Institut(ter): FORCE Technology	**Aktivitetsplan (titel):** Udvikling af hybride testmetoder for stor-skala mekaniske og strukturelle systemer **Idéforslags titel på bedreinnovation.dk:** Udvikling af hybride testmetoder for stor-skala mekaniske og strukturelle systemer	**Aktivitetsplan nr.:** A03	Infrastruktur

1) Manchettekst (kort resumé)

Nye hybride test- og valideringsmetoder til test af stor-skala mekaniske strukturer kræves for at sikre udviklingen indenfor vedvarende energi, det maritime og infrastruktur. Aktiviteten udvikler sådanne metoder i samarbejde med danske virksomheder.

2) Aktiviteten kort (resumé)

Udvikling og validering af store og fuldskala mekaniske systemer og strukturer er komplekst, tidsintensivt og dyrt for industrien. Danmark er førende indenfor vindenergi, marine og offshore industrien samt byggeri og infrastruktur. For alle disse brancher er udvikling og validering en udfordring, der vokser i takt med systemernes størrelse og kompleksitet.

I denne aktivitet udvikles og afprøves som proof-of-concept et nyt, hurtigere og billigere værktøj til test og modelvalidering af sådanne store, komplekse systemer. Værktøjet bygges med udgangspunkt i en udviklings- og valideringsplan, der udnytter en hybrid af fysiske test, avanceret computersimulering og næste generations overvågningsteknikker.

Udviklingen af disse hybride testmetoder vil fokusere på to områder (1) En hybrid af tests i forskellige størrelser og kompleksiteter og (2) En hybrid af fysiske og virtuelle tests, hvor computermodeller og fysiske testprogrammer integreres. Ved at integrere modellering og simulering på tværs af forskellige størrelsesskalaer, kan valideringsprogrammerne give hurtigere og billigere resultater. Derudover vil de nye services være nyttige for virksomheder placeret i hele forsyningskæden, da deres produkter eller systemer nu kan evalueres effektivt på komponentniveau.

For at engagere, dele viden med og lære af industrien, vil aktiviteten etablere et nært samarbejde gennem Advisory Board og demo-cases med industrielle og akademiske partnere. Endelig udvikles et videreuddannelseskursus med henblik på at imødekomme industriens efterspørgsel på kvalificerede fagfolk inden for mekanisk og strukturel testning.

3) Markedsbehov, erhvervs- og samfundsmæssige potentialer

Key industries in Denmark need next generation large- and full-scale mechanical and structural validation and testing services. Denmark is a world-leader in manufacturing and installation of wind-energy (more than 85.000 full-time employees linked to the industry)[1], buildings and large-scale infrastructure projects (almost 166.000 employees)[2], and marine vessels and systems (approx. 40.000 direct employees)[3]. Within these industries the mechanical and structural systems are of immense proportions, where newer and even larger projects have been announced or are already being pursued, e.g. 10+ MW wind turbines.

[1] http://www.windpower.org/en/knowledge/statistics/contribution_to_the_economy.html
[2] https://www.danskbyggeri.dk/presse-politik/nyheder/2017/byggebeskaeftigelsen-flader-ud/
[3] https://danskemaritime.dk/danskemaritime/den-danske-maritime-industri/

With their importance to the Danish industry and their need for mechanical and structural testing services these three industries: wind energy, buildings and large-scale infrastructure, and the marine and offshore sector, are the target groups for this activity.

Full-scale prototype testing with increasingly larger specimens is more expensive, must be overly simplified, and takes too long to complete; where a modular and smart solution can optimize the development and validation process. LORC is one of the largest test benches for wind energy nacelles world-wide and its HALT facility, at a capacity of 13 MW, was an investment total of 150 MDKK. Facilities such as the HALT facility have too high costs for SMEs, and continually building new test facilities, for even larger systems, is not an economically viable solution either.[4] Therefore, smart and optimized testing and validation solutions, which are accessible for companies throughout the entire value-chain, are necessary for the Danish industry.

Developing an intelligent, hybrid, and modular testing approach that supports industry development and validation needs will enable Danish companies of all sizes to compete on the international landscape.

