Modelling and Validation of Power Take-Off systems for Control Development

A guidance document

WES_LS04_ER_PTOmodelling

Revision	Date	Purpose of issue
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Contents

1 Glossary of Abbreviations

dof	Degree of freedom
I/O	Input/Output
IP	Intellectual Property
MATLAB	MATrix LABoratory - a commerical numerical computing environment
MIMO	Multi-Input, multI-Output
NWEC	Novel Wave Energy Converter', as in WES's second competitive call
OWC	Oscillating Water Column
PTO	Power Take Off
R&D	Research & Development
TPL	Technology Performance Level
TRL	Technology Readiness Level
USDoE	United States Department of Energy
WEC	Wave Energy Converter
WECsim	open source Wave Energy Converter simulation suite in MATLAB
WES	Wave Energy Scotland

2 Introduction

WES has identified the need for guidance on the specification and interfacing of models and simulations of Wave Energy Converters (WEC), and Power Take-Off (PTO) systems in particular, for use in control development and performance assessment work.

The aim of this report is twofold:

1. To provide a condensed background description of Power Take-off (PTO) modelling requirements and the specifications required by control developers to use in the development of practically realisable controllers.
2. To provide distilled guidance to control developers on PTO specifications and how to include this required functionality in their models, allowing them to characterise performance with respect to them and hence:
   a. get realistic results by modelling realistic PTOs
   b. offer specification feedback to PTO developers

3 Parallel and collaborative development in the WES programme

The parallel development of different aspects of the whole Wave Energy Converter (WEC) system may occur internally within an organisation with minimal barriers to integrated modelling and simulation (as in the historically typical WEC developer approach), or in different organisations as WES seeks to encourage and enable.

Development of integrated systems within a single organisation gives the advantage of good communication, common tools, and minimal IP concerns but this requires all engineering specialisms to be in-house and offers relatively little opportunity to try different technology options in parallel. A collaborative approach between developers of different sub-systems has the advantage of greater multiplicity in technologies and their combination, and the potential to apply specialists in individual fields to subsystem design including those with no previous involvement in wave energy.

The sector is not constrained to one approach or the other. The WES programme may include whole WEC developers and individual subsystem developers. WES seeks to provide all players the greatest opportunity to combine and improve technologies for the greatest overall advancement of the sector.

3.1 Early involvement of control developers

A major challenge in designing WEC and PTO systems for optimal performance under control systems lies in the representation of control drivers in the functional specifications. A major challenge of introducing control development activity to the WES programme lies in the representation of WEC and PTO technology in the control development framework.

The development of control algorithms requires realistic functional representations of the hardware to be controlled. While PTO and WEC technology requires an understanding of how the design features interact with control to achieve optimal performance. This suggests a dual pronged approach for introducing control expertise and development activity:

- Validation and sensitivity analysis of PTO functionality and parameters may be conducted by control developers in collaboration with PTO developers. This may make sense given the commonality of software tools and expertise applied in both validation of models and control system development.

- PTO system control sensitivities and design drivers may be examined by control developers independently, based on assumed model features covering a range of potential PTO technologies. With some background knowledge to avoid misleading assumptions, this may allow parallel development of control algorithms and the proactive driving of PTO requirements from the control perspective.

4 The Control Framework for Wave Energy

Wave energy is essentially a dynamics and control problem – how to create and control the relationship between motions and forces, and manage the resulting flows of energy. Whether control is an active computerised system or a passive feature of mechanical systems, the control framework defines the operating principles of the WEC concept including the Power take-off and other systems.

A high-level block diagram of WEC response control is shown in Figure 1 below. It is split into 3 main areas, the WEC hydrodynamic interactions with the sea (blue), the PTO hardware under control and interacting with the WEC hydrodynamics (green), and the control processes measuring the response of the WEC and systems and providing input controls to the PTO and other systems (orange).

The illustration below shows a useful separation of different functions that may be generally applied. However, the flows of information and forces may go through different systems simultaneously and interactively. For example, The PTO may be directly coupled to the hydrodynamic form (as in a pulsating hull system) so the response control acts on the PTO forces and WEC hydrodynamic properties simultaneously. The control of generation systems may also be treated separately with the decoupling effect of energy storage as shown below.

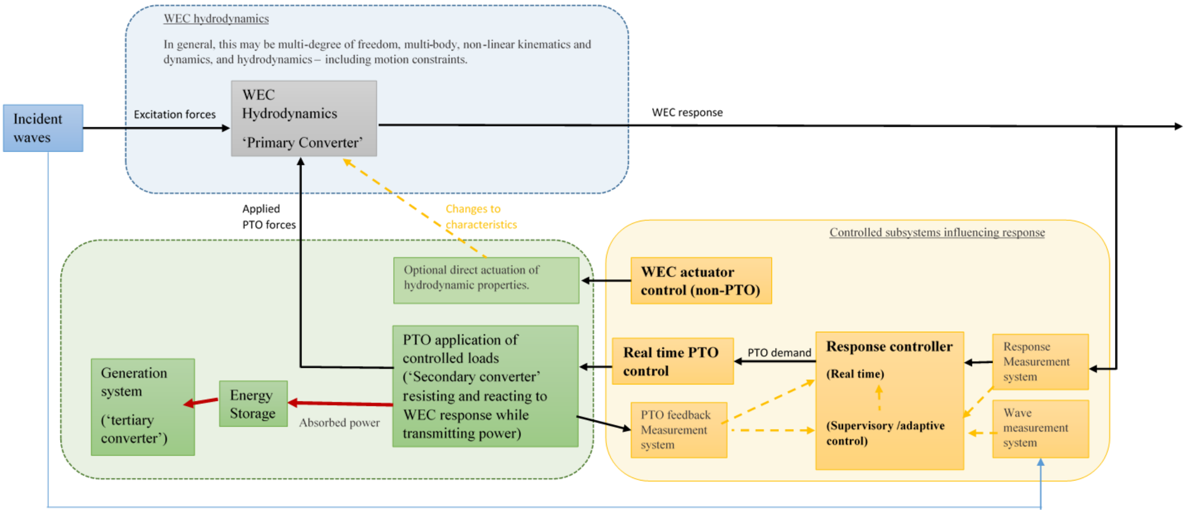

Figure 1: Schematic representation of the WEC response control loop, distinguishing between control, PTO, and WEC systems that may be developed in parallel by different technology developers.

