Derivation of a macroscopic nonlinear beam model for cables using homogenization

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Abstract

Floating wind turbines represent a significant innovation in renewable energy, by addressing the global demand for sustainable electricity while reducing carbon emissions. These turbines transmit the generated electricity to offshore locations through dynamic cables, which are subjected to complex environmental loading conditions including platform movements, hydrodynamic forces from ocean currents, and aerodynamic pressures from wave action. Accurate simulation results are essential to ensure the structural integrity and operational reliability of these cables.
The dynamic cable under investigation typically measures 100 meters in length and 10 centimeters in diameter. Its complex geometry and heterogeneous structure arise from multiple components such as metallic layers composed of wires with helical configurations. This cable exhibits nonlinear bending behavior as a result of contact nonlinearities. To predict its mechanical behavior accurately, a multiscale study is required to link the complex interactions occurring at the microscale to the resulting macroscopic beam-like behavior of the cable.

The solution to homogenization problems performed at the microscale reveals that the macroscopic behavior of the cable is hysteretic, which can be effectively captured using a rheological model, specifically the Bouc-Wen model (1, 2). Using this macroscopic model avoids the computational complexity associated with numerical strategies that couple microscale and macroscale analyses, such as FE^2 approaches, while maintaining reliable predictions of the mechanical response of the cable under a range of loading conditions.

The aim of this study is to introduce a reduced macroscopic model based on the Bouc-Wen framework, estimate its parameters using solutions from homogenization problems, and demonstrate the accuracy of this macroscopic model by comparing it with detailed finite element models.

To determine the parameters of the Bouc-Wen model, an initial microscale analysis is performed on a representative volume element of a cable corresponding to an axial period subjected to tension and uniaxial bending under periodic boundary conditions (3). This analysis captures the structural behavior during the critical stick-slip phases, enabling the determination of both stick and slip stiffness, as well as the threshold for transitioning between these phases. The parameter identification process requires only a limited set of computations corresponding to a series of uniaxial bending tests under a constant axial force.

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The Bouc-Wen model, formulated with parameters derived from microscale analysis, accurately captures the nonlinear hysteretic behavior associated with cyclic loading. This reduced rheological model, initially developed for uniaxial bending conditions, is then extended to account for multiaxial bending loads following the approach introduced by Saadat (4). This extension involves discretizing the three-dimensional bending space into n
theta equally spaced uniaxial systems. In each system, the uniaxial response is captured in a distinct plane where the loads and deflections are projected. The Bouc-Wen model, previously identified under uniaxial conditions, is used to represent the bending response of the cable in each plane. By combining these forces into the global system, the extended multiaxial model is able to accurately simulate the full 3D bending behavior of the cable, offering a comprehensive description of its mechanical properties.

The validation of the multiaxial rheological model begins with multiaxial loading conditions that vary over time according to the loading history. These loads are applied at the microscale on a 3D finite element model of a representative volume element within a homogenization framework. The results demonstrate that the macroscopic behavior is accurately predicted by the multiaxial rheological model. Furthermore, a structural analysis is performed. The extended multiaxial Bouc-Wen model is used for the macroscopic beam behavior, and its solution is compared with that of a detailed 3D finite element model of the entire cable, showing excellent agreement, even for multiaxial and multilayered cables with complex geometries.

These findings validate the ability of the proposed model to replicate high-fidelity simulations and confirm its accuracy in capturing the cable's complex mechanical behavior.

References

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