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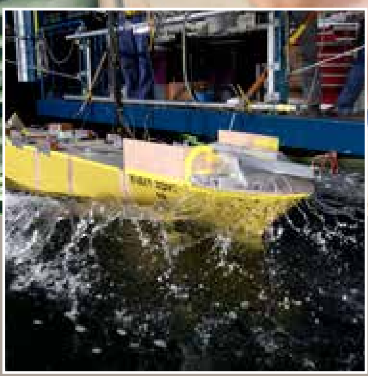
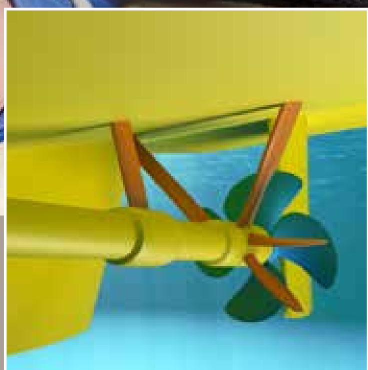
MARIN

report

CRS
Cooperative Research Ships
50 years of Commitment, Relevance & Sharing





Tackling the challenge of hydro-structural response **Propulsion design: from propeller analysis to integrated, propeller-aft body design** Five decades of research into manoeuvrability

report

colophon

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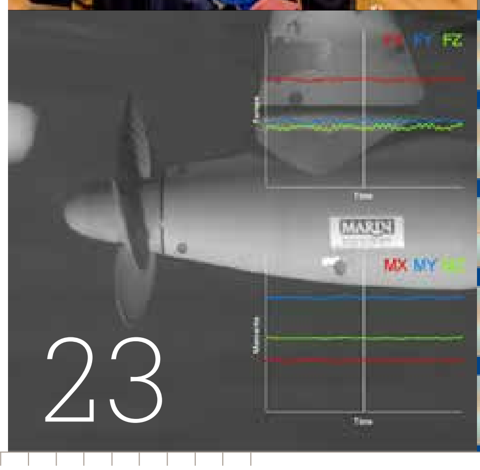
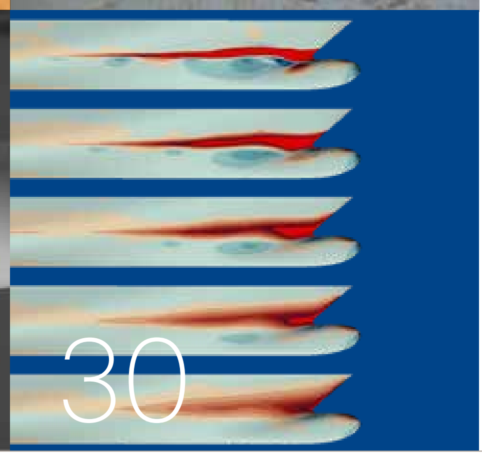




Dear Reader,

It has no office. It has no personnel. It has no director. But it exists and it has flourished for 50 years: The Cooperative Research Ships (CRS). This Report presents its simple secret: cooperation by committed people.

Public-Private Partnership (PPS) is popular nowadays. But it often means a lot of talking, paperwork and complex governance. It seems to require directors and offices.

CRS is different. For 50 years now, 20-25 maritime organisations perform research in the maritime field together for a yearly budget of around € 1.5 million Euros. Typically 10 working groups investigate topics that are of common interest to its members. CRS brings together shipyards, ship owners, navies, equipment suppliers, classification societies and research organisations. All just based on a gentlemen's agreement (the 'CRS Guidelines') and joint decision-making at the Open Meeting and Annual General Meeting. A simple organisation to stimulate complex research.

The CRS is real cooperative research. Members are not just paying their yearly fee: they are expected to be actively involved in the research work itself. So all the CRS members perform tasks in research projects, participate actively in working groups and form a network of specialists. An open network, where even competitors are willing to share knowledge and experience.

For its members CRS provides a maritime knowledge base, practical tools and improved insight into design technology and operational performance.

Over the years, CRS has become a unique community, in which sharing and cooperation are normal. It has created friendships based on the large commitment of the people and companies involved.

The cooperation in CRS is essential to make ships cleaner, safer, smarter and more efficient. In that respect, CRS is the perfect Public-Private Partner*ship*!

Bas Buchner
President

From left to right: Do Ligtelijn, Ed van Daalen, Marinus Oosterveld and Jan Blok

Cooperative Research Ships celebrates 50th anniversary!

As relevant today as it was in 1969

As Cooperative Research Ships (CRS) celebrates its 50th anniversary, we talk to some of MARIN's key figures – both past and present - about this unique alliance, which has carried out more than 100 ground-breaking projects.

Marinus Oosterveld, former President of MARIN, joined the research institute in 1961. In 1969 two of the 'CRS founding fathers' – Kockums shipyard of Malmö (Sweden) and Chantiers de l'Atlantique of St. Nazaire (France) – asked him to organise the first formal CRS event. Marinus became the first chairman of CRS until his retirement in 1996.

At that time there was simply no cooperation between the shipyards, ship owners or classification societies, he explains. "They never talked to each other. But then when they started to make contact through CRS and even with their competitors, they realised that they are all human beings!" he laughs.

Early days of CRS – increasing size of ships The real impetus in the early days of CRS was to get a group together so there could be 'a meeting of minds' about the ever-increasing size of ships. "Given the growing size of the ships, tankers in particular, it was getting difficult to solve problems. It was unknown territory for everyone." The first working group addressed the powering performance and motions in waves of full block ships with a low length-to-breadth ratio.

Jan Blok joined MARIN in 1974 and has been involved in numerous CRS working groups. In 2004 he was appointed Secretary of CRS. He worked within the organisation until his retirement from MARIN in 2009.

Jan comments: "Tankers had been roughly the same size until the 1950s, and then they were lengthened substantially in the sixties and we saw the super tankers arrive. They pretty much leapt from just 50,000 tonnes to half a million tonnes in 16 years! Steel plate thickness increased from 15 mm to 35 mm. I think this scared the hell out of designers and university researchers. There was a tremendous technical drive to address this development."

Do Ligtelijn agrees. Do spent his early career with propeller company Lips and he then joined MARIN in late 1978. He was a member of the CRS community on behalf of Lips in 1977 and 1978, and continued this on behalf of MARIN from 1979 to 1997. Do specialised in cavitation and related topics, and moved back to Lips (taken over by Wärtsilä in 2002) from 1998 until 2013, re-joining CRS from 2005 on. After his early retirement from Wärtsilä he became a part-time consultant on propellers and cavitation at MARIN, and officially retired in August last year.

"When looking back, like Jan said, it took indeed around a decade for the size of the ships to increase from 100,000 tonnes to 500,000 tonnes, when Chantiers, Kockums and other yards (for instance some of the major Japanese yards) started building super tankers. But of course, this fast increase in size was not only a yard issue: also Class had never seen anything like it, and had to develop rules for such ships."

Marinus points to a congress in the Netherlands at the time, which examined whether 200,000-tonne tankers could enter the access channel of the port of Rotterdam in only a 72-foot depth. "There was a lot of speculation that we would need a 1 million-tonne dock (which was actually built in Rotterdam later on by Verolme shipyards), but ultimately, the tankers never grew beyond 500,000 tonnes." However, these types of issues were very much the topics of the day, Jan says. And it is understandable how CRS started to develop around the topic of large tankers, given this revolution taking place in the industry, they add.

And this development was reflected in the membership. Marinus points out that there has been a significant change over the decades. Of the 14 organisations that were members in the first decade, nine were shipyards. Do adds: "When I joined in 1977, CRS members were either the builders of large tankers in Japan and Europe, the owners or the classification societies which had to deal with these tankers."

New developments – new members These days there are 23 members and the Group is much more diverse, and includes research institutes, classification societies, suppliers, yards, model basins and navies.

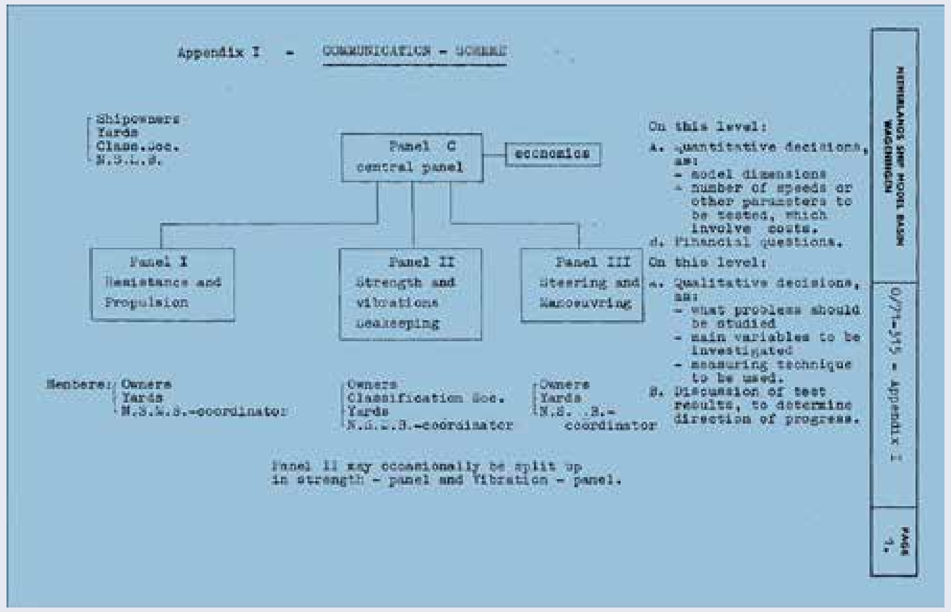
However it still retains the original spirit, Jan emphasises. "There are no real 'laws' in CRS. We are pretty much a lawless bunch," he laughs. CRS is not a regulatory or an advisory body. Do emphasises: "There is no bureaucracy or management layers - people remain members because CRS delivers results, and they can use them in their day-to-day business."

Ed van Daalen, the current CRS Secretary, says: "All the results of the research goes to members only and then it is up to them how the information is disseminated. Results are confidential and the property of the members."

And although it is half a century old, CRS still retains much of the original structure. The annual membership fee is 65,000 Euros. New members pay an entrance fee of 32,500 Euros and this gives them access to all the results of the current projects and their findings. In early June, CRS has its Open Meeting, whereby members discuss ideas for new projects. Then at the end of year the Annual General Meeting is held and the members decide which ideas they want to take on as research projects and how much funding they will get. Working groups take the projects forward. Members all benefit from the annual, 1.5 million Euro budget, and this leverage is especially important in a world where R&D departments are often shrinking.

Although over the five decades the membership numbers have remained relatively stable, there has been quite some change in the subjects being addressed.

Do summarises: "Until 1985, CRS mostly focused on large ships, whether this



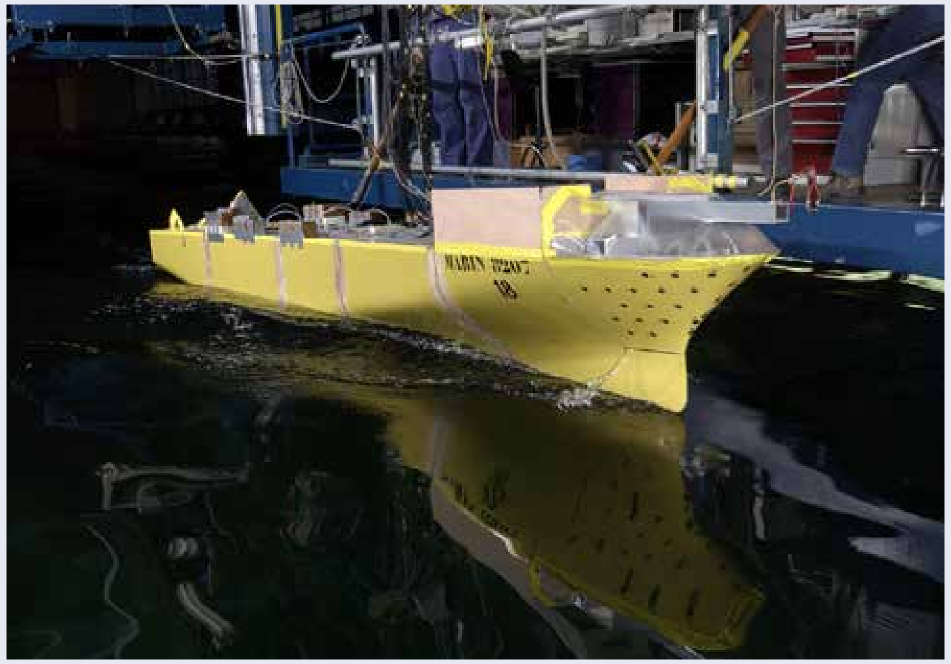
Blueprint of CRS: communication scheme of Large Tankers project (1971) concerned structural strength, motions or powering. At that time we were talking about 8-9 metre propellers, much higher power and consequently more cavitation, compared to what the maritime community was used to.” In that period CRS performed mostly experimental work at full scale, but also at model scale.

