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Robust lightweight design and digital twins considering manufacturing quality variation and sustainability requirements

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Abstract

Design of lightweight structures requires in practise optimization for minimizing structural mass with technical requirements such as design fatigue life and allowed vibration levels as constraints in the optimization. The motivation for lightweight design comes from the sustainability requirements, such as energy and materials efficiency, reduction of CO2 emissions, and the use of recycled and biobased materials. Recycled and biobased materials tend to have larger variation in material properties and manufacturing quality than traditional materials. By combining measurements (metrology), statistical analysis of measured data, reliability-based simulation, fatigue analysis, and optimization, the effect of the variation can be included in the design, while also considering the sustainability, cost, and performance requirements. The design requirements limiting the design space are treated as constraints in the optimization.

As mass of load carrying structures is minimized, stresses tend to increase if the loads remain unchanged. The welds are often the weakest link in fatigue critical structures. The fatigue strength of welded joints is affected strongly by the manufacturing quality variation. The quality variation and its effects on fatigue need therefore be considered in the design of lightweight structures.

The robust design approach uses statistical distributions to represent the variation and uncertainty of the measured design parameters. The variation and uncertainty are compensated in the robust design approach by control parameters, such as dimensions defining the component shape. In addition, definition of quality levels for local geometry and defects can be used as control parameters for welds, castings, and AM components. The robust design approach allows definition of quality levels and thereby allocation of high quality only where needed (and lower quality elsewhere).

The product performance vs. variation of design parameters is studied by reliability-based design optimization (RBDO) using the various design, sustainability, etc. requirements as constraints. The variability and uncertainty of the design parameters and factors contributing the most to the overall product performance can be determined by uncertainty quantification (UQ). RBDO and UQ, together with systematic use of hierarchical, modular modelling are combined as robust design process. Condensed information of product performance vs. various scenarios can be extracted from the robust design process for customers and stakeholders for the basis of their decision making already in the concept design phase, enabling co-design in the product development projects. The robust design process provides predictions of complex interdisciplinary effects on performance, sustainability, and cost with reliability estimates, thus enabling multicriteria-decision-making under uncertainty.

The monitored manufacturing quality data and the simulated loading events serve as the statistical design data in the robustness optimization. The realised manufacturing quality and the configuration of each individual product are used in model-based monitoring of remaining fatigue life during operation. The individual load histories and models representing the deviations are the digital twins of the individual products of the fleet. The digital twin representation is used already in the design phase for evaluating the uncertainties and allocating additional tests and measurements to the factors with the highest contribution to the product performance, to decrease uncertainty in a controlled way. As the RBDO and the UQ use Monte Carlo simulation and parametric surrogate modelling, the surrogate models representing the products with manufacturing deviations can be used as digital twin models in the operation phase. The digital twin models will then contain the corresponding manufacturing quality deviation information and they thus enable the prediction of the individual remaining fatigue lives of the products with high accuracy, as the effects of the manufacturing quality can be considered in monitoring and fatigue life assessment during operation.

The statistical distributions, probability of detection (POD) curves, and geometric tolerances serve as interfaces in the robust design process information flow. The statistical distributions of the measured geometrical deviations and the POD curves

defining the inspection data are used as input in RBDO and UQ. The manufacturing quality, design parameters in structural optimization, and dimensional measurements are planned, analysed, evaluated, and defined using geometric tolerances and multicriteria-decision-making considering the quantified uncertainties and the variation of manufacturing quality and its effects on product performance. The tolerances are used to pass the target quality information from design to manufacturing. The measured geometrical deviations and the analysed distributions are fed back from manufacturing and quality assurance to design.

Hierarchical modelling is used in fatigue analysis, enabling the selection of suitable accuracy vs. modelling effort along the project progress. The effective notch stress (ENS) method is used in early design phase for parametric studies and optimization of weld dimensions and weld quality parameters. Fracture mechanics can be used for predicting for example the crack lengths versus various loading conditions detected during monitoring, for example for defining the inspection intervals and to increase the accuracy of fatigue life predictions during operation.

The robustness optimization and digital twins are demonstrated using a mock-up welded structure representing an industrial structure. Minimizing the mass of the structure is the objective function in the optimization, while the required fatigue life at the target reliability is defined as constraint. The digital twin models represent the fatigue lives of each individual structure of the manufactured series. The RBDO enables fleet-level robust design considering the monitored manufacturing quality, while the digital twins enable the real-time monitoring of the remaining fatigue lives of the structures within the fleet individually based on the actual realised manufacturing quality.

Keywords: digital twin, quality, optimization, uncertainty quantification, reliability, robust design, fatigue, sustainability

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