Each of the above industries is key to Denmark, where the supply chains are a large collection of SMEs up through large enterprises. In the wind industry in particular, a fierce global competition is apparent, and several countries are aspiring to become home to the leading companies. The European Union competition law prohibits the use of state subsidies for industry. However, an exemption is made for financing research, and research and innovation facilities. Some of our neighbours have realised this and are investing in still more advanced test facilities. Hence, Denmark, with very few funding sources available for test facilities, is forced to develop innovative ways of responding to the needs of the industry. Activities as this one that provide smarter and more efficient test and validation solutions are necessary. The industry group, MegaVind has identified the needs for testing capabilities for SMEs that they may supply quality components[5]. In addition, OffshoreEnergy.dk has identified the need to facilitate access for SMEs to test and demonstration facilities.[6]

This activity will build upon the capabilities of testing infrastructure and address three-fold the development of testing and validation methods for components of a scale and complexity that can no longer be validated by a simple prototype test. The activities will focus on (1) Optimized mechanical testing, (2) Next generation measurement and monitoring programs from the digital innovation sector and (3) Linking these two with hybrid testing—combining simulation and physical testing. The industry will be further supported with new knowledge and resources distributed to the industry through close collaboration and with a newly developed continuing education course on test engineering.

Hybrid testing programs will be developed, which will focus on novel testing concepts in two areas:

(1) Hybrid of testing sizes and complexities
(2) Hybrid of physical and virtual testing programs – integrating modelling and physical testing

On bedreinnovation.dk there were a total of 36 comments on the phase 1 application, and the above technical areas received positive feedback from the commenters, who highlighted that:

"Den viden der vil blive resultatet af projektet er yderst relevant for fremtidige test og valideringer af vore designs. Kombinationen af simulering og fysiske test sikrer en højere valideringsgrad og dermed reduceret projektrisiko. Projektet ide om at teste på delsystem og komponenter til brug af simulering af det komplette

[4] https://issuu.com/mediegruppen/docs/9716_discover_lindo_10_2018_dk
[5] http://megavind.windpower.org/download/3016/2017_megavind_annual_research_and_innovation_agendapdf
[6] http://northsearegion.eu/inn2power/about/

system eller konstruktion vil klart bringe os fremad.", **Jesper Uth, Senior Director, Test and Validation, Vestas**

Modular and component testing combined with next generation monitoring techniques in hybrid programs will become the new standard. Hybrid and component testing will offer more value than traditional sub-structural and full-scale testing programs through shorter, more cost efficient, and advanced testing programs. More cost-efficient testing enables a greater number of specimens to be tested and to raise the confidence in the reliability of a product. Finally, highly integrated modelling and testing programs will enable more information to be learned and create better simulations of a system's mechanical performance.

The need for better and smarter testing solutions were defined through one-on-one conversations with the industry. Key industry contacts that were influential in helping to define the activity plan will be forming the basis of an industry advisory board. It is expected that testing needs will continue to grow as mechanical and structural systems do as well, along with an even greater emphasis on reliability. It is expected 5 years after the start of the activity that 12 to 15 companies will use these services annually.

Finally, this activity aligns well with national strategies across a number of industries. In a 2017 report on future energy policy in Denmark that outlined the need to strengthen Denmark's lead in energy technology it was highlighted that "priority must be given to unique demonstration projects and testing platforms."[7] In FORSK 2025, this activity supports outlined research needs related to new materials for innovation and growth, future building and physical infrastructure, and the further growth of the renewable energy sector. Structural and mechanical testing and validation services will be an essential component of qualifying new products and technologies. Of potential interest will be evaluating and qualifying structures that are composed of novel materials and built with new manufacturing methods, e.g. 3D printing of steel.

4) Videnspredning og inddragelse

A focus of this application will be to set up and foster a successful dialogue, involvement, and exchange with the Danish industry. Within the target group there will be an effort to directly engage with a number of companies in each industry and with industry branch organisations, e.g. Danish Wind Industry Association, Offshore Energy, Fyns Maritim Klynge, Nordisk Vej Forum etc.