Then followed a period of about a decade during which specific phenomena were addressed that were also important for other types of ships - strength issues, manoeuvring, cavitation etc. That work was mainly conducted at model scale.

Stability is one such phenomenon and CRS has had several working groups looking at this issue over the years. Jan comments: “I think stability has always been a little neglected historically. In the 1990s stability issues were highlighted as the shape and size of ships changed. We had rolling and heeling problems on high-speed container-ships sailing in following seas. These ships, which were 300 m + long, and could be sailing with a full stack of TEU and yet for the stability calculations, we were using the same formula that was used in the 1800s!”

Computer codes CRS has also studied this issue for various navies, as frigates have similar problems. “What is the ultimate stability, the moment just before capsizing? We clearly can’t do this by model tests or at full scale,” Do says. The big boost in solving these issues came with the development of computer codes and these were applied in the various CRS projects, he adds.

Being typically modest, they don’t like to boast of CRS’ achievements. But Do does say, stability is perhaps one area where it is possible to see where CRS has made a difference. Projects have led to improved design procedures and the classification societies have then used the findings to improve stability rules. “This is especially important in the early design stage. CRS members can perhaps estimate the power requirements better and play with the ship dimensions, and this is all before the design is offered to the customer. The members integrate the results in their daily business and that is the beauty of CRS.”



Model test with a segmented ferry using a flexible backbone, ELAST project (1990)

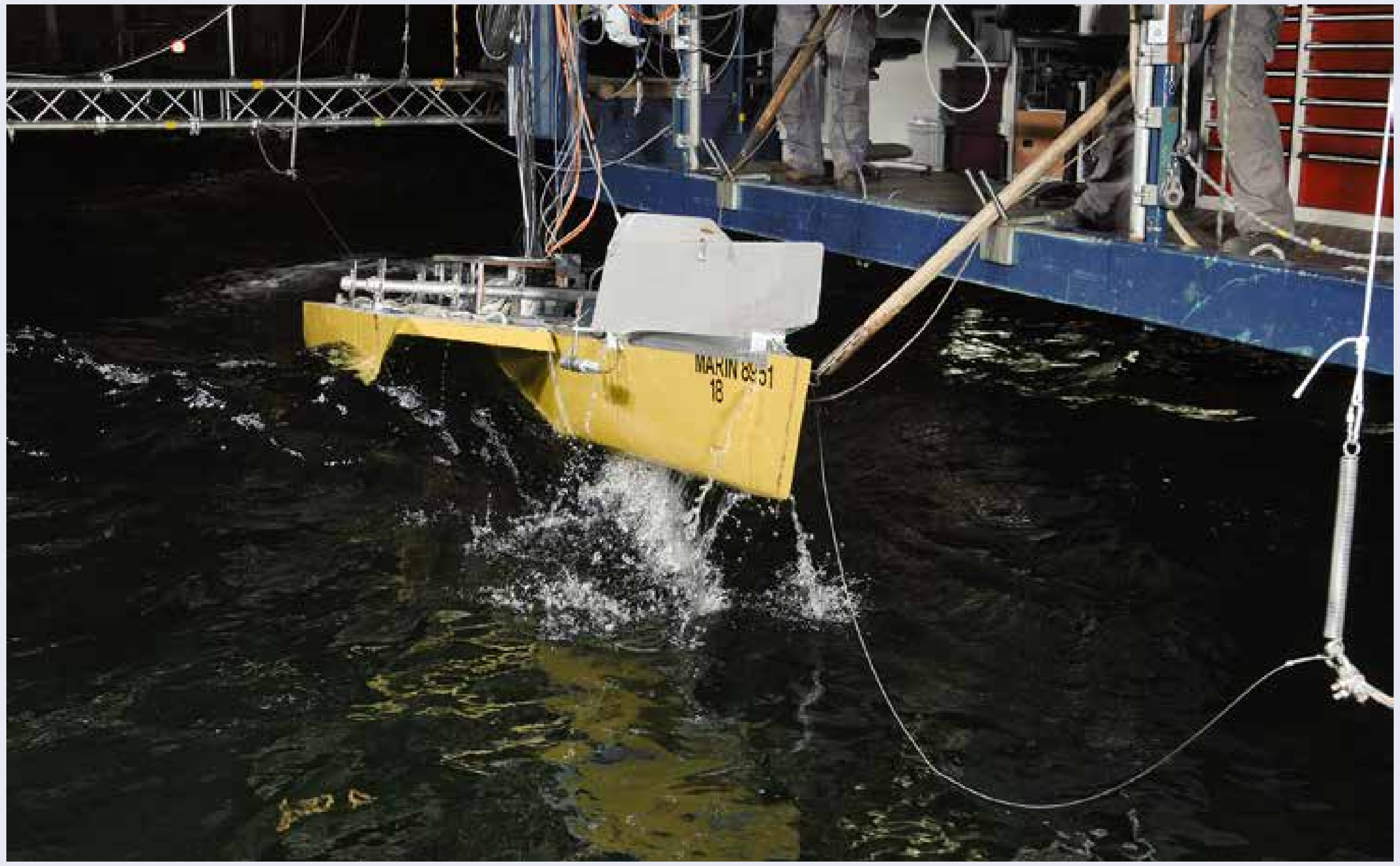
Between 1985-2010 there was much interest in design methods for various ship types. “The CRS working groups were examining design methods for ships like fast monohulls, catamarans, trimarans and SWATH ships.” From around the mid-nineties we moved on towards applying more computer simulations and developing software tools, thereby replacing much of the experimental work at model scale, he says. At the same time, the interest in experiments at full scale has increased, as this is important to validate predictions made by computational tools, adds Do.

Industry revolutions Additionally, CRS also addresses ‘ad hoc’ problems such as what happens in a crash stop situation with fixed pitch high skew propellers. Soon after the oil spill of the Exxon Valdez in Alaska, CRS performed a working group which investigated various alternative designs of oil tankers, aiming at preventing an oil spill after collission or grounding.”

The MARIN team says that CRS has an important role in bringing the ‘outer industry revolutions’ into daily practice.

Jan explains: “There is always the drive from outside, for instance if you consider the game-changing computer developments. In the future we maybe ask, ‘Can we get a ship out of a 3D printer? Is this viable?’ ” And although of course, this is not likely, he says computer developments have made a huge difference. “Consider CFD, this was a massive leap forward. Previously we would have to consider dividing vessels into 20 sections, and make calculations for each of these, but now I believe computers can calculate 1 million panels! Perhaps we even get to the situation when we can calculate motions of individual molecules. But then we have an abundance of data, too much. But at CRS we always have to make ourselves familiar with new ideas.”

CFD Do agrees: “At CRS we have always been somewhat dependent on computer hardware, which was in its infancy in the early days. Then in the 1990s software became more powerful, which made cavitation calculations possible. Strong computers are needed and we now have a substantial cluster at MARIN. But previously everything was solved analytically.”



Trimaran seakeeping tests for the TRIMAR project (2010)

Relevance of CRS Commenting on how CRS findings are used, Ed stresses: “The results from CRS projects come in many forms: design guidelines and software to name a few. These results end up on the desks of people working for the member companies, whether they are involved in model testing, designing, class regulations… We are all trying these concepts out and they infiltrate our everyday business. Ultimately, the research that we do should contribute to designing, building and operating better ships.”

Undoubtedly, they all agree that CRS plays a valuable role in improving the maritime world.

Cooperation is key Jan says that he has been involved in CRS and many commercial projects. “When sitting in MARIN’s towing basin with clients you absorb this knowledge and a lot of this was acquired in CRS. It has improved my knowledge and how I could help clients. CRS deals with real issues, and incorporates input from ship crews, designers etc.” Do supports this view, adding: “CRS for sure enriches my function as a project manager and in turn, it helps MARIN’s customers.”

Additionally personal contacts are very important, they stress. “Forming relationships is vital. Members in CRS are talking to competitors, and we know we can call on each other to help solve the most complex issues.” Jan adds: “We know who to contact, a personal relationship always helps and you know they are all extremely knowledgeable people.”

Going forward Ed stresses that it is vital to remain relevant for end users, with the right topics and at the right pace of research, as new developments go much faster these days. Marinus adds that CRS has broadened its topics and membership in order to stay relevant, and emphasises that MARIN should maintain its role as the facilitator, at the hub of the organisation. Do stresses: “CRS has to deliver results so people still want to join.”

They all conclude: “CRS is about research of the members, by the members, for the members. The spirit of cooperation is key!”

From left to right: Tobias Huuva, Loic Morand, Olav Rognebakke

Three working group chairmen reflect on 50 years of CRS success

With decades of experience between them, three longstanding chairmen share their thoughts on the importance of CRS to the maritime industry. In a typical lively CRS manner, they discuss the benefits, but also the possible areas for improvement, as well as answering the question as to whether CRS can stay ahead of the curve and even reach its centenary!

What made you get involved in CRS originally?

Olav Rognebakke, Chairman of RAW++ (Added Resistance in Waves) and Head of Section at DNV GL: "I was brought along to a meeting in the first year of joining my company. I wanted to get to know some people. It was quite an experience and that was already 12 years ago!"

Tobias Huuva, Chairman of SHARCS2 (CFD for Cavitation) and Manager Core Competence Team at Caterpillar Propulsion: "For me it was 10 years ago when I was working at Berg Propulsion and at that time I was looking at propeller analysis. I met some people from MARIN who stressed that they had a much better tool than I was considering. And it showed that we had to join CRS to get this fantastic tool called PROCAL!"

Loic Morand, Chairman of SPEED2DESIGN (CFD for Powering) and Head of the Hydrodynamic Department at Chantiers de l'Atlantique: "My first meeting was back in 1999 when I was introduced into a working group by Roger Lepeix."

In CRS, each project starts with an idea, followed by an initiative. Can you describe the path from conception to a mature project for your working group?

Olav: "RAW++ is a continuation of another working group. My own company and MARIN had a real passion for this topic so we joined forces for the first project, made a proposal and started to get others on board, making sure we had support. This process is an important part of CRS, setting out projects, lobbying and getting people around the table."

Tobias: "SHARCS2 is also a continuation, we have been going for six years now. We presented the proposal about cavitation simulations to bring in more people and it is working very well."

Loic: "The original idea for SPEED came from Raimo Hamalainen, now Head of Hydrodynamics at Meyer Turku, who asked me to chair."

Olav: "This process of using an existing working group and sitting together to make sure there is a continuation of the research is at the heart of CRS."

Tobias: "We make sure all members are listened to and have a chance to voice their opinion. This is important to have this climate in the group."

CRS currently has 23 members which can be divided into 'blood groups': research institutes, shipyards, class societies, suppliers and operators. Is this mix reflected in your working group?

Tobias: "In SHARCS2 I think we have 4-5 'blood groups'. This is important because you need some people to evaluate, some to analyse and some need deeper knowledge. This all broadens the research and brings input from different fields of the marine world to give insight into problems."

Loic: "Our members bring wide ranging views about the problem, we have different people from a range of organisations. Some people have very good theoretical ways of solving the problems. In parallel, we need people who are very pragmatic. We manufacture products that are not so simple, so the confrontation between these different people is very interesting!"

CRS is based on active participation of the members. How does this work for your working group and can this be improved?

Loic: "Sometimes the meetings can mean only a few people discussing special topics and then some members feel a little left out.

Data Driven Methodologies project in the making (Madrid, March 2019)

I think a good thing introduced by the very bad weather in Houston in 2017 is the Web Conference. Perhaps we can introduce special working group web sessions for 5-6 people with a specific task and then they could make a report for the relevant working groups."

Tobias: "Within CRS initially we tend to focus on one broad topic and then we eventually focus on one narrow part of that and by the very nature of the process, some people will contribute more than others. Perhaps the subject should be broadened to include other tools or evaluations so everyone has a task, not just the specialists."

