Final report

1.1 Project details

Project title	Wind load simulator for function and reliability test of wind turbine drivetrains
Project identification (program abbrev. and file)	EUDP J. nr. 64013-0523
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	R&D Test Systems A/S
Project partners	Aalborg University, Department of Energy Technology
CVR (central business register)	37844179
Date for submission	30-11-2017

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Abbreviations

AAU	Aalborg University
DUT	Device Under Test
FATLAB	Software programme for fatigue calculation developed in this EUDP project
HALT	Highly Accelerated Life Time
HIL	Hardware-In-the-Loop
R&D	The company R&D A/S
SoA	State-of-the-Art
TSDLAB	Test System Design LAB (a SW tool)
WLS	Wind Load Simulator
WLU	Wind Load Unit (same as WLS)
WP	Work Package

1.2 Short description of project objective and results

1.2.1 Short description of project objective and results

The objective of the project was to develop a scalable and replicable "load unit technology", capable of applying loads in six independent degrees of freedom.

The focus was to use this technology as a Wind Load Simulator (WLS) in test benches for function and reliability test of wind turbine drivetrains when installed in nacelles. Both functional and Highly Accelerated Life Time (HALT) test are sought executed.

The project result is a scalable WLS technology, implemented as a hydraulic actuated parallel machine, basing on the concept of a hexapod (Stewart-Gough platform).

Mechanical, hydraulic and control design has been performed for the WLS, making it suitable for testing wind turbines up to 10 MW-class. A demonstrator version of the WLS (scale 1:3 geometrical) has been designed, constructed and tested during the project, validating that the concept, control system and software performed according to requirements.

Mechanical validation has been achieved by showing that the WLS fatigue life and ultimate loads conformed to norms for steel constructions. Hydraulics for the WLS has been validated through simulation, conformity to norms, and checking that required hydraulic components are industrial available.

Commercially, during the final part of the project (summer, 2016), a turn-key order for HALT test bench with a full-scale WLS was received from a customer (LORC, Lindø Offshore Renewable Centre). This has been designed, implemented and commissioned, and was handed over to LORC by the end of 2017.

1.2.2 Kort beskrivelse af projektmål og resultater

Formålet med projektet var at udvikle en skalerbar "lastenhedsteknologi", der er i stand til at påføre laster i seks uafhængige frihedsgrader.

Fokus har været at anvende teknologien som en Vind Last Simulator (WLS) i en testbænk til funktion og pålidelighedstest af vindmøllers drivtog, når de er installeret i nacellen. Både funktionelle og kraftigt accelererede levetidstest ønskes udført.

Resultatet er en skalerbar WLS-teknologi, implementeret som en hydraulisk aktueret parallel maskine, der baserer sig på en hexapod platform (Stewart-Gough platform).

Mekanisk, hydraulisk og kontrolmæssigt design er blevet udført af WLS'en, hvilket gør platformen egnet til test af vindmøller op til 10 MW klassen. En demonstrator udgave af WLS'en (skala 1: 3 geometrisk) blev designet, konstrueret og testet under projektet, som efterviste konceptet, og at styresystem og software performede i overensstemmelse med krav.

Mekanisk validering er blevet opnået ved at vise, at WLS'en både i henhold til udmattelseslaster og ekstremlaster overholder designnormer of stålkonstruktioner. Hydraulik til WLS'en er blevet valideret gennem simuleringer, overensstemmelse med standarder, kombineret med at verificere at nødvendige hydrauliske komponenter er industrielt tilgængelige.

Rent kommercielt blev der i den sidste del af projektet (sommeren 2016) modtaget en ordre på en nøglefærdig HALT testbænk med en fuldskala WLS fra en kunde, LORC (Lindø Offshore Renewable Centre). Denne er designet, implementeret og indkørt, og blev endeligt overdraget til LORC i udgangen af 2017.

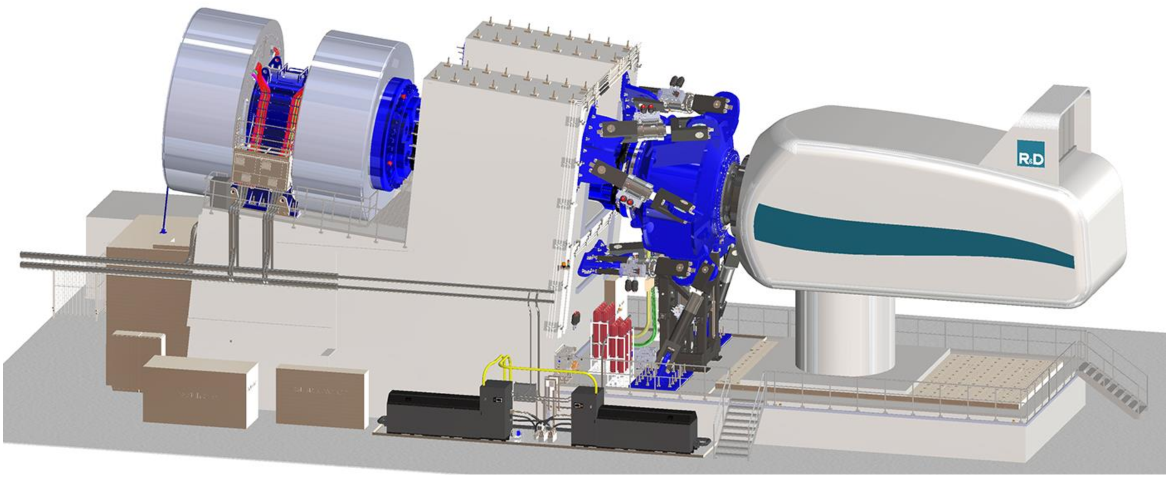
1.3 Executive summary

The EUDP project was a success, proving the feasibility of designing a Wind Load Simulator (WLS) for performing Highly Accelerated Life Time (HALT) testing of wind turbine drive trains. This report overall documents how this success was achieved within the scope of public dissemination. Non-public documentation is provided in the annex. A list of public available references can be found in Sec.1.5.4.

Success has been obtained through sound research and engineering within hydraulic, control and mechanical design, combined with a well-working cooperation between AAU and R&D.

The prioritization of research and engineering has been driven by reducing design and project risk, and focusing on tasks proofing feasibility. Hereafter, focus was given to detailed design work and validation of performance, which was achieved through test on the implemented demonstrator version of the WLS (hereafter named "demonstrator").

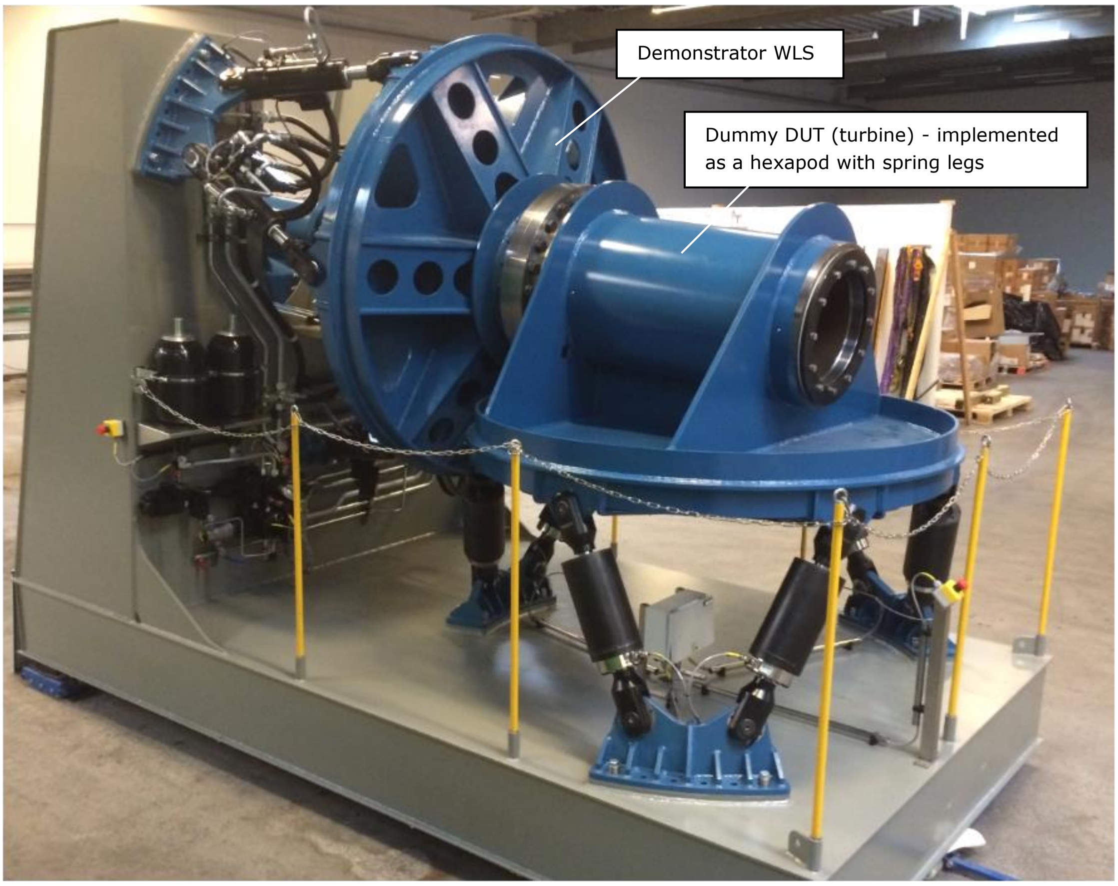
Commercial success is provided through the now sold, designed, commissioned and handed over full-scale test bench with a WLS to LORC. The project was conducted as a turn-key solution. A 3D of the design is given below. To give an impression of approximate size, the foundation for the test bench is built as a reinforced concrete foundation with a volume of approximately 1,500 m3 and two 14-meter-high pylons, a 6x11 meter tooling area for fastening the test nacelle and walls for the drive motor system. The WLS can apply a bending moment of up to 25MNm to the test subject in addition to the drive motor system and drivetrain, which can add a torque of 14.5MNm to the test subject.



The design has been carried aided by tools developed during this EUDP project and with the experience obtained from the demonstrator. The below picture of the demonstrator shown below clearly indicate the similarities of the two WLS designs.

WLS software and control components used on the demonstrator has been ported to the LORC WLS.

The design framework developed in the EUDP project has been applied to the LORC WLS design.



1.4 Project objectives

The overall objective of the project was to:

> *Establishment of a scalable technology platform for a Wind Load Simulator (WLS) unit with six fully decoupled degrees of freedom for test loads able to simulate wind loads for performing HALT tests, ULS tests, and functional tests*
>
> *(2-10 MW nacelles, tested at 4-8 months with cycle frequency in the range 0.5 - 2 Hz)*

The end commercial goal was to achieve a turnkey deliverable to a customer.

Technical and commercial milestones were met. Some divergence was encountered during the second part of the project execution, due to the commercial part progressing faster than expected. Customer interests and later order from LORC for a full-scale turnkey solution was ahead of the commercial milestones and ahead of the technical milestones (especially 11,12,13). However, the design tools developed during the EUDP project were for the most part sufficiently matured to enable their usage. Some re-prioritization of completion of the tasks were performed to align with the commercial requirements.

Budget and resource wise, challenges were encountered on the WLS demonstrator, especially regarding hydraulics and electric systems, which resulting in re-budgeting in order to utilize external specialists instead of the internal workshop. One part of the reason is that the design of the WLS demonstrator became more complex than anticipated during project scoping. Another reason was the increased size of the demonstrator to reduce impact of identified scaling effect. Finally, to improve validation credibility of concept, control and software, a “dummy” test object was also designed, named the “flexpod”. The flexpod was based on the hexapod geometry, but with springs with load cells instead of actuators. Unexpectedly, this device is now being offered as a solution for calibrating already existing test benches.