4.1 Functional Modelling and Simulation

Functional models may be combined in an analytical and simulation environment to quantify the performance of a system overall, and to understand the influence of different sub-systems and their characteristics. Modelling in turn checks and informs engineering design decisions and drives new ideas. This iterative modelling and validation approach is familiar to all engineering disciplines and technology developers and is increasingly well catered for by compatible descriptions and software tools.

A modular and consistent modelling approach with good communication may allow for parallel development of different systems by different developers, and potentially for the assessment of different subsystems adapted and applied in different combinations. For example, allowing a given PTO model to be adaptable for different compatible WEC concepts gives the opportunity to assess the relative merits of different combinations. Similarly, new control methods and processes may be developed and assessed using realistic models of different WECs and PTO systems in combination.

While superficially very attractive, such an approach may be prone to major pitfalls. Perhaps the most important adage to bear in mind here is "Garbage in; Garbage out". Our ambition should be staged and proceed only with a keen focus on consistency, validation, and communication:

- Consistency: Model features, methods of validation, and interfaces for communication should be consistently applied by developers.
- Validation: Models and hence the systems they represent must be validated with peer/expert review and physical testing, and consistently assessed in this regard.
- Communication: Conclusions should not generally be drawn or promoted from work based on models without some guidance from those who created them and/or the associated technology. Otherwise, essential features are likely to be misinterpreted or omitted.

4.1.1 Control development with functional modelling

The development of control systems requires mathematically defined functional models sufficiently representative of the real behaviour of the hardware 'plant' under control, in this case the WEC structure (and its hydrodynamic interactions) and the PTO system controlling the WEC response and transmitting power.

The development of control systems and processes, and any conclusions on performance projections, may be fundamentally flawed if such features of the PTO system are not captured and represented in the models applied in the development process. This is also true of hydrodynamic models.

The aim of this document is to highlight functional specification issues for consideration by both power take-off developers and control developers as they interface with each other to create and parameterise models representative of practically achievable systems and outcomes. This document also serves to guide the assessment of project outcomes by WES and enabling integration of different technology strands in a common programme.

4.2 Features influencing control stability

The control process generally involves control 'gains' from input motion to output forces. The response of the WEC resulting from changes in PTO force makes the whole dynamic system closed loop and hence generally subject to instability above certain gains. Depending on the relative influence of other factors, the gain margin of the control system may define the performance limit of the whole system.

It is therefore important that such constraints on the controllability are properly considered in the design of associated systems, represented in models where required, and communicated between developers of interfaced subsystems. Specific features of WEC systems likely to be important to control stability and performance are discussed directly in section 5.

4.3 Simplification of models

While the starting point of any model is generally a description of the underlying operating principles and physics of the system. Mathematical representations must make major simplifications and assumptions. Such simplification is implicit in any mathematical description where component effects are aggregated to capture behaviour only in terms of the gross influencing parameters. Familiar examples include the use of simple drag and lift coefficients to usefully describe the aggregate effect of immensely complex fluid-structure interactions.

The omission of details and lumping together of effects into simple models of the WEC and PTO system is necessary for efficient simulation and control development BUT the omission of some characteristics may also be critically damaging to the accuracy and usefulness of the model in that context. Models do not need to be particularly complicated or detailed, they just need to include the features necessary to represent behaviour important to whatever control process or performance assessment is being tested.

The development of optimal controls for practical application will rely on iterative optimisation of parameters using simulations of the whole WEC and PTO system. Even for relatively simple control functions, typical non-linear and coupled multiple degree of freedom formulations can lead to control parameterisations with multiple near-optimal solutions (local minima in the objective function), requiring computationally taxing stochastic methods of optimisation.

The optimisation of parameters for modern machine learning control algorithms is inherently 'NP hard' and conducted with extensive input training sets. Enabling these highly iterative optimisation approaches requires simulations to be as streamlined as possible for the purpose at hand. Models need to capture all necessary effects so the results are meaningful and may be practically implemented, but not be too computationally expensive to work with.

Sensitivity to any model simplifications should be assessed either through direct comparisons against more detailed models or with reasoned estimation. Judgment is required to achieve sufficient representation in the model without unnecessary detail slowing down any simulation work. This forms part of the model validation process with respect to the intended application.

4.3.1 Distinction between models and simulation

A model represents the system itself and can be used in different types of analysis, whereas a simulation uses a model to represent operation over time. Simulation is generally required where closed form analytic solutions are not tractable. Control is classically developed using analytical approaches on closed form models – the basis of much of the control literature on wave energy, and indeed in general control textbooks. This classical approach cannot include many important characteristics of real systems but it can usefully represent many of the most important. Some non-linearities such as fixed output constraints can be included using analytical methods but doing so is challenging mathematically.

Some important typical features of PTO systems are generally not included in the existing literature on WEC control and analysis due to difficulty, intractability, or lack of generality in approach. Others are ignored, or perhaps the developers are not aware of their importance. Actuation delays and compliance in the drive train appear to be in the latter category and are therefore emphasised here.