Olav: "A key point is how to distribute tasks and award projects to generate interest. Sometimes we don't necessarily follow the best way to progress the research. But we do it to get engagement and different input for a future activity."

Can you give an example of a research finding based on joint expertise or knowledge within your group?

Tobias: "Undoubtedly, the biggest outcome for us all is the propeller analysis tool PROCAL. The software developers of course developed the tool but there are also a lot of design tasks, validation tasks and evaluations coming from different members, which have made it a very successful, useful tool."

Olav: "We have seen a lot of contributions from different companies regarding safety analysis. There are the evident benefits of the MARIN model test results but it is hard to understand what is going on because we don't have the measurements that we would like to have for the safety aspects. It is very much a collaborative process to explain what's going on." He laughs: "There have been a lot of hypotheses and theories as we go, which have changed surprisingly often!"

Loic: "With the SPEED project there are many generic lines about friction resistance and turbulence models and about how to modelise in PROCAL. But I think the best result of the working group is actually the progress that each member has made in the way they perform their propulsion computations. People are becoming better and better and learning a lot about how to perform resistance, appendage and open water computations."

An odd question perhaps, but what are the benefits of being a chairman? Would you recommend it?

Tobias: "Being a chairman gives you a very good insight overall, and you get to lead the work. This overview is important when we put together our presentations and make the summaries for the Annual General Meeting. I think this is very valuable."

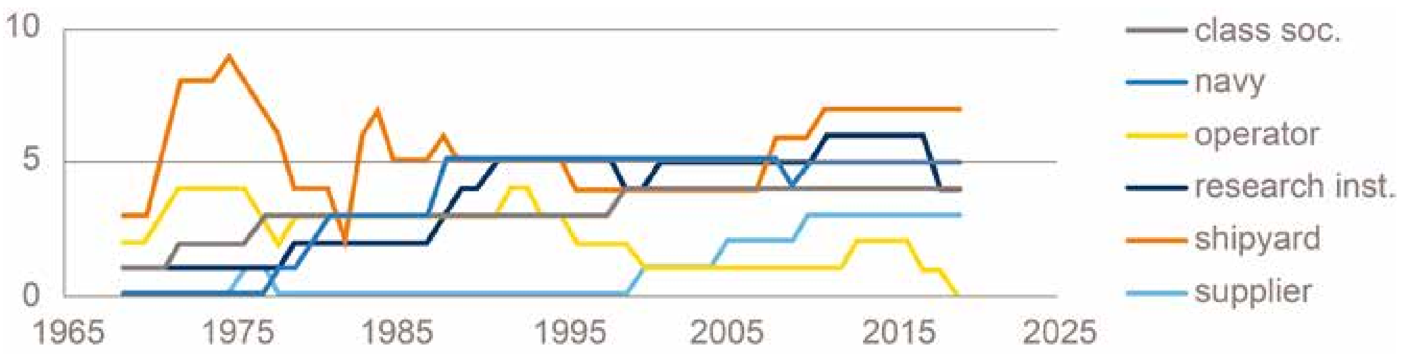
Olav: "Personally I like being active and to have a specific task. It is about meeting people, a learning experience and about doing something for the members – delivering good products to a nice group of people who I enjoy spending time with. There are many rewards, especially seeing that we are making progress."

Loic: "Sometimes during the life of a working group it gets 'stuck'. So you have to reconsider, and propose something in order to get it moving again. It is challenging, but it is also great when you are working with such enthusiastic people. I would encourage members to have this experience at least once."

Showing the camaraderie between the group, Olav jokes: "You need time for preparations and by the way Tobias – 'have you finished your report for the AGM?'" "Yes, for once!" Tobias laughs.

Can you reflect on the networking and educational aspects of CRS?

Tobias: "For us networking is an important part at both the meetings and at the dinner afterwards! This is when you get to know people in an informal setting, making it much easier to contact people."



CRS blood groups, 1969-2019

PRECAL workshop - knowledge transfer through software tools (Wageningen, December 2017)

Olav: "I second that, we meet a lot of people and become good friends, building up trusting relationships. Our organisations spend time on training and marketing, but I think it is just as well spent here because of the benefits of networking and training we get by participating."

Can you give an example of a 'CRS product' which benefits your organisation?

All: "Should we all say PROCAL?" they laugh.

Loic: "Yes PROCAL is key, but we use PRECAL for seakeeping, COGNAC for manoeuvring. Several CRS tools are an important basis of the tools in our shipyard."

"The tools are more adapted to our needs because we participate in the meetings in order to make them more useful for our requirements."

Tobias: "Our company regularly needs to use CFD developed in CRS. With CRS it helps making this a more stable process, acting as a buffer between the commercial things that we need to do."

Olav: "It is easy to focus on the tools but for my company, it is just as important to get the methodology and implement that and use CRS to validate it."

What are the strong and weak points of CRS?

Loic: "I think the relationship between the working groups could probably improve. Perhaps this can be improved by dedicated meetings. For example, there are opportunities in combining CFD computations with full-scale experiments. SPEED and RAW++ could also improve links."

Olav: "People tend to dive into their cave and after three years they come out with results. This is still a very efficient way of working within the groups. We have a very good model, I think there are definite benefits running it this way."

"We are doing very specific things now in CRS. The fact that we have this continuation of the groups all working on the same thing all of the time, getting results is fundamental."

Tobias: "However, topics are now coming across 'the old borders' and coming together as we are able to handle more complex issues, and have more pieces of the puzzle."

Do you believe CRS will live for another 50 years?

Loic: "In the last decade we have seen the number of members increase and we didn't expect that, I would be surprised if it doesn't last for another 50 years!

Olav: "We have a lot of good, really useful results. I don't see how we would get this same value for money anywhere else."

"Our strength is sharing and collaborating. You get something and give something. This is the essence of CRS and necessary for it to survive.

Do you have a clear message or recommendation for the CRS community?

Olav: "We have to find a better way to communicate what we have done. Internally, within our companies, and at conferences etc. It shouldn't be limited to only the annual report, or within SharePoint. We should explain what is being done within our own companies stressing that what we are doing is state-of-the-art. CRS is a driving force."

Tobias: "We are leading in many aspects but people don't know this externally. It is a very low hanging fruit to show that we are better than others!"

Olav: "There has to be knowledge transfer. We have a very good working model already."

Tobias: "Yes indeed but we need to maintain it and take the next steps. We must keep it going forward and keep it alive."

All: "We have to take good care of CRS!"

Cooperative Research Ships 1969-2019

The years 1969-2019 establish a half-century where mankind has achieved enormous technological progress in many areas, such as aviation (fly-by-wire), space exploration (Apollo 11, Hubble), computing (microprocessors), biology (Human Genome Project) and quantum mechanics (Standard Model particle detection). In the area of shipping and shipbuilding the technological 'leap forward' may seem less spectacular at first sight, but a closer look reveals that the achievements in this branch of industry are equally impressive.

Ed van Daalen, e.van.daalen@marin.nl

CRS members visiting MARIN's Depressurised Wave Basin (May 2012)

With roughly 5,000 years of shipping and shipbuilding – against a mere 100 years of aviation and space travel – it is not surprising that developments in this area in the past 50 years have been mostly evolutionary rather than revolutionary. Nevertheless, we have seen quite a few significant changes: Containerships have altered the face of shipping, including the character of port cities, and have had a huge impact on world trade and our way of life, at least for the majority of the world's population. Today, about 90% of non-bulk cargo worldwide is transported by containerships, and the largest can carry over 21,000 TEU. Gross tonnage of cruise ships has increased from 70,000 GT to over 220,000 GT, with huge implications on the design and operation of not only the ship itself, but also on the ports of call. Podded propulsors improved the steerability of many vessel types, from yachts to cruise ships. Unmistakably, ship transport is safer and cleaner than 50 years ago, where the volumes have increased way beyond expectations.

And how was CRS involved in these developments?

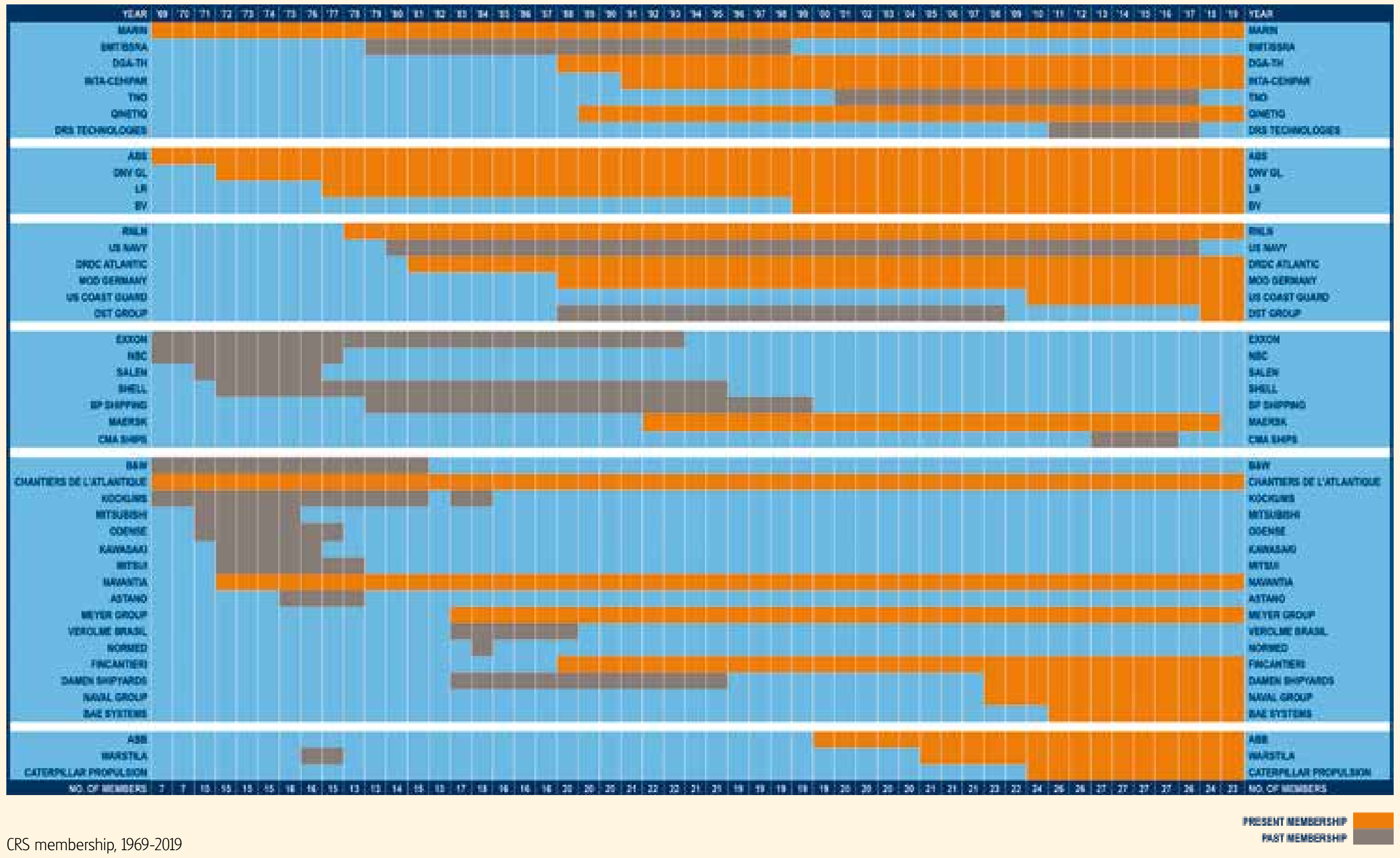
The early years: sowing the seeds CRS took its first steps in the *Large Tankers* project (LT, 1969), addressing problems originating from the ever-increasing size of tankers. The research was coordinated by three panels, named 'Resistance & Propulsion', 'Strength, Vibrations & Seakeeping', and 'Steering & Manoeuvring'. Joint research was continued in the *High-Powered Large Ships* project (*HPLS*, 1975), covering performance, cavitation and propeller-induced cavitation forces, while aiming at fundamental knowledge and extending the scope to other ship types. The Amoco Cadiz ran aground in 1978; in the same year, the *Segregated Ballast Tankers* project was started (*SBT*, 1978). Growing interest in the arctic areas gave rise to the *Ships in Ice-Covered Waters* project (*ICE*, 1980). The *Design for Service* project (*DES*, 1984) examined ship performance and behaviour in service conditions. Clearly, right from the start, research was extremely diverse and strongly linked to developments in shipping and shipbuilding.