Three key elements will be used to gain contact with companies throughout Denmark, which are:

1) Seminars and open-houses on full- and large-scale testing
2) Close collaboration with industry partners on demo-cases
3) Pilot course on test engineering education

FORCE Technology at Lindø Component and Structure Testing A/S (LCST) will be holding open houses and seminars regularly throughout 2019 and 2020 related to large- and full-scale testing. A minimum of two times per year the open houses and seminars will focus on mechanical and structural testing. FORCE will engage with Danish professionals and academics at these events on the development of hybrid testing methods, monitoring techniques, and continuing education courses. It is expected that contact with 100 plus companies per year can be fostered through the open houses and seminars.

Close collaboration and working partnerships will be established with several Danish companies through demo-cases. Three demo-cases will be pursued as part of this project, 1 from each industry group, e.g. wind, marine and offshore sector, and buildings and infrastructure. Demo-cases within test and validation

[7] http://efkm.dk/media/8275/energikommisionens-anbefalinger_opslag.pdf

work quite well as consortium projects; therefore, it is expected that an average of three to four Danish industry partners and a higher education institution could be involved in each demo-case.

For the continuing education course, a survey will be conducted to scope the necessary and optimum course content. Upon completed development, a pilot course will be conducted where it is expected that more than 15 individuals from industry will gain significant insight into state-of-the-art mechanical and structural testing methodology and practice. After completion of the project it is expected that the course will be conducted 2 times per year with a goal to reach 50 plus professionals yearly, where FORCE will continue to offer the course to industry within the myriad of other course offerings.

To help guide the project an industry advisory board will be formed. Representatives have been asked to be on the advisory board that have experiences and perspectives from all three industries that the application is targeting. It is expected that the advisory board will meet 2 times per year during the project period. Near project completion, it will be explored whether meetings with the advisory board will continue after the end of the activity.

Work with universities and higher-education institutions will be actively pursued, along with efforts to learn from their complementary knowledge and skills. Within mechanical and structural testing FORCE has strong contact with DTU, AAU, and SDU; where it is expected that one masters project per year will be supported by the activity. In addition, 2 marine engineering schools (SIMAC and Maskinmesterskolen København) will be engaged in the activity with student internships and bachelor projects.

DTU has significant research experience in hybrid and structural testing and the activity will work on profiting from this knowledge base that DTU has gained over the last years. In addition, collaboration with DTU on the development of a continuing education course in test engineering will ensure a robust pedagogy to the developed course content and training program goals.

Finally, the activities that are being pursued and the results will be publicized through industry trade magazines, scientific journals as is applicable, and at conferences and trade fairs. Minimum 2 publications will be targeted each year and attendance at 1-2 conferences or colloquiums (1 Danish or 1 international).

5) Konkrete aktiviteter

The main goal of the activity is to develop improved, cost efficient, and time efficient test and validation strategies and services through the use of new technologies and approaches in mechanical and structural testing. Hybrid testing and modelling is the central theme within the activities and it provides the link between testing, modelling, and monitoring at different size scales and with varying degrees of complexity.

This activity will develop the testing and validation methods into industry ready services. In addition, knowledge of testing and access to key information and skills for professionals will be made readily available to the industry through a developed course in test engineering.

Technology and service developments:

(1) Development of a modular testing methodology for mechanical and structural systems

   a. Define a general component and modular testing strategy for use in product development and new product validation testing

      i. Outline a test matrix which proceeds from material testing all the way to full-system testing and identifying testing steps along the way

ii. Define the link between modelling and testing at varying levels of testing matrix

b. Employ computer simulations to define the overall testing strategy and perform parameter sensitivity analysis

(2) Testing and modelling implementation

a. Design testing strategies for the different size-scales and complexities

b. Develop coupled physical and virtual testing: to test sub-systems and components and simulate the complete system

c. Implement sub-component testing programs

d. Conduct integrated sub-component tests and full-scale tests

(3) Next generation instrumentation and monitoring

a. Survey of available technologies for implementing industry targeted hybrid testing

b. Implement cutting edge monitoring and data acquisition together with big-data analytics to learn more from the testing

c. Develop the necessary monitoring and feedback loops for integrating the physical test in a virtual environment

Demo-cases

The activity will identify 3 demo-cases to develop and carry-out throughout the 2-year timeline. The demo-cases will be industry focused cases such that the service development will be useful across a set of industries. It is planned that 1 of the 3 demo-cases will be devoted to the component testing program of the Innovation Fund sponsored CeJacket project, which is further detailed in Section 7.