Another unforeseen challenge was encountered due to the AAU’s post-doc leaving midway due to unique job offer. This was mitigated by re-distributing project hours, and has aided in transferring the control knowledge to R&D from AAU.

The impact to the original time-schedule has mainly been due to the post-doc leaving mid-way and the increased commercially activities at R&D naturally drawing on the expertise of the resources also executing the EUDP project.

1.4.1 Project implementation and risk management

To achieve the objective and make the WLS a commercial use, providing value for both developer and customer, advances on many fronts were required. Generally, the project scope could easily increase beyond resources if all aspects had to be investigated.

To optimize project execution and effort, the first task to be performed (after IPR survey and SoAs) was a risk workshop, to pinpoint main project and technology risk, which could be distilled into tasks, and reduce time used on investigating more “trivial” engineering tasks.

The event was held with mix of participants (~15 people) from both R&D and AAU, representing specialist in all areas. A brief presentation was given of technology purpose, challenges and essential top-level requirements. The workshop generated a list of 131 risks, which were afterwards “scored”, see annex [1].

PART		CHARACTERISTICS OF FAILURE				1st RATING				ACTION-STATUS	
System/Category	Function / Part / Operation	Failure mode	Causes of failure	Undesirable customer effects Effects of failure on syst. / part / operation	Testing - Simulation - Verification	Po	S	Pd	RPN	Recommended action / mitigation	Planned action / mitigation
6. WLU control system	LAC force/moment sourcing	LAC control fidelity is not sufficient to provide LAC load accuracy required for HALT	insufficient model fidelity available for control.	Poor precision on LAC loads: inability to deliver required LAC load tolerances	1) state of the art model fitness study	6	7	8	336	this demonstrator project ultimately serves to validate the scale models	Demontrator designed for verifying control Sub-task titled: **Feasebillity study on controllabillity of Hexapod**
6. WLU control system	system models	Poor LAC controllabillity	Inprecise compensation for coupling restoring force and bearing friction	Poor precision on LAC loads: inability to deliver required LAC load tolerances	1) develop models of coupling are used to suppress coupling force 2) bearing friction influcence on drive torque and not the WLU LAC loads. Effect on WLU is suppressed by running roll in	6	6	9	324	1) observabilty analysis of bearing friction and coupling restoring force state variables 2) develop models 3) validate or estimate sufficiency of fidelity	Sub-task titled: **Identification and validation of certainty on coupling restoring force**
6. WLU control system	LAC force/ moment sourcing	insufficient controller stability	controller was not designed robust enough for LAC bandwidth, noise, and non-linear conditions	chattering in common form, loss of control in worst case	controller verified by control system verification and frequency anlysis	4	10	8	320	this risk reflects the risk of (late) model validation, not control stability for an adquate model	Demonstrator to verify hydraulic models

*Figure **Error! No text of specified style in document.**.1: A clipping from the result of the performed risk assessment*

Based on the risk assessment, tasks were defined, prioritized and integrated into work packages to mitigate high risks. Defined risk-tasks may be found in [2]. An example is shown below. This task deals with the risk that the WLS design is sensitive towards the stiffness of a wind turbine (i.e. how much a turbine deflects as a function of load).

Sub-task title:	Identification and validation of DUT stiffness range
1. Work package no.:	WP2 - Hydraulic Actuation System
2. Part of deliverable no.:	D2.3 - RS - All Hydraulic Components and Systems
3. Objective: (Why) (short description of why to do this sub-task)	Note: Common task for WP2-WP4 – most needed in hydraulics, but naturally performed with mechanical project lead. Multiple failure modes/risk have been identified to originate in uncertainty in DUT stiffness: • Wrong/conservative dimensioning of hydraulic power supply and control valves • Wrong hydraulic energy recovery topology if too large power ratings are used for business case • Requirement specification regarding requirement movement of WLU • Movement of WLU – expected operating conditions for bearings and seals • Design of control – suboptimal if designed to be robust over a large stiffness range
4. Scope: (What) (description on bullets of what to do in sub-task) (Sub-task must feed-in to deliverable as selected above)	It is assumed that it will be difficult to get customer to specify the requirements or stiffness upfront. Instead reasonable estimates have to be found, where-after these are approved by customers or experts in the field. • The work should define a stiffness model, providing the DUT movement in a test-bench when LAC force is applied • Obtain stiffness values for 5MW – 10 MW turbine. The best way may be to get operational data or experience from existing test-benches, i.e. at Vestas or Siemens. Otherwise estimates could be made from FEM analysis of a DUT, if sufficient data may be obtained. • The found stiffness and stiffness models should be approved by customers or experts in the field.
5. Deliverables: (Description and format on what to deliver, e.g. report, paper, software program etc.)	A report containing: • Documenting method for finding DUT model • A DUT stiffness model and expected behaviour • A DUT stiffness range with expected probability/distribution if possible, accepted by customers or experts in the field • Possible FEM models for identifying model
6. Success criteria: (Objective, need to fulfil, overall feed-in in relation to project, etc.)	An approved DUT stiffness range and model for use in the project
7. Budget (Estimate on hours for scope of work)	160 h

*Figure **Error! No text of specified style in document.**.2: Example of a "risk-task".*

Following the risk-workshop, a task-scoping workshop was performed to identify and prioritize remaining supporting sub-tasks to proof feasibility of the WLS. This workshop only included people part of the execution of the project. These sub-tasks are provided in annex [3]. A summary of the risk (R) and feasibility tasks (F) are given below, along with a status of which were executed. The prioritization was performed by assigning each task a risk score and a score for its importance for showing feasibility of the WLS concept.

Type	----------- **WP2 Task Titles** ------------	Deliverable	Budget [h]	Risk score [1-5]	Feas. score [1-5]	Total score [1-25]	Driver	Helpers	Feas. budget [h]	Go
R	Lumped parameter dynamic model of WLU and DUT	D2.2	240	3	4	12	RHH	TOA, MMP	72	1
R	Identification and validation of DUT stiffness range	D2.3	160	5	2	10	JGA	MMP	80	1
F	Create common model environment/architecture	D2.2	48	3	3	9	RHH	MMB, MBA	24	1
F	Terminology, reference frames and naming conventions	D2.2	37	3	3	9	RHH	MMP,TOA	19	1
F	Conceptual Design of Hexapod Actuators	D2.4	160	3	3	9	JGA	HCP	48	1
R	Actuator pin analysis and design with focus on ULS, FLS and micro fretting	D2.4	120	4	2	8	JGA	MMP	24	0
F	Baseline Actuation System Performance	D2.1	45	2	4	8	RHH	HCP	45	1
F	Definition of representative test cycles for design	D2.2	74	4	2	8	MMP	HCP, TOA	22	1
F	LAC load sensor	D2.3	120	2	2	4	JGA	PAR	108	0
R	Influence of wall and WLU platform compliance on power requirements	D2.2	74	3	2	6	RHH	MMP	22	1
R	Feasebillity of super imposing roll motion on hexapod	D2.4	37	2	3	6	RHH	MMP	37	1
F	Actuator Type and Performance	D2.1	37	2	3	6	RHH	TOA	30	1
F	WTG ULS+FLS rotor load modelling	D2.1	160	3	2	6	MMP	JGA	0	1
R	Capability Analysis of Spherical End Joints in Actuators	D2.4	160	4	2	8	JGA	MMP	16	1
R	WLS actuation power (OPEX) and cost (CAPEX) for obtaining feasible business case	D2.3	30	2	2	4	JGA	RHH	9	0

Type	----------- WP3 Task Titles ------------	Deliverable	Budget [h]	Risk score [1-5]	Feas. score [1-5]	Total score [1-25]	Driver	Helpers	Feas. budget [h]	Go
	Topology									
R	Accuracy specification for HALT TB	D3.2	90	4	3	12	JGA	RHH, MSP	63	1
R	Preliminary evaluation and optimisation of WLU to reach accuracy requirements	D3.2	160	4	5	20	RHH	WAC	112	1
F	Topology Investigation and Selection Tool	D3.2	120	4	5	20	WAC	RHH, MMP	96	1
R	Topology selection and gate	D3.2	24	4	5	20	JGA	WAC,MMP	24	1
R	Identification of proper scaling method and scaling effects	D5.1	80	3	4	12	RHH	TOA, HCP	64	0
R	Analysis of open-loop dynamics	D4.3	30	4	5	20	WAC	HCP	24	1
	Control									
F	Force control	D3.2	160	3	3	9	RHH	WAC,TOA	80	1
R	Feasibility study on controllability of Hexapod	D3.2	200	3	3	9	WAC	RHH,TOA	40	1
F	Control on chosen topology	D3.2	300	2	3	6	RHH	WAC,TOA	15	0
	SW									
F	SW-HW expectations for project	D3.2	40	2	2	4	MBA	WAC,MMB	36	1
F	SW Architecture & Interfaces	D3.2	120	2	2	4	WAC	MBA, MMB	60	0
F	Safety, Functional and Performance Requirements – Actuation and Control	D3.4	120	2	3	6	MBA	RHH	60	1
R	Investigation of sample time required for control	D3.2	40	4	1	4	WAC	MMB,MBA	4	0
R	Mechanical & SW Homing Calibration Functionality	D3.2	50	3	3	9	MBA	PAR	5	0

Type	----------- WP4 Task Titles ------------	Budget [h]	Risk score [1-5]	Feas. score [1-5]	Total score [1-25]	Driver	Helpers	Feas. budget [h]	Go
R	Method for evaluation of fretting	120	2	2	4	JGA		60	0
R	Guide line for cast components	120	2	3	6	JGA		36	1
R	TPS for EN-GJS400	60	2	4	8	JGA		3	1
R	Guide line for welded components	120	2	3	6	JGA		24	1
R	TPS for welded componnets	60	3	2	6	JGA		3	1
R	Development/implementation of fatigue calculation software	400	4	4	16	MMP		80	1
R	Guide line for calculation of Main shaft (rotating loads)	200	3	3	9			100	1
R	Guide Line for modelling of bearing in FEA	160	4	3	12	PAR	FMP?	48	1

Figure ***Error! No text of specified style in document.****.3: Overview of feasibility and risk tasks, and their execution.*

Overall the use of the risk and feasibility tasking workshop had the intended outcome of quickly identifying risky and critical aspect of the project across all system parts, thereby focusing effort. One learning is to try to be even more decisive during the scoring of risk and feasibility aspect, to get to the essential risk and feasibility tasks. Some overhead was generated in defining sub-tasks which were not executive due to prioritization or being less important than first assumed.

1.5 Project results and dissemination of results

As stated in Sec. 1.4, the project succeeded in meeting the overall project problem for which the project was proposed. A WLS technology platform was developed, sold to a customer, and is now ready to be used by the wind energy sector to improve reliability and thereby lower cost of energy.

An unexpected result is that the original hexapod design which the WLS was expected to be founded upon from the beginning, is not always the "best" solution. Other parallel actuator designs (like the one offered to the customer, having 9 actuators instead of 6) is often viable and desirable.

At start-up it was the assumption that the system should be kinematically determined. However, handling highly over-determined (kinematic) systems (i.e. more than six actuators) was shown not to be an issue, but on the contrary an advantage, offering a more flexible design. For example, it is easier to meet external layout requirements, load requirements and optimize power consumption.

Regarding the developed framework and design tools, the formulation is basically independent of its kinematics and can handle that the system may be over-determined.