1980s, 1990s and 2000s: further expansion and tool development Most of the seeds planted in the early years blossomed in the decades that followed. Valuable knowledge was collected through extensive research and in many cases this knowledge was implemented in software tools developed specifically for design studies. Potential flow theory and a good deal of empiricism formed the basis for long term software development, constantly improving the quality of prediction and extending the range of applicability.

In the area of manoeuvring, research continued in the projects *Manoeuvring in Early Design Stage* (*MED*, 1988), *Manoeuvring with Single Screw Ships* (*MAN*, 1993), *Manoeuvring with Twin Screw Ships* (*MANTS*, 1997), and *Manoeuvring with Pods* (*MAN3*, 2000). The *COGNAC* projects (2003, 2007) addressed the manoeuvring behaviour at low speeds, including crabbing.

When it comes to seakeeping, the development of a frequency domain linear potential flow code for hull pressure calculations for SWATH type vessels was started in the *SWATH* project (SW, 1990), which was followed by *PRECAL* (1996) and *PRETTI* (2003, 2007), extending the scope to flexible ships, multi-hull configurations and nonlinear time domain calculations. Nonlinear and viscous roll damping and roll stabilising devices were examined in *Roll* (*Damping*) (*ROL*, 1981 and *ROLL*, 2001), followed by *Roll Reduction* (RR, 2013, 2017). Experimental research into the phenomenon of added resistance in waves was carried out in the *RAW* project (1980). A series of projects focused on internal loads: *Hull Girder Loads* (HGL, 1984), *Sagging-Hogging / Sea Loads* (*SAGHOG/SL*, 1991) and *Transverse Loads* (*TRANSV*, 1998).

Structural analysis was explored in *Ultimate Strength* (*USTR*, 1980), *Ship Monitoring and Comparative Studies* (*SMACS*, 1998) and *Structural Load Requirements* (STRUC, 2001, 2006). Nonlinear effects in structural integrity assessment were addressed in *SANE* (2010) and *SIINE* (2014). Much effort was spent on the development of the *STRUC* software tool for assessment of structural integrity and fatigue life. Wave impacts and the resulting hydro-structural response were the subjects in *Bow Flare Slamming* (*BFS*, 1977) and *Slamming Loads on Ships* (*SLAM*, 1990). Research continued into the



CRS membership, 1969-2019

2000s in projects with appealing names such as *ELAST* (2002), *WHIP (*2005, 2009*) and WHAM!* (2012), connecting dedicated slamming calculation tools with the seakeeping analysis tools *PRECAL* and *PRETTI*. Green water and the related impact loads were studied in Green Water Loading (SLGR, 1992).

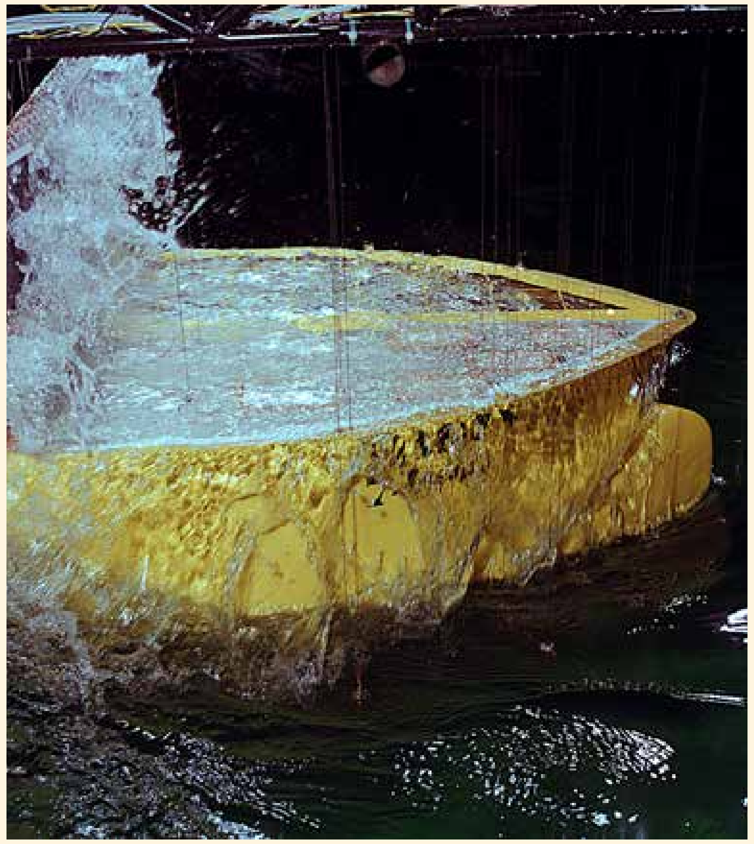
Propeller cavitation and the resulting erosion effects were studied in *CAV* (1983), PRES (1996, 2000) and EROSION (2005, 2008). *EROSION* (2005) and *EROSION-2* (2008). Comfort-related phenomena like vibrations and noise were addressed in *CAVDISC* (2006), *Broadband Propeller Noise* (*BROADBAND*, 2009), sequelled by *Broadband Noise and Vibrations* (*BROADBAND-2*, 2014) and *Onboard Noise and Vibrations* (*ONBOARD*, 2017). The development of a panel code for pressure calculations was taken on in *PROCAL (*2002, 2006*)* and continued in *PROPDEV* (2009), *PROPLOADS* (2011) and extended to ducted propellers in *PRODUCT (*2012, 2015*)*. The introduction of podded propulsors was accompanied by a series of projects: *POD (*2000, 2002*)* and *Loads on Pods* (LOP, 2006). Operations in arctic environments, including loads on propellers, were studied in *PROPOLAR* (2010).

Unfortunately, the era 1969-2019 witnessed many maritime disasters involving a large number of casualties, such as the capsizing of the *Herald of Free Enterprise* (1987) and the *sinking of the Estonia* (1994). These tragic events focused attention on the survivability of damaged ships. In CRS, this was reflected in projects such as *Ultimate Stability* (US, 1984), *Damage Stability* (DAMA, 1997) and *Ship Survivability (SHIPSURV*, 2003, 2009*)* which aimed at a ship survivability assessment procedure and the development of a simulation tool for progressive internal flooding.

Special design concepts were studied, shedding light on their powering, seakeeping and manoeuvring characteristics: *Fast Ships* (*FAST*, 1990), *Catamaran Design* (*CAT*, 1995), *Fast Monohulls* (*MONOFAST*, 2002) and *Trimaran Design* (*TRIMAR*, 2008). These projects provided a unique opportunity to validate the software tools developed in other projects using dedicated experiments.

The importance of high quality data from full scale measurements for validation and other purposes was recognised, which led to the *Full Scale Monitoring* project (*FSM*, 1992), followed by *Ship Monitoring and Comparative Studies* (*SMACS*, 1998).

2010s: new challenges, new techniques Meanwhile, the impact of shipping on the environment, both local and global, had become a growing concern in the maritime community. In 2011, the IMO made the Energy Efficiency Design Index mandatory for all new ships. These developments instigated a series of projects addressing efficiency and emissions of the power train: *Ship Performance and Fouling* (*ECONSHIPS-FOULING*, 2008), *Ship Emission Prediction* (*EMISS*, 2010) and *Design for Service* (*DESERV*, 2013).
To gather reliable operational data in a systematic way, a dedicated measurement campaign was set up in *In-Service Monitoring* (*CRISM*, 2012), providing valuable information for modelling and validation purposes. Recently, research into 'green propulsion' is carried out in *Learning about Energy-Saving Devices (LSD*, 2017*)*.



Sea Loads working Group, 1993

Computational Fluid Dynamics made its entrance in CRS with the *OSCAR* project (2011), exploring the application of CFD to problems which had been addressed so far with a combination of experiments, finite and boundary element methods, and empiricism. Quite soon, CFD methods were applied in all areas; powering: *SPEED* (2012) and *SPEED2DESIGN* (2016); cavitation: *SHARCS* (2013, 2016); seakeeping: *RAW+* (2012), *RAW++* (2016) and *SEAFD* (2015). The availability of user-friendly optimisation toolboxes was quickly exploited in *PROPAGATE* (2016, 2019) to develop an automated propeller design tool. The use of new materials for propellers and the related issues, such as erosion, are the subject of multi-disciplinary research in *Composite Propellers (COMPROP*, 2014, 2018).

CRS members and organisation Starting with seven members in 1969, the CRS has grown steadily, counting 23 member institutes and companies in 2019, spread over Europe and North America. Members are roughly divided into six groups: classification societies, navies, (commercial) operators, research institutes, shipyards and suppliers.
This unique blend of 'blood types' ensures that CRS research is versatile and that broad expertise is available within the CRS community. A representative steering group coordinates the annual Open Meetings and General Meetings, stimulating the initiation of new projects, and guarding the quality of the research results.

Today, the membership fee is 65,000 Euros per year, giving a 1.5 million euro annual budget, enabling about 14 simultaneous research projects. The logistics are coordinated by a (MARIN-manned) secretariat, which also maintains an ever-growing digital database of results, including reports and software.

CRS, quo vadis? Within a rapidly changing world, where new techniques emerge and become mature faster than ever before, CRS is facing the challenge to maintain its relevance for the maritime world, and for its members in particular. In the past, CRS has demonstrated its capability to grow and change, adopting CFD and optimisation methods and bringing new tools to the desktops of the member companies.
New trends and developments, such as data science and autonomous vehicles, provide new opportunities for research and will define the main CRS themes for the decades ahead. The future is in our hands ...

After 50 years of cooperative research, there is plenty of reason for the CRS community to look back with pride.
With over 120 projects completed, one can safely state that the CRS concept – 'research of the members, by the members, for the members' – has stood the test of time. The secret of this success is a dynamic group of research-oriented, open-minded people, willing to share pre-competitive knowledge by real cooperation. This is the true CRS treasure, which must be preserved for the next 50 years!

Risk reduction by cavitation control

As all kinds of stakeholders regarding cavitation-related issues are represented in CRS, cavitation has been a major research topic through the CRS lifetime. The aim was to increase knowledge and provide members with methods to reduce risk by obtaining better control of cavitation.

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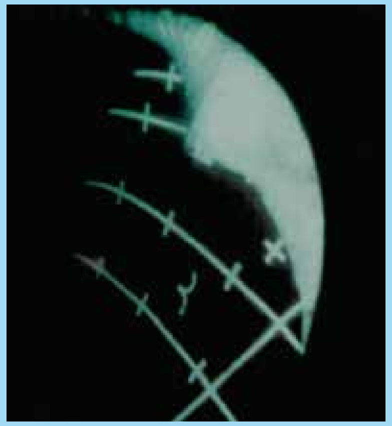
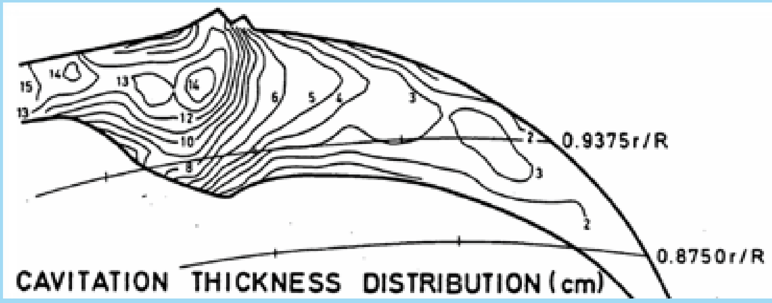




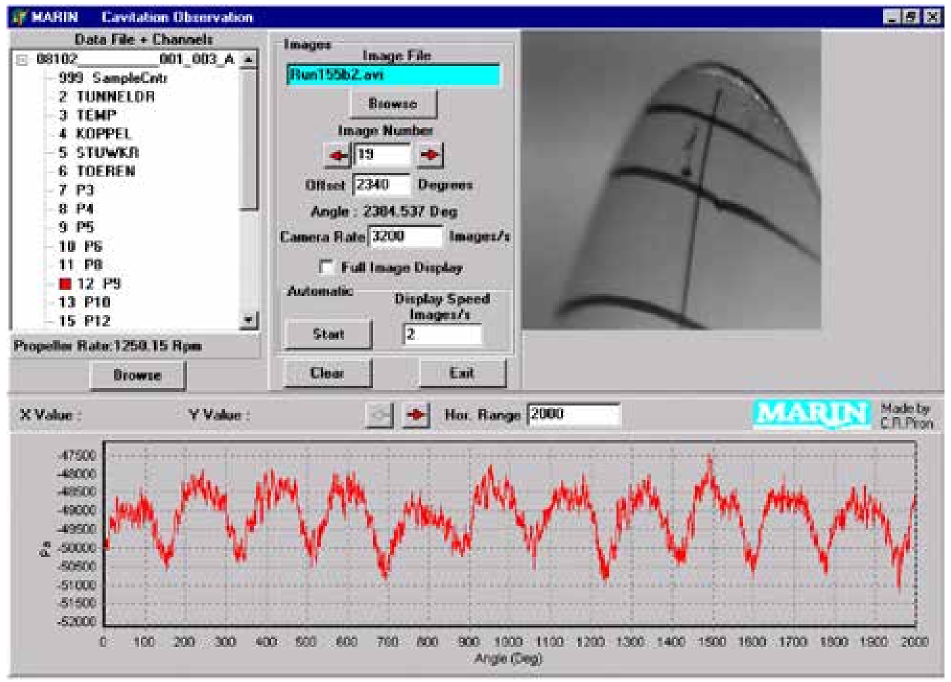
Observation of full scale cavitation by means of stereo photography (left) and the cavitation thickness distribution derived from that (right)

The early days of CRS had seen a trend of rapidly increasing power per propeller to levels beyond the experience of ship designers, operators, classification societies and propeller suppliers. With this development, cavitation became a more serious issue as it caused erosion of propeller blades, ship vibrations and noise.

