

Inertial Relief in Fluid Structure Interaction Problems with Analytic Sensitivities

Daniel J. Clemens*, D. John Neiferd, Neal L. Novotny, and Hollis A. Smith

University of Dayton Research Institute,
300 College Park, Dayton, OH
USA

ABSTRACT

Accurate modeling of aerodynamic forces and moments is critical for optimal aircraft structural design. Aircraft designs are often limited by tight weight constraints, so an accurate estimate of stress is necessary to prevent overdesign. Traditional multidisciplinary design optimization (MDO) approaches often rely on constraining a symmetry plane or reference point to prevent rigid body motion, which can lead optimization algorithms to produce unnecessary structure near these constrained areas. Inertial relief provides an alternative means by which to accomplish the structural analysis portion of aircraft MDO, as it allows for the analysis of unconstrained, free-flying bodies. In order to integrate into MDO algorithms, however, the inertial relief analysis requires support for design variable sensitivities. The U.S. Air Force Research Laboratory (AFRL) has developed the finite element and sensitivity analysis code Multidisciplinary Analysis and Sensitivity Toolkit v3 (MAST-3) as a nonlinear thermoelastic solver with analytical sensitivities for use in aircraft structural design optimization. This work details how inertial relief analysis with sensitivity support was integrated into MAST-3 and demonstrated using an existing AFRL generic aeroelastic flying wing model.

Inertial relief enables the analysis of free-flying structures by leveraging an accelerating (non-inertial) reference frame. The structure is constrained with zero displacement at the frame's origin, and the inertial load due to the frame's acceleration exactly cancels out any reaction forces at the constrained point. [1]. MAST-3 supports the definition of any reference point in Cartesian space, though notionally it is defined as the center of mass of the system. $\mathbf{u}_{tot}^{(rel)}$, of the system is written as the combination of rigid body displacements $\mathbf{u}_b^{(rel)}$, $\mathbf{u}_{(rel)}$.

$$\mathbf{u}_{tot} = \mathbf{u}_b + \mathbf{u}$$

The inertial accelerations about a reference point are known such that the inertial force moves to the right-hand side and the finite element approximation of the equations of motion for the system become

$$\mathbf{M}\mathbf{u} + \mathbf{K}\mathbf{u} = \mathbf{P} - \mathbf{P}_{ir}$$

where \mathbf{M} is the mass matrix, \mathbf{K} is the stiffness matrix, \mathbf{P} is the external force vector, and the inertial force $|\mathbf{P}_{ir} \equiv \mathbf{M}\mathbf{u}_b|$. The inertial load becomes design dependent through both the structure's mass and external loads. For instance, in a sizing optimization of plate thickness, the mass distribution, and therefore inertial loads, will change with each design iteration. This change will be accounted for in the sensitivity analysis.

From the above equations of motion, it is apparent that the inertial force term reduces the overall force applied to the system, which shows the importance of using this technique for MDO. Figure 1, below, provides a simple example of how using inertial relief reduces the global displacement of the system and eliminates the stress concentration created by a traditional, fixed boundary condition at the center of mass. In an aircraft MDO context, the stress concentration at the constraint would lead the optimizer to produce additional structure

Commented [NA1]: I might change this to "structural" or "thermoelastic" since that is the main contribution of MAST and the aero part is achieved through coupling (e.g. the SAMS iterates and MATADORS)

Commented [SA2]: I would rephrase this. This reads to me as, "the structure's inertia in the accelerating frame constrains the system," which is not correct. The constraint on the system is that the structure is fixed to the origin of the accelerating frame. The structure's inertia cancels out the reaction forces at the constrained point, relieving any artificial stress concentration.

Commented [SA3]: Since a major focus of the paper is on analytic sensitivities, it might be worth mentioning the design-dependence of the inertial load through the structure's mass, as well as any design-dependence of the external loads which determine the frame's acceleration.

Commented [CA4R3]: @NEIFERD, DAVID J CIV USAF AFMC AFRL/RQVC can you help me elaborate on this point a little more, since you are the sensitivities expert?

Commented [NA5R3]: You could say something like "The inertial load becomes design dependent through the structure's mass as well as through design dependent external loads. For instance, in a sizing optimization on the thickness of plates, the mass distribution and therefore inertial loads will change with each design update. This will be accounted for in the sensitivity analysis."

Commented [CA6R3]: I changed a few words, but kept the content the same. Should we add more about the specifics of the sensitivity analysis?

at that location to reduce the local stress to within allowable limits. This unnecessary structure is an artifact of numerical analysis and not the actual physics of the system, thus inertial relief provides an excellent means by which to produce a more optimal structural design.

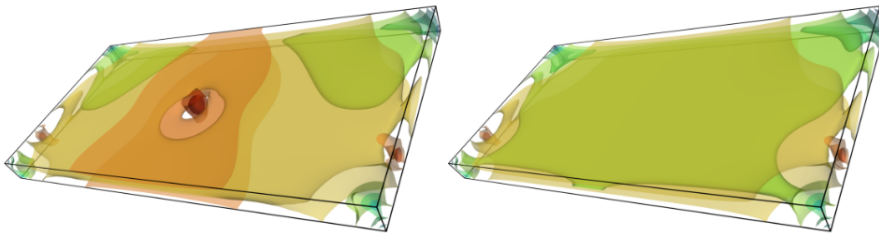


Figure 1 Simple inertial relief example stress contour plot. Left: Stress contour plot without inertial relief, showing the stress concentration at the constrained center of mass. Right: Stress contour with inertial relief, with the stress concentration eliminated

AFRL has already demonstrated aeroelastic optimization using in-house tools on a generic flying wing model, making it an ideal candidate to demonstrate the development and integration of inertial relief capability into a coupled fluid-structure interaction framework for MDO of aerothermoelastic structures [2]. The final paper will detail how MAST-3 was integrated into an AFRL MDO workflow similar to [2], with its analytic sensitivity support allowing for design optimization. With MAST-3 serving as the structural analysis tool in the MDO workflow, the flying wing model was optimized using inertial relief. This design optimum was compared to the aeroelastic design optima in [2] to illustrate the benefit of inertial relief to aircraft MDO.

References

- [1] Abaqus Analysis User's Manual, Version 6.6. Dassault Systemes Simulia, Inc.
- [2] N. Novotny, D. Sandler and N. A. Wukie, "Gradient-based aeroelastic optimization of a generic flying wing model," in *AIAA SCITECH 2025 Forum*, Orlando, 2025.

Commented [NA7]: I don't think mentioning TACS is needed since we don't plan to use it in this.

Commented [CA8R7]: Fair enough, I was just calling it out to reference what was done for Neal's aeroelastic flying wing optimization paper

Commented [NA9R7]: I agree it's good to mention Neal's other paper, but since we are trying to get away from TACS probably want to avoid calling it out by name right away in the abstract since we don't even use it in this particular work.