Another unforeseen effect of the project is the creation of a new business area for R&D A/S with mechatronic engineering and consulting as described in Sec. 1.5.3.

During the commissioning of the demonstrator, a Hardware-In-the-Loop (HIL) environment was developed, where the control hardware used by R&D A/S was configured to run up against a simulation (in Simulink). Resultantly, the control software could be fully tested before going to the real system. This practice is now normal procedure in R&D A/S, and has been crucial in executing the LORC project in a so short duration.

1.5.1 Main commercial results

The main commercial result is as stated previously, being able to both offer and provide a complete turn-key WLS solution to a customer.

With the acquired knowledge more offers are currently being made for other six-degree-of-freedom load units for customers. Their layout differs from the original hexapod, but control, actuation, software and design methodology remain the same.

Regarding utilization of the research performed in energy recovery (on the hydraulic actuation) during the project, that has not yet been realized due to the power consumption of the hydraulics is dwarfed by the losses in the electrical system proving the drive torque for the turbine (losses in a +8MW drive is larger than the losses in the hydraulics, where the grid requirement currently is 0.2-0.5MW). However, future larger system will make the energy saving technology relevant, at which it is expected to be taken to a commercial level.

The WLS technology is also being explored for other test types, where the test object is less stiffness, i.e. generating more movement, and thereby increasing power demands of the hydraulic actuation. These applications will also make the energy saving technology relevant.

Thus, the energy saving technology for the hydraulic actuation is expected to enable increased scaling of system and moving into other areas.

Another unexpected result is the “flexpod” used as a test dummy in the demonstrator, which is currently being marketed as a solution for calibrating existing test benches.

1.5.2 Main technical results

Each work package succeeded in generating a high amount of valuable knowledge, however, dissemination and making the obtained knowledge operational is just as critical to success. To that end, effort has been put into collecting the knowledge into design tools and guide-lines like TSDLAB and ATLAB, which are discussed in Sec. 1.5.5.2 and Sec. 1.5.5.4.

1.5.3 Project impact so far

With the LORC project being one of the biggest projects during the company’s history, and the fact that this EUDP project played a significant role in making it possible, it is fair to say that EUDP project increased company turnover. The WLS solution is also currently being offered outside DK, so future export is expected, also outside Europe.

During project start up, one mechatronic engineer (a Ph.D. with expertise in hydraulics and control) was hired into the company to take part in the project, and build up knowledge in these fields. This employee was quickly utilized across multiple of the company projects, being able to bridge between mechanics, hydraulics, control and software. As a result, currently eight more engineers from AAU with similar profiles (Master in Electro-Mechanical Systems Design or Mechatronic Control Engineering) have been employed, boosting the company's ability to provide turnkey solutions, where the solutions require both software, hydraulics, mechanics, electrical system and control.

Hydraulic design is now also performed internal to the company instead of by being offered to sub-contractors, and consultancy within hydraulic and control is now being offered and used by customers.

1.5.4 Dissemination of knowledge

The project knowledge has been disseminated trough:

Internal:

- Internal seminars
- Internal presentation
- Members of the EUDP protect function as specialist and tech-leads in company projects
- Reports and design guides
- Software tools – guide for FAST, TSDLAB, FATLAB (some public available)

Academic:

- Participation in conference
- Student projects at AAU
- Journal paper
- Software tools - FATLAB

Public:

- Software tools (some publicly available on-line)
- Articles in engineering magazines
- Homepage
- Linked-in
- Facebook
- Youtube

1.5.4.1 Public

The following engineering magazine articles and homepage articles has been published to continuously advertise the project, and to communicate R&D's increased focus on being a system integrator, applying mechatronic design approaches:

Energy supply:

- R&D bygger en af verdens største testbænke for LORC
  https://www.energy-supply.dk/article/view/291291/rd_bygger_en_af_verdens_storste_testbaenke_for_lorc
- Lindø skal have nyt testanlæg
  https://www.energy-supply.dk/article/view/290359/lindo_skal_have_nyt_testanlaeg
- R&D og Aalborg Universitet skal lave energi venlig test af vindbelastning
  https://www.energy-supply.dk/article/view/141297/rd_og_aalborg_universitet_skal_lave_energivenlig_test_af_vindbelastning

Jern & Maskinindustrien:

- Store emner og store kræfter
  http://www.e-pages.dk/aller/476/
- 25 års slid testes på et halvt år

https://www.jernindustri.dk/article/view/245825/25_ars_slid_testes_pa_et_halvt_ar

- Bedre test af vindmøller
https://www.jernindustri.dk/article/view/237708/bedre_test_af_vindmoller#

Homepage:

- Rico Hansen, Development Engineer
http://www.rdas.dk/karriere/moed-en-medarbejder/rico/
- Indkøring af en af verdens største testbænke
http://www.rdas.dk/nyheder/arkiv/2017/rd-indkoerer-en-af-verdens-stoerste-testbaenke/
- R&D reducerer risici ved systemløsninger gennem simuleringer
http://www.rdas.dk/nyheder/arkiv/2017/
- R&D bygger en af verdens største testbænke for LORC
http://www.rdas.dk/nyheder/arkiv/2016/halt-testbaenk-til-lorc/
- Oprustning styrker udviklingen af systemløsninger hos R&D
http://www.rdas.dk/nyheder/arkiv/2016/oprustning-paa-kompetencer/
- Demonstrator til ny energibesparende testmetode
http://www.rdas.dk/nyheder/arkiv/2016/demonstrator/

Youtube:

- Indkøring af demonstrator på Aalborg Universitet
https://www.youtube.com/watch?v=DXX95EXUmpo

1.5.4.2 Academic

- HyDrive Workshop Offshore Mechatronics - Developing test facilities for offshore industry / Rico H. Hansen (R&D)
See Annex [4] and https://sfi.mechatronics.no/wp-content/uploads/2016/03/Program-HyDrive-Workshop-2016B.pdf
- Fatlab: Free open-source fatigue analysis software
www.fatiguetoolbox.org
- Pedersen, Mikkel M., Multiaxial fatigue assessment of welded joints using the notch stress approach, International journal of fatigue, Vol. 83, Issue 2, pp. 269, 2016
http://www.sciencedirect.com/science/article/pii/S0142112315003680?via%3Dihub
- 9th semester project: Simon Christensen, Design of Stewart-Gough Platform as a Test Setup, 2014.
See annex [5]
- Master Thesis, Søren Christian Jensen & Niels Henrik Pedersen: Design and Control of an Efficient Hydraulic Actuation System for a Wind Load Simulator, 2015
See annex [6]
- Jensen, S.H. and Pedersen, N.H., ENERGY EFFICIENT HYDRAULIC SYSTEM DESIGN FOR A WIND LOAD SIMULATOR, School of Engineering and Science, 2014
See annex [7]
- Riisager,K; Donkov, V and Zeilmann,S.F.D. Investigation of Control Strategies for a Hydraulic Servo Robot, School of Engineering and Science, 2015
See annex [8]
- Master thesis, Christian Nørgård & Tobias Leth, Design and Control of a Stewart Gough Platform, 2014
See annex [9]

1.5.4.3 Internal dissemination

The most effective way to disseminate knowledge within R&D has been distribution of developed tools, brief courses in using them and letting key-persons from the EUDP project be included as specialist or tech-leads in the relevant project, thereby disseminating to colleague's the knowledge trough close cooperation.

Figure ***Error! No text of specified style in document.****.4: Internal opening ceremony for the demonstrator*

Most important design tools have been:

- HIL configuration for R&D's Beckhoff control hardware to run up against a Simulink model
- TSDLAB - for designing and evaluating test bench (Matlab platform)
- FATLAB – for calculating the design life of steel structures (Matlab platform)
- Guide-line for calculating lifetime of spherical joints
- Multibody-dynamic model of the WLS for simulation and generating load profiles for mechanical design

1.5.5 Summary of work package results

1.5.5.1 WP1 – Project Management

Overall the project management succeeded in making the project success, and being effective in using the resources.

The before mentioned approach to define task based on workshops on risk assessment and requirement to feasibility has proven effective to quickly concentrating engineering and research effort.

Main results of WP1 are summed up in the risk assessment provided in [1], the risk tasks defined in [2] and the feasibility tasks defined in [3].

From the start a documentation guide-line was released [10] to align documentation and filing of findings. This was later expanded in WP2 to include a brief documentation on terminology, defining applied mathematical notations, abbreviations, reference coordinate systems, key quantities, etc., see [11]. This was followed up with a guideline on how to store developed Matlab and Simulink models and functions, see [12].

1.5.5.2 WP2 – Hydraulic System

In the following, some insight into parts of the research performed in WP2.

As identified during the risk assessment one of the key information is the top-level load requirement for the WLS. To this end a study was made on identifying the required load to perform accelerated lifetime testing of a 10 MW wind turbine. These are given in [14].

To find dynamic load requirements, wind loads were also simulated in FAST (a free aeroelastic computer-aided engineering (CAE) tool for horizontal axis wind turbines) for a 5 MW turbine, and afterwards scaled to 6, 8 and 10 MW turbines. Calculating the equivalent loads required for performing a HALT test yielded loads in the same range as found in [14].

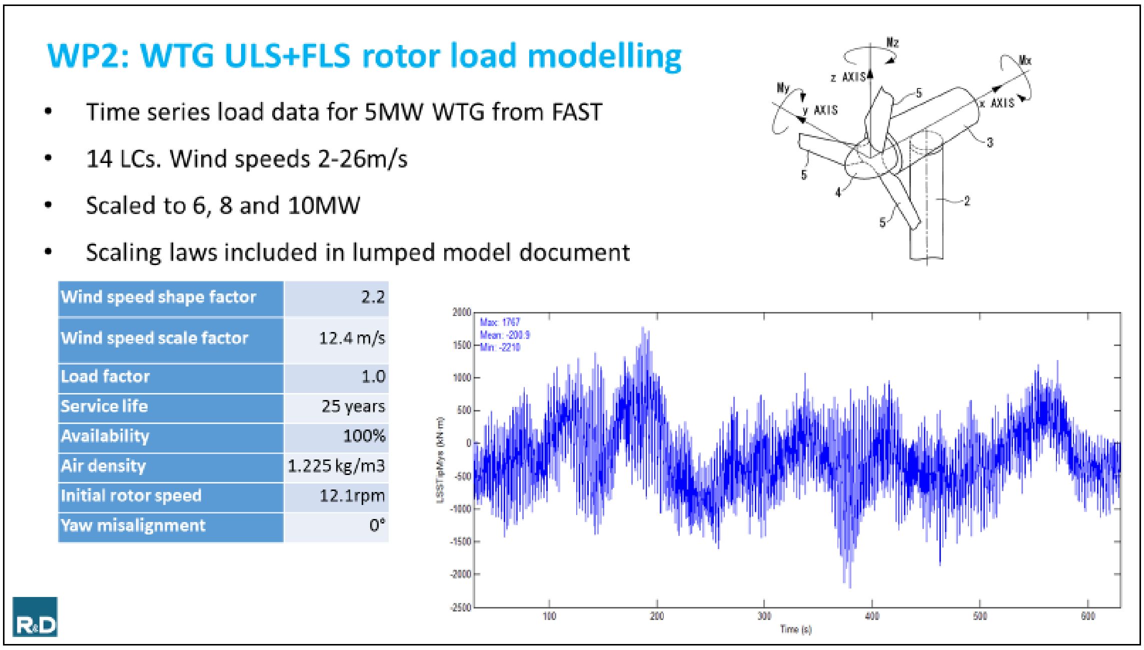


*Figure **Error! No text of specified style in document.**.5: Simulation of wind loads in FAST.*

The next part was to identify the expected movement of a DUT under load. A screenshot of a performed analysis is seen below, where deflection of all parts of the system is included. These found deflections was synthesized into an equivalent stiffness matrix to be used in further analysis. The stiffness results were included into the top level requirements for the WLS.

