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FELiCS: A Versatile Linearized Flow Solver for Multi-Physics Applications

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Software

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Summary

The analysis and control of flow instability is crucial in many fields of engineering and science, ranging from aerodynamics to combustion. While computational fluid dynamics solvers can simulate the full nonlinear behavior of flows, the analysis of small perturbations is often more efficiently handled by linearized models. These models provide valuable insights into flow stability, receptivity, and input-output interactions. Consequently, open-source software (OSS) tools for linear stability analysis represent a relevant asset for researchers and engineers studying complex flow dynamics.

`FELiCS` is both a monolithic codebase executed via configuration files, as well as a flexible Python package designed for the linear stability and sensitivity analysis of complex fluid flows. It solves the linearized equations governing flow motion, turbulence transport, acoustics, and reacting flows using the Finite Element Method (FEM). Designed as a versatile tool, `FELiCS` enables global stability analysis, resolvent analysis, and input-output analysis (or "forcing-response-analysis") within a single framework. In addition, its modular functionalities can be used in the form of a Python package to incorporate linear equations into personal Python scripts, such as for base flow computations, data assimilation or sensitivity calculation among others. Thus, it addresses the need for a user-friendly tool that combines these diverse analytical capabilities.

Statement of need

Several tools exist for stability analysis, which are specialized for specific flow regimes, flow equations and/or high performance computing. For instance, NekStab (Frantz et al., 2023) offers efficient parallel computation for incompressible flows while using Nek5000's spectral elements discretization (Fischer et al., 2007). Similarly, Nektar++ (Cantwell et al., 2015) supports finite element discretization for various equations, while relying on complex spectral/hp elements in C++. Other tools like Linstab2D (Martini & Schmidt, 2024) and BROADCAST (Poulain et al., 2023) (based on FOTRAN and Matlab, respectively), discretize with finite differences, while using structured or quasi-structured meshes. The Python toolkit Resolvent4py (Padovan et al., 2025) provides matrix-free and high-performant parallelized linear analysis capabilities for large problems which requires the user to supply the linear operator.

`FELiCS` (Thomas L. Kaiser et al., 2023) addresses a gap in the functionalities of these existing tools by providing a user-friendly, Python-based tool for various types of linear stability calculations on unstructured meshes with various physical models. On the one hand, the monolithic code version can be easily used without any prior knowledge in Python. This enables multiple types of analyses, including global modal analysis to assess linear stability, resolvent analysis to identify amplification mechanisms, and input-output analysis to determine transfer functions between input (boundary) forcing and system output. On the other hand, the FELiCS gives users the freedom to define customized analyses or to integrate FELiCS into external workflows. This significantly simplifies tasks requiring linearized fluid equations, such as data assimilation or sensitivity calculations. Additionally, embedded post-processing scripts allow users to work with analysis outputs directly within the FEM framework.

The software serves a wide range of users and is designed to answer the needs of three different types of users:

- For applied users, who run the complete monolithic workflow, pre-written scripts controlled by JSON configuration files handle stability analyses without requiring in-depth Python knowledge.
- Advanced users can import FELiCS as a library within their own Python codes, accessing equations and solvers in an object-oriented manner for complex tasks like data assimilation or gradient-based optimization.
- Finally, the code's modular architecture allows developers to easily adapt and expand the software, such as adding new physical models, following guidelines available in the repository.

Features and examples

FELiCS implements a wide array of linear and nonlinear equations, including incompressible and compressible Navier-Stokes, density variations in the low-Mach number limit, and chemical reaction models with progress variables, which can be used in any combination. The physical modeling supports heat and mass transport, eddy viscosity for turbulence, sponge layers for boundary damping. Upcoming updates plan to include Reynolds-averaged Navier-Stokes linearized equations and additional reaction models. The software offers an accessible interface, available both as a command-line tool and as a Python-importable module. Users control solver parameters via simple JSON configuration files and can import meshes from GMSH (Geuzaine & Remacle, 2009) while exporting results to H5 and XDMF formats for visualization in Paraview (Ahrens et al., 2005). Comprehensive user support, including tutorials, how-to guides, and detailed descriptions of the governing equations and models, are provided on the documention website. Under the hood, the software ensures high performance and numerical stability by leveraging the PETSc (Balay et al., 2019)/SLEPc (Hernandez et al., 2005) toolkit for linear algebra and the FEniCS package (Alnæs et al., 2015) for the FEM framework. The modular, object-oriented architecture further facilitates the extension of new physical models. All these functionalities can also be used by importing FELiCS as a Python package and do computations like solving for a base flow, data assimilation or sensitivity analysis in simple scripts. The code ensures robustness through both minimalist test cases in a separate repository and automated unit tests.