Aspects of cavitation were already studied within the first CRS projects in the seventies, but from the eighties on, extensive research focused on cavitation alone was carried out. In the first project a knowledge basis was formed. CRS members provided data from hull-pressure fluctuation measurements and cavitation observations on board ships. These included unique measurements of cavitation thickness on full-scale propellers.

Together with an assessment of the then available prediction tools within the CRS membership, the state-of-the-art knowledge on cavitation could be described and gaps in the knowledge identified and subsequently studied. Much work was devoted to the influence of the velocity distribution in the ship's wake, as this is strongly related to cavitation dynamics, which are determining for erosion and vibration excitation issues. The sensitivity of analytical prediction methods, regarding effects of variations in propeller geometry or wake, was also studied. This was verified by experiments on model- and full-scale.

The effects of propeller manufacturing tolerances on cavitation were also investigated. It was concluded that, in order to obtain better control of cavitation for specific applications, tighter tolerances than the standard ones should be specified. In addition to unique datasets, a major deliverable of the project was a set of guidelines for the reduction of excitation forces due to cavitating propellers. This provided a practical help for ship operators, shipyards, classification societies and propeller designers, enabling them to discover potential cavitation-related issues in the early design stage, as well as how to mitigate such problems once they occurred on a ship.



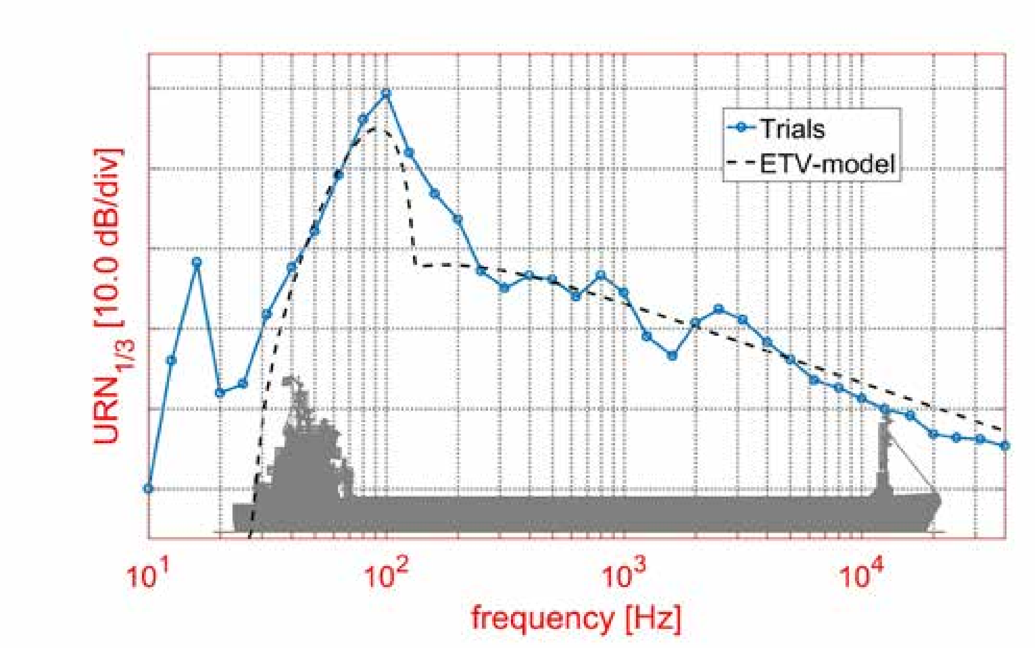
Screenshot of CRS software application for the analysis of pressure signals due to cavitating propellers

Extending on vibration excitation

In the 1990s CRS cavitation-related research focused on cavitation-induced hull excitation, in particular at higher harmonic and broadband frequencies. The experiences of several CRS members made it clear that there was a need to develop guidance and prediction methods that could be applied at the design stage of a ship. A study of model propeller test data showed that the harmonic character of higher blade rate orders was intermittent, which tended to be reflected in the frequency domain as a broadband character. This suggested that the intensity and the phasing of cavitation events lay at the origin of the broadband problem. Next, a general method for decomposing a pressure signal into its continuous harmonic and impulsive components was developed and this meant that the characteristics of different cavity structures, in terms of their signal generation, could be understood. Detailed model testing and efficient software, allowing simultaneous visualisation of high-speed video images, pressure time series and corresponding pressure signals were vital here.

In the last phase of this research the knowledge gained and the tools developed were validated. A large amount of valuable ship scale data was made available by CRS members for no less than eight ships. Maximum hull pressures and source strengths computed showed reasonable results for the first blade rate component but failed to produce useful results at the higher harmonics. Further study of the excitation caused by cavitating tip vortices was therefore necessary.

Example of damage to a propeller blade due to cavitation-induced erosion



Comparison of measured URN levels with those predicted by CRS developed software

Extending on erosion The costs of repairing erosive damage to a propeller or rudder are high, whereas fuel costs rise when propeller blades are roughened by erosion. Early in the 21st century the EU-sponsored cavitation erosion research project EROCAV was conducted. One deliverable was the "Cavitation observation handbook", of which the importance was such that the EROCAV membership approved dissemination of it beyond the limits of its sponsoring members.

Within CRS it was considered important to investigate basic physics of hydrodynamics, material response and cathodic protection. This became possible by applying new experimental techniques. One of the CRS members developed an Acoustic Emission (AE) technique by which crack growth in materials can be related to the energy of imploding cavities and applied a sonotrode technique to test the response of different materials, material treatments and cathodic protection. Another new technique was high-speed video. The AE technique was simultaneously applied with high-speed video recordings of the cavitation to a number of rudders at full-scale. Fundamental knowledge on cavitation dynamics was increased by model-scale experiments in a high-speed cavitation tunnel on a foil. Recordings of up to 50k frames per second were made of imploding cavities, synchronised with AE measurements. The erosion studies were concluded by issuing jointly written design guidelines for rudders and propellers, providing concrete practical guidance.

Broadband excitation and noise
The work done on broadband hull excitation in the 1990s was continued. In addition to the issues addressed then, Underwater Radiated Noise (URN) of merchant ships was studied because of its effect on the behaviour of marine mammals and fish. New prediction methods for broadband noise emitted by either tip vortex cavitation (ETV model) or sheet cavitation were developed, making use of results obtained by the boundary element method PROCAL that was also developed through CRS. Available empirical methods were evaluated, and the structural response of the ship by broadband excitation was investigated using finite element methods, as well as statistical energy analysis type computations. Computational models were validated using data obtained from sea trials that were sponsored by CRS. The URN was measured from a military research vessel, a general cargo vessel and a containership. Of these latter two vessels, the hull pressure fluctuations and structural vibrations were also measured, from which the relation between hull-pressure fluctuations and URN could be investigated. The developed computational models were used in a propeller design study to evaluate efficiency, hull pressure fluctuations and URN, and became part of the CRS propeller software suite. This software suite is currently being extended with a semi-empirical method to predict the noise inboard of the vessel by cavitation.

The CRS research line on cavitation spans a period of some 35 years. Based on knowledge gained about basic aspects of cavitation and related hull-excitation, research expanded on more specific aspects, like higher harmonics, broadband hull excitation and cavitation erosion. Recent work includes URN. CRS members contributed by carrying out parts of the research and by making data and research methods available. Practical guidelines and validated prediction methods were the result, and these contribute to achieving the higher goal: the reduction of risk for the member organisations in their daily business by gaining more control of cavitation.

How good is our understanding of reality ?

The added value of full-scale measurements

If innovation is the engine that drives ship designs, tools and procedures to higher standards beyond far horizons, then full-scale measurements take the role of the navigation instruments to avoid problems en route and to ensure progress in the right direction.

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The dramatic, 350 TEU, container loss incident by the Dutch islands in early 2019 illustrates the knife edge where modern technology operates between efficiency and safety. Unfortunate surprises occur despite standards, tools and procedures. Continuous data collection and evaluation is needed to check if our understanding and representation of ships and offshore structures is in line with their true behaviour at sea.

Many full-scale measurements have been conducted over the history of CRS. Speed trials, noise and vibration measurements, resistance, wave conditions and structural loads are just a few. The most recent MARIN data collection campaign for CRS was the CRISM project in cooperation with two leading container ship operators. This aims to collect a long-term reference data set for environmental conditions, structural integrity, powering efficiency and inertial loads in general.

The data is used to validate recently developed CRS tools and to determine the relevance of new phenomena that have surfaced with the increased sizes of modern box ships. Typical examples are large motions and the effect of hull flexural dynamics on structure and cargo stowage.

A particular challenge for safety, weather and seakeeping related phenomena, is that measurements need to run for a very long time to capture the rare conditions where incidents and damages are likely to occur. Customised indicators are needed to index the terabytes of years of high-resolution data for specific phenomena. Indicators for new phenomena derived from Joint Industry Projects such as Lashing@Sea, TULCS and SPA, can be stored in databases alongside plain sensor data to allow quick and intuitive interpretation of otherwise overwhelming data.

MARIN and CRS use this essential information to verify present design and operational practice, identify needs for adjustments with respect to safety and efficiency, and ultimately to provide a sound basis for ongoing innovations.