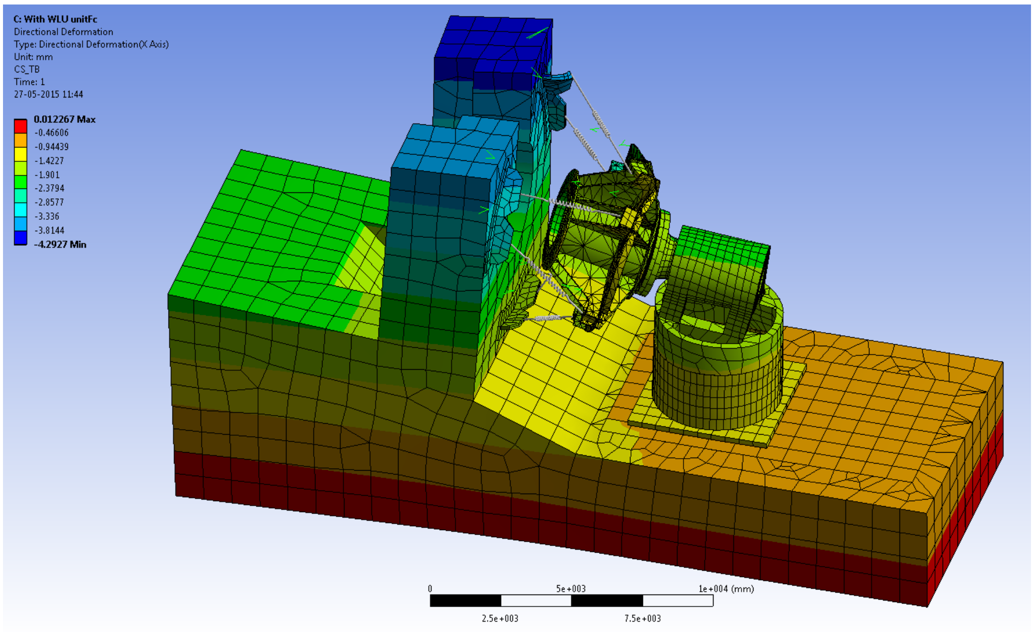


Figure ***Error! No text of specified style in document.****.6: Analysis of expected system stiffness*

Regarding concept optimization of the WLS, it quickly became evident that performing the optimization would become a problem due to the complexity.

The overall goal is to:

- Low implementation cost
- Low power consumption
- High accuracy/controllability
- High reliability

These were converted to these quantifiable performance criteria:

- Minimize actuator size
- Maximize accuracy/sensitivity of system
- Minimize platform diameter
- Maximize controllability
- Minimize power consumption

But these must be optimised under limitations like:

- Build in-length of actuators (function of actuator size)
- Space between actuator joints (function of actuator size)
- Bearing and shaft diameter

And then finally there is a wide range of un-quantifiable aspects which are just as important as:

- Impact on foundation design
- Assembly and ease of maintenance
- Cost efficient to produce (Symmetric design)
- Coupling movement
- Layout providing a good bearing solution
- WLS platform structural design
- Actuator feet design
- Misalignment in actuator spherical joints
- Symmetric or asymmetric actuators

So, the problem becomes:

- The optimal solution is driven almost equally of "practical aspects" and performance criteria.
- An automatic optimization will probably never capture these aspects
- The cost function alone is too complex to describe properly
- The top-level requirements are also often a part of the loop as these often contains "nice to have" in the first iterations

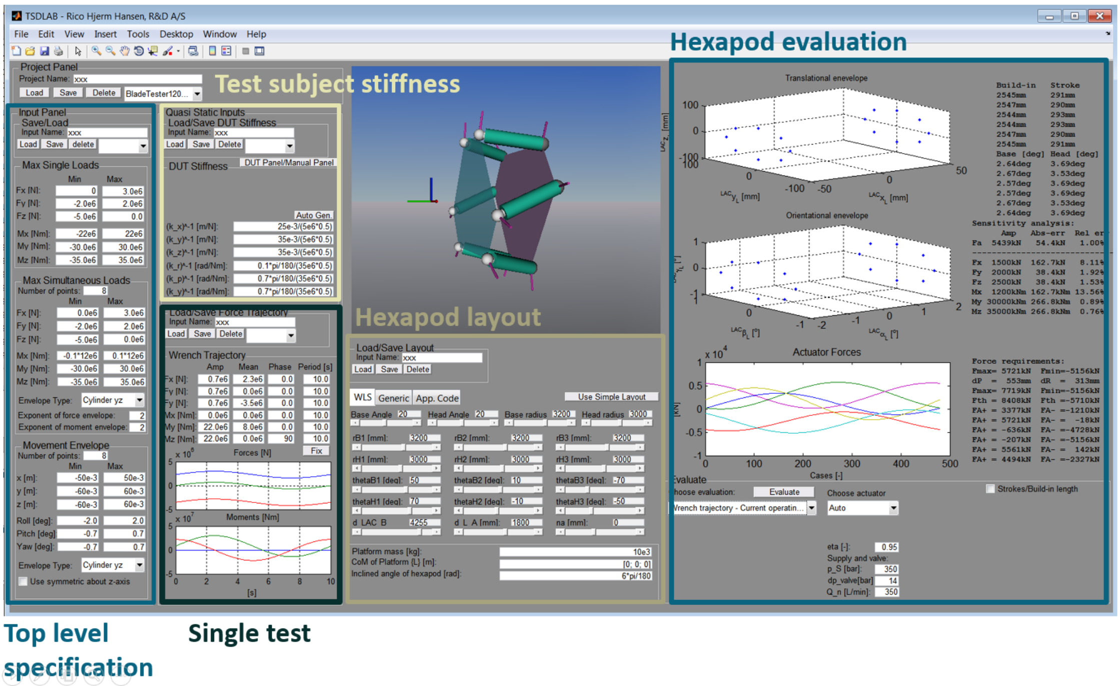
To deal with this, the method of choice became a design tool, allowing easy change of layout of the concept while on the fly evaluating key properties of the system:

- Actuator size
- Accuracy of system
- Required misalignment of spherical joints
- Required stroke of actuators
- Required movement of coupling
- Power consumption
- Required HPU size
- Required valve size for actuators
- Utilization of actuators

The tool base on providing a top-level performance specification, which also can be changed on the fly

- Load envelope of system (Both dynamic and static loads)
- Movement envelope of system

The design tool was names Test System Design LAB (TSDLAB), and a screenshot is provided below. A demonstration of TSDLAB can be found in [4].



TSDLAB was also used to design the demonstrator as shown below.

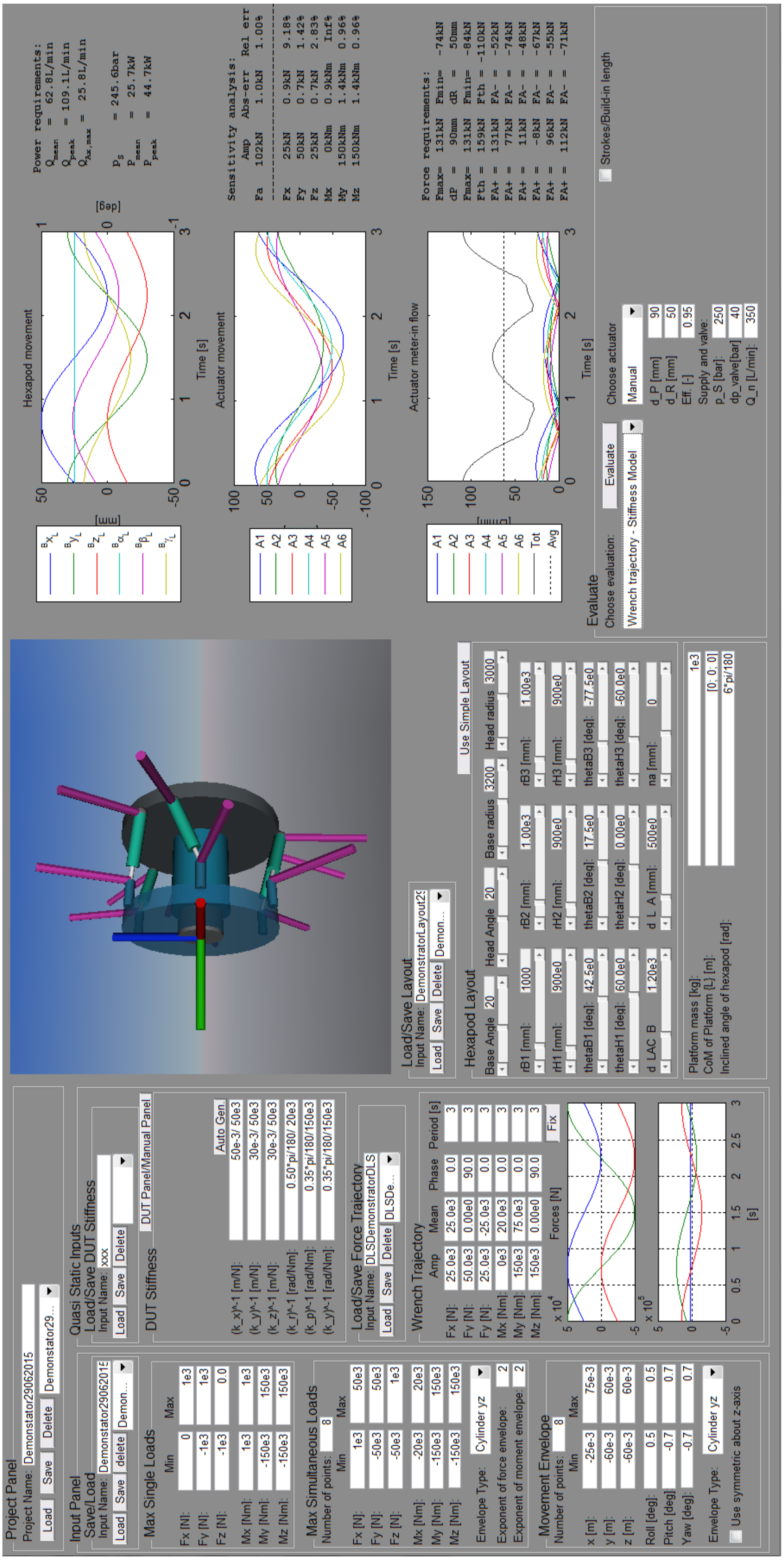

Project Panel
Input Panel
Max Single Loads
Max Simultaneous Loads
Movement Envelope
Quasi Static Inputs
DUT Stiffness
Wrench Trajectory
Load/Save Layout
Hexapod Layout
Use Simple Layout
Hexapod movement
Actuator movement
Actuator meter-in flow
Time [s]
Power requirements:
Sensitivity analysis:
Force requirements:
Evaluate
Choose evaluation:
Wrench trajectory - Stiffness Model
Choose actuator
Manual
Supply and valve:
Strokes/Build-in length

*Figure **Error! No text of specified style in document.**.7: Demonstrator design using TSDLAB.*

For hydraulic design, control design, and identifying loads, a complete dynamic simulation model of the system was developed. The multi-body dynamic model is documented in [14]. An execution of the complete Simulink model of the system can be seen in [15]. All sub-models are parametrized to work with the possible range of actuator, valve, mechanical sizes, etc. used for the 2-10 MW configuration of the WLS system.