The demo-cases will be pursued as collaboration projects where the goal will be to have a small consortium of 3 to 4 partners that are active in each demo. The demo-cases will be developed to show representative testing, modelling, and instrumentation solutions within the hybrid testing objectives. Large-scale testing is quite resource and time-intensive; therefore, it would be unrealistic to try to complete additional demo-cases, otherwise quality could be compromised, and the necessary elements of each demo-case could not be included.

Continuing education course in test-engineering

A central part of the activity - due to expressed need from the industry - will be the creation of a continuing education course in mechanical and structural test engineering. The course will cover the topics of testing and measuring for standard mechanical testing programs. Topics on more advanced course content including sub-component testing and advanced measurement techniques will be discussed with the industry on their relevance for this continuing education course.

The continuing education course will be designed and laid out with professors and researchers from the mechanical and civil engineering departments at DTU.

The development of the course will proceed after the following plan:

1) Survey the target group to assess their needs and focus areas for a test engineering course(s), i.e. course length, course content, frequency, etc.

2) Outline and design a course in test engineering for mechanical systems

3) Collaborate with DTU and international universities and researchers on developing the theoretical and practical training elements

6) Nyhedsværdi og ambitionsniveau

This activity will pursue an ambitious program to address relevant and real needs for the industry. New cost effective and industry available testing knowledge and services will be built on top of existing principles and currently research-based solutions.

Henrik Stang, Professor, Vicedirektør, Centerleder CASMaT, DTU Civil Engineering, nicely captures the goals of the project and its timing within the industry:

"Forslaget er yderst relevant og vel-timet i forhold til udviklingen på området. Den seneste udvikling inden for styrings-, kontrol- og måleteknik - sammen med udviklingen i avanceret konstruktionssimulering - peger netop i denne retning. Det er meget vigtigt, at I tager denne udfordring op – disse testmetodikker kommer givetvis til at blive standardværktøjer på en lang række industrielle områder i fremtiden."

FORCE has a long history of supporting the Danish industry in their new developments and failure analyses. FORCE has for several years been performing standardized services within the areas of mechanical and structural testing and modelling. Within the current running performance contract *Store konkurrencedygtige konstruktioner*, FORCE has been able to successfully implement service offerings in the area of large- and full-scale mechanical testing and validation. Where Danish industry now has a competent industry focused service provider for traditional large- and full-scale testing. To move from these traditional test and validation methods and to stay ahead this new activity will help the industry push the next level of developments, advanced and hybrid testing, monitoring, and education services are a necessity.

Currently within structural and mechanical development and validation programs; testing and modelling services exist quite separate from each other and their ability to interact in integrated solutions is limited. In addition, few guidelines or development approaches are available for defining modular or sub-component testing programs, which can help provide lower cost and more reliable testing.

A few individual programs have started within Denmark and internationally, working to create modular, sub-component and hybrid testing programs. At DTU, researchers in civil and mechanical engineering have been working on hybrid and component testing for the last 6 to 7 years.

Internationally, two notable projects working on more efficient and component testing are:

(1) JaCo – Improved Fatigue Life of Welded Jacket Connections[8] (2,4 M£) – OCAS NV (Belgium) focus on efficient testing technologies to reduce the necessary time for fatigue testing.
(2) Future Rotor Blade Concept[9] (10 M€) – Fraunhofer IWES (Germany) focus on developing a component testing program for the next generation of turbine blades

None of the programs have taken an integrated approach to work on defining truly industry-ready hybrid testing solutions that are cost-effective programs targeted at companies throughout the entire value chain of the target group in this activity.

