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A formal theory for estimating defeaturing-induced engineering analysis errors

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Abstract

Defeaturing is a popular CAD/CAE simplification technique that suppresses 'small or irrelevant features' within a CAD model to speed-up downstream processes such as finite element analysis. Unfortunately, defeaturing inevitably leads to analysis errors that are not easily quantifiable within the current theoretical framework.

In this paper, we provide a rigorous theory for swiftly computing such defeaturing-induced engineering analysis errors. In particular, we focus on problems where the features being suppressed are cutouts of arbitrary shape and size within the body. The proposed theory exploits the adjoint formulation of boundary value problems to arrive at strict bounds on defeaturing induced analysis errors. The theory is illustrated through numerical examples.

Keywords: Defeaturing; Engineering analysis; Error estimation; CAD/CAE

1. Introduction

Mechanical artifacts typically contain numerous geometric features. However, not all features are critical during engineering analysis. Irrelevant features are often suppressed or 'defeatured', prior to analysis, leading to increased automation and computational speed-up.

For example, consider a brake rotor illustrated in Fig. 1(a). The rotor contains over 50 distinct 'features', but not all of these are relevant during, say, a thermal analysis. A defeatured brake rotor is illustrated in Fig. 1(b). While the finite element analysis of the full-featured model in Fig. 1(a) required over 150,000 degrees of freedom, the defeatured model in Fig. 1(b) required <25,000 DOF, leading to a significant computational speed-up.

Besides an improvement in speed, there is usually an increased level of automation in that it is easier to automate finite element mesh generation of a defeatured component [1,2]. Memory requirements also decrease, while condition number of the discretized system improves; the latter plays an important role in iterative linear system solvers [3].

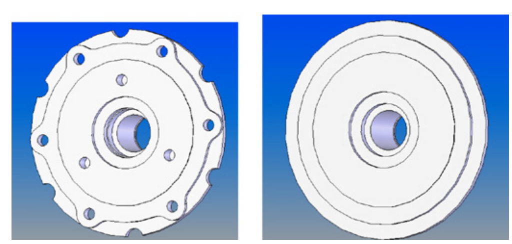

Fig. 1. (a) A brake rotor and (b) its defeatured version.

Defeaturing, however, invariably results in an unknown 'perturbation' of the underlying field. The perturbation may be 'small and localized' or 'large and spread-out', depending on various factors. For example, in a thermal problem, suppose one deletes a feature; the perturbation is localized provided: (1) the *net* heat flux on the boundary of the feature is zero, and (2) no new heat sources are created when the feature is suppressed; see [4] for exceptions to these rules. Physical features that exhibit this property are called *self-equilibrating* [5]. Similarly results exist for structural problems.

From a defeaturing perspective, such self-equilibrating features are not of concern if the features are far from the *region*

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of interest. However, one must be cautious if the features are close to the regions of interest.

On the other hand, non-self-equilibrating features are of even higher concern. Their suppression can theoretically be felt everywhere within the system, and can thus pose a major challenge during analysis.

Currently, there are no systematic procedures for estimating the potential impact of defeaturing in either of the above two cases. One must rely on engineering judgment and experience.

In this paper, we develop a theory to estimate the impact of defeaturing on engineering analysis in an automated fashion. In particular, we focus on problems where the features being suppressed are cutouts of arbitrary shape and size within the body. Two mathematical concepts, namely adjoint formulation and monotonicity analysis, are combined into a unifying theory to address both self-equilibrating and non-self-equilibrating features. Numerical examples involving 2nd order scalar partial differential equations are provided to substantiate the theory.

The remainder of the paper is organized as follows. In Section 2, we summarize prior work on defeaturing. In Section 3, we address defeaturing induced analysis errors, and discuss the proposed methodology. Results from numerical experiments are provided in Section 4. A by-product of the proposed work on rapid design exploration is discussed in Section 5. Finally, conclusions and open issues are discussed in Section 6.

2. Prior work

The defeaturing process can be categorized into three phases:

(a) *Identification*: what features should one suppress?
(b) *Suppression*: how does one suppress the feature in an automated and geometrically consistent manner?
(c) *Analysis*: what is the consequence of the suppression?

The first phase has received extensive attention in the literature. For example, the size and relative location of a feature is often used as a metric in identification [2,6]. In addition, physically meaningful 'mechanical criterion/heuristics' have also been proposed for identifying such features [1,7].

To automate the geometric process of defeaturing, the authors in [8] develop a set of geometric rules, while the authors in [9] use face clustering strategy and the authors in [10] use plane splitting techniques. Indeed, automated geometric defeaturing has matured to a point where commercial defeaturing/healing packages are now available [11,12]. But note that these commercial packages provide a purely geometric solution to the problem ... they must be used with care since there are no guarantees on the ensuing analysis errors. In addition, open geometric issues remain and are being addressed [13].

The focus of this paper is on the third phase, namely, *post-defeaturing analysis*, i.e., to develop a systematic methodology through which defeaturing-induced errors can be computed. We should mention here the related work on reanalysis. The objective of reanalysis is to swiftly compute the response of a modified system by using previous simulations. One of the key developments in reanalysis is the famous Sherman–Morrison and Woodbury formula [14] that allows the swift computation of the inverse of a perturbed stiffness matrix; other variations of this based on Krylov subspace techniques have been proposed [15–17]. Such reanalysis techniques are particularly effective when the objective is to analyze two designs that share similar mesh structure, and stiffness matrices. Unfortunately, the process of defeaturing can result in a dramatic change in the mesh structure and stiffness matrices, making reanalysis techniques less relevant.

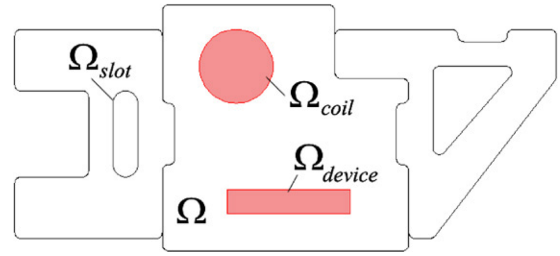

Fig. 2. A 2-D heat block assembly.

A related problem that is *not* addressed in this paper is that of *local–global analysis* [13], where the objective is to solve the local field around the defeatured region after the global defeatured problem has been solved. An implicit assumption in local–global analysis is that the feature being suppressed is self-equilibrating.

3. Proposed methodology

3.1. Problem statement

We restrict our attention in this paper to engineering problems involving a scalar field u governed by a generic 2nd order partial differential equation (PDE):

$$\nabla.(-c\nabla u) + au = f.$$

A large class of engineering problems, such as thermal, fluid and magneto-static problems, may be reduced to the above form.

As an illustrative example, consider a thermal problem over the 2-D heat-block assembly Ω illustrated in Fig. 2.

The assembly receives heat Q from a coil placed beneath the region identified as Ω_{coil}. A semiconductor device is seated at Ω_{device}. The two regions belong to Ω and have the same material properties as the rest of Ω. In the ensuing discussion, a quantity of particular interest will be the weighted temperature T_{device} within Ω_{device} (see Eq. (2) below). A slot, identified as Ω_{slot} in Fig. 2, will be suppressed, and its effect on T_{device} will be studied. The boundary of the slot will be denoted by Γ_{slot} while the rest of the boundary will be denoted by Γ. The boundary temperature on Γ is assumed to be zero. Two possible boundary conditions on Γ_{slot} are considered: (a) fixed heat source, i.e., $(-k\nabla T).\hat{n} = q$, or (b) fixed temperature, i.e., $T = T_{\text{slot}}$. The two cases will lead to two different results for defeaturing induced error estimation.