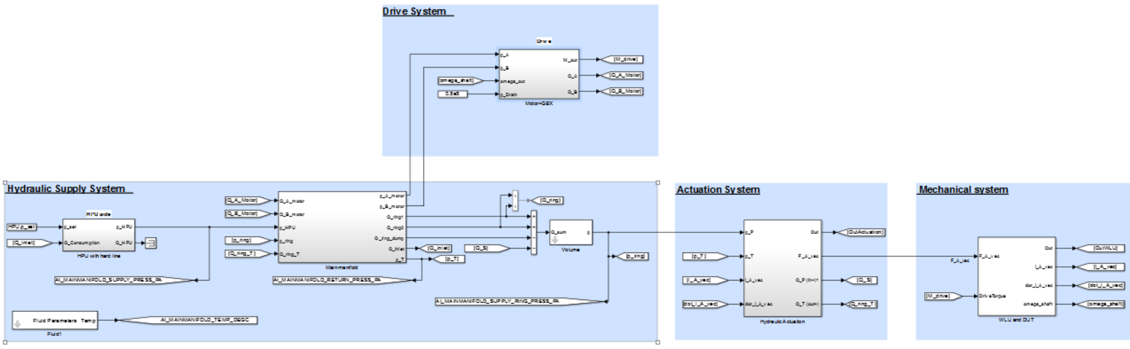


*Figure **Error! No text of specified style in document.**.8: Overview of the sub-systems of the Simulink model of the demonstrator.*

A 3D visualization of a simulation can be found in [15] and is shown below. 3D visualization has been used extensively to aid validation and to aid dissemination of knowledge.

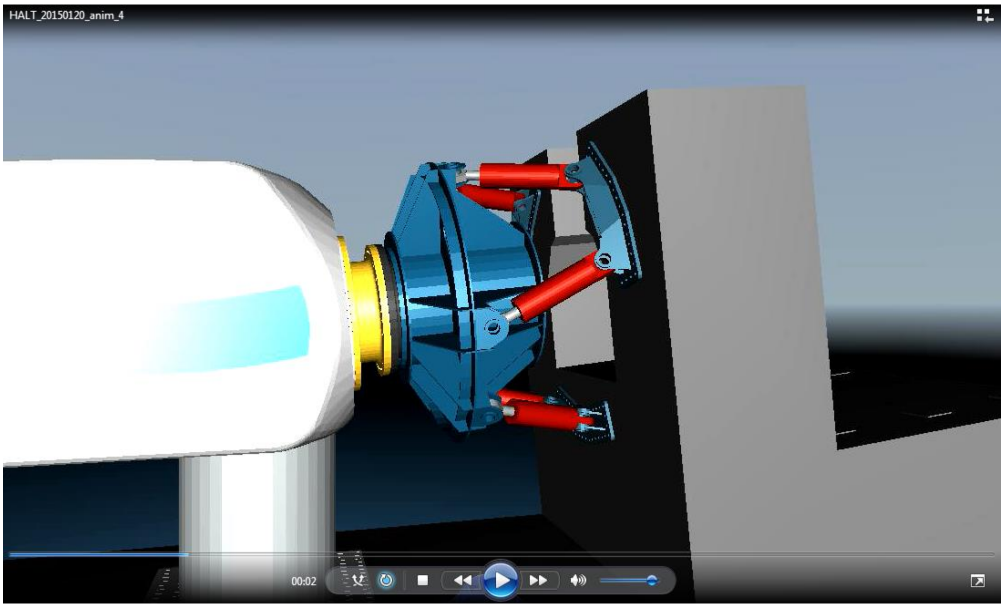


*Figure **Error! No text of specified style in document.**.9: 3D visualization of a simulation of full-scale system with DUT.*

Simulation of the demonstrator behaviour has also been performed extensively to validate the model with measurements. A video of a demonstrator simulation can be found in [16].

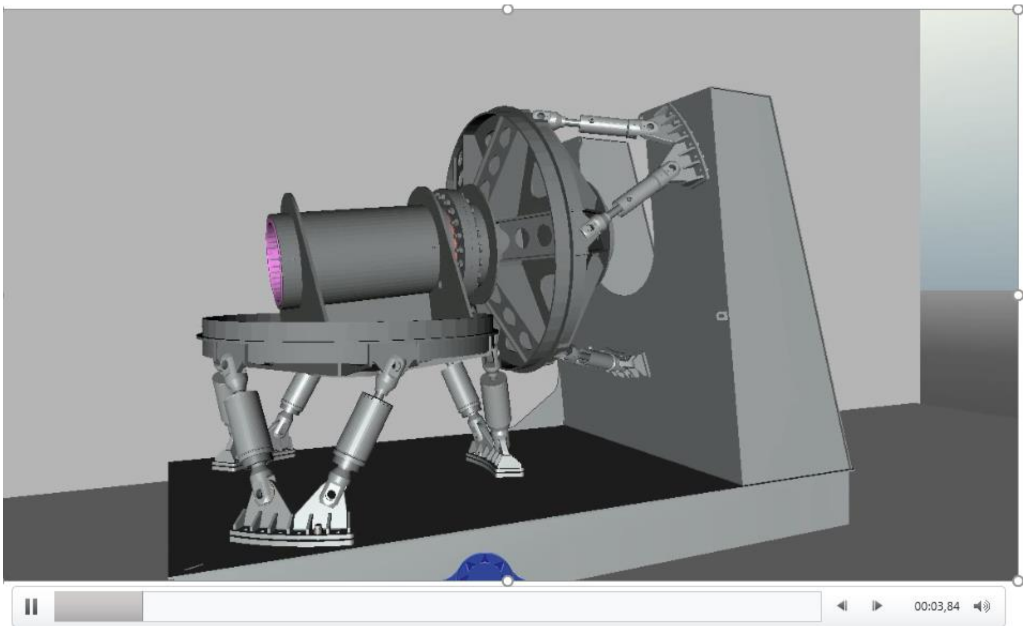


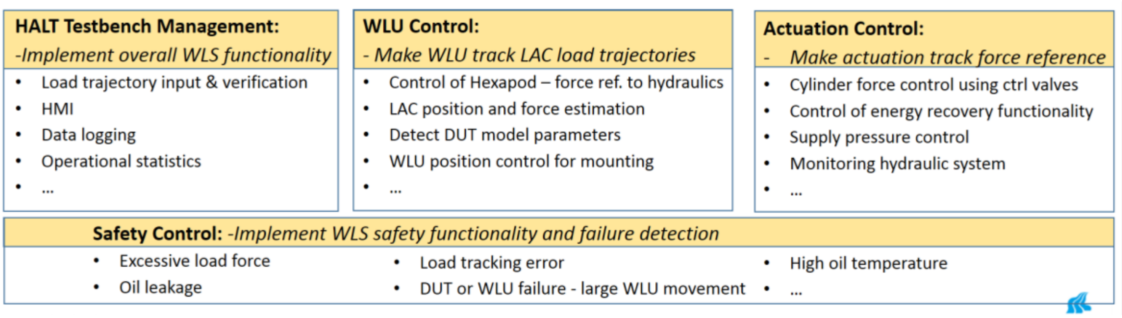
Figure ***Error! No text of specified style in document.****.10: 3D visualization of simulation of demonstrator with flexpod DUT.*

A risk in project is the build-in-length of the hydraulic actuator, as long actuators makes the design expensive. A study was made on actuator and can be found in [18]. These results were used in the design.

The complete requirement specification for the hydraulic actuation system can be found in [17]. This specification constitute the basis for the requirement specification used for the WLS hydraulics in the LORC turnkey project.

1.5.5.3 WP3 – Control System

The control task of WP3 was broken into the following pars,



where the main focus of the EUDP project were the area:

- WLU control
- Actuation control

Two control topologies were investigated as shown below. The single axis control topology is the simplest, and through simulation, the single axis control topology was found to be adequate. Here each actuator has a local force controller receiving load reference from an overall WLU controller, mapping WLS load references into actuator loads.

The single axis control topology was tested on the demonstrator, see WP5.

The MIMO control topology has also been implemented and is available if higher performance is required. Here the WLU controller directly control all actuators without using a local force controller.
It was found that the natural frequency of the actuators be around 50 Hz, so sample frequency of the actuator control is recommended between 500 Hz – 1000 Hz. The WLU controller may be operated at a lower frequency ~100 Hz using the single axis load control topology

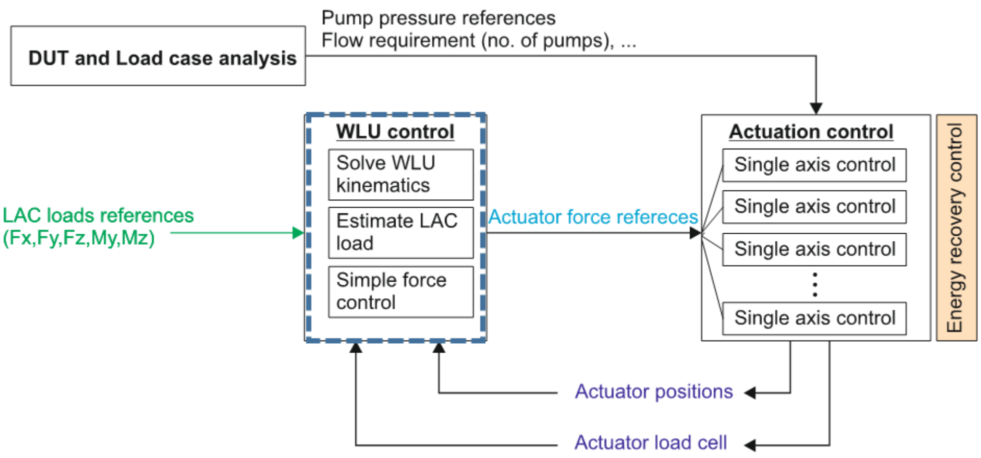


*Figure **Error! No text of specified style in document.**.11: Single axis control topology*

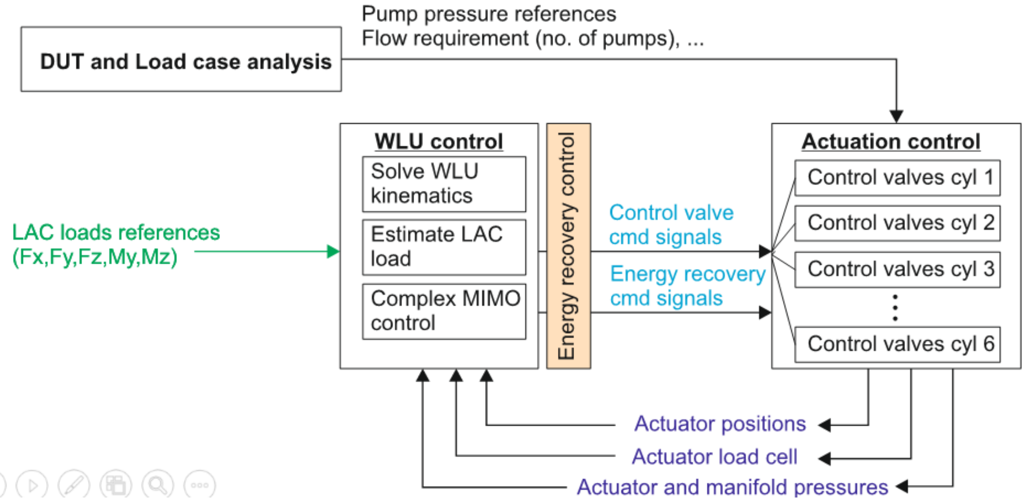


*Figure **Error! No text of specified style in document.**.12: MIMO control topology*