Modern control and technology developers alike are now comfortable in the simulation environment, which makes for convenient common representations and the use of common simulation platforms.

4.4 Functional decomposition

'Functional decomposition' is general term for the common approach of using modularly defined functional 'blocks' linked together to represent a bigger system. Each block has a function easily described and parameterised and its Inputs and outputs may be linked with other blocks to form more complex systems, which may in turn be modularised into wider systems.

Such an approach is embodied in the general-purpose simulation tool MATLAB Simulink, in which the open source WEC-sim simulation suite has been developed. Documentation is available online including detailed descriptions of the extensive library of built-in functional blocks (as shown in Figure 2). WEC-Sim is discussed in section 4.8.

https://uk.mathworks.com/help/simulink/index.html

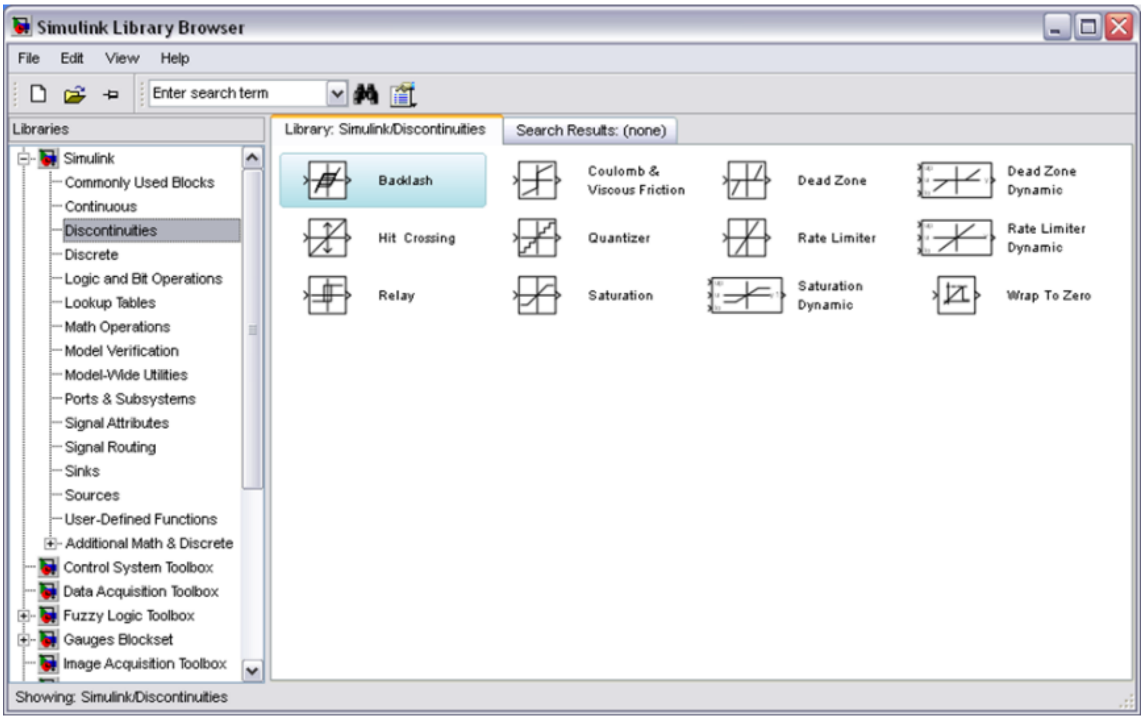

Figure 2: The MATLAB Simulink environment library of standard functional blocks. These may be connected into system models of arbitrary complexity for time-stepping simulation. Add-on tools allow for automated fitting of parameters to match experiments and optimisation of parameters against performance metrics.

4.5 Steps to an accurate and representative system model

A consistent process is sought for the definition and validation of models for simulation of different WEC subsystems. This process can be described through the following stages:

- System design and description
- Model definition: function, modularisation, and parameterisation
- Engineering of physical systems
- Validation and verification of models
- Sensitivity analysis and design feedback

These activities form an iterative process during staged technology development, and should be the basis of communication between interacting PTO and Control developers. The flow of information between engineering, modelling, and validation activities is set out in Figure 3 and explored further below.

