISATIONS

Characterising the fatigue resistance of assemblies and structures is crucial when designing surface ships and submarines that will be sailing for thirty to forty years. But this is a lengthy and costly process. Collaboration with the researchers at ENSTA Bretagne* aims to develop a method that could significantly speed up these fatigue tests, initially for welded joints.

Alongside buckling and impacts, fatigue is an important damage mode to be considered for military ships. Hulls undergo the effects of waves (for surface ships), or pressure variations as a result of immersion cycles (for submarines). On-board nuclear propulsion reactors undergo variable thermal and mechanical stresses and the components of the propulsion chain vibrate, rotate, support their own weight, are subject to high torque variations at starting, stopping and speed changes.

FATIGUE EVERYWHERE, BUT HIGHLY LOCALISED DAMAGE

"The entire ship is subject to what we call 'loading', which are static or dynamic forces" explains Florent Bridier, research engineer at CESMAN**. *"However, the damage due to fatigue is extremely localised. It can for example be incipient cracking of one millimetre wide, in a weld 10 millimetres thick, on-board a frigate 100 metres long."* Extensive work is carried out on an ongoing basis to improve the monitoring and detection of any cracks.

Naval Group is also conducting evaluations as of the ship design stage, when choosing a material, an assembly method, a type of structure, etc. These sometimes rely on calculation methods required by the regulations, for instance for the components of the nuclear propulsion reactor. But fatigue data (loads to which a part is subjected, frequency and number of cycles over its lifetime) can also be defined with the customer or through in-house technical instructions at Naval Group, which enhances the company's know-how. *"Some loads data can be easily obtained for small systems"* adds Julien Beaudet, research engineer at CESMAN. *"However, we have no satisfactory framework to assess the loads experienced by a complete ship's hull for 30 to 40 years."*

REPRODUCING REALISTIC LOADING CONDITIONS

It should be remembered that the fatigue computational methods developed by the naval classification companies, such as Bureau Veritas, are designed for commercial ships – which generally follow shipping routes and avoid storms – rather than for military ships, which are active in all weathers, on all the world's oceans. So, the fatigue strength testing conditions must be based on feedback, or on instrumentation in service on naval structures.

The fatigue strength can be validated by simulation, with techniques based on mathematical formulas or on numerical methods, such as the finite elements method, or by tests simulating the traction, compression, bending type loads, at temperatures which may be high and in representative environments (such

*ENSTA Bretagne (École nationale supérieure de techniques avancées de Bretagne): Brittany National School for Advanced Techniques.

**CESMAN: Naval Group's naval structures and materials expertise centre.

as seawater). Modelling and testing are often combined. For example, before fatigue tests on a transmission shaft subjected to bending, thrust and twisting, simulation will check whether these three phenomena do actually have an impact on the part. If twisting has no effect, the test on the real part will not reproduce this and will be simplified. However, the length and cost of testing remain significant constraints. For the fatigue evaluation of a new material, two weeks to a month are frequently needed, with 10 to 30 test pieces at several hundred euros a piece.

DIMENSIONING DESPITE DISPERSION

A scientist studying a phenomenon hopes to obtain laws and precise correlations. R&D work on fatigue is an exception to this rule: test results always include a dispersion because the fatigue response of the materials and assemblies is inherently variable.

Fatigue is subject to the influence of numerous factors: manufacturing defects, creation of residual stresses during welding, minimal geometrical deviations on large parts, and so on. Even when several test specimens from the same structure are tested, we can observe as many different lifetimes as there are test specimens. For the fatigue dimensioning of parts and structures, the engineers therefore use analysis methods taking account of this inherent dispersion.

SELF-HEATING, A NEW METHOD TO SPEED UP TESTING

Why does it take so long? The traction machines, with limited frequency, sometimes have to carry out millions of loading cycles. Moreover, if they are to be valid, the tests must cover a broad range of loading levels and numbers of cycles. Finally, several test pieces must be tested in the same conditions in order to reproduce the dispersion of results inherent in fatigue behaviour (see box).
Over the years, the definition of faster and cheaper tests has thus become a priority for Naval Group, which drew on the expertise of an academic partner to develop them. At the end of 2015, Naval Group set up the Gustave Zédé* joint laboratory with ENSTA Bretagne. *"This laboratory enables us to set up a long-term partnership and promote the transfer of know-how and innovations"* explains Florent Bridier. *"More specifically in the area of fatigue, we looked at rapid characterisation by self-heating, a method developed by researchers from ENSTA Bretagne."*

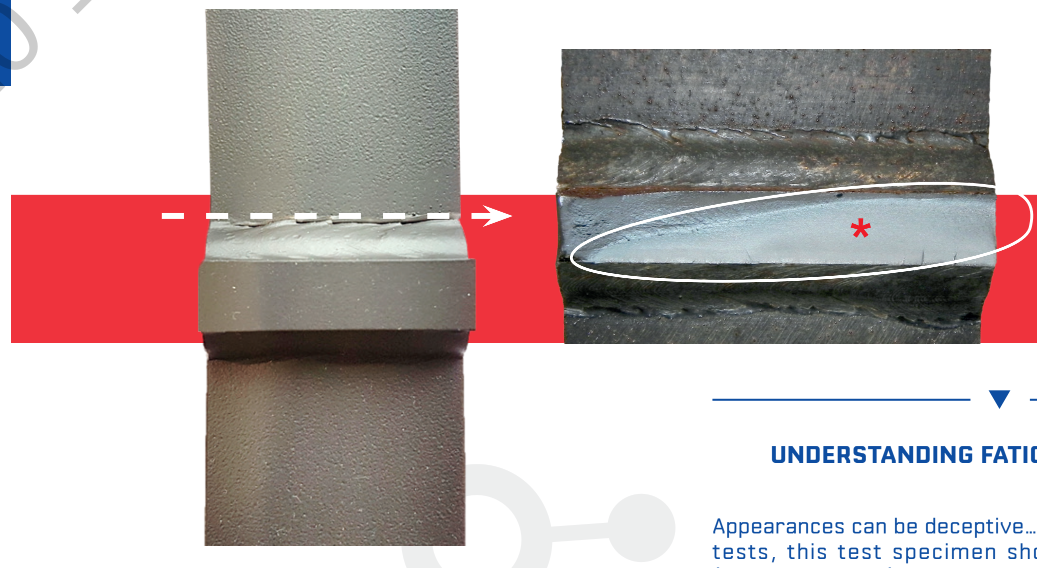
Any part subjected to cyclic loads experiences heating. This can be due to two phenomena: thermoplastic coupling, induced by the reversible deformation of the part; and "intrinsic dissipation" which indicates local and irreversible yielding of the microstructure, in other words, damage.

A THESIS MAKING THE TRANSITION FROM HOMOGENEOUS MATERIAL TO WELDED JOINT

As recalled by Florent Bridier, *"ENSTA Bretagne* was already using this test for homogeneous materials, where heating and stresses are uniform. Together, we decided to extend it to welded joints, our primary mode of assembly: each of our ships containing several kilometers of these!"* A CIFRE* thesis was started in 2017 with the aim of resolving a primary difficulty. The welded joint, which is by its very nature: heterogeneous, is subject to local stresses which generate local heating. This local heating, which is also heterogeneous, had to be measured throughout the entire part. But how?

The solution came from the use of a digital thermal camera which films the samples during the test and shows the temperature gradients, with a precision of better than one tenth of a degree Celsius. After post-processing, these digital images deliver valuable information on the thermoelastic coupling, the pertinent number of cycles for a fatigue test or crack initiation (see box). Subsequently, other post-processing will be developed to characterise the intrinsic dissipation.

Much work still remains before this research is complete, with the self-heating test being extended to other types of joints and preparations for industrial transfer. However, researchers may well have come up with a method capable of speeding-up fatigue tests and bringing down the cost. *"On a homogeneous material, ENSTA Bretagne has already demonstrated that one or two specimens were enough to obtain results as reliable as those of our tests"* states Julien Beaudet. *"If the same goes for the welded joints, the duration of a test will be brought down to one or two days and its cost will be divided by ten."*



* LOCATION OF FATIGUE CRACK PROPAGATION

UNDERSTANDING FATIGUE MECANISMS

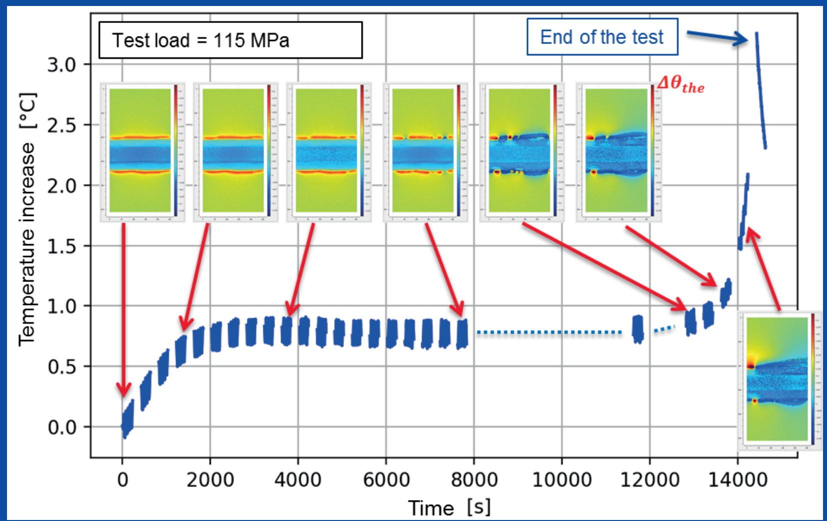
Appearances can be deceptive… After fatigue resistance tests, this test specimen shows an incipient crack (left-hand photo) which would appear to be minimal. However, if it is bent to breaking, one can see that at depth (right-hand photo), the fatigue crack has propagated extensively.

*Gustave Zédé (1825-1891) was a French engineer and the architect of the Gymnote, France's first military submarine.

*In France, the so-called "CIFRE programme" supports Ph.D. students to pursue doctoral studies within industrial compagnies, in collaboration with universities.