The problem of WLU control problem was further decomposed into an observer problem (to account for not being able to directly measure the applied load at the DUT) and a control problem. The controller operating on the demonstrator is shown below:

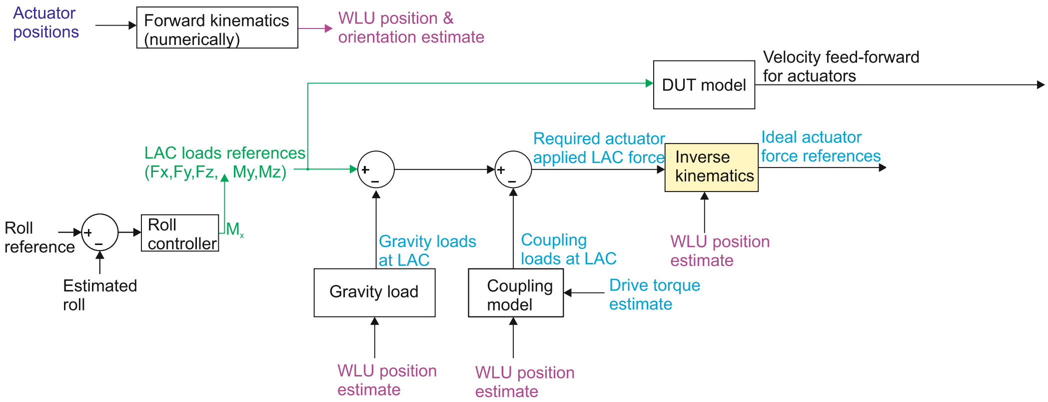


*Figure **Error! No text of specified style in document.**.13: Controller used on the demonstrator and used as template for the full-scale solutions*

The observer for estimating applied loads to the DUT was constructed as:

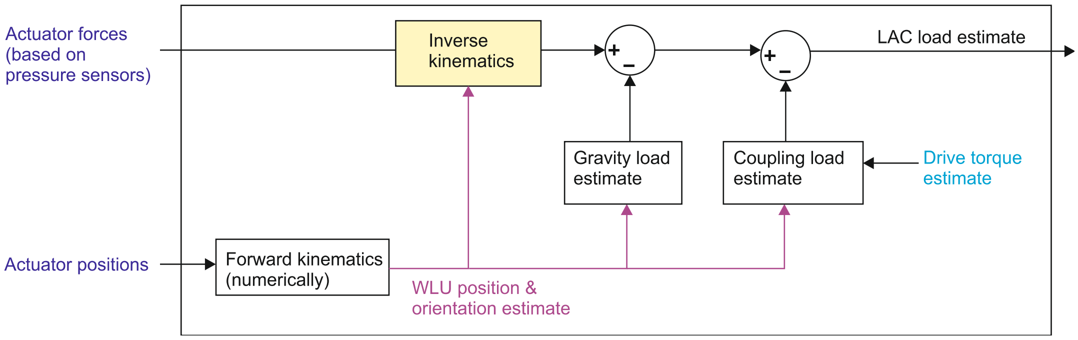


*Figure **Error! No text of specified style in document.**.14: Example of an observer for the WLS*

Thus, the applied load at the flange of the DUT is estimated through the actuator forces. The above shows how the actuator loads are modified to allow this load estimation.

WP4 – Mechanical System

The mechanical scope of the EUDP project is illustrated below. Here the WLS is split into its fundamental components. The base for designing the components are the loads determined in [13], which are converted into actuators loads using TSDLAB.

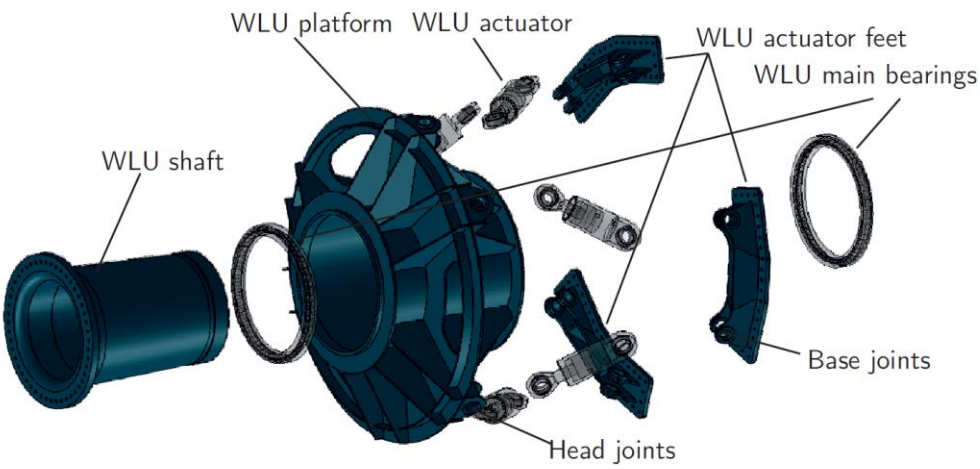


*Figure **Error! No text of specified style in document.**.15: Mechanical components of the WLU*

One of the challenges with the design is the fatigue assessment, as the loads are multiaxial with non-linear load-stress relationship. This is illustrated below. Thus, the loads are relative complexed, so defining the conventional stress-ranges used in design is difficult. To overcome this a SW tool (FATLAB) was developed to perform the fatigue analysis instead.

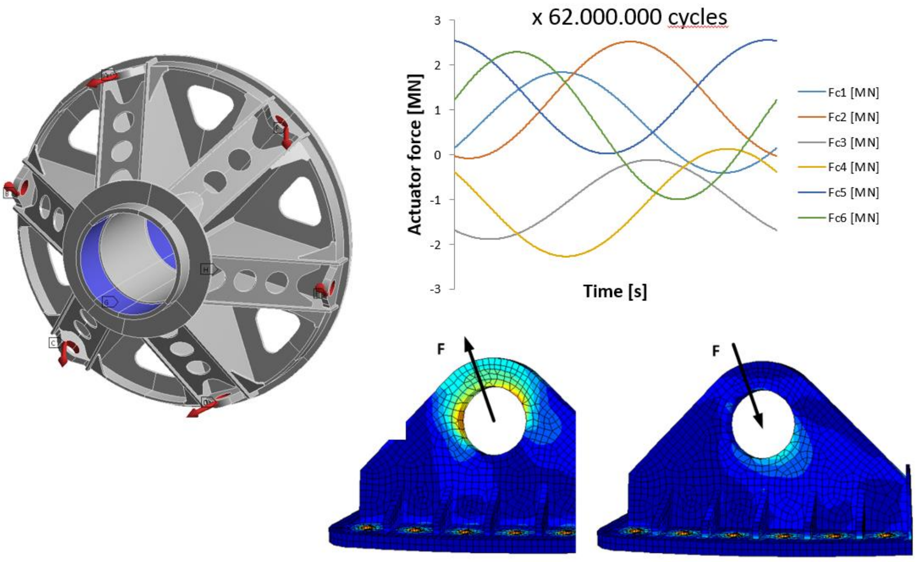


*Figure **Error! No text of specified style in document.**.16: Illustration of multiaxial loading problem.*

FATLAB works by postprocessing results from FE analyses and combining these with load-time series in order to perform a detailed fatigue assessment of a component.

In principle Fatlab determines the stress-time history for all nodes in the model from the inputs supplied to the program, then performs cycle-counting and calculates the damage sum using Palmgren-Miner and a user-defined SN curve. Results are then visualized either as contour plots for all nodes or can be studied in more detail for single nodes. Flowchart of how the SW is working is given below, and the SW tool has been maid available at: http://fatiguetoolbox.org/

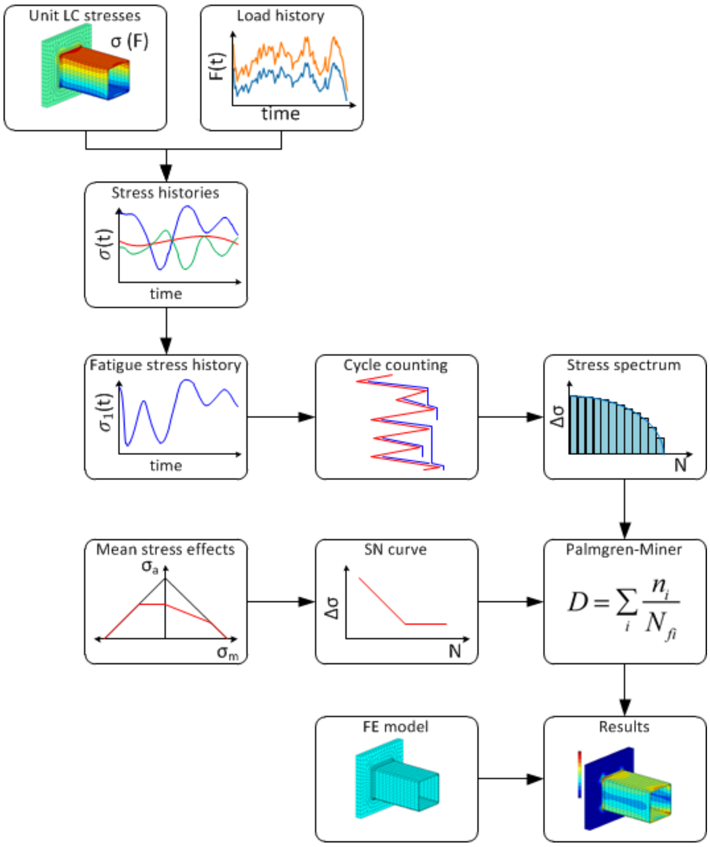
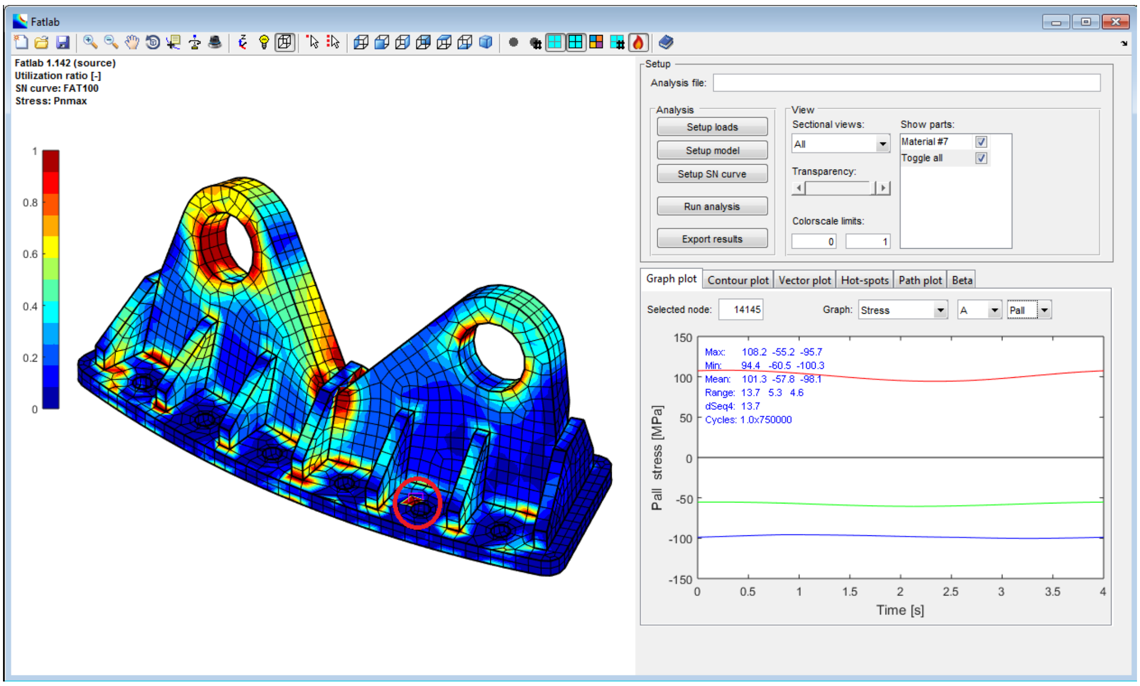
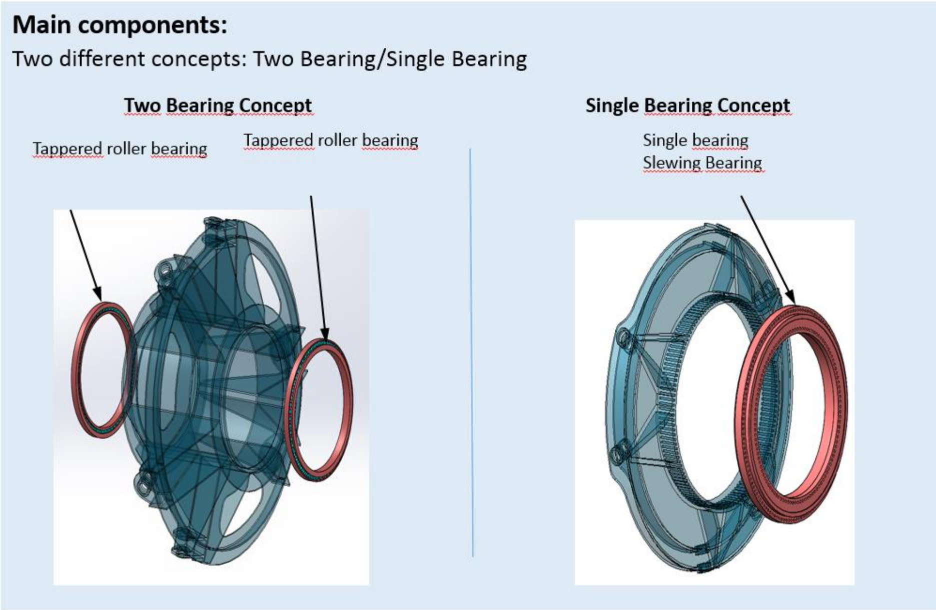