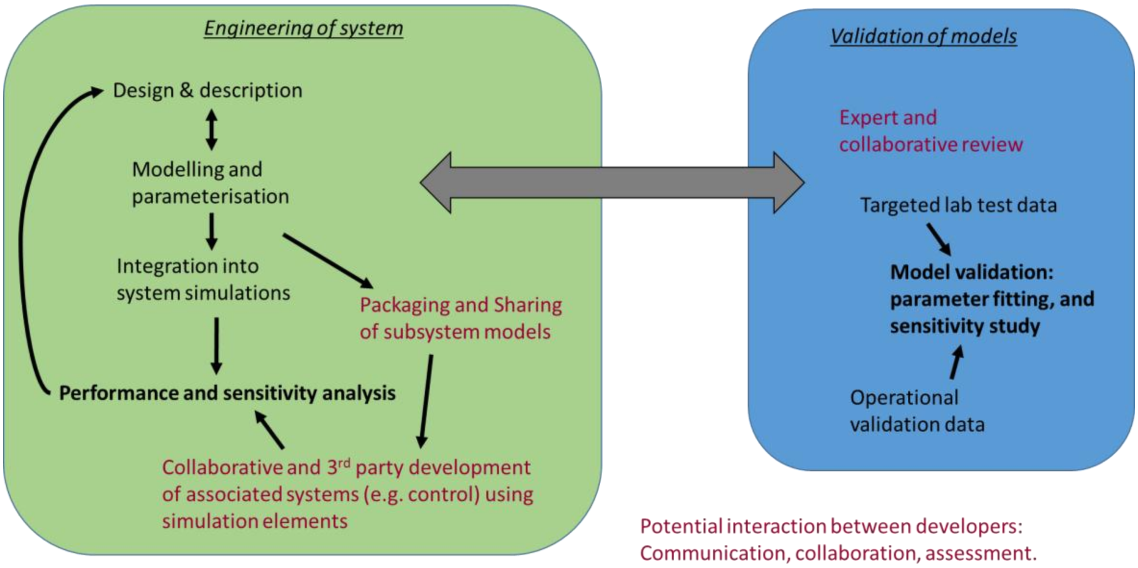

Figure 3: Modelling and validation in the engineering process undertaken by individual technology developers, with external and collaborative review, interfaces, and sharing of models.

4.5.1 Engineering of system

Design and description: Technology developers must necessarily describe in some detail how their system is intended to function and what mechanisms are involved. This description can be distilled into mathematical models capturing the essential functions of the system. This modelling is generally an essential part of the engineering design process and should lead naturally to more general purpose models and simulations.

Modelling and parameterisation: The technology developer is likely to be best placed to define and quantify models of their systems as this is an essential part of the engineering work they are undertaking. However, the technology developer may or may not be best placed to create modular simulation blocks for use by control developers and other users. It is likely that dialog is required for a consistent and sufficiently representative model for control development work. Similarly, a control process may only act through interfaces representative of those included in the physical systems it controls so such interfaces must also be well defined and communicated.

Integration into system simulations: Models and simulations may be usefully created for individual subsystems to operate from prescribed inputs (i.e. open loop) or within a simplified representation of the whole system (e.g. simplified hydrodynamics, and/or with basic non-optimised control algorithms). The performance and suitability of a subsystem can only be fully assessed in the context of the wider system within which it operates. A sub system model may be usefully simplified and/or modularised for inclusion in a wider system simulation, provided any omitted detail does not impact the results significantly. The judgement on what is acceptable simplification for a given application may not be obvious depending on interactions with other systems. Validation is therefore required not just for the module itself but at each stage of integration. Comparisons with physical and operational testing should be applied where possible to assess how representative an integrated model is of the real system.

Performance and sensitivity analysis: Various performance measures may be defined for individual subsystems and for whole WECs. These are drivers of the engineering design process such as Wave power capture and conversion, perhaps balanced against cost drivers such as maximum and fatigue loading. For example, a PTO system design may be optimised against latency, responsiveness, and conversion efficiency measures, while a whole WEC system should have quantifiable power capture performance that may be optimised through all subsystems and the control system design. Sensitivity studies using models allow the performance impact of different model parameters to be assessed and for the engineering options for achieving improved performance to be assessed and prioritised. Sensitivity studies may also be conducted as part of the validation process.

Packaging and sharing of subsystem models and collaborative and 3rd party development of associated systems (e.g. control) using simulation elements: WES hopes that developers of control systems may adopt third party models (e.g. WECs and PTO systems) for use for the development, testing, and optimisation of control processes. Such models should be progressively validated as technology goes through staged development and testing programmes. There may be a commercial requirement to withhold engineering details of such systems and only relate validated functional models without descriptions of how that function is physically achieved. Similarly, control developers may share controllers with other developers to allow sensitivity study and iterative design optimisation, and these might also be 'black box'. Collaboration could allow for technology development on multiple fronts in parallel with feedback of sensitivities and engineering drivers.

4.6 Validation of Models

It is of paramount importance that models include the features necessary for realistic behaviour when operating in conjunction with other systems. This may be especially challenging when creating models suitable for use by specialists in other disciplines, or third parties, to whom the existence or effect of some features may be unknown.

The intention is to create a consistent process of validation across the WES programme and hence consistent models for ongoing integrated development activity. The guidance issued by WES is to assist in identifying and quantifying the necessary model features to achieve validity for use by other technology development strands - in particular, for the use of PTO models by control developers and for the specification of PTO system requirements and sensitivities by control developers.

Validation of a model is not an event but proceeds in parallel with design development and integration with other development streams such as control processes and structural design. New features and new interactions are the subject of new models, which must in turn be validated with increasing focus as the technology develops.

Can the model capture all the required effects properly, as deemed by all stakeholders? – this makes it 'Face valid' against specification.

This may be initially provided by:

- Review and discussion
    - Internal review against guidance specifications and WES guidance
    - External expert review and query

    - Collaborative review: exchange of views between developers on what is important and how to best represent these effects in models
- Sense checks
    - changes to the model parameters create expected changes in behavior.
    - ‘glass box’ testing shows signals and elements in different parts of the model behave and are quantified as expected. (i.e. not just that the whole model conforms to I/O expectations in aggregate, but that all contributing elements are operating as expected). This also offers deeper insight into the various interacting sub-systems/elements and leads to sensitivity analysis.
    - Aggregate signals such as efficiencies of different stages, and comparisons between signals check out with expectations and general understanding. For example, signals are consistent with physical operation in expected ranges.
- Sensitivity checks
    - Assessment of relative importance of changes to model parameters to different aspects of behavior (these may also feed back into other design drivers such as cost).
    - Sensitivity to disturbance and measurement noise
    - In validating against experiments (see below), sensitivity analysis extends to the sensitivity of model accuracy to variations and errors in estimated parameters.

Does the model fit all the required effects as measured from a real system under test? – this makes the model validated with experiment.