[8] https://www.carbontrust.com/offshore-wind/owa/demonstration/jaco/
[9] https://www.windenergie.iwes.fraunhofer.de/en/press---media/future-rotor-blade-concept.html

Lower cost testing, which is being targeted in the activity plan and utilizes modular and sub-component testing, is a necessity for SMEs seeking accessible and high-quality testing and modelling validation services. The ability to include more testing samples is a must as industries are optimizing design solutions to save weight and costs in their final products without compromising on robustness and safety.

The hybrid testing in this work will take the benefits from the research-based test programs at DTU and translate them into viable industry applicable solutions. In addition, the previous international work on component testing will help to define a starting point in the design of the appropriate component testing approach and testing methodology.

Hybrid testing programs have the potential to provide a number of advantages for the industry, which will be targeted in this activity. Through hybrid testing, complex cases can be broken down into smaller and more manageable testing and modelling programs. Hybrid testing programs provide advantages by closely linking physical testing and computer simulation between direct coupling of the two environments, which will enable faster and more accurate modelling and testing programs. Where greater efficiency and accuracy will enable studying more load cases and design variations in greater detail than previously.

In addition, testing and modelling validations which were previously investigated quite statically will be able to better capture the dynamic and non-linear behavior of some systems, which was identified on bedreinnovation.dk:

"Ofte er komponenter på skibet designet og verificeret enkeltvist, men det er deres opførsel i et dynamisk og ikke-lineært system, der er interessant.", **Ingrid Marie Andersen, Senior Naval Architect, AP Møller-Mærsk**

By developing hybrid testing methods and methodologies along with knowledge centers, private industry can gain independent insight and acceptance into the newly proposed methods. Within this activity, new tools and information will be made available for the industry during product development, new product validation and failure assessment programs.

Large- and full-scale testing infrastructure and developments are often handled at knowledge institutes as not many companies have the ability or the need to fully establish these services and knowledge in-house.

At completion of the activity, the industry will have implementation-ready solutions that employ the use of smart technologies and hybrid approaches in testing, modelling, and next generation monitoring.

7) Vidensamarbejde og -hjemtagning

This activity will be able to benefit from the complementary knowledge and services that exist at Danish higher education institutions and at international knowledge centers.

FORCE along with LCST have established formal collaboration with the departments of civil and mechanical engineering at DTU at their new testing facility CASMaT. Strengthening this collaboration and the exchange of testing expertise will be a focus within the project. Furthermore, two collaborative projects involving AAU and SDU, respectively, are further detailed below.

In addition, international collaboration and knowledge sharing will be pursued as part of the project. Large- and full-scale testing activities tend to exist at a few knowledge institutes throughout Europe. Significant experience and direction for new developments can be gained from networking and knowledge exchange with these international testing institutes. As part of the project, FORCE will work on establishing a network for these large-scale testing facilities to exchange knowledge and experience.

This activity will be used to partially co-finance an Innovation Fund Grand Solutions project, CeJacket, that targets jacket solutions for offshore wind turbine foundations. FORCE has a role in the project to define and conduct scaled testing for evaluating the performance of novel jacket manufacturing methods. There is close synergy between CeJacket and this application as goals of both projects are to design a component testing program, which is useful for characterizing and validating a new product. In addition, next generation monitoring will be conducted using online automated ultrasonic inspection. It is expected that this project will be used to fulfill milestone 1.2. The CeJacket project partners are Siemens Gamesa Renewable Energy, Ørsted, Blade Industries A/S, Aalborg University, and FORCE.

In addition to the CeJacket project, FORCE is engaged in further work in optimized solutions for jacket technology utilizing high-strength steel as part of a consortium with Ramboll, SDU, Bladt Industries A/S, SSAB and FORCE. The new project is applying for EUDP funding. There are a significant number of synergies between this activity and that on high-strength steel jacket nodes, which is looking at using novel materials and manufacturing methods in offshore jacket foundations. Validation of these new materials and production methods will need to be sought with testing and modelling methods, which are complementary to those that are being pursued in this project.