*Figure **Error! No text of specified style in document.**.17: Flowchart for FATLAB*

An example is given below, where FATLAB has been used to analyze the actuator feet of the demonstrator under the given design loads.



Regarding bearing setup for the WLS, both single and double bearing solutions have been investigated. Dependent on application both solutions are possible, however as the load increases the two-bearing solution is favourable with current available bearings.



The WLU platform has also been investigated and analysed using FATLAB. The design is feasible (Some areas are over utilized in the example, but solutions has been found to reduce utilization). Potential still exist in reducing steel consumption and complexity for production:

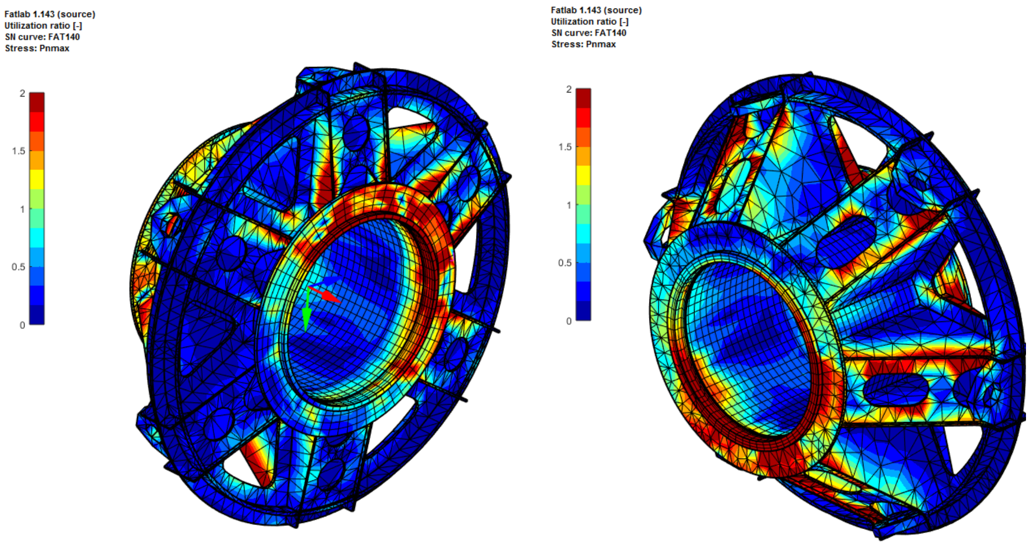


*Figure **Error! No text of specified style in document.**.18: FATLAB analysis of WLU platform.*

Design of the actuator feet can be found in [19] and actuators in [18]. Design of the main shaft is provided in [20] and spherical joint analysis in [21]. The components have all been found feasible both regarding fatigue and extreme load capability.

1.5.5.4 WP5 – Demonstrator

The demonstrator layout is documented in [22] and its size is approximately a geometrically scale 1:3 of a full-scale machine. The scaling laws used is provided in [14].

The primary goals of the demonstrator are (prioritized) the following areas:

1. Controllability
2. Accuracy ("Measurability")

3. Realistic hydraulics – conventional
4. Software and algorithm validation
5. Controller hardware

The secondary goals are to validate:
- Actuator design
- Mechanical design
- Structural validation
- Coupling restoring forces
- Safety hardware
- HMI/MES-layer

This gives the resulting requirements:
- Similar sensitivity, similar kinematics, similar (variable) DUT stiffness
- Similar sensitivity, similar kinematics, LAC load sensor
- Reasonable flows (>50 L/min peak per actuator), similar pressure overhead, similar ratio between valve bandwidth and system natural frequencies
- Controller able to execute algorithms, similar sensoring principle
- Reasonable power level and flow (>50 L/min)
- Demonstrator looks similar to full scale, possible to increase movement
- Able to use similar HW as R&D final HW

Which provide the outcome of the demonstrator:
- Controller topology validation, model verification
- Accuracy validation
- Controller topology validation, hydraulic model verification, hydraulic components validation
- Verification of implementation of forward kinematics, inv. kinematics, overall controller algorithm, etc.
- Hydraulic models and concept verification
- A commercial value
- Control HW verification

These requirements have been the main design drivers, and the resulting design is shown below. The system comprises six cylinder with control valves, a link-coupling and hydraulic motor for driving the main shaft. A rotating main shaft is included to test the disturbance for this into the WLS.

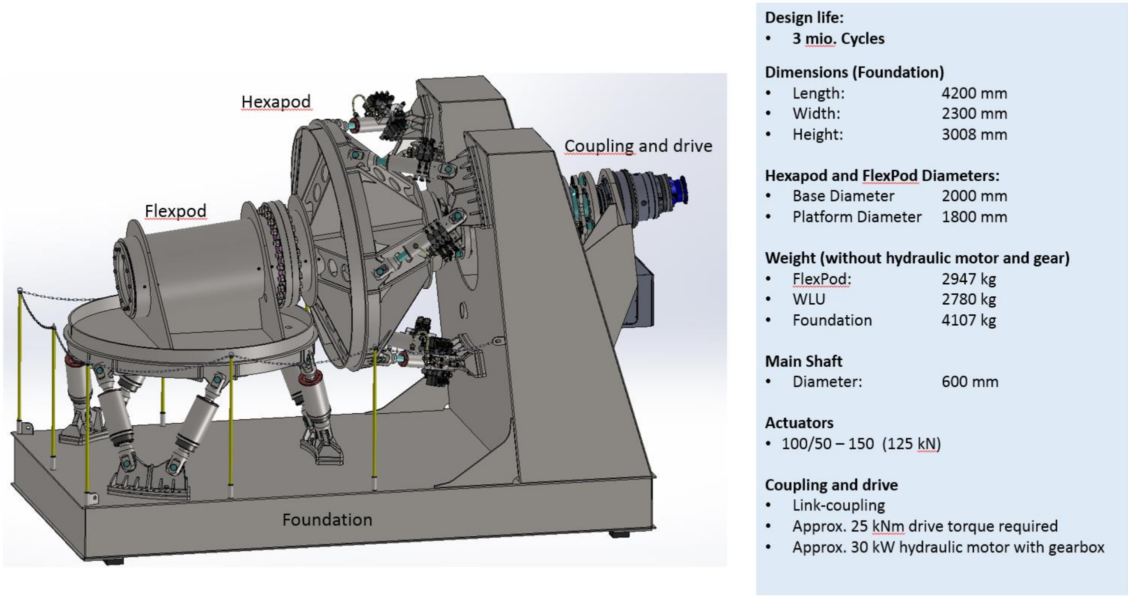
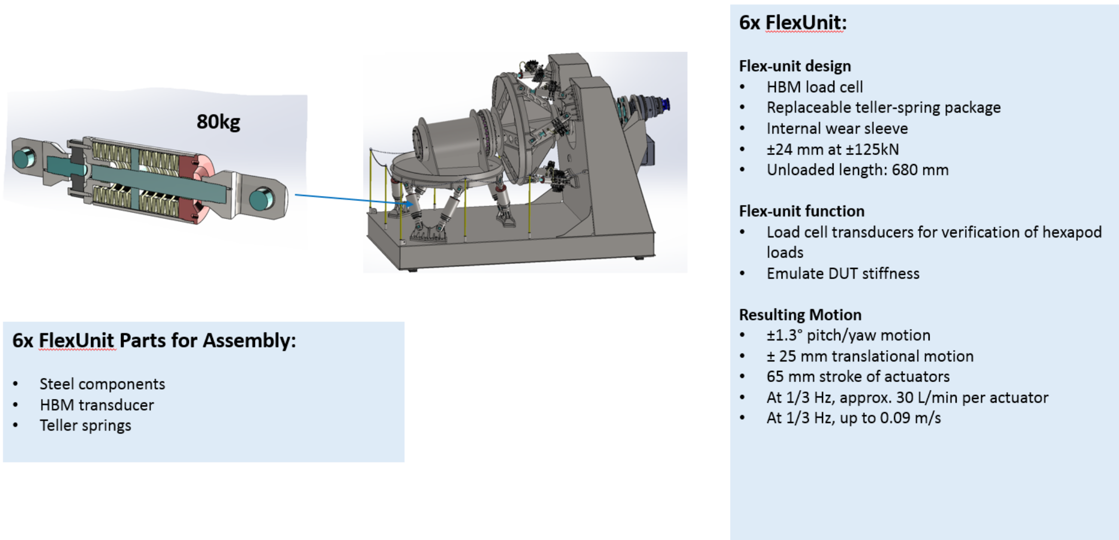


*Figure **Error! No text of specified style in document.**.19: Demonstrator design*

As DUT a flexpod was designed based on the hexapod concept. By having spring packages in the “legs” the flexibility of a DUT could be emulated, and using load transducers in the legs, the WLU loads were validated.



The finished demonstrator is shown below. Pictures from the production and assembly can be found in [23]. The specification for the hydraulics can be found in [24] (the actuators were designed and assembled by R&D).