The real systems may be anything from isolated lab experiments on components and subsystems through to fully integrated full scale testing and operational testing. The potential for scale effects and for unexpected interactions between subsystems & components makes the verification process a staged one that may progress with the staged technology development programme.

Requirements for experimental validation are:

- Experiments show measured outputs corresponding to those of the model given the same inputs
- Experiments are repeatable
- Test cases should cover the full range of behavior:
    - Whole system testing aspires to characterise all operating states for greatest insight and visibility of characteristics for comparison with models. These include: quiescent, static, steady state and time varying frequency response, transient response, amplitude dependence, and including constrained variables and other imposed or implicit non-linearities.
- Identification and estimation of model parameters from measured data – this may be through direct inspection and/or through numerical fitting methods.
    - Physics based models based on design insight will tend to allow for more robustness and clearer identification of parameters in experimental data.
    - A modular approach using direct physical interpretations and parameters also provides good feedback on the cause of errors in assumptions and any omitted features.
    - Models based on more abstract system identification methods are harder to interpret and may be more prone to usage errors and inadvertent abuse in

overfitting. These methods can however be applied to a ‘black box’ without knowledge of the system.

- Reproduction of results using models for different input cases.
    - Crucially, the model must remain sufficiently accurate against a range of input-output experiments when using the same fixed parameters. Inevitably, a model with parameters tuned in one state will be less representative in others, but the extent of any errors may be quantified and the implications for any applications of the model understood.
    - The input cases should represent transient and dynamic effects, and should exhibit any non-linearities inherent in the system. For example, step responses of different magnitudes and conditions, and a range of different input amplitudes and frequencies.
    - Test cases may be created specifically to help isolate and quantify individual parameters, or gain insight into any inadequacies in the parameterization of the model. For example, to directly exhibit static friction characteristics in a free-wheeling system. This approach also serves to avoid parameters being ‘fudged’ to superficially fit a narrow range of test cases overall without accurately reflecting the internal processes on which some measurements and interactions may depend.
    - A bottom up approach to modular testing validates the model elements that make up the integrated system first. For example, individual switching elements, or individual contributions to losses in a flow path or drive train. This offers greater visibility and insight when modelling the integrated system.
    - The term ‘Glass box’ testing (as distinct from ‘black box’ testing) may be used to describe a validation process isolating different elements of the model through dedicated measurements and test cases. This approach requires knowledge, insight and access to the different model elements and an understanding of how they operate and relate to the targeted tests. The engineer can use their insight to direct targeted tests and attempt to reveal individual parameter fits and/or suspected flaws in the model.

4.6.1 Simulink validation and sensitivity analysis tools

The MATLAB Simulink design optimisation toolbox may assist in in the validation and sensitivity analysis of PTO and WEC models implemented in Simulink, in addition to offering ongoing optimisation of study of engineering design and control parameters.

The examples provided in the following web link demonstrate the process of model validation against experimental data and the potential for then analysing the sensitivity of performance indicators to different model parameters. These parameters may correspond directly to engineering design opportunities.

https://uk.mathworks.com/products/sl-design-optimization/model-examples.html

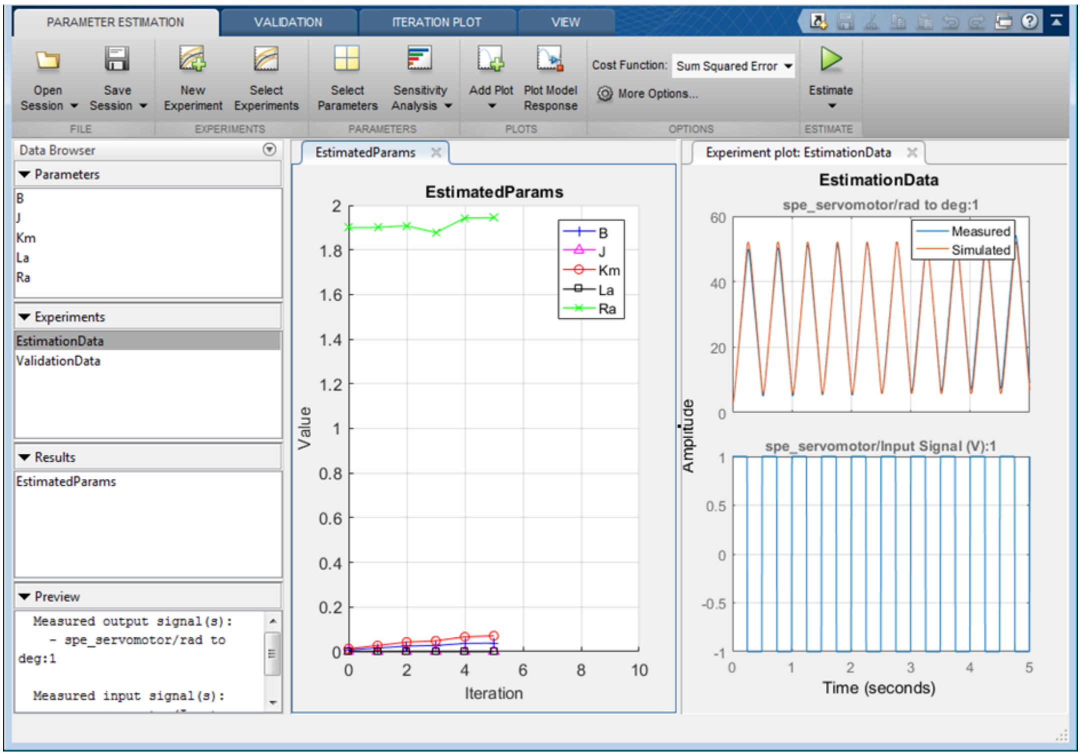

Figure 4: The Matlab Simulink model parameter estimation and validation GUI. An iterative process adapts the model parameters to best fit experimental output data against the simulation outputs given the same inputs. Different experimental test cases can then be checked against the model running with those optimal parameters.