The following image shows the time/temperature rise curve for a part (here a stiffener welded to a plate) subjected to fatigue testing, as well as a map of its heating due to thermoelastic coupling. The map clearly shows the plate (in green), the stiffener (in blue) and the two weld beads (in red) which heat up more owing to the concentration of local stresses in the vicinity. Over time, discontinuities appear in the beads, which gradually turn blue, indicating a local drop in temperature due to the initiation of a fatigue crack: this leads to local relaxation of stresses.

As for the time/temperature curve, it shows when the fatigue test can be ended: if the temperature does not stabilise during a loading block; this means that the endurance limit has been exceeded and that plasticity (intrinsic dissipation) assumes an important role in the behaviour of the material.



Example of time-temperature curve

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WHEN IT COMES TO DEALING WITH CORROSION, IT'S ALL HANDS ON DECK!

Corrosion is the number one enemy for ships. It is a complex and varied phenomenon which has triggered numerous preventive strategies, as well as a continuous R&D effort. 2019 notably marks the end of the NITRU research project, carried out by Naval Group with 11 partners. They focused on a key subject: the impact of nitriding processes on the corrosion resistance of stainless steels.

So why worry about the corrosion-resistance of a stainless steel? Because nothing can withstand marine corrosion… it's only a matter of time. Even if stainless steel, which contains at least 11% chromium, spontaneously covers itself with a passive film of chromium oxide, this protective film ends up becoming insidiously impaired. To the naked eye, there is only a tiny spot of corrosion, no bigger than a pinhead. But deep down, oxidation is in full swing and a considerable volume of the metal is eaten away, with a growing risk of part failure.

This is why Naval Group joined the NITRU project in 2015, alongside partners such as Airbus and Safran. *"We wanted to find out whether nitriding processes could improve the mechanical properties of martensitic stainless steels while reinforcing their resistance to corrosion"* explains Simon Frappart, research engineer. On frigates, parts such as the helicopter deck landing grid can be concerned.

THREE GRADES OF STEEL AND SEVERAL PROCESS TEMPERATURES

The literature clearly indicated the direction to be followed. There was no point in wasting time on high-temperature nitriding (550°C and over): this leads to the formation of chromium carbides which "pump" the chromium from the matrix, thus reducing the protective effect of the passive surface film. However, a lower temperature process such as ion (plasma) nitriding was worth studying. *"We worked on three grades of steel and several process temperatures, from 350°C to 510°C"* highlights Simon Frappart. *"We investigated two questions: what is the impact of nitriding on the metallurgical microstructure? And, above all, after this nitriding, what happens to the mechanical properties and corrosion resistance of the steel?"*
Considerable characterisation resources were mobilised: scanning and transmission electron microscopes, X-ray diffraction, glow discharge mass spectroscopy to determine the concentration profiles of nitrogen and chromium… The electrochemical behaviour of the surfaces was studied, sometimes on a record scale with zones of 20 to 30 square microns. Finally, mechanical tests and corrosion tests in artificial seawater were carried out.

Example of a corroded part when basic protecting rules are not complied with

EVEN BACTERIA TAG ALONG !

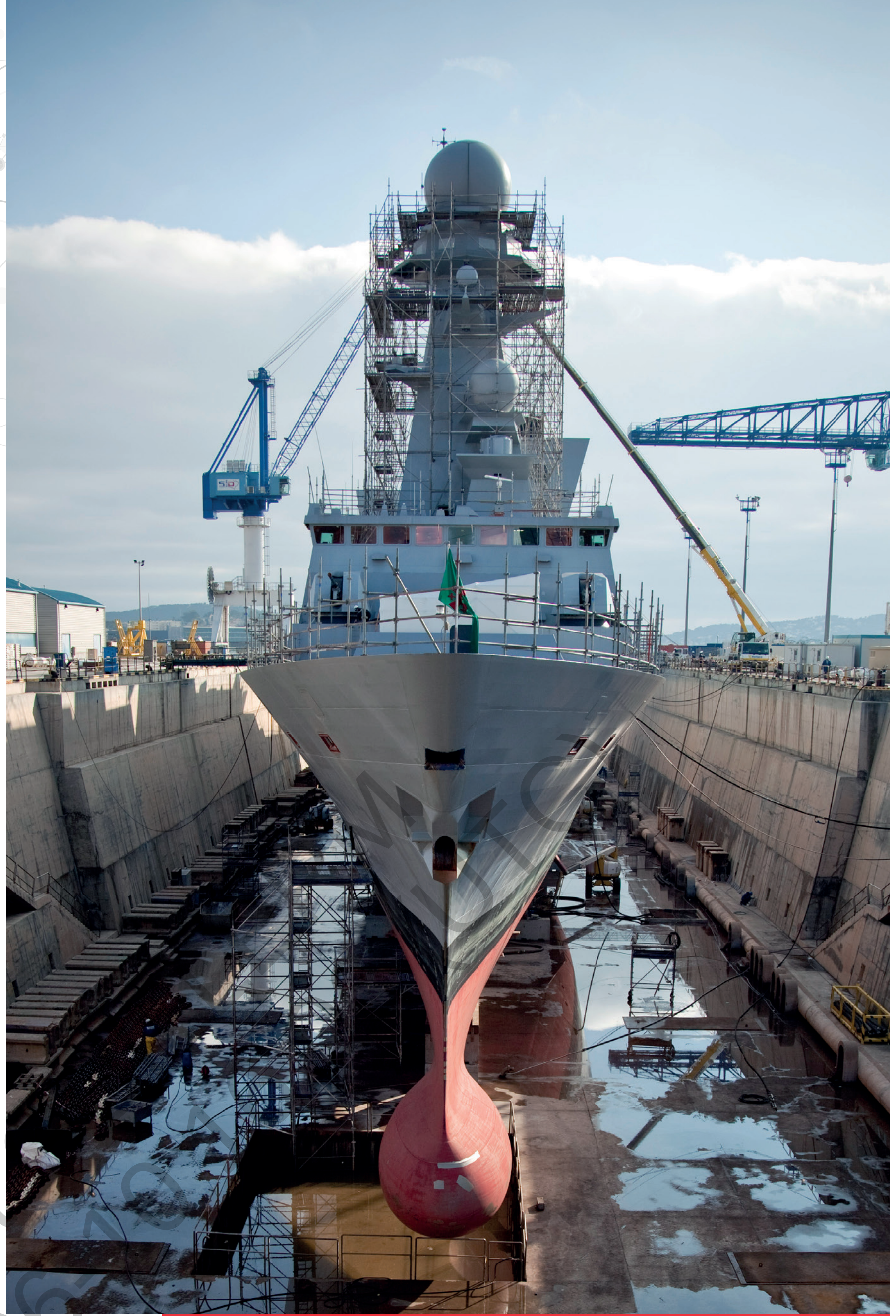
Microbial corrosion (or "bio-corrosion") is corrosion associated with the action of the micro-organisms present in the corrosion system. It is the result of an unfavourable combination of three factors: environment, micro-organisms and metal. If a metal is immersed in seawater for a few minutes or a few hours, micro-organisms will begin to colonise its surface and create a biofilm. These micro-organisms act directly – for example electroactive bacteria attach and accelerate the exchange of electrons – or via their metabolism – for example, sulphate-reducing bacteria reduce the sulphates contained in the seawater to sulphides – to accelerate an already established corrosion process or create the conditions favourable for it to become established. In both cases, the rate of corrosion increases.

MANAGING CORROSION, RATHER THAN ELIMINATING IT

The result of these three years of work: *"Martensitic steels are good candidates for nitriding, but that does not change the basic problem"* states Simon Frappart. *"When the process temperature is low, the mechanical and tribological properties are insufficient. When it is higher, these properties improve, but the resistance to corrosion is impaired."* Despite this seemingly disappointing conclusion, the picture is not all black. Naval Group learned much about nitriding, notably from Safran, which has been using it for a long time now. The lessons from the project were input into a toolbox which, given the stakes of corrosion, can never contain too many tools.

"Corrosion is an inevitable phenomenon and one that is impossible at present to detect with a sensor" explains Anne-Marie Grolleau, Head of the Naval Research marine corrosion laboratory. *"Similarly, modelling attempts by certain universities come up against the variability obstacle. Corrosion depends on too many factors: seawater conditions, bacteria content, geometry and metallurgy of the parts, local electrochemical phenomena, etc."*

So, how does one fight this old enemy which never gives up? With strategies and technologies that bypass it, contain it or slow it down. You cannot eliminate corrosion, only manage it.



"You fight against corrosion with strategies and technologies that bypass it, contain it or slow it down. You cannot eliminate corrosion, only manage it."

Anne-Marie Grolleau, corrosion expert

APPLIED STUDIES, TESTING AND FUNDAMENTAL RESEARCH

Examples? Parts which rust fast but are easily replaced are switched out during maintenance. Cathodic protection, which has been around for 200 years, is extensively used: a sacrificial anode corrodes and thus preserves the more vulnerable parts located nearby. Metals are not covered with paint, but with "paint systems" consisting of several coats – at least three – with complementary properties. *"We are making progress on these subjects through applied studies, tests, expert analysis, from which we learn lessons, along with fundamental research carried out with various academic or industrial partners"* adds Anne-Marie Grolleau.

However, certain applications are so specific to Naval Group that it is sometimes impossible to use the experience of other industrial firms. For example, the bases of offshore platforms are permanently under water, whereas submarines alternate between phases in and out of the water. *"This can lead to corrosion-friction phenomena on certain equipment, with small vibrations that weaken the passive surface layers."*

TESTS IN SEAWATER

It is notably to recreate these specific conditions that Naval Group carries out tests in natural seawater in its Cherbourg laboratory (see box). It also has an impressive range of characterisation equipment.
To understand how difficult it is to fight corrosion, one must remember that it manifests itself in several forms. Small pits on the surface of the stainless steel indicate "localised" corrosion. However, it can also be generalised, with an entire part being affected. There is also fatigue-corrosion, specific to structures subjected to cyclic motion; stress corrosion, if an immersed part undergoes continuous or residual loading; corrosion in a nuclear environment, due to the effects of pressure, temperature and ionising radiation. *"We have to deal with all these mechanisms, which adds a further level of complexity"* concludes Anne-Marie Grolleau. The University of La Rochelle, which is a long-standing partner of Naval Group, is now training "specialist corrosion engineers". They would seem to have a secure future.

