Reduced Order Simulation Surrogate for Wind Turbine Component Design

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1. Abstract
Small changes in the structural dynamic properties of wind turbine components can have a large influence on the ultimate and fatigue loads they experience. This is due to strong coupling between the aerodynamic (aero), control-system (servo) and structural (elastic) behaviours of the wind turbine system. Therefore attempts to design these structures using algorithm-driven numerical parameter studies are more likely to lead to feasible designs when the load calculation is integrated into the optimization problem formulation. Industry-standard aero-servo-elastic (ASE) simulation codes are, however, too computationally expensive to iterate in the constraint evaluation of a highly-dimensional design optimization problem. More efficient load simulation methods are needed to make optimization algorithms practical for the structural design of major wind turbine components.
A reduced-fidelity ultimate and fatigue load approximation method is proposed as a means to conduct sizing optimization for lightweight structures. The new method, termed ROSS for reduced order load simulation surrogate, leverages FEM substructuring operations and surrogate modelling to reduce the degrees of freedom in the load simulation. This speeds computation and reduces the dimensionality of the design space (to select terms in the condensed mass and stiffness matrices). In the first step, all design load cases are simulated for each sample point in a design of experiments (DOE) on the reduced design space. Then ultimate loads and damage equivalent fatigue loads (DEL) are calculated and a metamodel is calibrated to approximate the DEL for arbitrary mass and stiffness matrices. Finally, the constraints can be analysed for the original set of design variables by a sequence of substructuring, metamodel evaluation and static FEM analysis using the approximated ultimate loads and DEL.
The additional FEM calculations and metamodel evaluations are orders of magnitude faster than the many ASE time series simulations which they replace. This enables optimization algorithms to design lightweight (flexible) turbine structures with a highly dimensional design space exhibiting a large range of natural frequencies. Uses for ROSS extend beyond constraint evaluation for frame optimization problems; the method can also be utilized to replace the static load assumption in topology optimization schemes.
2. Keywords: approximation, sizing, frame design, reduced order simulation surrogate (ROSS)

3. Introduction
The Intergovernmental Panel on Climate Change recently ranked onshore wind as having the lowest lifecycle equivalent CO_2 emissions per kWh of all commercially-available electricity generation technologies. In many scenarios, it also has the lowest cost per kWh [1]. Structural optimization research is a priority for the wind industry since lightweight structures improve both the numerator and denominator of these key selling points which have driven the growth of wind power. The steel and concrete mass in the tower and foundation are the primary sources of emissions [2] and costs related to wind energy. Lighter structures enable more cost-effective manufacturing, logistics and erection of taller towers supporting larger rotors (which increase energy production and amortize fixed costs) [3]. A 2014 review of optimization methods applied to wind turbine structures references 130 scientific papers, 90 % of them published since the year 2000, demonstrating the emergence and rapid development in this research niche [4]. The authors identify computationally-expensive simulations as the main obstacle preventing search algorithms and automated design of experiments from replacing “manual optimization” in selecting the design parameters of wind turbine structures.

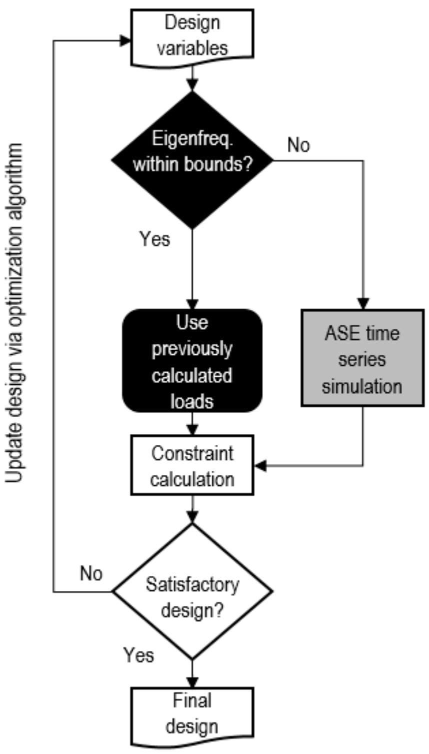
3.1 Load Calculation
The structural finite element models used in wind turbine simulation models are generally very simple. Coarsely discretized beam models with as few as 28 degrees of freedom (DOF) are used in industry to model the entire rotor-nacelle-tower-foundation system [5]. The computational expense involved in load simulation is driven by the need to increment the states of the aerodynamic and controller models together with the structural response in small time steps. This co-simulation of the entire turbine system operating state in the time domain is necessary to account for the significant non-linear coupling effects between the wind field, rotor aerodynamics, structural kinematics and control systems (e.g. active blade pitch, generator torque, nacelle yaw control, etc.). This requires numerous ASE time series with different initial conditions and simulated events (including emergency stops and system failures). In this way, all possible scenarios which could generate an ultimate load are simulated.