4.7 Models for collaborative use in Simulation

The creation of working models for use by third parties (for example, implemented as a black box simulation block) may stray into the realm of software engineering. For example, models may require validation against 'edge cases' caused by unforeseen inputs and input combinations. Flaws may go unnoticed during development because the models are implicitly constrained at the input stage in the original context but not in others. It is most important that the model does not produce erroneous results under new input conditions, especially where these results may not be recognised as erroneous. Models using abstracted functional representations are particularly prone to such issues. For example, look-up tables and best fit curves may result in rubbish outside of the intended input range. Therefore, the full range of potential inputs should either be validated to some extent or range checked to avoid errors being misinterpreted. In specification, the validated range of inputs should be clear.

4.8 WEC-Sim

WEC-Sim is an open source modelling toolbox built into the MATLAB Simulink modelling and simulation environment. It is under development in the USA by Sandia National Laboratories (SNL) and National Renewable Energy Laboratory (NREL). The goal is to allow the simulation of arbitrary WEC types, and in combination with different subsystems, in a self-contained set of modular tools suitable for collaborative development work and onward open source development. The hydrodynamics modelling uses boundary element methods to derive classical hydrodynamic coefficients associated with the equations of motion of the WEC. These can then be implemented and solved in Simulink time-stepped simulations, allowing arbitrary forces to be included from PTO and mooring models.

The WEC-sim framework can allow for collaborative and comparative modelling of different subsystems and for parallel development activity. For example, control algorithm development and optimisation may in theory be conducted in parallel on a validated WEC and PTO system model provided by collaborating developer(s). Such an approach relies on consistent validation and good communication between developers.

The home page of the project is below, providing access to all documentation and downloads required to build WEC-sim into an existing MATLAB installation provided the Simulink, SimScape, and SimMechanics toolboxes are also installed.

https://wec-sim.github.io/WEC-Sim/index.html

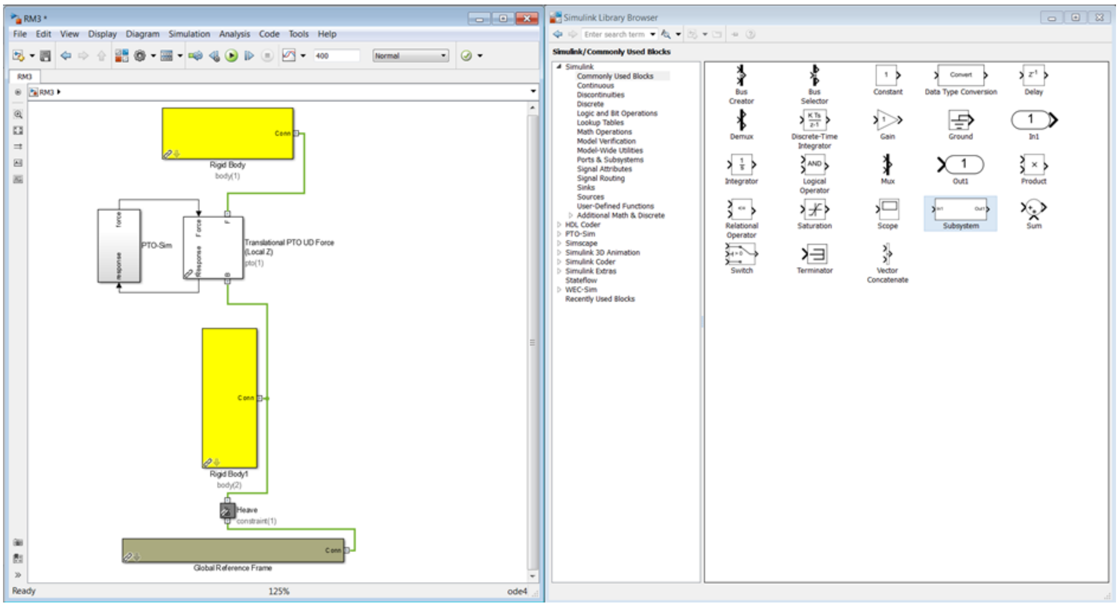

Figure 5: The MATLAB Simulink simulation environment including the WECsim modules

The PTO modelling functionality available in the recently released version 2 is described through simple examples (described in more detail in the following paper), with online documentation and tutorials on how to work with and develop PTO modules available from the WEC-Sim website.

http://energy.sandia.gov/wp-content/uploads/2014/06/SAND2015-2069C.pdf

These simple examples offer a very helpful starting point but does not yet include many of the features discussed in this guidance required to represent PTOs for realistic control development and performance assessment. Models suitable for onward development of control processes and performance assessment would rely on the direct involvement of PTO and WEC developers and a robust process of validation as set out in this guidance document.

5 Specific modelling issues to consider for WEC systems

A number of typical features of WEC integrated PTO and Control systems are highlighted here for special consideration in models used for control development. Many characteristics of physical PTO and WEC systems may determine the performance limitations of the system in a way not obvious to the independent technology developer.

While several important effects are directly discussed below, and advice given for their inclusion in models; there is no catch-all for every different PTO and WEC system or how they may be applied in different scales or combinations. Some effects will be specific to certain technologies and may not be covered here directly. The validation and review process should therefore be staged and tend toward the circumspect based on the general model validation approach outlined above.

