Development of a Doublet-Lattice Method Program for Aeroelastic Analysis in Conceptual Aircraft Design

Context and motivation

Research and technology in the field of aviation is providing the industry with tools to face ever more urgent environmental and economic concerns. In aircraft design, effort is focused on cutting development times—thus, costs—and optimising life-cycle, mission-oriented performance of products. As the complexity of these challenges and proposed solutions grows, the inherently multi-disciplinary nature of aircraft design can no longer remain an afterthought; instead, it should be harnessed throughout the design process. The CEASIMpy environment, currently in development at CFS Engineering SA, is a response to the emerging need for rapid and repeated multi-disciplinary prototyping software from the earliest stages of design, serving as a unifying framework for aerodynamics, structures and flight dynamics tools.

Objective

To lay the groundwork for the extension of CEASIMpy to dynamic aeroelasticity, in the form of a Python/C++ module for calculation of unsteady aerodynamic loads on arbitrary aircraft configurations, using the Doublet-Lattice Method (DLM).

Conceptual Aircraft Design and Dynamic Aerelasticity

The prediction of flutter requires coupled modelling of both structural dynamics and unsteady aerodynamics (as well as an interpolation scheme if the numerical grids mismatch). The complexity and computational cost of such models often exceed feasibility at earliest design stages—this is especially true for conceptual design, where many low-detail prototype configurations must be evaluated. However, detecting undesired aeroelastic behaviours early on can prevent having to resort to costly a posteriori solutions.

The Doublet-Lattice Method

DLM is a numerical method used to calculate unsteady aerodynamic pressure distributions over nonplanar lifting surface configurations subject to oscillatory deformation modes. First presented in 1969 by Albano and Rodden[1], and refined later by Rodden[2], the method still finds use today, bridging a gap between semi-emirical ‘handbook’ methods (not applicable to novel aircraft configurations) and high-fidelity CFD (computationally expensive).

The method is based on oscillating lifting-surface theory. The wings are idealised as continuous sheets of ‘acceleration potential doublets’, elementary solutions to a linearized, potential-flow variant of Euler’s equations of motion. This gives an integral equation relating the pressure difference field to the local downwash (induced by structural displacement modes, given the impermeability condition).

\[
\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = \delta_0 \frac{\partial^2 \delta}{\partial t^2}
\]

This integral equation is solved by applying a particular discretisation scheme to each lifting surface, sub-dividing it into “panels”, finally yields a linear system.

Development process

After thorough documentation of the theory found in literature, an implementation of DLM was written in Python and C, from scratch. Integration with CEASIMpy was ensured by providing compatibility with the CPACS aircraft definition format developed at DLR, around which the environment is built. The resulting program is capable of extracting lifting surface configurations even from complex aircraft geometries defined in CPACS, and automatically generating a grid suitable for DLM (see demonstration for bowing configuration below).

Performance

Computationally demanding routines of the program were written in C, yielding an increase in performance in excess of an order of magnitude compared to pure Python; a significant improvement if many model evaluations are required, as might be the case in optimisation or conceptual design.

Validation

The validation process begins with the verification of the kernel function, which appears in the calculation of the downwash coefficients (relating the velocity at each panel’s collocation point to the pressure difference induced by every other panel’s doublet segment). The kernel function is separated in a planar and non-planar component for better accuracy. For both, the present program produces results in excellent correspondence with literature.

The validation is extended to calculations and convergence studies on simple rectangular lifting surfaces, subject to manually input polynomial modes. Results match reference results, for both the original (quadratic interpolation of kernel function) and the refined (quartic interpolation of kernel function) variants of DLM.

Conclusions

The resulting program is a successful proof of concept. Initial validation efforts have proven encouraging. Future work should be focused on extending validation to more complex (realistic) aircraft configurations, which will require coupling with computational structural dynamics models, and knowledge of inertial properties.

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