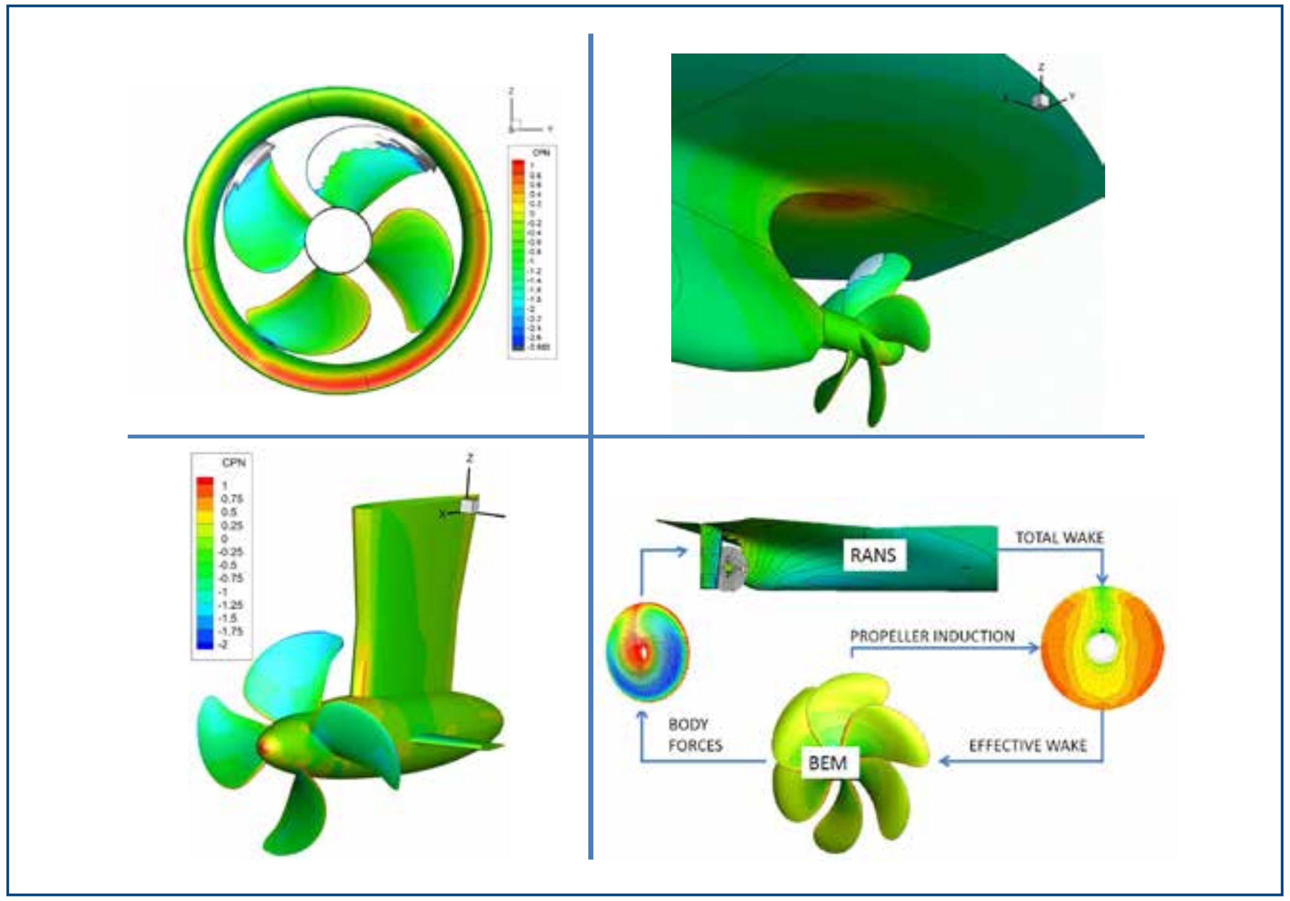
Specially designed MARIN measurement container (right bottom) on the NYK Argus

Instrumented lashing rods on the NYK Argus

Propulsion design

From propeller analysis to integrated propeller-aft body design

In the year 2030, the French Naval Architect Monique Lorand was tasked to optimise a preliminary ship design in only 24 hours – a task deemed impossible some 15 years before. The reason that she showed no signs of stress while doing this was that she had great confidence in a toolbox of software with state-of-the-art CRS tools and optimisation techniques. She and her staff had learned how to use these tools within CRS projects and dedicated workshops. In fact, the resulting high quality, integrated design was considered one of the main reasons for the success of her shipyard.



Examples of PROCAL based applications

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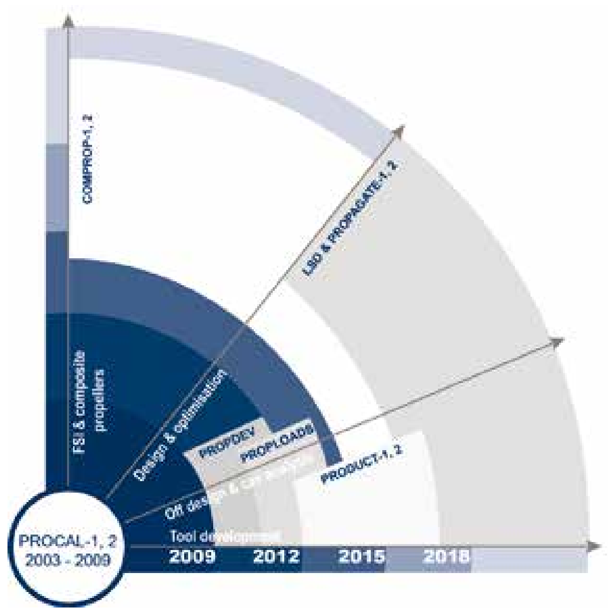
CRS propeller design developments in a nutshell The development of Monique's toolbox had started long before 2030, on a cold and dark December afternoon in 2002 in Wageningen, where some 15 men of different origin had gathered around a projector and screen, discussing a proposed sequel to the PIF working group. The PIF project officially ended that day and yielded three different ways to provide inflow fields for propeller analysis. This discussion appeared to be the perfect breeding ground for a propeller analysis tool, designated PROCAL, for which a three-year project was approved the next day at the AGM.



Development of propulsor related tools and applications

The PROCAL group started working on a baseline panel code, including a first version of a cavitation model. After three years, further developments and validation appeared necessary (PROCAL-2), resulting in a mature tool for the analysis of open propellers. In 2009, the PROCAL development continued as a side track in PROPDEV and PROPLOADS, realising, amongst other achievements, the coupling of PROCAL to RANS methods. Further developments addressed ducted propellers (PRODUCT-1,2) and the application of PROCAL for automated propeller design (PROPAGATE-1,2), as well as for Energy Saving Device designs. The use of PROCAL for flexible composite propellers is another important development, necessitating a coupling of the PROCAL code with a FEM code.

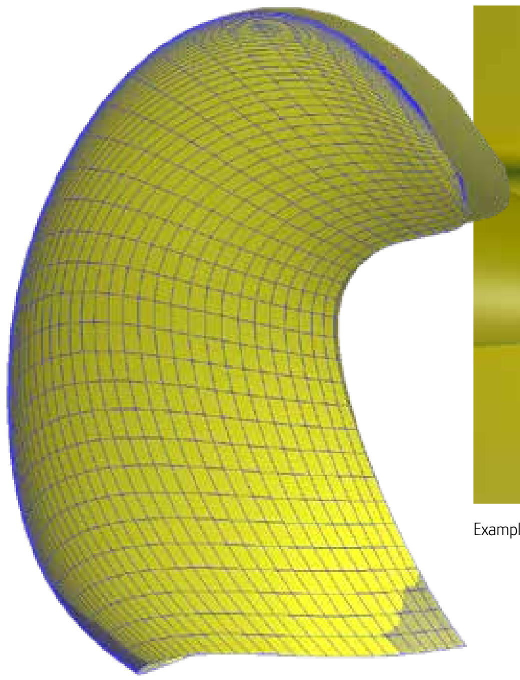
As a result, CRS developments would enable Monique Lorand to produce an optimised design in 24 hours which required only 8 hours of her own time!

No carpenter without a hammer: PROCAL In 2003, MARIN was given the task of developing the BEM code PROCAL. Although work started from scratch, use could be made of multiple BEM codes for propellers that were available at MARIN, as well as knowledge of a BEM developed in cooperation with the University of Lisbon (IST). Important requirements for the PROCAL code were determined to be robustness, low CPU time and easy maintenance. This resulted in a code that could predict unsteady sheet cavitation on propellers operating in a ship wake with the resulting hull-pressure fluctuations. Simultaneously, the graphical user interface PROVISE was developed by which the user can easily import propeller geometries, generate surface panels, perform computations and analyse results. Hull-pressure fluctuations can be computed by the acoustic boundary element method EXCALIBUR, developed at MARIN.

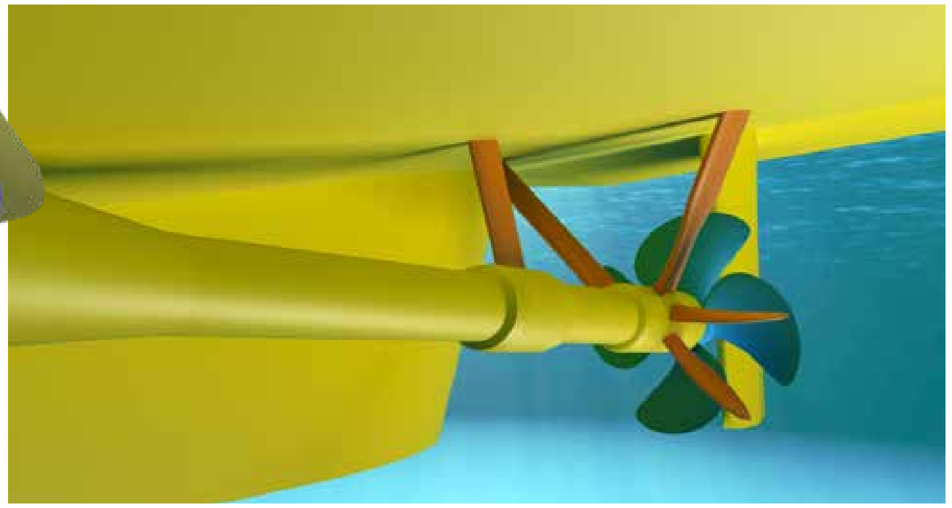
An important input to PROCAL is the effective wake field of the ship in which the propeller operates. At the beginning of the century, this wake field used to be obtained by a model-scale measured wake field that is made effective and scaled to full-scale Reynolds numbers with the tools developed in the PIF group for example. However, with RANS methods becoming mature in predicting the ship wake field, a coupling procedure between RANS and BEM was developed in the PROPDEV and PROPLOADS groups. The coupling was made using PROCAL's body forces in RANS and the effective wake field was obtained by subtracting PROCAL's propeller-induced velocities from the RANS total velocities. The approach was then successfully used in 2013 to analyse the shaft loads from a VLCC in a manoeuvre for which both full RANS and full-scale data were available. For a cruise vessel, the influence of the shaft alignment on the wake field and propeller cavitation behaviour was studied in detail, making extensive use of RANS and PROCAL computations.

The structural response of the propeller to the hydrodynamic loading was analysed through the coupling of PROCAL and FEM packages. Additionally, the structural response of the hull due to propeller-induced hull-pressure fluctuations was studied, using the coupling between EXCALIBUR and FEM.

Ducted propulsors At the end of PROCAL 2 in 2009, there was a strong desire to extend PROCAL's capabilities to ducted propellers. It was estimated that more than 50% of the propellers designed by manufacturers in CRS are to operate



Example of a PROCAL-TRIDENT analysis of a flexible composite propeller blade: deformed blade with bent tip (in foreground with blue grid) versus rigid blade (in background)



Example of the result of an optimisation exercise with a PreSwirl Stator for a twin screw ship

inside ducts. After three more years, thanks to MARIN's close cooperation with IST, it became clear how ducted propellers should be modelled in a boundary element method. It appeared to be very important to iteratively align the wake of the propeller blades with the flow. The reduced velocity in the boundary layer on the duct had to be taken into account when aligning the tip vortex. PROCAL was then extensively validated for ducted propellers. A very interesting validation study was using full-scale observations of cavitation on the propeller of a VLCC with the largest ducted propeller ever built. These observations were made by CRS way back in the seventies.

Optimising propellers CRS propeller tools were put to good use from 2016 onwards within the PROPAGATE group from 2016 onwards, in which an automated propeller design workflow was created. This consisted of a geometry generator, an optimisation routine, a workflow manager and goal & constraint functions. These functions quantified blade stress, radiated noise, propeller-induced hull-pressure fluctuations and cavitation erosion risks - all quantities that are in direct competition with fuel efficiency. Towards the end of the project, workflows emerged that can go toe-to-toe with classical design methods.

Flexible propulsors Monique had been using composite materials in her Pre-Swirl Stator design for some time and used to work in close cooperation with a propeller manufacturer on composite propeller designs. Tools to enable them to do this had been developed a decade before within COMPROP. First, a tool for the analysis of flexible propellers in open water was made. PROCAL and the FEM package TRIDENT, developed by LR-MARTEC, were coupled in an iterative way, including geometrically nonlinear effects. COMPROP-2 then extended this tool by enabling the analysis for in-behind ship conditions, applying the methodology developed at TU Delft using several FEA packages.

Where are we heading? In 2019, Monique was still taking classes at university, unaware of the propeller toolbox and guidelines that were being developed in CRS for hull-propeller-ESD integration. Tools and guidelines that lead to the design of a ship that is ideally suited for its mission. Whilst the vision is there, and early demonstrations of propeller and ESD optimisation have been proven, the tuning of tools, optimisation strategies and skills for using it, is expected to remain a challenge for CRS for another 50 years!