At Naval Group, as elsewhere, many marine corrosion tests are – for practical reasons – conducted using artificial seawater. However, the Cherbourg laboratory enjoys a rare luxury: the permanent availability of real seawater. It is brought in from the nearby harbour by a pipe and continuously renewed by pumps. This water feeds tanks in which full-scale tests can be performed on large parts. They frequently last several months. The longest ones, performed and analysed under a project with the University of La Rochelle, lasted six years: corrosion works slowly…

The access to natural seawater, rich in micro-organisms, bacteria for example, enables the bio-corrosion phenomenon to be reproduced (see box on bacteria). In the same way, algae, molluscs, shellfish can attach themselves to the surfaces, as at sea. This fouling phenomenon makes ships heavier, reduces the thermal efficiency of the cooling systems and can hide incipient corrosion. Finally, it is essential to test the coating and cathodic protection systems used on ships in conditions as close to real life as possible.

1


2


3


#1 View of the seawater pool on the Cherbourg site. The seawater in it is permanently renewed, for long-duration corrosion resistance tests on large sized parts.

#2 A truly unique laboratory: it benefits from running seawater for corrosion testing of small sized parts.

#3 Test loops for full-scale testing and validation of seawater circuits.

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NON-DESTRUCTIVE TESTING:
A RIGOROUS MANAGEMENT OF IMPERFECTION

Inspecting a mechanical component without damaging it, characterising a defect without seeing it, accurately predicting its development: non-destructive tests (NDT) are both a science and a technique, implemented using a variety of methods. They are omnipresent at Naval Group, where they accompany the entire lifecycle of ships, and are the subject of R&D efforts focusing on five priorities.

Two figures enable the importance of NDT at Naval Group to be appreciated: at CESMAN* it mobilises a team of 17 experts who, depending on the situation, can draw on a dozen methods. Notably those most commonly used in industry: ultrasounds, radiography, eddy currents, acoustic emission, dye-penetrant, magnetic particle, X-ray diffraction, etc. *"We carry out training and technical support for shipyard operators, procedure qualifications, expert analyses, defect analyses"* explains Patrick Recolin, NDT senior expert. *"At the same time, we carry out R&D into more efficient inspections, reduced environmental impact and adaptation to changing materials and technologies."*
First area: increased sensitivity and precision, which are obviously decisive for the quality of ships, their reliability and their lifetime. The process involves a number of steps: the CESMAN team carries out experimental tests and simulations, integrates these methods into its expert analyses and then gradually transfers them to production and maintenance.

"We carry out R&D into more efficient inspections, reduced environmental impact and adaptation to changing materials and technologies."

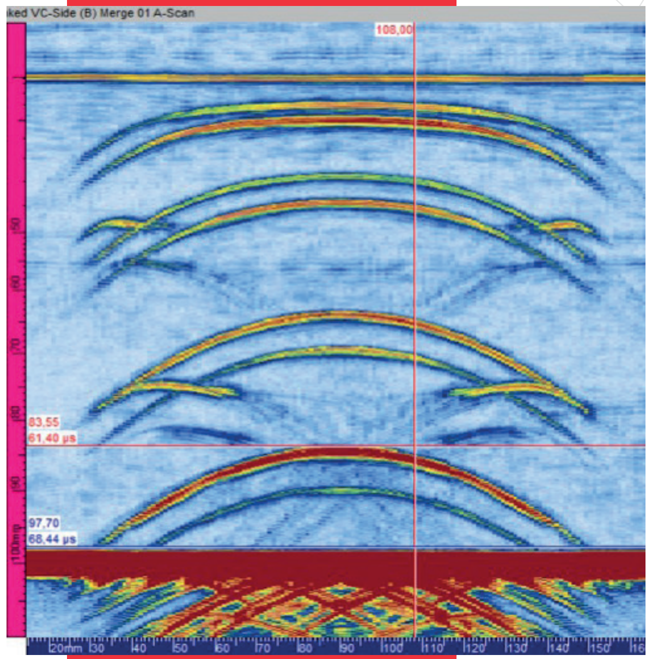
Patrick Recolin,
non-destructive testing expert

COMPLETE INSPECTION OF A WELD 100 MM THICK

Recent advances notably include the improved inspection of thick joints (up to 100 mm), so that they can be completely inspected in a minimum of time. The basic method is "Time Of Flight Diffraction" (TOFD), which consists in positioning ultrasound sensors opposite each other, either side of a joint, and operating them in emission/reception. Depending on their angle of refraction, the ultrasound beams intersect at different locations in the volume to be inspected. If one of them returns an echo, then it has encountered a defect; it is then possible to determine its position and size by reconstruction.

The productivity of TOFD is enhanced by the fact that it uses multi-element sensors to emit and receive several beams at a time and cover a wider area at each monitoring position. However, the greater the thickness of the weld, the more focal laws must be created to determine the emission/reception refraction angles needed for complete inspection of the volume. *"At present, no 'off-the-shelf' software can perform these calculation"* Patrick Recolin informs us. *"On the scale of a joint 100 mm thick, it would take days to define these focal laws."*

* CESMAN: Naval Group's Naval structures and materials expertise centre.



TOFD: AN ADVANCED NTD TECHNIQUE

This eight-element TOFD inspection of a gauge block with standardised defects shows that it is possible to detect notches over a width of 100 mm.

FOR A NEW ASSEMBLY, A NEW NDT METHOD

The team therefore developed its own computational tool and validated it on gauge blocks containing standardised defects and then on submarine hull joints. It was a complete success: the signal/noise ratio is excellent, the zone to be inspected is covered better in terms of both width and depth, with fewer multi-element sensor movements along the joint. Furthermore, the method indicates on which side of the joint the defect is located. If it needs repair, the operators know where to excavate.

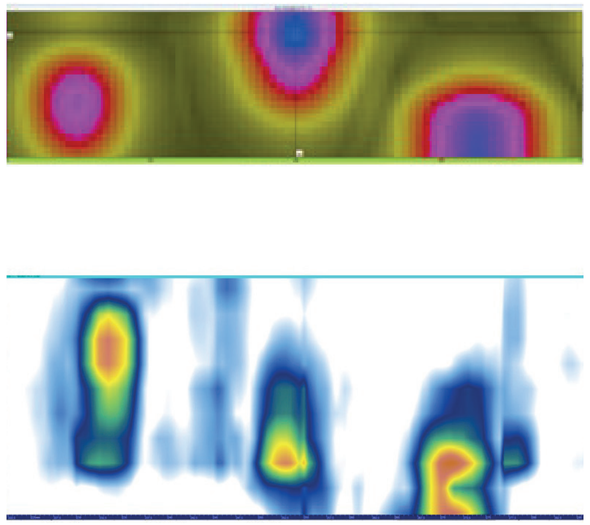
Second area of R&D: NDT of new types of assemblies. The CESMAN experts for example looked at a dissimilar metal weld between a ferritic steel and a stainless steel. With the conventional angled longitudinal wave ultrasounds method, detection sensitivity was limited and the inspection reliability was too variable. The new method uses a 64-elements sensor, each element of which can function in emission and reception. It is thus possible to sweep the zone to be inspected without moving the sensor, modifying the function assigned to each element as required. One then need simply define the focal laws needed for inspection of the entire length of the joint.

"We carried out acquisitions on a reference block and compared them with a simulation of inspection with the CIVA software"* explains Brice Marie, engineer in charge of this subject. *The results are comparable and show that we can guarantee the detection of a defect at least 3×15 mm^2 (height×length) in size, in the worst-case conditions and whatever its location."* The procedure has been incorporated into a qualification procedure, for use on nuclear power plants in the near future.

REDUCING ENVIRONMENTAL AND HEALTH IMPACTS

Third area of R&D: reducing environmental and health impacts of NDT. A radiographic inspection, for example, uses ionising radiation. If performed on a ship in the maintenance phase, the personnel liable to be exposed to radiation must be evacuated; all the ongoing work is therefore interrupted. Another example is dye-penetrant, which sprays a product revealing surface defects. This employs aerosols, flammable substances, cloths, etc. Hardly favourable conditions for inspection work in a confined space.

It was precisely to replace dye-penetrant inspection that Bastien Lavie, an engineer working with the NDT team, evaluated the multi-element eddy current method. These sensors create eddy currents which circulate locally in the material and are disrupted by discontinuities or variations in the properties of the part. *"In the absence of any pre-existing references, we decided to check whether the method was at least as good as dye-penetrant: detection of surface defects 0.11 mm wide, 1 mm long and 0.25 mm deep"* explains Bastien Lavie. *"We just needed a sensor suitable for our requirements. A supplier developed one at our request, by combining two models from its catalogue."*



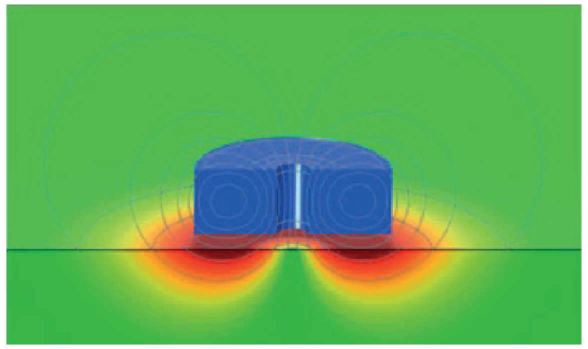
NUMERICAL SIMULATION AND NDT

To evaluate the new NDT method using 64-elements ultrasound sensors, acquisitions on a reference block (top) were compared with a simulation using the CIVA software (bottom).

"We are adapting our NDT techniques to new materials and new production processes."

