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VIVyD: an open-source initiative toward a unified framework for VIV modeling

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SUMMARY:
This work introduces VIVyD, an open-source Python framework for the unified modeling and analysis of vortex-induced vibrations (VIV). The platform is designed to overcome the fragmentation of existing approaches by providing a modular and extensible environment integrating models, solvers, stochastic forcing, datasets, and post-processing tools. VIV models are implemented as standardized, object-oriented components, enabling consistent comparison and straightforward extension. The framework supports time-domain simulations and facilitates reproducible evaluation against reference datasets. Distributed via PyPI and developed collaboratively on GitLab, VIVyD aims to serve both the scientific and industrial communities. By promoting transparency, reproducibility, and community contributions, the project seeks to establish a robust foundation for the development, validation, and application of VIV models.

Keywords: fluid-structure interaction, vortex-induced vibrations, modeling, open source, unified framework

1. INTRODUCTION

Vortex-induced vibrations (VIV) arise when alternating vortices shed from a bluff or slender body generate unsteady lift forces transverse to the incoming flow. When the vortex shedding frequency approaches the natural frequency of the structure, a resonance phenomenon commonly referred to as lock-in occurs, whereby the shedding synchronizes with the structural motion. This nonlinear fluid–structure interaction can induce large-amplitude oscillations, leading to fatigue damage, serviceability issues, or even structural failure.

Since the mid-20th century, a wide range of models and methods have been developed. Specifically, three main types of models are commonly identified (Païdoussis et al., 2010). First, the linear models describe the flow-induced forces without fluid-structure interaction. Second, the fluidelastic feedback models (Marris, 1964; Blevins, 1990) assume that the force applied on the structure depends on the state of the structure, thus introducing nonlinear terms. Finally, the wake-oscillator models (Hartlen and Currie, 1970; Tamura and Matsui, 1980; Facchinetti et al., 2004) represent VIV as the result of the interaction of the structure with its wake (Nakamura, 1969; Funakawa, 1969), represented by a system of two coupled differential equations. The wake-only models (Rigo et al., 2022) can be interpreted as a degenerate case of the last family of models, where the structure is disregarded and the focus is on the dynamics of the wake alone. These models can account for wind turbulence through stochastic terms, which exist in different definitions as well (Vickery and Clark, 1972; Vickery and Basu, 1983; Lupi et al., 2019; Denoël, 2020).

As a result of this diversity in VIV modeling, standard design methods often yield significantly different predictions for identical configurations, with reported discrepancies sometimes exceeding 100% (Wertz, 2015). This lack of consistency reflects the absence of a shared framework for model comparison, validation, and integration.

To address this limitation, the present work introduces the foundations of an open-source, unified framework for VIV modeling. The proposed initiative takes the form of a Python-based package, designed both as a development platform (hosted on GitLab) and as a user-oriented toolbox (distributed via PyPI). Its objective is to facilitate the integration, comparison, and extension of existing models, while providing structured access to reference datasets and benchmarking tools.

The proposed framework is intended to serve a dual purpose: (i) to support the scientific community by offering a collaborative environment for the development, evaluation, and dissemination of VIV models, and (ii) to provide practitioners with a modular and accessible tool for engineering applications. Beyond technical implementation, the initiative aims to foster community engagement and convergence toward shared modeling practices.

2. METHODOLOGY

VIVyD is an object-oriented Python framework in which models, solvers, stochastic processes, datasets, and post-processing tools operate as interoperable modules. VIV models are implemented as classes derived from a common interface, ensuring standardized inputs and outputs while allowing extensions through inheritance. Each model simulates the time-domain evolution of coupled wake–structure dynamics from consistent representations of flow and structural parameters, enabling direct comparison across heterogeneous approaches.

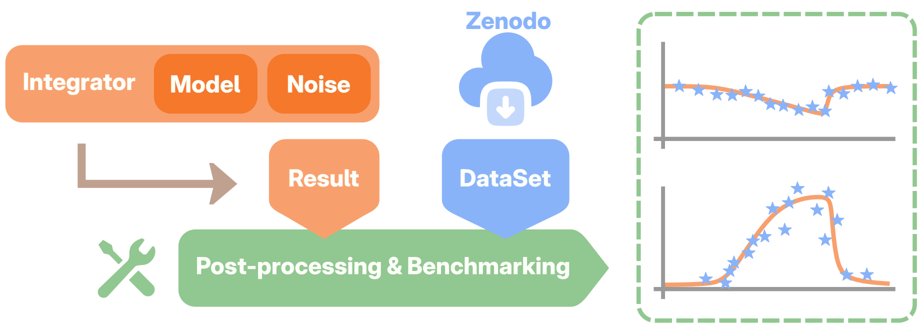

Figure 1. Representation of the workflow proposed by VIVyD.