Podded propulsion, a novel propulsion type providing new hydrodynamic challenges

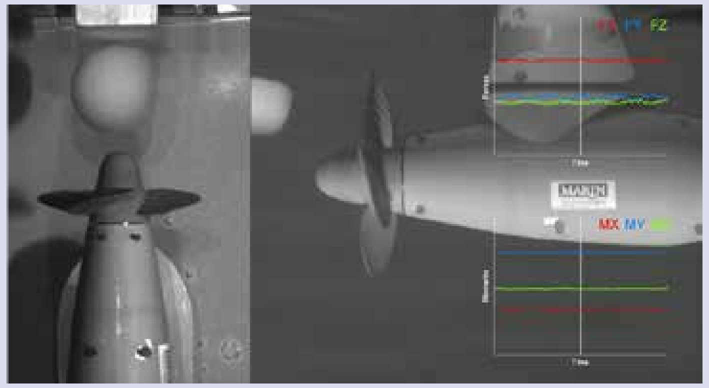
CRS pioneers podded propulsion research throughout the decades

In the mid-nineties, a novel propulsion type made its appearance in the maritime market - podded propulsion. The first installations were on ice-going vessels, but a few years later, the cruise shipbuilding industry followed. Initially, the advantages of more freedom for the inner layout and improved comfort, with even better efficiency resulted in the rapid introduction of several pod designs by different manufacturers.

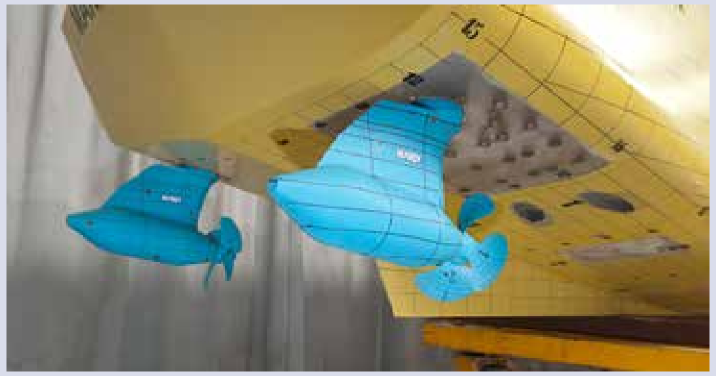
However, with the first vessels being delivered successfully, new questions came back from the yards and ship operators. The success also made it clear that the potential of this new propulsion type was not fully understood. Within the CRS the proposal for the first POD Working Group was awarded in 1999, followed in typical CRS tradition by POD-2. The research was focusing on how the pod had to be integrated into the ship design from a hydrodynamic point of view. Feasibility studies were carried out on various ship types, from cruise liners and ferries to a shuttle tanker.

Even fast vessel concepts, with large vessels operating with pods at speeds of 38 knots were investigated in the MONOFAST working group. Although these concepts were never built, they were important for the development of knowledge on podded propulsors. Besides powering and comfort, the merits of podded propulsion for the crabbing performance of passenger ships were discovered.

After 10 years of general design knowledge built up on pods, the research became more focused on the loads on the pods and their propellers. For the 'Loads on PODS' working group a 6-component balance was developed to measure the forces and moments in 3 different directions on the propeller during its operation. The main focus of the work was on how these loads changed during the steering of the pod unit and what the forces would be at the bearings. In the PROPOLAR working group, this same sensor was used to measure the single impact of an ice block on a single blade. For various EU projects and JIPs such as the CD-series and the TT JIP, the groundbreaking work of CRS provides a knowledge base.



Force due to ice impact at the instantaneous point in time as indicated by the white line in the time series showing the three force and moment components



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Segmented model with flexible beam (ELAST project)

Tackling the challenge of hydro-structural response

Evaluating the wave induced, structural response is of fundamental importance in the process of the design verification of a ship's structural integrity. CRS is performing state-of-the-art research in this field.

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Hydro-structure interactions include a variety of complex physical phenomena which should be taken into account from both the quasi-static (low frequency wave loading), and fully dynamic (springing, whipping…) points of view. The most critical part of the problem is related to the efficient modelling of the seakeeping behaviour, which should include both the global (wave diffraction and radiation) and the local (slamming, sloshing, green water …) effects for a ship sailing with arbitrary speed in heavy seas. Due to the extreme complexity of the different phenomena involved, and in spite of all the past and recent developments, all the details of the hydro-structure interactions are still not fully mastered today.

Forced motion experiments (WHIP-1 project)

CRS's research efficiently combines numerical, experimental and full-scale monitoring activities, which are all used together in order to ensure the validity and reliability of the final numerical tools. Several working groups are taking care of the different aspects of hydro-structure interactions, using both the simpler but faster potential flow-based models, and the more complex but computationally expensive CFD models.

Hydro response Calculating loads on ships and, thereby, the motions in waves has been done since the sixties. At first this was done using a 2D approach (strip theory) and this was corrected for the effect of forward speed. In the late seventies and eighties 3D methods were developed, very often these methods also needed some tricks to include forward speed effects. An example of a development of the latter option is the CRS program PRECAL. The common approach in these methods was the assumption of small disturbances relative to the equilibrium position. This assumption resulted in a linear program.

A number of accidents (e.g. sinking of the Estonia in 1994) showed that extreme loads are clearly very important and also that these are outside the scope of programs based on a linear approach. These conclusions led to the development of the time domain program PRETTI, which uses the linear hydrodynamic results of PRECAL and adds nonlinear effects due to the actual immersion of the hull.

It was assumed that in deploying such a simplified approach - ignoring the nonlinear effects in the dynamics - the main components of the nonlinear loads were captured. Although this approach is still state-of-the-art for long duration simulations, it excludes slamming events. Therefore, a long-term research programme was started resulting in a string of CRS projects: SLAM, ELAST, WHIP-1,2 and WHAM. The work evolved from drop tests on 2D ship sections to several model test campaigns using 3D segmented models and flexible beams to model the structure of the ship. At the same time, a software development programme was started to include hull bending modes in both PRECAL and PRETTI. This evolved into a full restructuring of both codes – which was quite a project on its own.

15 years of slamming studies
The slamming problem was, and still is, a very hard nut to crack. Two approaches were developed, one 2D method based on a strip theory type approach and a 3D momentum method. Both methods give good results for head seas cases, but impacts in quartering waves appeared to be much harder to predict. In fact, it appeared that really extreme impacts were caused by relatively short and steep waves. It is not necessary that the complete bow emerges just before such an impact. This implies that approaching the slamming problem by a drop test simulation has its limitations. After studying the slamming problem for some 15 years, we had to conclude that the model of the incoming wave (linear Airy model) also needed to be improved to properly describe the velocity in the crest of steep waves.

SLAMFLOW The new approach to tackle the slamming problem is to make use of CFD calculations; this is done in the SLAMFLOW project. Today's large computers have no problems handling grids with a number of cells in the order of 10^7. Such grids can solve the local flow problem sufficiently accurately to have a good impression of impact pressure and duration.

However, extreme values cannot be determined by only CFD. Long-duration simulations with CFD are totally unrealistic. Therefore, approximate methods are required that are able to select the critical events that

Stresses in the frigate type hull structure obtained with the STRUC tool

Free running experiments with a model having 10 segments in the bow area (WHIP-2 project)

can then be evaluated using CFD. In this way the probability of the event is determined by the approximate method, while the magnitude of the impact (and its consequences) are determined by CFD results.

Structural response Once there was a tool available that could calculate pressures on the hull of a ship, the STRUC-1 working group was started up in 2001. The goal of this working group was to provide the link between the hydrodynamic calculations and the structural calculations. The approach taken was a one-way coupling. Unit panel pressure load cases were defined to be calculated by different finite element solvers. Combined with transfer functions of the calculated pressures, this results in transfer functions of stresses.

The developed tool STRUC takes care of the necessary interfacing between the two programs and determines the long-term fatigue damage and extreme load assessment. The basis for the structural CRS tool was ready. As nonlinearities in the loads have an important contribution to fatigue and ultimate load assessment, these were addressed as part of STRUC-2. This working group also changed the way the loads were translated from the unit pressure to the unit wave method. Once the number of hydrodynamic panels exceeds the number of load cases, the latter is a more efficient method.

SANE to SIINE The SANE working group that followed collaborated closely with the PRETTI-2 working group. As a result of PRETTI-2's activities, the hull bending modes were included in PRECAL. The STRUC software now served not only as a post-processor for PRECAL, but also as a pre-processor in which the global bending modes were determined. Additionally, the SANE working group carried out more extensive validation work of the tool and its robustness. The most recent group SIINE finished this work in 2018.

An important topic within the working groups was the user-friendliness of the tool. The operational profile used in the long-term assessment has a clear and significant effect on the analysis. Its definition is therefore very important. As such it should be clear to the user of the tools how this definition is properly done. Nonlinear work performed in STRUC-2 was revisited and is now an integral part of STRUC. Finally, the testing and validation of these state-of-the-art tools and their capabilities was completed.

Acceleration turn in Seakeeping and Manoeuvring Basin (MORE project)

Five decades of research into manoeuvrability

In the quest for supertankers 50 years ago, the CRS investigated the effects of ship size on the controllability, and in particular how adequate controllability could be achieved. Today, the ship types and the requirements for manoeuvrability have changed, but the CRS applied research still holds.

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The unique composition of CRS working groups means that the research finds its way into practical applicability. Developed tools and knowledge ensure a competitive advantage in the day-to-day business of shipyards, class societies and shipowners.

Why was the manoeuvrability of large tankers so different from smaller ships? In the 70s, economy of scale pushed to achieve larger and larger ships, allowing the installed power per tonne displacement to reduce. From a manoeuvrability point of view, this had two consequences. Due to the larger ships, the ship reacted much slower and therefore, the stopping distances increased. When the helmsmen gave rudder, the reaction time was longer. The second consequence was related to the Froude number. Due to the increasing length and the same speed, the design Froude number reduced. This means that it was interesting to design ships with larger block coefficients. However, to achieve acceptable added resistance in waves, the bow section became sharp. This has led to fuller aft ships. These fuller aft ships result in less flow over the rudder and hence, less control. Moreover, it resulted into different lift characteristics for the hull and therefore, different directional stability.

Awareness about the impact on directional stability led to investigations concerning the effect of the hull form. In particular, the increasing fullness of the aftbody on the course-keeping ability was a growing concern. Investigations were carried out systematically, both by captive tests in rotating arm basins and free running model tests. This showed which aft body shapes lead to problems. CRS has also merged this knowledge into practical software tools, so that shipyards and designers could use this

Discussing the effect of propeller turning direction on manoeuvring and course keeping (MORE project)

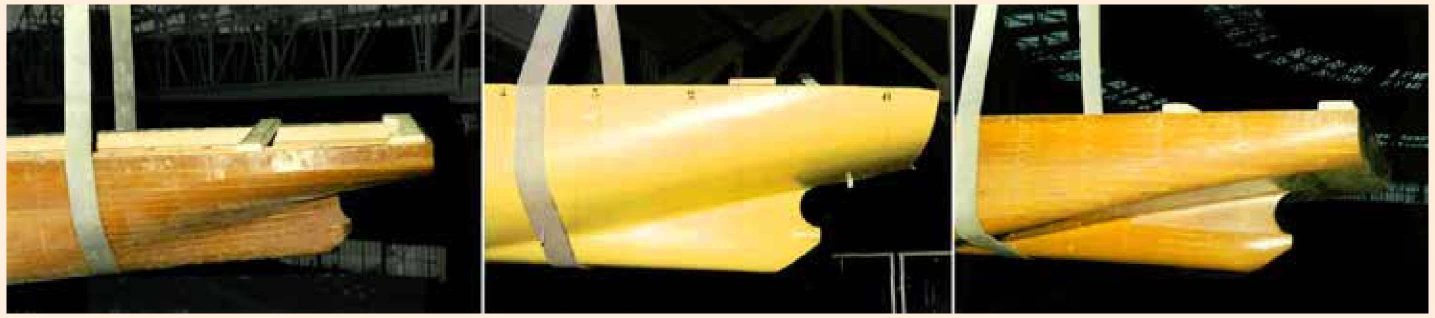
to their advantage and had knowledge that their competitors did not have.

Which applied research did CRS perform?