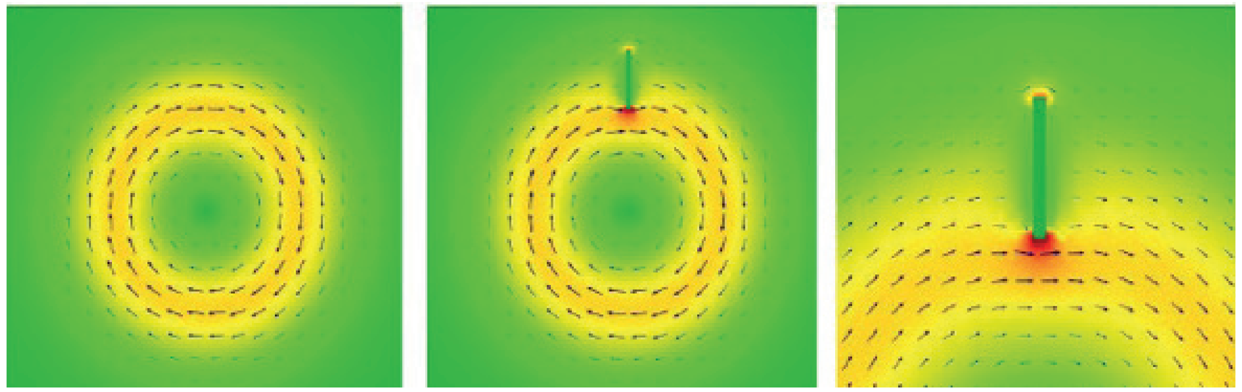
Bastien Lavie and Brice Marie, non-destructive testing engineers

* CIVA is an "off-the-shelf" simulation code, initially developed by CEA LIST, and today the benchmark in non-destructive testing.



EDDY CURRENT NDT

Eddy current NDT uses sensors creating currents by magnetic induction in conducting materials (on the left, the magnetic field around a coil and the currents it induces). The presence of a defect in the part can be seen by the modifications it creates in the density and distribution (bottom) of the eddy currents.



NDT AT ALL STAGES IN THE LIFE OF A SHIP

NDT is present at all stages in the lifecycle of ships. Regarding, for example, the design of a component or a part of the structure, the CESMAN team checks that it will be easily inspectable: is it accessible? Is there enough room to install sensors at the necessary distance? Criticality is also taken into account: if a critical weld is impossible to inspect, the drawings go back to the design office.

When manufacturing is launched, the suppliers of semi-finished products (sheets, tubes, bars, etc.) entrust their certified operators with the NDT governed by standardised methods. The ship is then built. Its assemblies (welds, bonds, threaded fasteners, etc.) are inspected in part or in full. For example, the welds on submarine hulls are inspected in full.

NDT is a part of the periodic maintenance programmes conducted every eight to ten years. After years at sea, ships all have defects. The aim is to detect them, compare them with predetermined thresholds and establish their harmfulness if these thresholds are exceeded: do they need to be repaired, or not? Finally, the defects detected on the ships in service are individually assessed by means of NDT.

TOMORROW, INSPECTING 3D PRINTED PARTS

In the near future, the Naval Group ships will no doubt contain items made using additive manufacturing (3D printing): this technology is something that now cannot be ignored. But how to calibrate the inspection of these parts given the total lack of knowledge of their fatigue or corrosion performance? Against what criteria do we determine the size and shape of an acceptable or unacceptable defect? This is the goal of I-AM-SURE, a FUI* project in which Naval Group is taking part, alongside Airbus, Thales, CETIM**, CEA***, etc. The consortium is focusing on metal parts with significant safety implications and are studying three NDT techniques: contactless ultrasounds, acoustic emission and X-ray tomography.

TOMORROW, AUTONOMOUS SENSORS AND CONTINUOUS NDT ?

The detection of surface penetrating defects was evaluated on reference plates and then on ships undergoing maintenance. The verdict was positive. *"We can also carry out these inspections with no prior stripping of paints. By comparison with dye-penetrant, it is both faster and has no environmental impact."*
The R&D work being done also concerns new materials and technologies; this is for example the case of additive manufacturing (fourth area of R&D, see box). Finally, the fifth area of R&D concerns tools for real-time monitoring of structures. *"With autonomous, communicating and very low consumption stress, strain and defect detection sensors, NDT would become continuous"* explains Patrick Recolin. *"But these methods would supplement rather than replace those in use today."*

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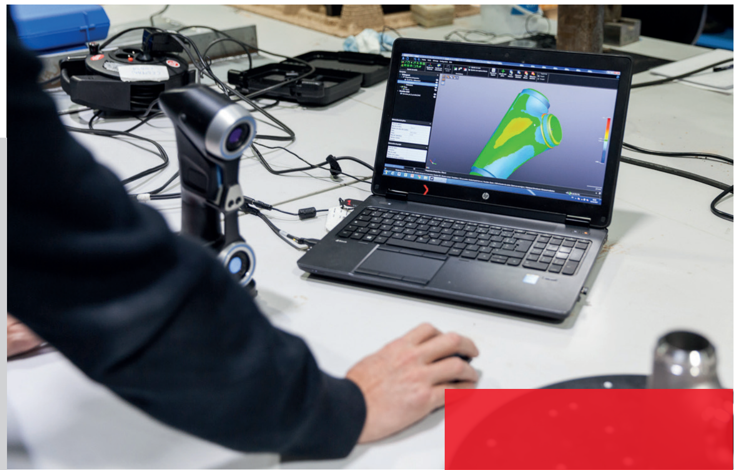


NDT of a component produced with additive manufacturing

* In France, FUI is a public funding programme geared toward industrial applications of R&D.
** CETIM (Centre technique des industries mécaniques): French Technical Centre for Mechanical Industry.
*** CEA (Commissariat à l'énergie atomique et aux énergies alternatives): French Alternative Energies and Atomic Energy Commission.

TITANIUM IN PURSUIT OF NEW APPLICATIONS

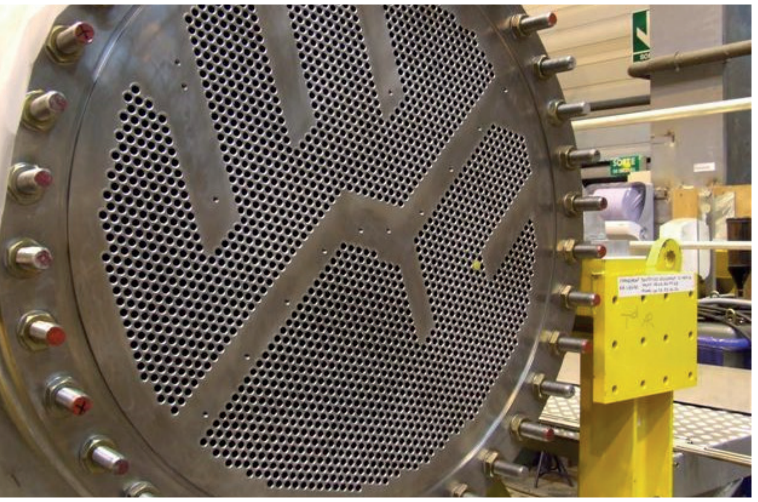
Titanium is already extensively used in Naval Group ships, more specifically for parts in contact with seawater. However, the exceptional qualities of this material make it suitable for other applications, such as nuclear propulsion reactor parts or rotating mechanical parts. However, two difficulties still need to be overcome: titanium can become embrittled by the formation of hydrides and its tribological behaviour is up to now unsatisfactory.

Titanium won over the aeronautical sector owing to its light weight: it is half as dense as a nickel-based alloy. In ship-building, it is above all its corrosion resistance that earned it its place. *"Its properties in this area are unparalleled"* explains Thierry Millot, materials expert at CESMAN*. *"The heat exchangers designed by Naval Group are made almost exclusively of titanium and we use it to a lesser extent on the seawater systems needed to cool certain on-board equipment."* Before the arrival of titanium and super-alloys, some copper alloy or zinc-plated steel equipment needed to be regularly replaced during major refits. Their lifetime is now the same as that of the ships. The *Le Triomphant* class submarines were the first to benefit from this step forwards.

The low density of titanium is also an advantage. It notably allows to reduce weight at the rear of the ships, which is already heavy enough owing to the propulsion system. Mechanical strength is also among its major qualities, with a yield strength up to three times greater than that of an austenitic stainless steel. *"The seawater systems of submarines are subjected to the immersion depth pressure"* recalls Thierry Millot. *"These are critical parts which must offer a high level of safety."*

TWO GRADES BEING STUDIED: T40 AND TA6V

Even the price of titanium is not necessarily an obstacle. It is easily offset by the minimal maintenance costs, owing to the absence of corrosion. This multi-talented material could thus aim for new applications, but for the presence of two serious weaknesses. The first is the possible formation of hydrides which embrittle it when in contact with hydrogen. The second is its poor tribological performance. When subject to friction, titanium seizes: it heats, it tears, it almost welds to the adjacent part… Naval Group is therefore carrying out research programs on these two subjects. They concern the two grades of titanium accounting for 95% of in-house applications: T40 (pure titanium) and TA6V (alloy containing a little aluminium and vanadium).



The sensitivity to hydrogen appears in highly specific contexts, in particular when the titanium cohabits with less noble alloys which require cathodic protection (see box). Owing to the cathodic water reduction reaction, the excess hydronium H+ ions can bond to the surface of the metal and diffuse inside it at the atomic scale. Depending on the alloys, this configuration can lead to the formation of hydrides, which are very hard and brittle. The mechanical properties of the material are thus degraded.

*CESMAN: Naval Group's Naval structures and materials expertise centre.

CATHODIC PROTECTION, THE ACHILLES' HEEL OF TITANIUM

Although resistant to marine corrosion, titanium could be embrittled by hydrogen owing to galvanic coupling with less noble metals, which must be given a cathodic protection device (galvanic anode or imposed current).The system incorporating a galvanic anode comprises an anode consisting of a material with a lower electrochemical potential than that of the metal to be protected (zinc or aluminium-indium anodes for example) and a cathode which is the metal itself. This approach enables a sufficiently low potential value to be reached for the metal such as to ensure its protection. As for the anode, it corrodes faster than the cathode, which is why it is called "sacrificial".
If cathodic protection is excessive, it triggers the production of hydrogen which can be absorbed into the titanium and eventually embrittle it by the formation of hydrides on the surface or within the volume. Depending on the case, the impact on the mechanical properties can be local or concern the entire part.

IN SEAWATER, DEPOSITIONS CAN STOP THE HYDROGEN

"We are carrying out experimental testing and modeling, notably as part of a thesis with the University of La Rochelle" explains Simon Frappart, research engineer in charge of this work at CESMAN. *"We are attempting to answer several questions: what are the main drivers that control the formation of hydrides? Does this happen predominantly at the surface or within the bulk? What are the repercussions on tensile strength, fatigue and crack propagation? Are the degraded properties acceptable with respect to in-service constraints?"* Understanding these phenomena is a long-term objective. This first thesis will be followed by a second one, more specifically dedicated to assessing the impact of the hydrides in the temperature conditions of a nuclear reactor primary system. *"We are looking at a time-frame of 15 to 20 years"* states Thierry Millot.
This is also borne out by the natural seawater tests being conducted on the Cherbourg site. Several titanium test specimens have been placed under cathodic protection and then subjected to constant traction. Some will remain in this situation for a year. Without waiting until then, the researchers take samples at regular intervals to monitor the formation of hydrides and measure the changes in the mechanical properties.