Depending on the system in question, some effects outlined here are likely to be crucial to the accuracy and usefulness of models for control development and performance assessment. Others may be inconsequential and a waste of time to model. Determining appropriate omissions and simplifications requires judgement with respect to the potential effects, and informing efforts on validation and sensitivity analysis. Many of these effects are very familiar to engineers generally and are represented in 'canonical form' in the basic Simulink library.

5.1 Output load saturation

An economic WEC and PTO is likely to be rated for a limited range of potential load application, otherwise expensive capability would be severely under-utilised. This means that in anything but the smallest seas, load limits will be reached and any assumption of linearity in the modelling or control formulation is lost. Basic load saturation does not have direct stability implications for the control system but represents a complexity in the formulation and optimisation of parameters. In multiple degree of freedom (MIMO) systems, the breach of linearity may make robust stability analysis very challenging.

It is therefore important that any limits in the applied load are properly represented in descriptions and models of the PTO system. These limits may in turn be a function of another process variable, for example the working pressure of a fluid power system. The representation then depends on the extent of model simplification and focus of the development work. For example, a fixed value of load limit (for example a simple saturation block) may be reasonably assumed for steady state cases (e.g. in 1 sea state at a time) for some development purposes. For others, additional model elements would be required to represent variation in load limits. The choice is a matter for the developers and review process with due regard for validation, sensitivity, and accuracy.

5.2 Rate limits and more general amplitude dependence

In addition to limits in PTO load, there may be fundamental limits in the rate of change of load. The model and parameters must represent the phenomenon accordingly, with a distinction drawn between linear (or linearisable) systems and those that are not. Rate limits may manifest as a constant rate limit with no significant effect below that value (as might occur for example due to the hard flow limit of a pump), or they may manifest in a more complex form (for example a more gradual saturation in an electromagnetic system) giving continuous amplitude dependence.

Some systems may have linear characteristics limiting the rate of change of output force (for example due to internal inertia) that may be represented by a linear transfer function (a difference equation in the time domain).

5.3 Kinematics and PTO coupling description and constraints

The relationship between the WEC hydrodynamic response and that of the PTO and its components may be defined by kinematic and dynamic functions that relate the degrees of freedom defined for the PTO inputs and outputs to those used to described the response of the WEC. It is generally convenient to use the same coordinate system, and where possible align controlled coordinates with those of the WEC response - for example, the angle of a flap to the input angle of a rotational PTO system on the same axis.

A linkage or gearing arrangement requires a modelled representation of the kinematics, with the additional requirement to capture any influence such a relationship has over other potentially important effects such as backlash or structural compliance, which may be geared or act in sequence as a result. Some geometric functions relating the controlled PTO motion to the WEC motion may be suitable for linearisation in simplified models (for example, the travel of an arc through a small angle range) provided the effect of such geometric nonlinearities is insignificant. While the selection of any simplifications should be through a robust validation and sensitivity analysis, other 'drive train' effects are perhaps more likely to cause critical problems in the model accuracy, such as defining control stability margins.

Typically, some degrees of freedom of a WEC are not controllable but still may be intrinsic to the control process and performance. These must be represented in any model used for control development if the control behaviour is sensitive to them.

5.4 Latency

Delays are unavoidable in practical digital control systems (and in simulations using explicit numerical solvers such as Euler's method), and they cause major limitations on control performance generally.

The impact of delays in different parts of the control loop is cumulative, resulting in a total latency between a control action and any subsequent change to the demanded control action as result of feedback effects. In a linear system, the delays may be lumped together in the open loop transfer function for analysis. The total delay may be very small relative to the wave period but still induce instability at high frequencies through interactions with the PTO and WEC structural and other compliance, backlash, etc.

Any delay whatsoever (e.g. even just the sampling period or simulation time-step) is associated with the instability of mass terms (terms based on acceleration measurements) in the control at the delay period and therefore targeted compensation must be included to implement such terms.

The high effective gains relative to system inertia typical in WEC response control systems means that delays measured in milliseconds can define the performance limitations of the entire system. The delay between control signal and actuation must therefore be quantified accurately.

The delays introduced by different elements of the PTO system should be quantified, with the option to lump them together where unaffected by non-linearities or interactions. Depending on the particular technologies involved, the delay in force application from command signal is likely to be of greatest importance. Step response experiments should quantify this along with rate limitations.

Where delays are not fixed, the variation should be represented in the modelled or action taken in the engineering design to set them fixed in the control process and a worst case assumed.

5.5 Hysteresis

Depending on the nature of the effect, rate independent (i.e. memory dependent) hysteresis is associated with phase shifts in the control signal path that may have a similar impact to latency. A phase shift is induced because the current output state depends on historical states but depending on the controller this may or may not also be associated with effective gain reduction for unconditional stability. Hysteresis may offer a stabilising influence with respect to limit cycles and if it acts to effectively add damping to the system.

Electromagnetic and Magneto-restrictive PTO systems may include rate-independent hysteresis phenomena describable through classical hysteresis models. Quantised force actuation may require hysteresis in some form to avoid limit cycles around force transitions.

Complex impedance terms (e.g. the effect of damping on a spring function) are sometimes described in terms of a 'Rate dependent hysteresis'. By definition, any modification of the overall effective impedance of the controlled system may cause instability if the effect is to induce an overall closed loop gain greater than one while the output phase lags by more the 180deg.

Avoiding negative performance impact depends on the controller and therefore any control algorithms developed for applications with PTOs exhibiting hysteretic behaviour must include this effect in development models. The PTO developer must include, implicitly or otherwise, any such characteristics in their models and parameterisations. Models including dynamic and nonlinear effects such as rate-independent hysteresis may be validated through experiments using cyclic and irregular inputs of different frequencies and amplitudes.