Additionally, accurate calculation of the fatigue load necessitates that all normal operating conditions are also included in the simulation. Thus any change in a wind turbine's structural design that affects its dynamic response (i.e. changes in stiffness, mass and damping matrices) will have a unique influence on each time series history and an unpredictable influence on the ultimate and fatigue loads [6]. This necessitates that new structural designs can only be analysed in conjunction with new ASE simulations (typically using proprietary ASE codes which contain aerodynamic and controller parameters closely guarded by wind turbine manufactures). A notable consequence is that wind turbine structures must be designed together with the wind turbine system. It is therefore very difficult to change the rotor, tower or foundation design for an existing turbine without working together with a manufacturer to simulate the loads; accommodating modifications to other components or systems are usually needed (especially controller modifications).

3.2 Existing Methods to Accelerate Load Simulation

As it is impractical to iterate an expensive simulation for each point sampled in a design space, all previous efforts to apply optimization algorithms to wind turbine structures have sought to avoid or limit the number of ASE time series used to evaluate structural design candidates. The most common approach is to assume fixed ultimate and fatigue loads if the natural frequency for the candidate design remains within a given tolerance from the design used to calculate the applied loads. This engineering assumption is permissible under some wind turbine design certification codes. (A natural frequency calculation tolerance of 5 % is allowed in the GL certification guideline for towers [7].) This method, depicted in Fig.(1), has been applied by Yoshida at Fuji Heavy Industries in 2006 [8] and the wind turbine design consultancy Windrad in 2014 [9] to optimize the thickness and diameter distributions of tubular steel towers. The computational savings of this technique are, however, limited to applications where the design variables have a small effect on the natural frequency and mode shapes (i.e. fine-tuning of a design using a small range of inputs).

Alternatively, Long, Moe and Fischer recently demonstrated in 2012 that a frequency domain analysis technique can be applied to estimate the ultimate and fatigue loads for design spaces with a wide range of structural dynamic responses [10]. This method cannot, however, model time history-dependant ASE effects which have a large influence on ultimate and fatigue loads, such as controller response to gust disturbances. Other published methods include the use of readily-computable proxy data to steer search algorithms toward designs with favourable structural dynamic response. A recent example is the use of tower top deflection under static load as a measure of fatigue damage in the sizing optimization of a tower and foundation by Nicholson in 2013 [11].



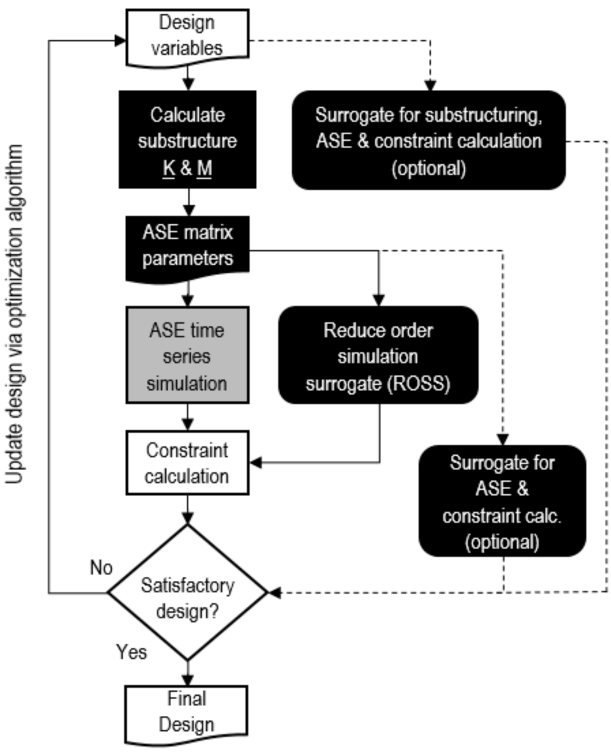


Figure 1: (left) Optimization via static loads assumption for structural constraint analysis