"Our researches on titanium aim at demonstrating its performances, in new configurations or for new applications."

Thierry Millot, materials science expert

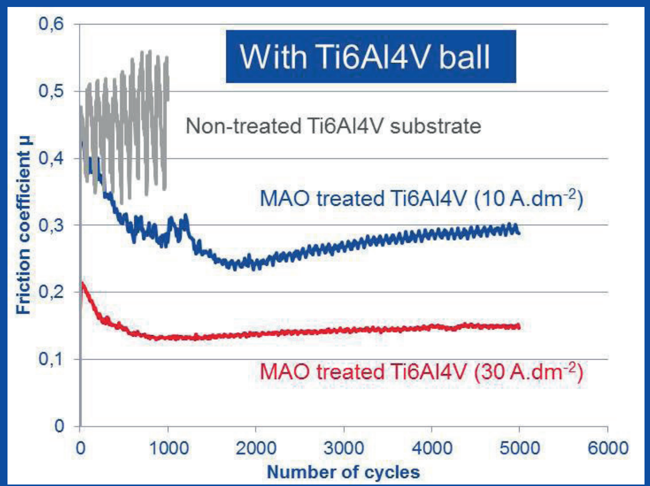
MICRO-ARC OXIDATION TO IMPROVE TRIBOLOGICAL BEHAVIOUR

"With the help of the Marine Corrosion laboratory in Cherbourg, we aim to study phenomena specific to seawater" adds Simon Frappart. *"It notably contains the magnesium hydroxide and calcium carbonate which, under certain polarisation conditions, form a calcareous deposit on the titanium, which can block the absorption of hydrogen"*.

The second priority, improving the tribological behaviour of titanium, should broaden the scope of applications within the next five to ten years. The primary targets are rotating mechanical parts such as bearings, shafts or valves. *"We aim to improve the properties of the material by means of surface functionalisation"* explains Aude Mathis, who completed a Ph.D.

The history of titanium is shorter than that of most metals. It was isolated for the first time in 1825, obtained with a purity of 99 % in 1910, although an industrial process did not appear until 1939. Its growth was also slowed down by its high cost; titanium parts are still very rare in cars, except in automobile racing.

The short history of this material explains why its properties and behaviour remain poorly understood. Thus, while conducting its own research, Naval Group is also investing in a number of collaborative programmes to benefit from the experience of other activity sectors. Most of the programmes are headed by the IRT M2P: MAO (Micro-Arc Oxidation), AFTER-ALM (surface finishes after additive manufacturing), ATLAS (surface treatments for threaded fasteners). The ANR* project TESAMI for its part concerns the use of titanium in an irradiated environment. Two other IRT M2P projects are under preparation: MUTAN, on the same subject as TESAMI, and INFINITI on surface treatments for titanium.



INVESTIGATING THE EFFICIENCY OF MICRO-ARC OXIDATION

Three TA6V titanium surfaces, one not treated and two treated by micro-arc oxidation (MAO), were subjected to contact wear tests to evaluate their dry friction coefficient. The ball used for these tests was made of TA6V. The two surfaces treated perform significantly better than the untreated surface. In particular, the treatment at 30A/dm2 led to stabilisation of the friction coefficient over 5,000 cycles; the considerable oscillations caused by seizing observed on the untreated TA6V were significantly reduced, or even eliminated by the MAO treatment.

on the subject before joining Naval Group. *"The technique adopted is micro-arc oxidation (MAO), a high-power plasma-assisted electrochemical process."* It has been studied for five years under a collaborative project (see box) led by IRT* M2P (Materials, Metallurgy and Processes). One of its high-profile members was the Safran aerospace group.

MAO enables a coat of low friction coefficient ceramic type oxide to be deposited on a surface. It has proven efficient for deposits of several hundred microns on aluminium. On titanium, the operation is more delicate and the maximum was a few tens of microns.

*ANR (Agence nationale de recherche): French National Research Agency.
**IRT(Institut de Recherche Technologique): French technological research institutes.

IMPROVING TRIBOLOGICAL PROPERTIES WITH MICRO-ARC OXIDATION

On the right, an uncoated titanium bearing which has undergone a contact wear test: it shows signs of material tearing characteristic of seizing.

On the left, the same bearing protected by MAO treatment, before performance of the wear test.

BROADENING RESEARCH FOR OTHER SURFACE TREATMENTS

"However, our dry and seawater friction tests showed that this thickness was sufficient" adds Aude Mathis. *"MAO treatment significantly lowers the friction coefficient, notably on TA6V, and reduces or even eliminates the tendency to seize."* However, this does not solve everything. MAO is a very energy consuming process which would be extremely expensive on an industrial scale. In addition, mechanical and fatigue tests have shown that the cohesion and adherence of the ceramic layer need to be improved. *"We will continue to study MAO, which is well-suited to our applications on parts of a few tens of square centimetres"* she concludes. *"At the same time, we aim to broaden our research to other types of surface treatments."*

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05

DATA PROCESSING

SUBMARINE NAVIGATION: THE DEPTH-CONTROL CHALLENGE

An autopilot is a major challenge for submarine navigation performance and the future development of autonomous underwater vehicles. Controlling the course, depth and heading of the ship in complete safety, using available data and despite only partial knowledge of the parameters: this is the purpose of a control algorithm developed by Naval Group, notably by the teams of its subsidiary Sirehna.

By helping to improve submarine navigation and increase the availability of its crew, the autopilot has become one of the key systems on these ships. It is also one of the most critical for operations, in particular for maintaining its immersion depth. At high navigation speeds, for example, a piloting failure can have serious consequences and the submarine could suddenly rise to the surface or dive beyond a depth that is critical to its integrity.

The design of a reliable and robust autopilot system is thus a major technical challenge for the automation specialists. One of the chief difficulties? Designing a control system while managing the uncertainties intrinsically present in the models used to develop on-board systems. The engineers at Sirehna are also working on innovative methods aimed at taking account of these uncertainties as precisely as possible.

AT THE HEART OF AUTOPILOT

At the heart of the piloting system lie the control laws determining a relationship between deviations from the submarine's instructions (heading, attitude, immersion) and the hydroplane and rudder gear commands. During design stages of control systems, the automation specialists use a dynamic model of the submarine. *"The dynamic model is the real key to design"* explains Julien Moresve, automation expert at Sirehna. *"It is based on equations describing its navigation behaviour. For example, they reflect how the speed of advance or the immersion of the ship changes when the hydroplanes or propeller rotation speed are modified. The precision of this model determines the accuracy of the simulations performed for the implementation of an autopilot."*

The submarine dynamic model used by Naval Group is a standardised model. It is theoretically capable of representing any submarine and uses about a hundred parameters, the identification of which enables the model to be adjusted to a particular ship. There are three main methods for defining a model. The first relies primarily on empirical data, such as the shape of the submarine. Although quick, it is not considered to be particularly reliable and is less and less used. The second consists in using numerical simulations of fluid mechanics, reproducing the hydrodynamics of the submarine. This gives better results than the empirical approach, but requires considerable computational resources.

FUNDAMENTALLY UNCERTAIN DYNAMIC MODELS

The third is based on measurements taken on submarine mock-ups, whose behaviour at sea can be recorded. These tests are generally longer and more costly than the empirical and numerical approaches, but provide data which, when combined with the simulation results, enable extremely precise dynamic models to be produced. *"However, the dynamic model of a submarine remains fundamentally uncertain, because the behaviour of the submarine is not frozen in time. It evolves in a changing environment, its load varies according to its missions and it undergoes the effects of ageing of its equipment and structures"* explains Julien Moresve.

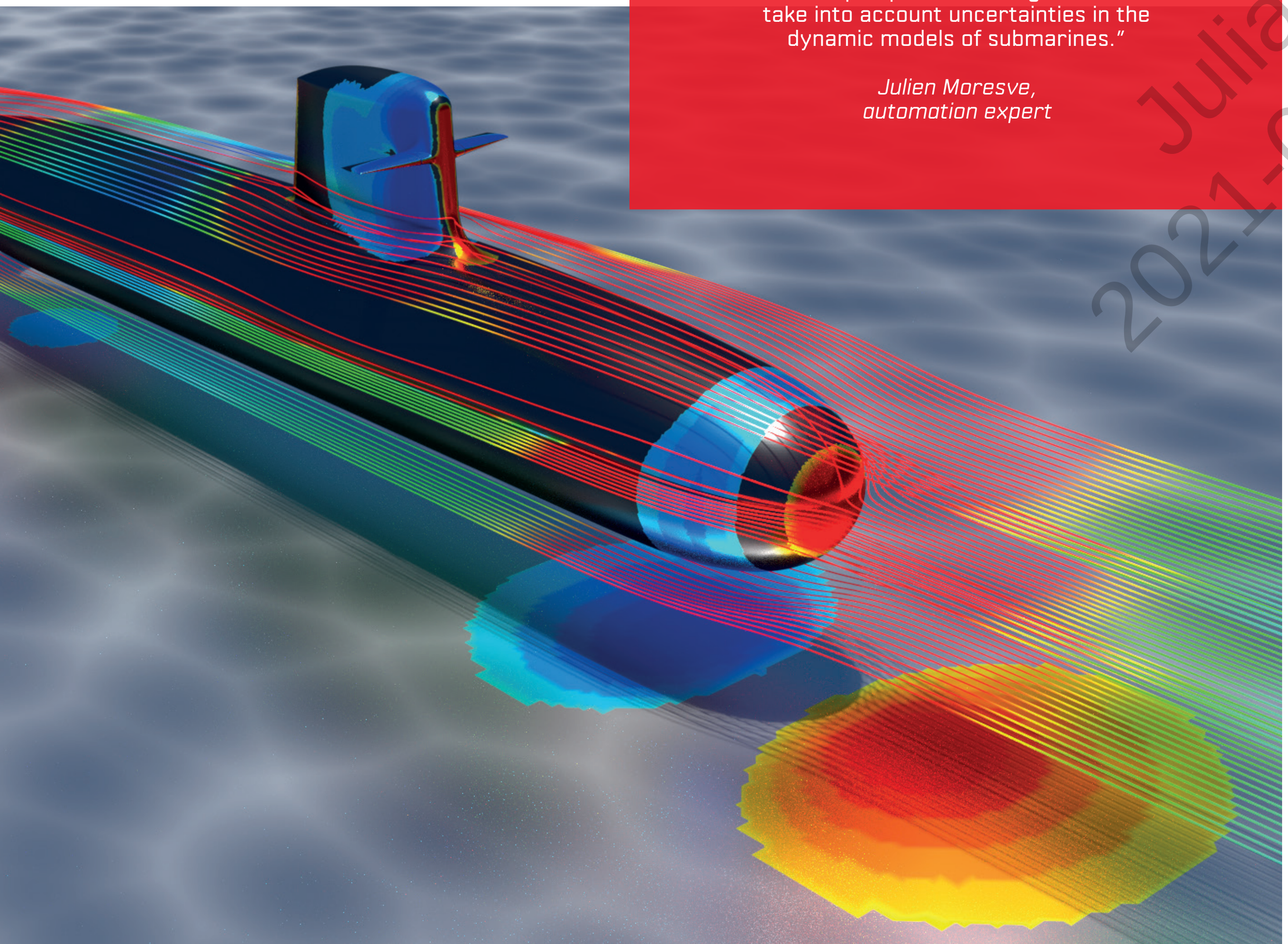
The specifications of the piloting system, which define the constraints and performance requirements, also contain a part of uncertainty. They can be expressed in a general manner (for example maintain heading and depth without bias or without exceeding given turning circle or attitude conditions) or more specifically, using templates to be adhered to. For the expert, *"these specifications for example make it possible to control the sensitivity of the submarine's states as a function of the frequency of the disturbances to which it is subjected. For example, one can thus control the frequency at which the submarine's hydroplanes and rudder are excited in order to increase its acoustic discretion."*