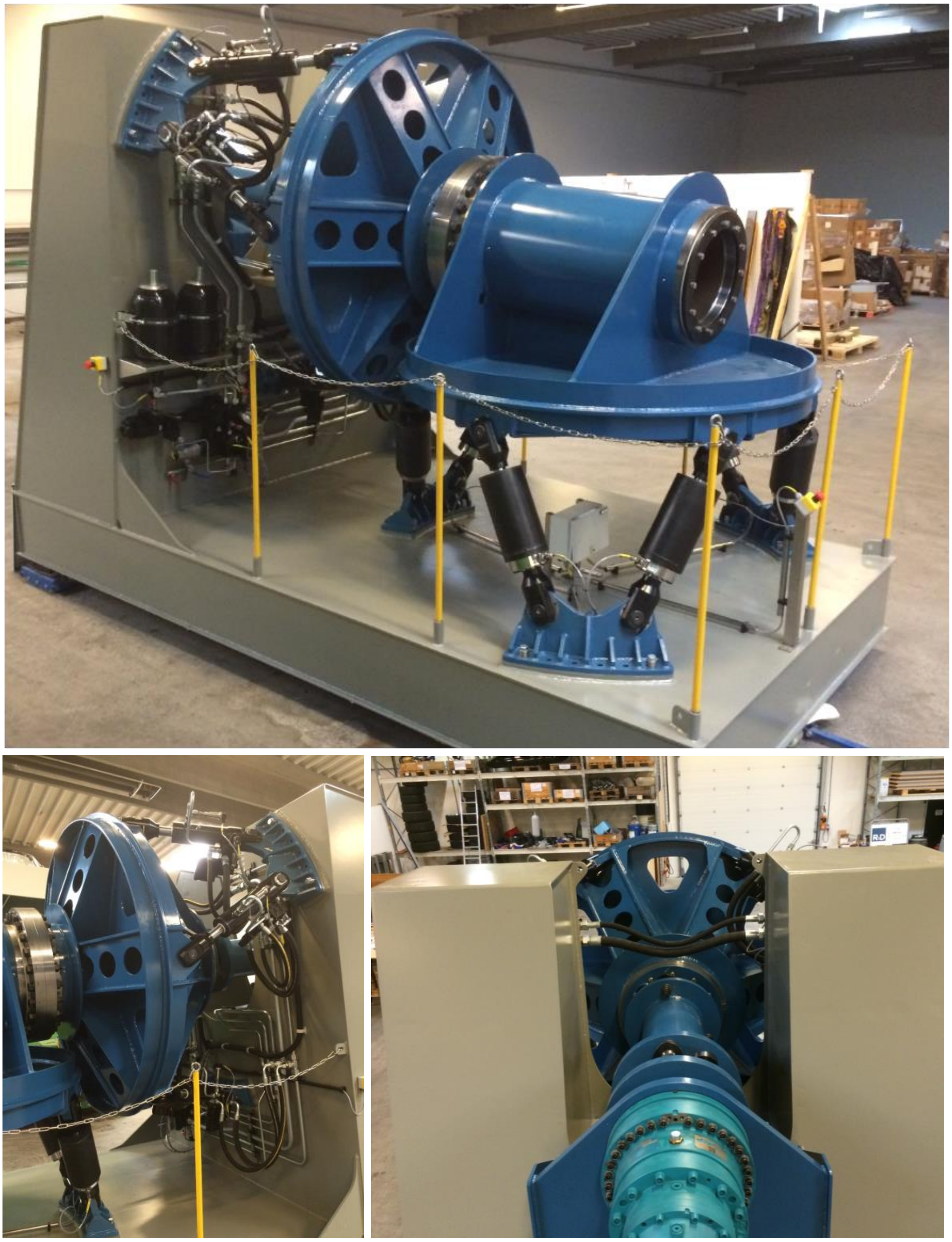


Figure ***Error! No text of specified style in document.****.20: Demonstrator assembled at R&D's workshop.*

The demonstrator was commissioned during 2016 with complete control SW. Below are screenshots from the HMI:

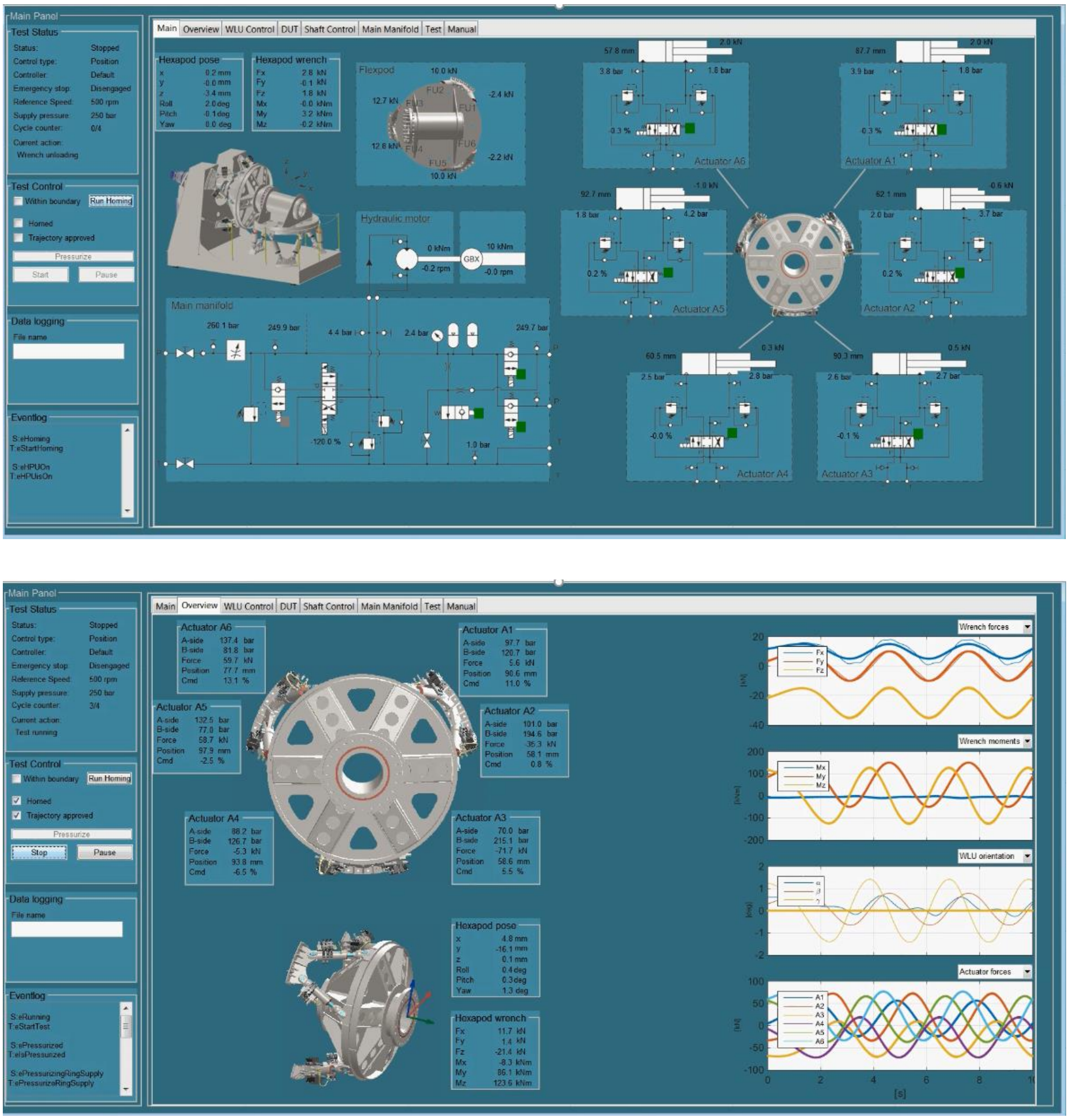


*Figure **Error! No text of specified style in document.**.21: Screenshots of the HMI from operation of the demonstrator.*

The demonstrator in operation can be found at:
https://www.facebook.com/rdasdk/videos/1934571800114176/

The demonstrator has been used to validate and optimize:

- Controllability
- Accuracy ("Measurability")
- Hydraulic system
- Software and algorithm validation
- Controller hardware
- Concept

1.6 Utilization of project results

The results have already been utilized (internally and commercially) at R&D A/S:

- TSDLAB is being utilized and is already being further developed
- HIL simulation from SW design and commissioning is being utilized and is being developed further
- Simulink model of WLS is being used and is being developed further
- FATLAB has not been fully integrated yet, but it is planned to increase usage
- WLS design frame-work has been used in a full-size version
- Flexpod marketed as a test bench calibration unit

Regarding energy policy objectives, the test bench at LORC is now going to be used by the wind energy sector, reducing cost of renewable energy.

1.7 Project conclusion and perspective

The overall conclusion of the project is that it is possible to design a Wind Load Simulator (WLS) unit with six fully decoupled degrees of freedom for performing HALT tests.

For the hydraulic part of the WLS, it was found that current system sizes may be implemented with conventional servo hydraulics, however, as WLS size increases in the future, future regenerative hydraulic designs become necessary to reduce power consumption, and reduce flow requirements.

For the mechanical part of the WLS, the design in current size is obtainable with sound engineering, however for increased sizes, the WLS design is increasingly dependent on that for example larger and more durable bearings are developed.

Control wise, performance is adequate with identified algorithms and control hardware. The future effort is going to be within increasing accuracy of load estimation for the WLS, as customers have increasing needs.

A crucial learning is that the key to successfully continue developing better solution for the WLS is acknowledging the mechatronic aspects, and remember to optimize system wide instead of over-focusing sub-system optimality. This is started through tools as TSDLAB, and is going to be explored further in the coming years.

To gain competitive edge future effort is also going to further stream-line the tool-chain and expand the use of simulation models in HIL setups for reduced commissioning and increased reliability.

1.8 Annex

[1] \Annex\EUDP-WLS-WP1-FMEA Rev 2.6.pdf
[2] \Annex\EUDP-WLS-WP1-Risk mitigation task scopes
[3] \Annex\ EUDP-WLS-WP1-Feasebillity sub-tasks
[4] \Annex\Developing test facilities for offshore industry 02-03-2016.pptx
[5] \Annex\Design of Stewart-Gough Platform as a Test Setup.pdf
[6] \Annex\Design and Control of an Efficient Hydraulic Actuation System for a Wind Load Simulator.pdf
[7] \Annex\ENERGY EFFICIENT HYDRAULIC SYSTEM DESIGN FOR A WIND LOAD SIMULATOR.pdf
[8] \Annex\Investigation of Control Strategies for a Hydraulic Servo Robot.pdf
[9] \Annex\Design and Control of a Stewart Gough Platform.pdf
[10] \Annex\EUDP-WLS-WP1-General Project Guidelines-Rev00.pdf
[11] \Annex\EUDP-WLS-WP2-Terminology-Rev00.pdf
[12] \Annex\EUDP-WLS-WP3-MatlabStructure-Rev00.pdf
[13] \Annex\EUDP-WLS-WP2-WTG rotor load calculations-Rev00.pdf
[14] \Annex\EUDP-WLS-WP2-LumpedModel-Rev01.pdf
[15] \Annex\EUDP-WLS-WP2-HALTsimulation.avi
[16] \Annex\EUDP-WLS-WP2-Demonstrator 3D video.avi
[17] \Annex\EUDP-WLS-WP2-Hydraulics and Controls RS -Rev00.pdf
[18] \Annex\EUDP-WLS-D2.4-Hexapod actuator concept analysis-Rev00.pdf
[19] \Annex\EUDP-WLS-WP4-Structural Analysis Feet-Rev00.pdf
[20] \Annex\EUDP-WLS-WP4-Main shaft-Rev00.pdf
[21] \Annex\EUDP-WLS-WP4-Spherical Bearing Analysis-Rev00.pdf
[22] \Annex\EUDP-WLS-WP5-Demonstator Layout-Rev00.pdf
[23] \Annex\EUDP-WLS-WP5-Assembly Pictures
[24] \Annex\EUDP-WLS-WP5-Hydraulic system rev01.pdf