Figure 2: (right) Proposed reduced order simulation surrogate (ROSS) method

4. Proposed Aero-Servo-Elastic Surrogate Optimization Method

The present work introduces a new approach that models loads independently for each design point using a surrogate model. The metamodel is calibrated from a DOE of industry-standard aero-servo-elastic time series simulations. The ultimate and fatigue load responses are approximated for select parameters in the generalized mass and stiffness matrices, which are linked to the original design variables using an intermediate substructuring operation.

4.1 Process Flow

The general process flow for using ROSS to accelerate constraint calculations for structural component design is depicted in Fig.(2). To initialize the ROSS approximation the following procedure is proposed:

(0) Perform "SubDOE" using the design variables (and their bounds) as inputs and the reduced stiffness and mass matrices as outputs. (Optional.) A 2-level fractional-factorial experiment such as an orthogonal array is recommended if the number of parameters is very large.
(1) Perform "SimDOE" using select terms in the mass and stiffness matrices as inputs for the aero-servo-elastic time series simulation and the post-processed ultimate and fatigue loads as outputs. Use results from (0), if available, to eliminate unnecessary factors and establish bounds for the intermediate variables.
(2) Fit "ROSS" approximation to the SimDOE.
(3) Integrate load simulation approximation into the constraint evaluation of the design optimization process.

The dotted lines shown in the process flow represent alternative pathways that may further accelerate a ROSS optimization. Depending upon the computational expense involved in the substructuring and constraint evaluation, it may be beneficial to calibrate additional approximations for these processes. Particularly, the SubDOE data from step (0) can be leveraged to build an approximation without any additional (sampling) computation, provided the error is acceptable.

4.2 Reduced Order Structural Model

Modal condensation is commonly applied to reduce the degrees of freedom in ASE wind turbine simulation codes, which are based on the general equation of motion for linear dynamic systems, Eq.(1),

$$\underline{M} \cdot \ddot{\underline{x}} + \underline{D} \cdot \dot{\underline{x}} + \underline{K} \cdot \underline{x} = \underline{f} \tag{1}$$

where

$\underline{M}$, $\underline{K}$, $\underline{D}$: are reduced mass, stiffness and damping matrices of the structure,
$\underline{f}$: is a vector of external time- and position dependent forces acting on the reduced structure and
$\underline{x}$: is a time-dependant displacement vector of the nodal positions of the reduced structure.

A practical example of this so-called substructuring process is the common practice of using static condensation and Guyan reduction to generate reduced mass and stiffness matrices for an offshore foundation [5, 12]. Although the designer may have a very large set of design variables to select (e.g. cross section dimensions, frame element endpoints, etc.), the detailed FEM model might be reduced to a single node with 6 degrees of freedom (or less) so that the loads can be calculated with the ASE code. If off-diagonal terms of the reduced mass and stiffness are sufficiently small, orthogonality conditions can be assumed and the mass and stiffness matrices can be further reduced to 6 terms each. Thus regardless of the number of design parameters and their values, only 12 parameters must be passed to the industry-standard ASE simulation in order to evaluate a design alternative for this example. (The damping matrix can be calculated from the mass and stiffness matrices using the Rayleigh method [13]). In fact, it is sometimes possible to reduce this number of "ASE matrix parameters" to 8 due to symmetry (as is the case for a rotationally-symmetric foundation or a tripod structure) or even less if the range of values for a specific term in the reduced mass and stiffness terms is small and therefore has a negligible influence on the ASE load calculation.
The proposed ROSS method simply exploits this existing reduction method built into the ASE by performing the SimDOE on the few significant and unique degrees of freedom in the ASE simulation, rather than the larger set of design variables. This saves computational expense when the structural design parameter count is large, as the dimensionality of the SimDOE is comparatively smaller.