"The 'guaranteed simulation' methods will help develop real-time navigation systems."

Alexandre Lefort, automation research engineer

"We develop depth control algorithms which take into account uncertainties in the dynamic models of submarines."

Julien Moresve, automation expert



INTERVAL ANALYSIS, A VALUABLE TOOL FOR AUTOMATION SPECIALISTS

In order to manage the uncertainties of the dynamic models, the Advanced Automation and Dynamics department at Sirehna is developing an innovative design method. *"The idea is to produce control laws which meet all the constraints imposed by their specifications, whatever the uncertainties of the model in a specified domain"* explains Alexandre Lefort, research engineer in charge of these researches, part of a CIFRE* thesis with ENSTA Bretagne** (marine robotics STIC laboratory team headed by Benoit Clément). *"The key-tool in this innovation is the so-called 'interval analysis'. In the equations and algorithms of the dynamic model, numbers are replaced by intervals. The calculation results are thus valid for a range of values rather than simply for point values. In theory, this enables all the uncertainties in the model to be taken into account."*
The control law generated is then validated by an "interval guaranteed simulation" algorithm. In the calculation, the aim is to evolve the uncertain dynamic model of the submarine equipped with the synthesised pilot. The guaranteed simulation determines a range in which the submarine navigates with certainty; it is then checked that the pilot's requirements are adhered to for all the uncertainties considered.
This method is of particular interest for the submarine design process. In these early stages, the uncertainties on the input data are considerable and the designers could hesitate between widely differing designs. With the interval analysis, it becomes possible to design control laws with formally guaranteed performance for this entire range. The method can provide the architects with valuable information about the achievable performance and sometimes leads to very early consolidation of certain design choices.

*In France, the so-called "CIFRE programme" supports Ph.D. students to pursue doctoral studies within industrial compagnies, in collaboration with universities.
**ENSTA Bretagne (École nationale supérieure de techniques avancées de Bretagne): Brittany National School for Advanced Techniques.

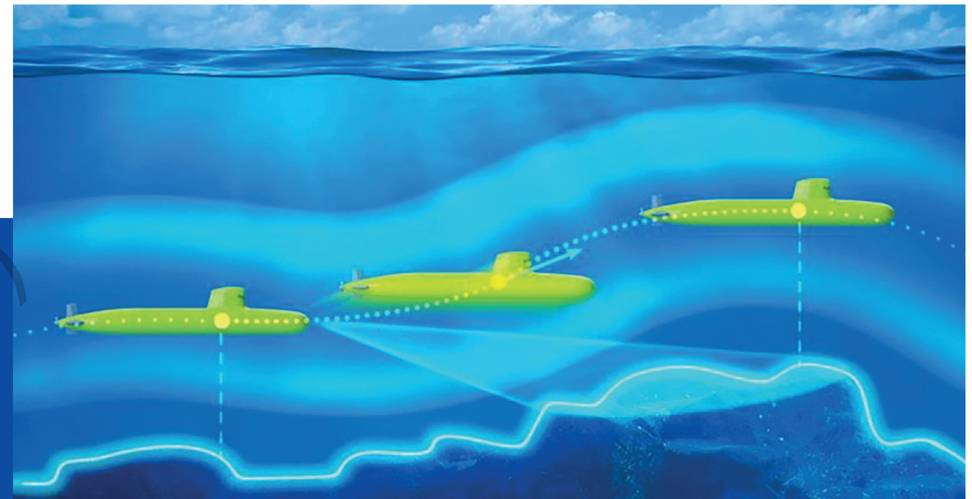
PROMISING APPLICATIONS FOR NAVAL GROUP

"This also helps consolidate future tests on mock-ups, whose behaviour is by definition poorly known, by preserving their control laws" states Alexandre Lefort. *"As the knowledge of the submarine model becomes fine-tuned, the uncertainties are reduced and it is then possible to find a new control law at least as efficient as the initial law"*. When deployed in conjunction with artificial intelligence programs, the interval analysis tools could have promising applications in the future. As the engineer and Ph.D. student explains, *"an adaptive control law, using neural networks, could choose its proposals from a range of controllers with performance validated by formal interval methods, which would improve its robustness."*

Guaranteed simulation tools could eventually also be carried on board and the Commanding Officer will then be able to anticipate the effect of his orders on navigation. Guaranteed simulation will then produce all the submarine's possible courses, taking account of the uncertainties on its dynamics: the system will then become a true real-time navigation aid.

GUARANTEED SIMULATION TOOLS ON BOARD

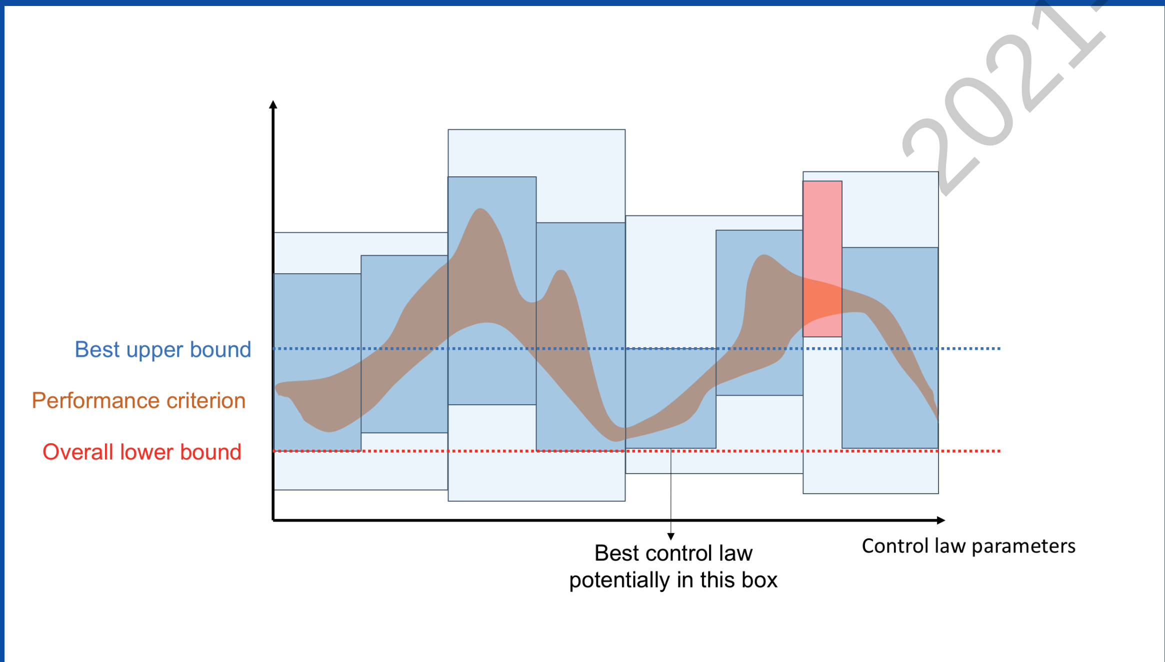
The guaranteed simulation tools could eventually be carried on-board submarines. They will then give valuable information about the course over the coming minutes, taking account of the control law, uncertainties in the submarine dynamics and sensors. According to certain hypotheses, it will thus be possible to insert this course within a "guaranteed navigation tube", to be compared with the authorised immersion-speed domain.



WHAT IS INTERVAL ANALYSIS?

Interval analysis consists in replacing the values of the parameters of the dynamic model by intervals within which they vary, which enables a whole class of models to be considered rather than a single model. The size of these intervals depends on the level of uncertainty and the confidence in the identification method which is used to establish the value of the model's parameters. Similarly, the specifications of the piloting system are translated into mathematical criteria, which enables the design constraints, and their uncertainties, to be taken into account.

The generation of the control law then becomes a "constrained optimisation" problem formulated on performance criteria. The constraints, expressed in the form of formal equations, are integrated into an optimisation algorithm termed "interval branch and bound algorithm". The latter enables an overall solution to be found, one that is guaranteed for all the model uncertainties considered in the optimisation problem.