CRS established a working group with a budget to investigate these issues. CRS members needed to know what it would take to reach acceptable stopping distances. The loads that acted on the propeller were very unconventional during stopping manoeuvres. Research took place while measuring the strength of the propellers, and the rapid change of the turning direction of the engine. The Manoeuvring in Early Design Stage working group (1988-1991) and the MAN working groups (1992-1996) focused on the possibility of predicting the cross-flow drag coefficients using segmented model test results. Segmented model tests were carried out to obtain insight into the distribution of manoeuvring forces over the length of a ship. Re-analysis of existing segmented model tests of the so-called 'Todd series' formed the start of the MPP program. Testing of the first version of MPP revealed a good correlation for most ships, except modern tanker forms which had the 'pram' stern. To correct for this, a modern tanker hull was selected to conduct further segmented model tests. This hull form was both lengthened and shortened so that data for different hull forms became available. Hydrodynamicists such as Geert Kapsenberg, Jan Hooft, Ian Dand and Wim Beukelman performed groundbreaking investigations and set-up the cross flow drag method to quantify the non-linear manoeuvring forces. At that time, this was unconventional, but the scientists were convinced that they were on the right track. While somewhat quirky, this has resulted in improvements that otherwise would not have been possible. And it has led to a practical and robust tool for CRS members!

Since 1990, the following working groups have all played a role:

- LB: tankers in light ballast conditions
- MED: manoeuvring in early design
- RUD: rudder design manual
- MAN: manoeuvring predictions
- MANTS: manoeuvring for twin screw vessels
- MAN3: manoeuvring predictions for podded vessels
- COGNAC: low speed manoeuvring (crabbing)
- COGNAC-2: crabbing in the neighbourhood of quays



Three aft body shapes

To measure the crabbing performance, large models need to be used. The model on the photograph was the CRS base model for many crabbing tests in deep and shallow water

- MANWAV and MANWAV-2: methodologies to predict manoeuvring behaviour in waves
- MORE: manoeuvring in operational conditions.

The CRS working groups consist of scientists and practical ship designers. This interesting combination assures that not only fundamental research is carried out: at the end of the day, this always culminates in a software tool or prediction method. The resulting practical prediction method can be applied very rapidly, so that the ship designers can use them to create a manoeuvring prediction within 5 minutes.

What is the key to the CRS success?

The beauty of the CRS model is that the developments are not curiosity-driven, but a direct consequence of developments in ship design. On one hand, designers had a direct need and on the other hand, the quirky scientists had opinions.

The MED project was driven by awareness that a full aft body had a detrimental effect on the course-keeping. The MAN project was a direct consequence of the start of the development of the IMO requirements for ship manoeuvrability. The first non-mandatory A751 requirements became active in 1993, while the mandatory ones became active in 2003.
MANTS occurred at the same time as the development of the larger cruise vessels (end of last century). MAN-3 was established following the introduction of the podded propulsor to the market.
Even the latest developments regarding manoeuvring in waves (the MANWAV working groups) are occurring at the same time as the IMO required investigations related to the minimum power requirements for low powered ships. But also other ships need to demonstrate their ability to have adequate manoeuvring characteristics in waves and in wind nowadays.

The interesting part of the working groups is not only the result, but the way in which the result is achieved. The eclectic nature of the members of the working groups means that there is a good balance between applied research and practical applications in day-to-day work.

Manoeuvring and course keeping in waves

Since 2012, manoeuvring research of the CRS has also focused on special and unconventional manoeuvres such as acceleration turns and turn-on-the-spot manoeuvres. The manoeuvres in waves are of particular interest: course keeping, track keeping and the ability to turn.
First, we developed knowledge and tools in the MANWAV project: insight into the autopilot, propeller loads and ventilation in waves, and the response of the engine to these. A large effort went into the investigation of the best way to quantify the 2nd order wave forces in irregular waves and the methodology to augment it to the manoeuvring simulations. Prior to the now selected solution, a fully coupled theory and de-coupled theory have been developed to investigate which would best suit the needs of the CRS.
At last, the MORE project is applying and validating the simulation methodologies. Practical operational manoeuvres are simulated with the tool and validated with model tests on a ship while manoeuvring in waves (see also cover illustration).

Ability to predict the added resistance of ships in waves has matured

Over the last five years the RAW working groups in CRS have investigated the nature of the added resistance of ships at sea and the merits of alternative ways to predict its magnitude.

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The investigation made use of MARIN's potential flow Rankine source code FATIMA, and CFD contributions from DNV GL, Lloyd's Register, ABS, Bureau Veritas, Chantiers de 'l Atlantique, Navantia and MARIN. CETENA examined the impact of course-keeping. These numerical results were compared with scale model tests at MARIN and DGA.

In the first years, the work focused on the added resistance of a container ship, a full block tanker and a fast, naval hull in waves from four directions. We learned that the added resistance is not always described adequately in terms of a quadratic transfer function, and the work in later years has focused on deviations from this concept.

Prediction techniques The dispersion of the reflected and radiated waves at forward speed is a key element in the relative wave elevation in the diverging flow at the bow and the associated contribution to the added resistance. To account for this, the potential flow calculations were performed with a Rankine source code.

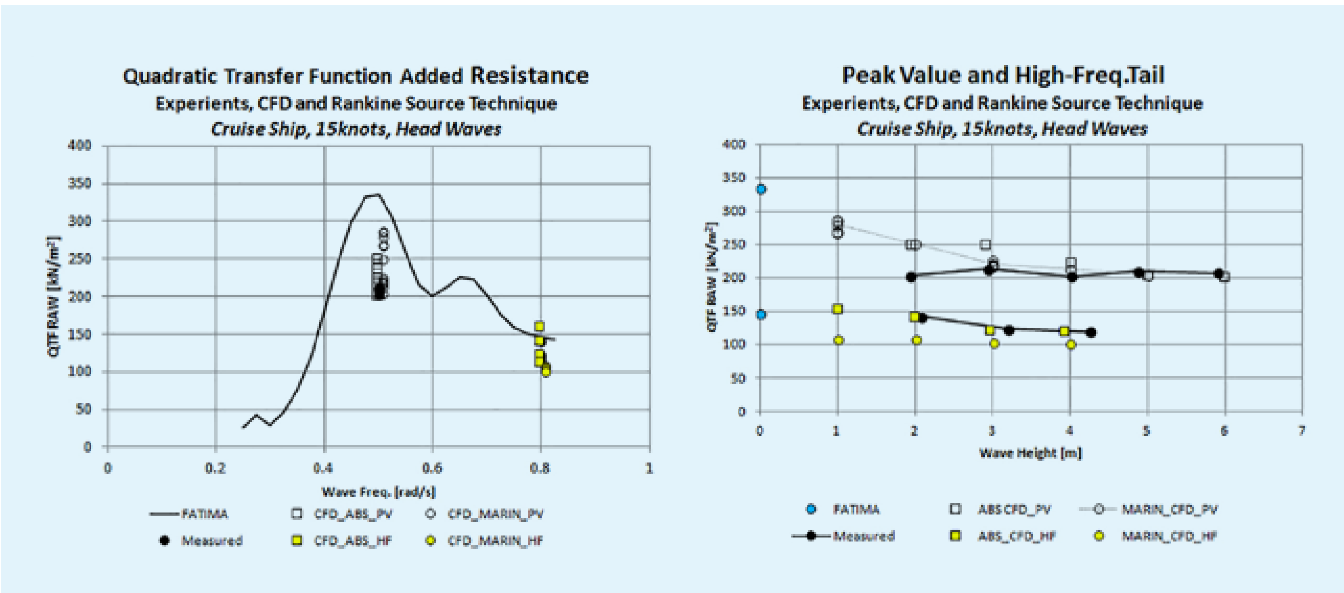

Figure 1: Quadratic transfer function of the added resistance of a cruise ship, Fn=0.150, in head waves, comparison of results from a Rankine source code (MARIN), CFD (ABS, MARIN) and experiments (DGA)

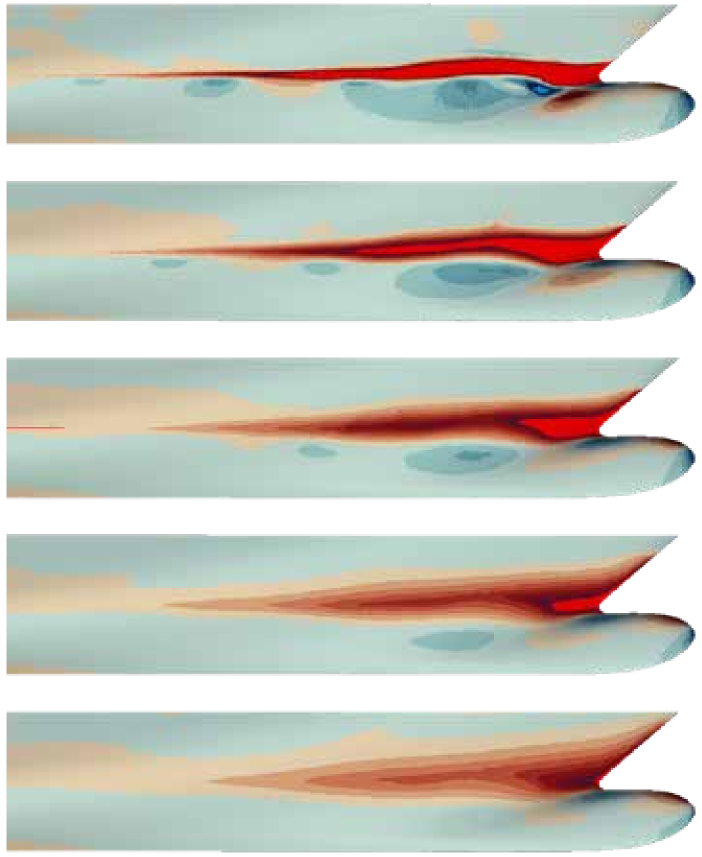

Figure 2: Local added resistance as a function of wave height at the peak of the QTF, Cruise ship, Fn=0.150, Head Waves

The analysis of the (negative) contribution of the second order pressure drop to the added resistance made clear that the results of the FATIMA code required a correction for local spurious effects.

Various working group members performed CFD calculations using RANS codes, namely Star-CCM+, OpenFOAM and ReFRESCO. The accuracy of these calculations increased in the course of the project as the parameters influencing the quality were discovered. Among the key parameters, the quality of the propagation of the incoming, radiated and diffracted waves was highlighted, as well as the convergence of the coupled system per time-step. Other key points were the location at which the reference wave is determined, and the magnitude of the reference resistance in calm water. CRS has certainly advanced the ability to generate optimised CFD meshes for seakeeping applications and the RAW working groups have contributed significantly to this development.

One important finding for accurate predictions based on model tests is that it is essential to control and fix the speed of the model for the assessment of the difference between the resistance in waves and the resistance in calm water. This was why MARIN used a semi-captive set-up in the first sets of experiments. Tests at DGA were performed with a towed model. All results made clear that the accuracy of the derived added resistance is not self-evident. Amongst other precautions, careful monitoring of the reference resistance in calm water proved essential to obtain accurate results.

Counterintuitive finding The most important finding from the investigation is that the three prediction methods yield a consistent impression of the added resistance of a ship in waves. Another, quite remarkable and counterintuitive, finding is that for ships with a substantial bow flare, the peak value of the quadratic transfer function (QTF) of the added resistance showed a marked decrease with the wave height.

Figure 1 illustrates these findings with the QTF of the added resistance of a cruise ship at a moderate speed in head waves. The fact that the added resistance QTF shows a decrease in higher waves may appear counterintuitive. In the first instance this phenomenon was attributed to the fact that the reflected and radiated waves show a transition to a non-linear flow regime, demonstrated by the observed spray. In a later stage we realised that the CFD shows that the mean pressure drop – just below the free surface – is also highly dependent on the wave height. Figure 2 shows the change in the mean pressure experienced by the hull as a function of wave height. Several of the phenomena in low waves where the steady flow plays a role, disappear in higher waves.

Non-quadratic behaviour As the potential flow methods, CFD and experiments show a consistent picture, we conclude that the prediction of added resistance has become mature. We also conclude that the added resistance of ships with considerable flare at higher speed shows a non-quadratic behaviour in higher waves. The dependency of the added resistance on wave height is less than quadratic.

Considering the rather delicate (hull form, speed and wave height dependent) changes in the pressure field and the level of expert judgement that is still inevitable in setting-up and interpreting the potential flow, CFD and model test results, the prediction of added resistance still comes with some level of uncertainty. However, we feel that the predictions are certainly sufficiently accurate to find the delicate balance between building and operational costs in ship design.

report

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