8) Sammenhæng med instituttets strategi og afsæt i instituttets ressourcer

This activity closely aligns within the two main components of the FORCE strategy through (1) its position in the value chain and (2) its relevant underlining themes.

This activity supports the value chain within, primarily, the *Design & Development* phases of a mechanical and structural product or system, and secondarily, also the *operation and deployment* phases. Testing and the associated modelling can be an essential tool for the industry during product development steps as well as for validation of new designs, materials, or manufacturing methods before a system is ready to be put into service. Within a product or systems operational and service lifetime, faults or failures can be explored through testing and modelling.

Thematically, this activity aligns with 3 key themes from the FORCE strategy, which are 1) *Målgruppe 2.0* – target group 2), *Digitalisering 2.0* - digitalization and 3) *Samarbejde 2.0* – collaboration.

Within each of the industries in the target group, Denmark is recognized as a world-wide leader. It is a particular goal within the strategy of FORCE to target service development towards industries where Denmark is an established leader and will continue to be as not only the large companies but also the full value-chain and its associated SMEs excel.

Within digitalization, this activity will uniquely pursue moving test and validation of large mechanical structures and systems into the next generation by bringing together physical testing along with digital innovations in simulation and advanced monitoring. This combination brings together the benefits of physical testing and hybrid simulation into one integrated solution.

Within collaboration this activity will establish a unique collaboration between industry, higher education institutions, and international knowledge centers. Collaboration will be sought out within four key areas of the project:

1) Guidance in the activity from an industry Advisory Board
2) Small industry-based consortia for the demo-cases
3) Collaboration with higher education institutions for student work and to establish the continuing education course on test engineering

4) International collaboration through establishing a network for large-scale mechanical and structural testing facilities

9) Tidsplan og milepæle

Year 1

Knowledge collaboration and competence building

1.1 Outlining and start-up of 2 demo-cases – establish project consortiums within the relevant industries (marine and offshore, and infrastructure and buildings).
1.2 Completion of 1 demo-case from CeJacket project – testing demo which illustrates sub-component, modular, and scaled testing, and advanced monitoring.
1.3 Participation in 1 conference.
1.4 Highlight the activity focusing on its development goals and preliminary technical developments in 2 publications, e.g. trade magazine, journal publication, news article, etc.

Development of technological services

1.5 Testing matrix for the target group that outlines modular and sub-component testing and modelling approaches within product development and validation services.
1.6
1.7 Conduct survey and analysis on test engineering education course to establish the basis for the development of the course outline and content.
1.8 Develop tools for conducting hybrid testing – linking modelling and physical testing.
1.9 Survey available technologies within monitoring and instrumentation for implementation within next generation and smart monitoring campaigns.

Knowledge disseminations

1.10 Establishment of advisory board and conducting 2 meetings.
1.11 Hold 2 open houses and micro-seminars at LCST with focus on large- and full-scale mechanical testing solutions.
1.12 Support bachelors and Masters' student projects (completion of minimum 1 project).

Year 2

Knowledge collaboration and competence building

2.1 Complete remaining 2 demo-cases within industry sectors of marine and offshore, and infrastructure and buildings.
2.2 Participation in 1 conference.
2.3 Highlight the activity focusing on the technical developments from year 1, in 1 publication, e.g. trade magazine, journal publication, new article, etc.

Development of technological services

2.4 Implementation of hybrid testing and modelling in a development or new validation testing case – conduct along with a demo-case from 2.1.
2.5 Implement advanced monitoring and instrumentation testing solutions – conducted along with a demo-case from 2.1.
2.6 Develop course syllabus and materials for test engineering education.

2.7 Complete pilot course run in test engineering education.

Knowledge disseminations

2.8 Continued meeting of advisory board with a further 2 meetings.
2.9 Hold 2 open houses and micro-seminars at LCST with focus on large- and full-scale mechanical testing solutions.
2.10 Support bachelors and Masters' student projects (completion of minimum 1 project).
2.11 Establish international network on large- and full-scale testing.