PRINCIPLES OF THE "INTERVAL BRANCH AND BOUND" ALGORITHM

The performance criterion is evaluated on increasingly small intervals, within which the values of the control law parameters evolve. The interval evaluation gives a guaranteed framework for the real value of the criterion (blue boxes). For a given set of control laws, the algorithm - which uses successive steps - only chooses those with the best performance. At each step, an upper bound is calculated for the performance criterion evaluation, for all the intervals considered. If the lower bound of one of these boxes is greater than this value, this means that all the control laws it contains are less efficient than this bound and they can thus be deleted. Eventually, only a small number of boxes containing the optimal controllers will remain.

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SURVEILLANCE: SEEING AND RECOGNISING USING "LEARNING" ALGORITHMS

The use of cameras for maritime surveillance is now widespread. To differentiate between nearby surface ships using images taken – thus avoiding all false alerts – Naval Group is developing algorithms for video extraction, course tracking and classification of listed elements. The engineers who initiated this work are concentrating on the reliability of these algorithms, now available as prototypes.

Whether on-shore or on-board, maritime surveillance cameras can now be used to obtain information going far beyond what can be seen by the human eye. They use image processing and a series of algorithms capable of determining courses (positions, speeds, etc.) and the identity of listed elements. This "smart surveillance" can be used in numerous situations, such as management of port activities, collision prevention, obstacle avoidance, detection of abnormal behaviour, or anti-piracy measures. The promise is the following: to provide increasingly efficient decision-making aids and, eventually, consider autonomous navigation.

A RELIABLE BACKGROUND ABSTRACTION METHOD

In order to see and recognise a ship, the image analysis proceeds with several steps. The images obtained are first of all processed in order to establish the presence of any mobile elements. If it is to be reliable and robust in a marine environment, this first extraction phase must take account of numerous natural, complex and unpredictable phenomena which alter the images over a period of time. These, for example, comprise light variations, wave movement, wind and ship's wakes which all complicate image processing. These phenomena need to be controlled in order to be able to detect the presence of ships without exceeding an acceptable level of false detections.
Over a period of time, the processing of the detections in successive images makes it possible to deduce the course of the objects identified and to discard those with unrealistic movements.

Finally, a third stage is to identify the class to which the possible ships belong. All these processing steps allow the use of visual data for fully autonomous mission performance, such as for example deciding on what manoeuvres to carry out if there is a risk of collision. With a fixed camera, simple and efficient video extraction is possible by "background abstraction". This method enables the background of the scene to be separated from the potentially interesting objects in the foreground and has therefore been extensively used in traffic monitoring or people tracking applications. It has been adapted to a marine environment by the Naval Research CEMIS*/3A team to take account of a dynamic background. Despite changing parameters, such as waves on the surface of the water or wind-induced camera vibrations, its reliability has been established.

*CEMIS: Naval Group's center of expertise and management of information and signatures.

SURVEILLANCE AT SEA

Cameras can be used to detect an obstacle or a ship and determine its course, but also to identify to which class of ship it belongs, using a recognition algorithm based on machine learning.

A SINGLE CAMERA FOR ESTIMATING COURSES

The background is thus explicitly modelled by a linear dynamic system, which monitors the brightness of each pixel and isolates groups of pixels with brightness different from that of the surface of the water. The difficulty of this operation is clear when one considers waves or reflections on the surface of the water! It is nonetheless possible, by means of mathematical processing using a robust "Kalman filter", also optimised by experts from Naval Research.
When isolated from the background, the particular pixel groups corresponding to the various objects are created. They are then processed by an algorithm which is able to track them and filter false alarms. *"Our method can estimate the course of objects on the surface of the water with a single camera"* explains Dann Laneuville, senior expert in information processing systems algorithms at CEMIS. *"To expand the process to airborne objects, a number of distributed cameras are required."*
With an on-board camera on a ship or drone, the observation point changes permanently and it is no longer possible to extract moving objects by background abstraction. It is then necessary to adopt an appropriate extraction method that is more complex. The latter detects the pixels for which the movement is different from that of the overall optical stream, owing to the movement of the camera, observed between two consecutive images. These pixels are then grouped using a sophisticated clustering algorithm.

THE VIDEO EXTRACTION PROGRAMMES WILL SOON BE IMPROVED

"As this on-board camera detection algorithm is complex, it requires the considerable computing capacity today available with graphic processing units (GPU)", points out Adrien Nègre, research engineer at CEMIS. This new algorithm, which is currently a prototype, will very soon be integrated into the video extraction and tracking programmes developed by Naval Group. In parallel, a learning extraction technique is currently being studied for fixed objects (buoys, etc.) and will supplement the video extractor developed.

The use of video data could be taken even further, by adding recognition of the type of ship identified and tracked. This is the challenge being addressed by Quentin Oliveau, research engineer at CEMIS, using a new algorithm to identify the class of the ship. This algorithm, based on automatic learning techniques, can transfer each group of pixels concerned into a vector (a table of numbers), which will then be associated with a class of ship according to its characteristics. The operator would then, for example, be able to accurately determine whether the track on the screen is that of a sailing yacht, a fishing boat, a container carrier or a military ship.

A LEARNING ALGORITHM

"Even if ship recognition is a relatively simple concept, the algorithm it uses is particularly sophisticated as it improves its performance through learning" emphasises Quentin Oliveau. The algorithm transforms the images into a "signature" enabling the examples of different categories to be separated.
This transformation can be performed by "supervised" or "semi-supervised' algorithms, which are different in that they integrate unlabelled images into the learning process. This integration nonetheless requires that assumptions be made about their nature. Explanation: provide the algorithm with a series of images of well identified ships, thus creating an inventory of reference vectors (with front, side or top views depending on the utilisation context), then supplement with images of unclassified ships... and it will itself calculate into which category these new ships should be placed, by "comparison" between the calculated vectors and the vectors in its basic "library".
The algorithm thus succeeds in making this prediction itself, by learning from annotated images, even if these images are few in number, as can be the case for new ships or strategic ships, which are rarely photographed.

"For the automatic recognition of ships at sea, we develop an algorithm that improves on its own thanks to 'machine learning' techniques."

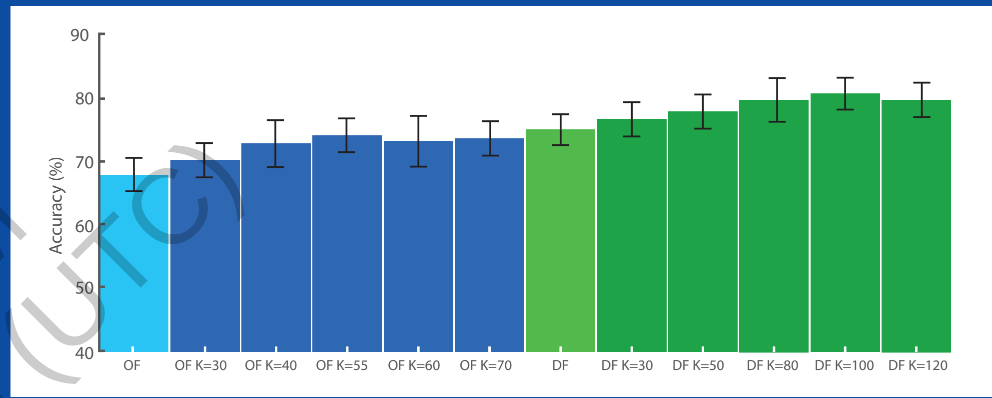
Quentin Oliveau, research engineer in algorithms

SIRENHA PLATFORM IN OPERATION TO TEST SOME ALGORITHMS DEVELOPED BY NAVAL GROUP

*CEMIS: Naval Group's Centre of Expertise and Management of Information and Signatures.

A LEARNING ALGORITHM

The recognition tool developed by Naval Group is based on algorithms originally developed for civil applications. When applied to the naval field, the tool uses a learning technique exploiting a set of ship images associated with their categories (freighter, sailing yacht, fishing boat, etc.). The algorithm uses these databases to learn characteristics, which are not necessarily interpretable, enabling it to recognise these different types of ships.
The difficulty of the problem lies, on the one hand, in variations within the categories: a sailing yacht may have one or more masts, raise its sails or leave them furled, etc. and, on the other, in the considerable similarities between categories: the different types of commercial ships, such as oil tankers and freighters, are very similar. The greater the number of annotated images, the better the performance of this algorithm. In the future, the algorithm's learning phase will be improved by taking advantage of a larger database, including data produced by realistic image simulators.



LEARNING PERFORMANCES OF THE ALGORITHM

The figure shows the correct classification rate obtained on a ship detection problem using images (OF and DF indicates two ways of describing them). The OF and DF columns represent reference values obtained after learning on these two types of representations. The other columns correspond to the results obtained after attributes learning, following the algorithm proposed by different numbers of attributes [noted K]. It can be seen that attributes learning improves the performance obtained with the reference method and that the correct classification rate tends to increase with the number of attributes.

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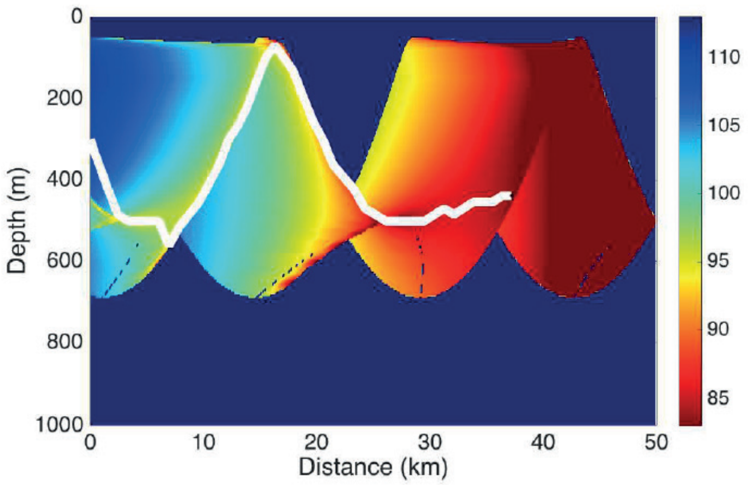
OPTIMISED LISTENING AND TRACKING, WITHOUT BEING HEARD!

In order to detect and accurately locate a ship solely from acoustic waves reception, a submarine must be able to position itself with respect to its target and adapt its course to optimise its tracking. This optimisation, combined with the constraint to avoid being detected, is one of the research topics of Dann Laneuville and Adrien Nègre, research engineers at Naval Research, in partnership with experts from Inria Bordeaux. Their goal: to produce a trajectory calculation algorithm for the submarine, which is both pertinent and effective in the presence of possibly multiple targets.