The modular architecture, represented in Fig. 1, allows users to interchange models, solvers, and stochastic forcing without modifying the core system. Numerical integration relies on a unified interface that can call either internal routines or external libraries such as SciPy. Configurable stochastic generators, including colored-noise processes, enable the representation of turbulence following existing models. A simplified example of use of the program is illustrated in Fig. 2.

```python
from vivyd import modeling, integration, stochastic, postprocessing, database
model   = modeling.Tamura(...)
noise   = stochastic.NoiseGenerator(psd=stochastic.WhiteNoise())
result  = integration.euler_explicit(t_tab=..., model, noise)
dataset = database.load(query='ULiege_expELIArmus')
fig = postprocessing.plot_compare(result, dataset)
```

Figure 2. Simplified example of a code snippet using VIVyD.

New models are added through a class template ensuring ecosystem compatibility. Reference implementations from the literature are already included. In particular, the current implementation focuses on a generalized dimensionless equation for wake-oscillator models, which can be written as

$$\begin{cases} \Omega = \Omega_0(1+\eta_0) \\ \ddot{y} + 2\xi\dot{y} + y = M_0 q + \eta_1 \\ \ddot{q} + \Omega(aq^2 + b\dot{q}^2 - c)\dot{q} + \Omega^2 q = A_2\ddot{y} + A_1\dot{y} + A_0 y + \eta_2, \end{cases} \tag{1}$$

where $y(\tau)$ relates to the motion of the structure and $q(\tau)$ describes the motion of the wake. The $\eta_0(\tau)$, $\eta_1(\tau)$ and $\eta_2(\tau)$ terms are colored stochastic processes, which can be used as sources of turbulence (Denoël, 2024). The dimensionless time τ is defined with respect to the natural frequency of the structure. The remaining symbols represent parameters that hold different definitions, depending on the precise model that is used. Table 1 shows which subset of parameters are non-zero for each model currently implemented.

Table 1. Subset of generalized parameters activated by each model currently implemented.

Models	y	q	ξ	M_0	Ω	a	b	ε	A_2	A_1	A_0	η_0	η_1	η_2
Hartlen and Currie, 1970	×	×	×	×	×		×	×		×				
Tamura and Matsui, 1980	×	×	×	×	×	×		×	×	×				
Facchinetti et al., 2004	×	×	×	×	×	×		×	×					
Rigo et al., 2022		×			×	×	×	×						×
Denoël, 2024	×	×										×		

Datasets, stored externally on Zenodo, are accessed through dedicated loaders. Benchmarking tools support systematic model evaluation and user-defined validation workflows with flexible performance metrics.

3. CURRENT STATUS AND OUTLOOK

The framework currently supports single-degree-of-freedom configurations and a selection of established VIV models for cylindrical geometries in an air flow. Initial capabilities also include generation of samples of η_0, η_1 and η_2 for time-domain simulations. Fig. 3 shows an output of VIVyD for the wake-oscillator models already implemented.

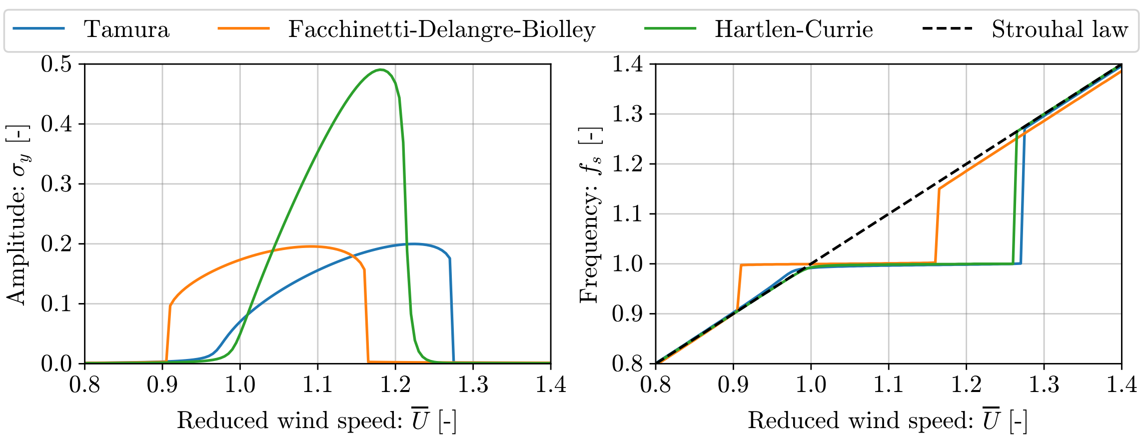

Figure 3. Evolution of the amplitude of the structural vibration (top) as well as the vortex shedding frequency (bottom) as a function of the reduced wind speed close to the lock-in range.

Ongoing developments aim to extend the framework toward multi-degree-of-freedom systems, three-dimensional structural effects, and finite element coupling. Future extensions will also incorporate engineering design approaches and advanced uncertainty quantification tools, with the long-term objective of establishing a comprehensive computational ecosystem for VIV analysis and benchmarking. Modern high performance computing techniques will be added, enabling CPU or GPU parallelization. Extending the project to hydrodynamic VIV can be considered in the long term. A collaborative wiki will evolve in parallel with the software development.

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