FELiCS supports a diverse range of applications demonstrated in numerous published studies. These include the analysis of combustion instabilities in turbulent jet flames and gas turbines (Casel et al., 2022; Thomas Ludwig Kaiser, Oberleithner, et al., 2019; Thomas Ludwig Kaiser, Lesshafft, et al., 2019; Thomas Ludwig Kaiser et al., 2023; Saldern et al., 2025; Wang et al., 2022) and aeroacoustic noise prediction for airfoils (Demange et al., 2024, 2025). It has also been applied to flow instabilities in gas (Moczarski et al., 2024) and water turbines (Müller et al., 2022), turbulent mixing (Thomas Ludwig Kaiser & Oberleithner, 2021a, 2021b; Lückoff et al., 2021), coherent structure modeling in turbulent jets (Kuhn et al., 2021; Saldern et al., 2024), and linear analysis based on PIV measurements (Fuchs et al., 2025; Klopsch et al., 2025). Further use cases encompass sensitivity and adjoint-based analyses (Knechtel et al., 2024; Müller, Saldern, et al., 2024) as well as shape optimization (Müller, Reumschüssel, et al., 2024).

To illustrate the capabilities of the software, Figure 1 presents results from various multi-physics applications and displays incompressible resolvent modes in a cardiovascular flow (Figure 1(a)) (Villié et al., 2025), compressible resolvent mode of a flow around an airfoil (Figure 1(b)) (Demange et al., 2025) and an incompressible resolvent mode in a turbulent separation bubble (Figure 1(c)) (Fuchs et al., 2025). Figure 1(d) shows a resolvent response mode of a turbulent methane-air flame (Thomas Ludwig Kaiser et al., 2023).

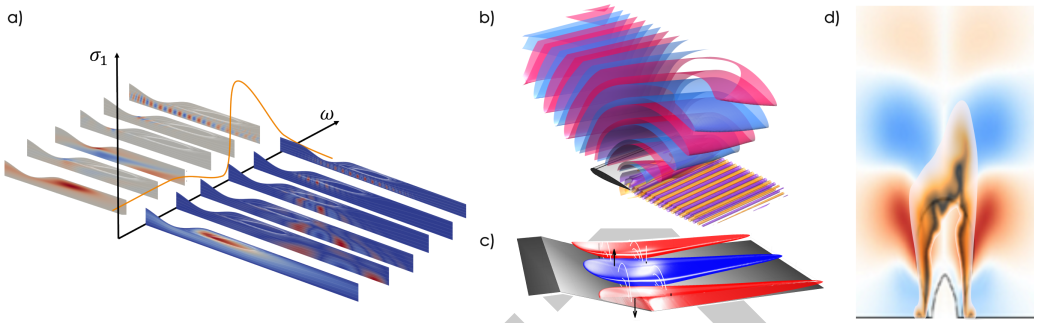

Figure 1: Visualization examples: a) Optimal forcing and response resolvent modes of a stenotic flow; b) Compressible resolvent response mode, two contour levels showing hydrodynamic and acoustic pressure fluctuations around an airfoil; c) Isocontour of the optimal resolvent mode in a turbulent searation bubble; d) Compressible resolvent mode with a flame model around a reacting jet.

Figure 2 presents post-processing analyses examples. Figure 2(a) demonstrates shape optimization applied to an unstable eigenvalue w.r.t. wall-normal shape deformations, while Figure 2(b) shows the structutral sensitivity analysis in a 2D cylinder flow.

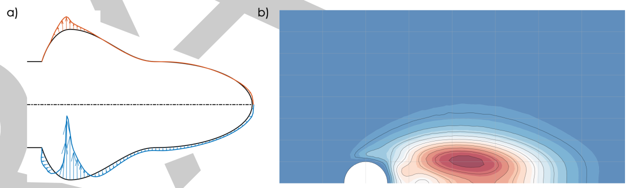

Figure 2: Post-processing examples: a) Growth rate sensitivity of the most unstable eigenvalue w.r.t. wall-normal shape deformations of a runner crown geometry in a turbulent Francis turbine flow; b) Structural sensitivity analysis in a 2D cylinder flow.

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