With its passive sonar, a submarine has acoustic measurements for locating ships around it, by means of a so-called "Passive Target Motion Analysis" (TPA) algorithm. By capturing sounds emitted by noise sources, the sonar can deduce the direction from which they come at any given time. In certain conditions, the tracking algorithm can then locate the ships by time integration of these directions.
That's the theory. In practice, the acoustic data are uncertain because sound propagation through water varies according to the environment. For example, the temperature of the water, which differs according to the depth, or the nature of the seabed, influence the wave propagation, which may occur along curved paths, thus creating areas of silence where detection is impossible (see figure).



EXAMPLE OF PROPAGATION AND SIGNAL LOSS DIAGRAM

The diagram is given for a sound source situated at a depth of 500 m and a range of 35 km from the carrier, whose initial immersion depth is 300 m. The colour shows the level of signal loss in decibel versus the range (horizontal axis) and depth (vertical axis). The white curve represents the depth trajectory calculated by the algorithm according to an "optimised listening" criterion, which involves minimising the signal loss and placing the submarine in the red zone.

CONTROL BASED ON A "COST FUNCTION"

In order to locate a noise source without itself being detected, a submarine must be able to move and manoeuvre vertically and horizontally. The challenge? Triangulate the information received from the emission directions and determine the position of the noise maker by integrating it over time. At the same time, it must adjust its own depth in order to receive the echoes emitted by the contact – while attempting to prevent its own sound echo being perceived by the target ship with an "acoustic advantage" type criterion. The work accomplished at Naval Research addressed this first aspect by developing a specific algorithm. The latter analyses the data, taking account of a set of uncertain variables, such as the environment and position of the target, which are be estimated by trajectory algorithm such as TPA. It thus controls the depth of the submarine using a "cost function" based on the sound level propagation diagram. The aim is then to find the minimum values of this function, based on input data such as the submarine position and speed, and the estimated target position, while taking account of environmental data (velocity profile, depth and type of seabed, etc.). The control trajectory order is then calculated in real-time, so as to optimise the submarine's depth track.

RAPID PROVISION OF KEY DATA

One of the difficulties of this method is the cost function's dependence on the distance between the submarine and the target ship. This data is unknown when the first echo is received. Later on, it remains uncertain because it is theoretically using a contact motion analysis function. To take these uncertainties into account, the method draws on the formalism of the so-called "Markov Decision Processes" (MDP), adapted to the context of optimum control in the presence of uncertainties. The numerical resolution of the MDP uses the principle of finite horizon dynamic programming and the algorithm can be split into several phases (see diagram in box), which allow real-time determination of the subsequent optimum depth commands to be applied to the submarine over time.

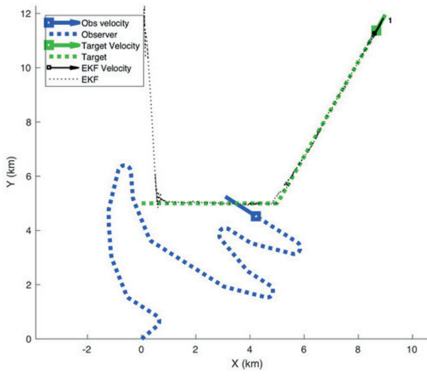
The process is far from over: the aim is then to optimise the course to be followed to best determine the position and range of a noise-maker moving linearly at constant speed. This point is, at least in theory, relatively simple; one must position oneself behind the noise-maker while zig-zagging horizontally around its course. *"In practice, and notably when the position and motion of the target are initially undetermined, this principle can be implemented thanks to an algorithm capable of determining the correct initial manoeuvre to be carried out. The aim is to obtain reliable and precise information on the position and behaviour of the target as quickly as possible, despite considerable uncertainties"* explains Dann Laneuville.

"We are developing an algorithm capable of producing reliable and accurate data on a target, despite uncertainties on its course."

Dann Laneuville, algorithm expert

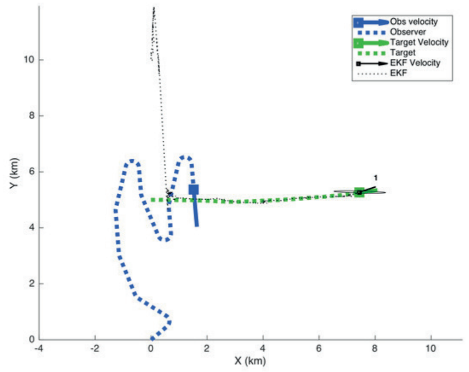
A SHIP'S COURSE CHARACTERISED IN 30 SECONDS

The methodology described above is then used, but with a different cost function – it uses the change of the angle under which the target is seen, rather than the loss of signal level, and it produces a heading rather than a depth command. The algorithm then proposes an optimum trajectory as of the first moments of tracking (see figures).



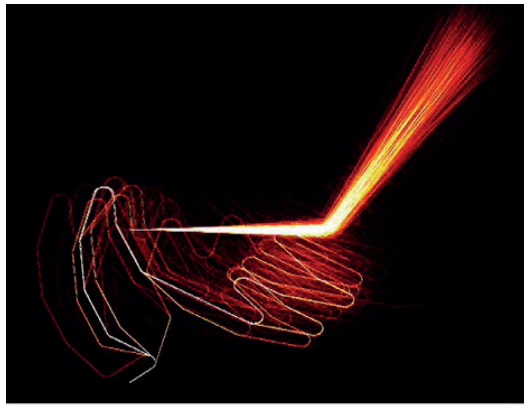
AN EXAMPLE OF TRAJECTORY ANALYSIS CALCULATED FOR A TARGET WITH QUASI-UNIFORM MOTION

The figure indicates that the motion analysis algorithm converges immediately after the first manoeuvre; the trajectory calculated for the submarine comes very rapidly close to the best theoretical trajectory.



AN EXAMPLE OF TRACKING OF A MANOEUVRING TARGET

As soon as the target manoeuvres, the control tends to reposition the submarine in the optimal configuration, that is by zig-zagging behind it.



AN EXAMPLE OF MONTE-CARLO TYPE SIMULATION

The dotted yellow lines represent a random selection of the possible trajectories of the target in the (x,y) plane. The dotted yellow lines represent all the optimum trajectories calculated by the algorithm to best evaluate each of the target's trajectories.

"So, despite the uncertain initial conditions, the algorithm is able to elaborate a trajectory command enabling the movement of the target ship to be located and characterised in 30 seconds" emphasises Adrien Nègre. These numerical optimum trajectory calculation methods were then tested in several configurations, for example integrating a target which is manoeuvring and using so-called "Monte-Carlo" simulations (see figure). They demonstrated their ability to numerically resolve this complex problem reliably, despite all the uncertainty surrounding the data.

What is the next step in this work? Researches will focus on accounting for constraints regarding the submarine's heading control, for instance to evaluate the influence of the "baffle" (a conical blind zone aft of the submarine) of a cylindrical hull antenna, so that the command does not place the target in the sonar's blind zone.

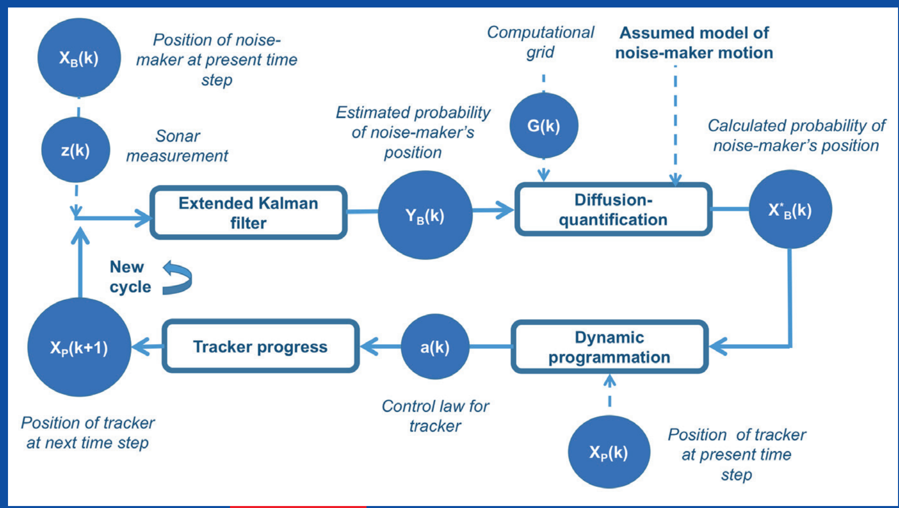
A COMBINATION OF VARIOUS ELEMENTARY ALGORITHMS

Naval Group researchers have developed an algorithm capable of finding a control law defining an optimal trajectory for a submarine tracking a target. The diagram next page illustrates its principle.

The control law is built up iteratively at various moments of an observation horizon. At any given moment, a sonar measurement [noted z(k)] gives the position of the noise maker [noted XB(k)], while that of the tracking submarine is known [noted XP(k)]. A set of possible target trajectories is produced from this measurement by means of a so-called "Extended Kalman Filter" (EFK). These are represented by a probability density [noted YB(k)] characterised by statistical values, such as the mean or the variance, which are evaluated using the Kalman filter.

The extrapolated movement of the target is then described by its "prediction equation" which estimates its future positions. As calculating an exact solution to this equation proves very difficult, it is resolved using a numerical method. The probability of the target position [noted X*B(k)] is therefore calculated at different moments, on a set of points constituting a "grid" [noted G(k)]. The trajectory of the target is thus represented as a so-called "Finite-State Markov Chain". This step, referred to as "diffusion and quantification" is thus able to calculate the most probable trajectories in each grid.

The aim is then to find a control law which adjusts the navigation of the tracking submarine to that of its target. The command to be found aims to optimise detection of the target over the observation horizon. It is obtained by minimising the variations in the relative angular position of the noise maker and tracker. This operation is carried out by a so-called "finite horizon dynamic programming" method: starting from the final moment of the observation horizon, the algorithm gradually back-tracks to the current moment to find the rudder angle control sequence. The control law thus obtained [noted a(k)] is applied to the submarine, which reaches a new position at the next moment [noted XP(k+1)]. A new cycle is repeated and begins with measurement of the position of the noise-maker.



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