4.3 Parameter Bounds for ASE Simulation

The minimum and maximum values for the studied terms in the reduced mass and stiffness matrices have a strong influence on the performance of the ROSS method. Ideally, these limits are calibrated to the most extreme possible output values for the substructuring process considering the given bounds of the structural design variables. If the bounds are too wide, the density of sample points in the design space is reduced (costing surrogate accuracy) and the computational expense must be increased to compensate. If the bounds are chosen too narrow, the ASE loads approximation will be invalid and the optimization is likely to perform poorly and suggest many infeasible designs.

4.4 Constraint Calculation using ASE-calibrated Surrogate

The ultimate and fatigue loads estimated by the ASE surrogate require post-processing in order to calculate the constraints included in the design optimization. The structural constraints typically include verification of strength, stability, extreme deformation and fatigue. These analyses are possible by statically applying the ultimate loads and fatigue DEL using nonlinear static FEM. Although such FEM calculations are orders of magnitude faster than the ASE, it is likely that FEM is still too slow to search the design space unless the number of parameters is very low. Therefore metamodel optimizations methods are likely necessary.

Examples of surrogate-based structural optimization using static load under stress constraints can be referenced from Rudolf et al. [14] and the aforementioned work by Nicholson [11]. Some structures, such as tubular towers, can be verified against all constraints using simple engineering equations in place of FEM. This negates the need to use a surrogate (other than the ASE) to search the design space (and avoids the error associated with the additional approximation).

4.5 Limitations and Assumptions of ROSS Method

The modal reduction schemes used by most ASE turbine simulation codes assume linear-elastic behaviour of the substructure elements. Effects such as the catenary sag in guyed supported structures and nonlinear soil stiffness cannot be modelled within (single node) condensed matrices and require additional degrees of freedom. As the number of active ASE matrix parameters increases, the computational expense associated with the use of these terms for the SimDOE rapidly increases. In these cases it may be more beneficial to perform a surrogate model optimization using the original structural design variables for the SimDOE rather than a potentially larger set of ASE matrix parameters, especially if this will reduce the dimensionality of the ASE experiment.

Additional limitations are associated with the excitement and damping of higher-order modes in the reduced structure. The higher-order mode shapes and frequencies of the substructure are omitted from the ASE model. Therefore the resonance of individual members (if any) in the substructure is not accounted for in the load calculations. This should be considered if applying ROSS to study a truss structure. Similarly, geometry-specific external forces (such as aerodynamic damping, hydrodynamic loading and wind loading) are held constant under the ROSS method despite them being a function of the structural design. Regardless of these shortcomings it is important to remember that ROSS is a design tool – not a verification tool – and the method is an improvement versus optimization under a static load assumption.

5. Conclusion, Recommendations and Future Work

This work addresses a major obstacle to the widespread adoption of computer-aided structural design optimization in the wind industry by introducing a faster alternative to time series simulation that is also more accurate than assuming static loads. The proposed decoupling of the design variables and load simulation suggested by the ROSS method takes advantage of the existing substructuring operations used in modal ASE codes. This enables the loads for a very large number of design variables to be approximated from a dataset calibrated from a reduced set of parameters. In addition, the same ROSS model can be reused to study new design problems with unrelated variables. For example, only one ASE matrix parameter DOE could be used in the design optimization of both an offshore tripod foundation and a jacket foundation. Main limitations of the ROSS method are associated with having too few nodes in the AES simulation (i.e. the excitement and damping of higher-order modes, modelling of structural nonlinearities and modelling of external forces). Attempting to resolve these issues by using larger substructures defeats the purpose of ROSS if the number of ASE matrix parameters exceeds the number of design variables.

Applications for the ROSS method extend beyond sizing optimization and frame design. Cast components such as slab foundations, rotor hubs and some nacelle structures might use ROSS within topology optimization schemes to update their boundary conditions and penalizations functions between iterations. In this way the changing mass and stiffness matrix terms of the lighter and more flexible structures are accounted for in the loads and beneficial dynamic characteristics can be used to arrive at lighter designs. The published method remains in development and is currently being applied to optimize the design of a cable-truss tower for a 2.5 MW commercial wind turbine prototype with 140 m hub height.

6. Acknowledgements
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