5.6 Backlash and dead zones

Backlash is a type of hysteresis that appears in mechanical systems as play between gears or bearings causes a decoupling of the drivetrain load on motion reversal. This effect can induce unacceptable limit cycles across the backlash range as a function of the closed loop control gain. It is therefore important to include or rule out this effect as a constraint on system performance.

This may be considered a special part of the compliance in the load path (see below) because it occurs over a small range of motion, but unlike typical structural compliance it is non-linear and memory dependent and therefore requires dedicated modelling functions. Backlash is however straightforward to estimate, parameterise, and quantify in experiments.

A single backlash element is described by the range of free motion that is travelled on load reversal before the drive train is recoupled. A backlash block is included in the Simulink standard library. The effect of multiple instances is cumulative through the drive train and may be subject to effective gearing through the system kinematics. Backlash may be practically eliminated by design in some types of PTO. In others, it may be a primary performance limitation under high gain control.

Similar to backlash but not hysteretic, 'dead zones' in the drive train may be a feature of non-mechanical PTO elements also capable of inducing limit cycles and limiting control gain. A pure dead zone can be defined as a range of unimpeded motion on reversal of force. This effect also has a dedicated standard block in Simulink.

5.7 Structural and other compliance

In some WEC designs, for example an oscillating water column driving airflow through a turbine, compliance between the PTO and the WEC motion is an obvious and essential feature of the model. In others, the PTO motion may be via a 'rigid' link between multiple bodies or a fixed anchor point, but some compliance remains inherent in the structure of the WEC and the components of the PTO. While an order of magnitude stiffer than the driving hydrodynamics, this structural compliance may still play a defining role in the limitations of the controlled system.

Where input motion measurements are taken on or between compliant structures then this effectively introduces additional stiff degrees of freedom to the control process, with modes capable of unstable response under control. The relatively high frequency of such 'structural modes' of response can make them particularly problematic in conjunction with latency and actuation delays, which can result in phase inversion and instability at those high frequencies.

The location and method of sensing is therefore important in avoiding strong coupling of structural modes with delays in the control loop. Options should be reviewed carefully between developers.

The specification of compliance may be implicit in some model functions (for example, fluid compressibility in a fluid power PTO, also required for volumetric efficiency calculations, is defined in terms of closed volume and fluid bulk modulus) while others may require special treatment to capture. Structural compliance may be from both PTO components (e.g. connection rods) and the wider WEC structure (e.g. effective stiffness of the load attachment points defining deflections with respect to the bulk rigid body motion). It may be appropriate for the specification to be described initially in terms of the engineering design features – for example, dimensions and materials of compliant elements on the structural load path. This may then be modelled as a linear transfer function representing the effective mass and stiffness (also including some nominal damping for numerical stability of simulations) for use in efficient simulation and control analysis..

5.8 Other effects

Mechanical friction will always play some part in the WEC load regime, but it is expected to be relatively insignificant to the energy absorption and system response when compared to primary loads. Sensible levels of friction are not expected to be destabilising or problematic to control systems. This should however be quantified through estimations and experiment where possible. It is very likely to be included in models as a source of energy loss in performance analysis, allowing control sensitivities to also be validated.

Due to scaling issues, friction and backlash are likely to play a more significant role in scaled tank tests so special effort should therefore be made to measure and include these effects in models used for agreement studies and control application in tank tests.

5.9 Disturbance and noise

In addition to signal noise, disturbance in control inputs can result from shock loads and vibration, which may be a side-effect of the PTO system operation itself. The modelling of structural compliance as a disturbance term is described in the existing control landscape report section 4.4.2, and the positioning of and general specification of sensors is also covered in section 6. PTO developers should be familiar with these issues and able to convey the type and location of sensors and any assumed signal processing and associated effects on signal latency and frequency response.

Models should implicitly include the most dangerous disturbance effects associated with structural compliance in the drive train affecting signal measurements. Sensor noise may be included if it is deemed to be a concern, although this would typically not be expected to be the case.

5.10 Fault handling and diagnostics

The behaviour of systems under likely fault conditions is a major design driver and likely to be a major feature of practical control systems. Fault conditions may require special control processes for detection, safe handling, and maintenance of availability. Models should be adaptable to fault conditions as required for such development work and for assessment purposes. The choice of fault cases and the nature of the solution (e.g. elimination by design, redundancy and handling, control features etc.) is a topic beyond the scope of this report but should be considered appropriately at each stage of the development process.

It should be acknowledged that control faults (e.g. software bugs) have the potential to cause major failures. Protection and fault handling systems should therefore also be properly considered from the control perspective.

It is expected that focus may shift onto such detailed topics in later stages of WEC development where a more integrated and focused approach to detailed design is required.

5.11 Modelling efficiency, energy storage, and electricity generation systems

Electricity generation systems may be decoupled from the response controlling elements of the PTO by an energy storage mechanism. The control of generation systems is therefore a rather different topic from WEC response control and is in many ways more familiar to general industry, able to make use of standard equipment and methods.

Sources of loss should be implicit in the functional models of the PTO system. For many components, such as generators and motors, look-up tables based on empirical data are a standard and efficient way of representing loss behaviours in simulations. Energy storage models may not be a strong influence on response control issues, but are important to losses and hence overall performance assessment. The energy recovery behaviour of storage models may involve complex physical processes exhibiting hysteric functions. Dedicated tests are required to characterise this and validate models.

Ultimately, validation of conversion efficiency may be conducted in staged testing like other aspects of the PTO function. It is however, very important that the inputs are realistic if realistic conclusions are to be drawn from the results. For example, irregular wave excitation of the correct distribution of wave groups. This is discussed in the Control landscape report.