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Review of options for structural design sensitivity analysis. Part 1: Linear systems

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Abstract

The paper reviews options for structural design sensitivity analysis, including global finite differences, continuum derivatives, discrete derivatives, and computational or automated differentiation. The objective is to put these different approaches to design sensitivity analysis in the context of accuracy and consistency, computational cost, and implementation options and effort. Linear static analysis and transient dynamic analysis are reviewed. In a separate appendix, special attention is paid to the semi-analytical method. A future paper will address design sensitivity analysis in non-linear structural problems.

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1. Introduction

There are currently four broad categories of methods in common use for obtaining the derivatives of performance measures with respect to structural parameters: (a) overall finite differences; (b) discrete derivatives; (c) continuum derivatives; and (d) computational or automatic differentiation. The differences between these methods are particularly important for shape sensitivities, because shape design variables change the discretization, i.e. mesh or grid, when numerical techniques such as finite element, boundary element, or meshfree methods are used. In this paper, the sensitivity is defined as a derivative of a performance measure with respect to a design variable.

Except for the finite differences option, the other three come in direct and adjoint methods (called the reverse mode for automatic differentiation). In the direct mode, one obtains the derivatives of the entire

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structural response, and often of intermediate quantities as well. The sensitivities of performance measures can then be obtained from the chain rule of differentiation. In the adjoint mode, one defines an adjoint problem, which depends on the performance measure. The sensitivities of performance measures can then be obtained using the structural and adjoint responses. Thus not all system response sensitivities are required, which is particularly advantageous in cases with many design variables, but few performance measures of interest.

One criterion for choosing a class of methods is accuracy. Clearly, accuracy of the sensitivities may influence the optimization solution, the required number of optimization cycles and premature convergence. Unfortunately, accuracy is subjective, and here we differentiate between accuracy and consistency. We define *accuracy* to be the difference between the derivatives we obtain and the exact derivatives obtained from an exact solution of the governing continuum equations. Obviously such an exact solution is not known for most practical problems and can only be approximated by sufficiently accurate numerical models. We define *consistency* as the difference between the derivatives we obtain and the exact derivatives of the numerical model. Thus, in the context of consistency the accuracy of the underlying (numerical) model used for the response functions is irrelevant. The difference between consistency and accuracy is due to the fact that the accuracy of the numerical solution changes over the design space, and different discretizations may be used for evaluating response functions and derivatives. These definitions are illustrated in Fig. 1 for a noiseless response (a), as well as a noisy response (b). This noise could, for example, be the result of remeshing.

The choice between the different options for calculating derivatives is also influenced by two other criteria: *computational cost* and *implementation effort*. The objective of the present paper is to focus on papers that provide guidance on the choice of methods based on the three criteria: accuracy and consistency, computational costs and implementation efforts.

Design sensitivity analysis has been addressed in other survey papers. We first refer to the review by Haftka and Adelman [1], which is already somewhat dated. Kwak [2] and Hsu [3] summarize available techniques in computational shape optimization. The review of Ref. [4] is focused on aerodynamic optimization and related (multidisciplinary) complexities. Kleijnen [5] describes the use of sensitivities in a broad sense.

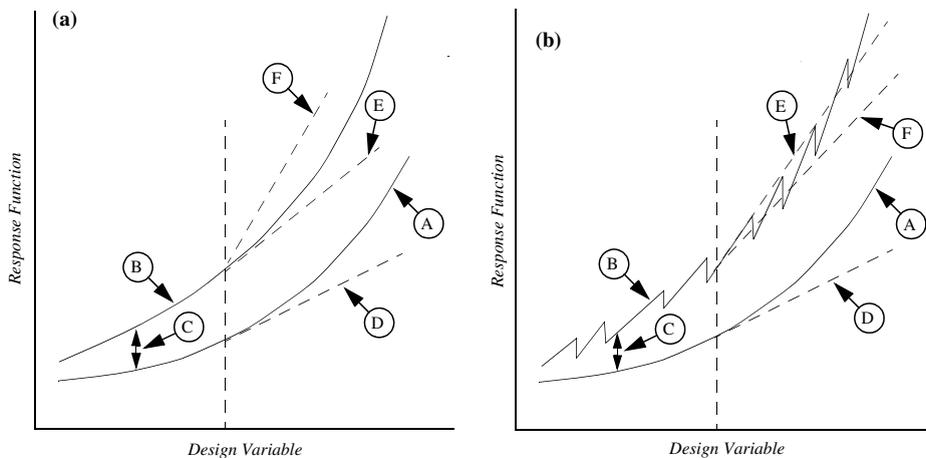


Fig. 1. Sketch of response and different sensitivities for a nearly noiseless simulation (a) and a noisy (possibly due to remeshing) simulation (b). The curves labeled “A” correspond to the exact solution of the governing continuum equations. The computational counterparts are denoted “B”. The differences between these curves is the modeling error, denoted “C”. Exact derivatives are identified with “D”. Consistent derivatives are labeled “E”, whereas non-exact and non-consistent COMPUTED derivatives are denoted by “F”.

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