International Journal of Renewable, Green, and Sustainable Energy (IJRGSE)
eISSN: 3087-4300
Volume03 Issue10 | Page No: - 01-06

Received: 03 Sep. 2026, Revised: 11 Sep. 2026, Accepted: 25 September 2026, Published: 03 October 2026

DOI: https://doi.org/10.55640/ijrgse-v03i10-01

A Dynamic Vibration-Based Approach for High-Efficiency Energy Extraction from Fluid Flows

Dilan Perera [1]
[1] Department of Renewable Energy Engineering, University of Ghana, Accra, Ghana

Nethmi Fernando [2]
[2] Department of Renewable Energy Systems, University of Colombo, Colombo, Sri Lanka

ABSTRACT: Flow-induced vibration (FIV) represents a potentially effective mechanism for converting kinetic energy available in fluid flows into useful electrical power. Unlike conventional turbines, vibration-based energy harvesters can extract energy through the interaction between unsteady fluid forces and compliant structural elements, reducing dependence on continuously rotating components. This paper develops a dynamic vibration-based framework for high-efficiency energy extraction from fluid flows by synthesizing established findings on vortex-induced vibration, hydroelastic response, oscillating foils, hydrokinetic converters, and structural damping. The proposed analytical framework considers flow velocity, structural mass, damping, stiffness, oscillation amplitude, vortex shedding, and energy-conversion efficiency as coupled variables. Particular emphasis is placed on synchronization between structural oscillation and vortex formation, because this interaction governs the available mechanical energy and consequently the electrical output. The literature indicates that low effective damping can increase vibration amplitude, while excessive damping can suppress oscillatory motion and reduce extractable power. Conversely, controlled damping can improve net energy extraction by balancing structural response and energy transfer. The framework further incorporates geometric modifications, multiple-cylinder arrangements, rotating-cylinder configurations, rod attachments, and passive turbulence-control mechanisms as strategies for enhancing fluid–structure interaction. The resulting synthesis establishes a research direction in which vibration amplitude alone is not treated as the principal performance metric; instead, maximum useful power is associated with an optimized relationship among hydrodynamic excitation, structural dynamics, and energy-conversion loading.

KEYWORDS: Flow-induced vibration, hydrokinetic energy harvesting, vortex-induced vibration, dynamic energy extraction, fluid–structure interaction, vibration-based energy harvesting, structural damping, hydroelasticity, power conversion.

1. Introduction

The increasing demand for renewable energy has stimulated interest in energy-conversion technologies capable of utilizing naturally available fluid motion. Wind and flowing water contain substantial kinetic energy, traditionally exploited through rotary turbines. However, turbine-based systems require rotating machinery and may involve relatively complex mechanical infrastructure. An alternative approach is to exploit flow-induced structural oscillations as the primary energy-conversion mechanism. In such systems, the interaction between fluid motion and an appropriately designed structure generates oscillatory mechanical motion that can subsequently be converted into electrical power.

Flow-induced vibration occurs when unsteady aerodynamic or hydrodynamic forces interact with a flexible or elastically supported structure. Cylindrical bodies are particularly important because vortex shedding produces alternating transverse forces capable of exciting structural oscillation. The resulting fluid–structure interaction can become strongly nonlinear when the structural frequency approaches the characteristic vortex-shedding frequency. Investigations of hydroelastic cylinders have demonstrated that mass and damping significantly influence the dynamic response of vibrating bodies (Khalak and Williamson, 1996). More recent investigations have extended this understanding to elliptical, square, D-section, and rotating circular geometries (Zhao et al., 2014; Zhao et al.,

2018; Zhao et al., 2019).

The possibility of converting this oscillatory response into useful energy has motivated hydrokinetic vibration converters. The VIVACE concept, for example, uses vortex-induced motion for energy harvesting, while subsequent studies have examined the effects of damping, turbulence control, and multiple-cylinder arrangements on conversion performance (Lee and Bernitsas, 2011; Chang and Bernitsas, 2011; Kim and Bernitsas, 2016). These studies demonstrate that energy extraction is not simply a consequence of producing large structural oscillations. Instead, the energy-conversion mechanism itself modifies the effective damping of the system and therefore changes its dynamic response.

The central problem addressed in this paper is therefore the development of a conceptual dynamic framework in which fluid excitation, structural vibration, and energy extraction are treated as a coupled system. The objective is to identify the principal mechanisms governing high-efficiency extraction and establish how geometric configuration, structural properties, and controlled damping can be coordinated to improve performance.

The significance of this approach extends beyond conventional hydrokinetic devices. Oscillating foils have also been investigated as power-extraction systems, while passive flapping structures demonstrate another pathway for converting fluid motion into mechanical energy (Kinsey and Dumas, 2008; Wang et al., 2017). Consequently, vibration-based energy extraction can be interpreted as a broader class of fluid–structure energy-conversion systems rather than a technology restricted to cylindrical hydrokinetic converters.

2. Literature Review

The theoretical foundation of vibration-based energy extraction originates from the coupled relationship between vortex shedding and structural motion. Khalak and Williamson (1996) demonstrated the importance of mass and damping in the dynamics of hydroelastic cylinders. Their work established that structures with low effective mass and damping can exhibit substantial vibration amplitudes when fluid excitation becomes synchronized with structural motion. This observation is particularly relevant to energy harvesting because oscillatory amplitude represents an important component of the mechanical energy available to a transducer.

However, high vibration amplitude does not automatically imply high net power output. Soti et al. (2018) examined damping effects on vortex-induced vibration and their implications for power extraction, emphasizing the dual role of damping. Structural damping dissipates energy, whereas harvesting damping intentionally removes mechanical energy from the vibrating structure. Thus, an energy harvester must introduce an appropriate amount of effective damping without suppressing the fluid-driven oscillation.

The role of geometry has also been extensively examined. Zhao et al. (2014) investigated fluid–structure interaction around square cylinders at different angles of attack, demonstrating the importance of body geometry in determining the surrounding flow structure. Studies of D-section cylinders further showed that an afterbody is not necessarily essential for generating vortex-induced vibration (Zhao et al., 2018). Elliptical-cylinder studies likewise demonstrated that both structural damping and geometric characteristics affect the resulting vibration response (Zhao et al., 2019; Lo et al., 2023).

Rotational motion provides an additional degree of control. Experimental investigation of a rotating circular cylinder showed that in-line flow-induced vibration can be strongly influenced by rotation and fluid–structure coupling (Zhao et al., 2018). This provides an important design perspective because controlled rotational conditions may be used to modify excitation characteristics rather than passively accepting the natural vortex-shedding state.

Hydrokinetic energy-conversion studies have further demonstrated the practical importance of multi-body interactions. Lee and Bernitsas (2011) investigated VIV energy harnessing at high damping and high Reynolds number, while Chang and Bernitsas (2011) examined passive turbulence control within the VIVACE concept. Kim and Bernitsas (2016) extended the concept to multiple-cylinder synergy, indicating that suitable interactions among neighboring cylinders can influence overall converter performance.

Another enhancement strategy involves modifying the wake structure. Wang et al. (2020) investigated rod attachments to cylinders as a means of enhancing vortex-induced vibrations for hydrokinetic power generation. Such modifications demonstrate that energy harvesting performance can be increased by deliberately manipulating vortex formation rather than relying solely on increasing structural compliance.

The literature also encompasses non-cylindrical oscillatory systems. Kinsey and Dumas (2008) studied an oscillating airfoil in a power-extraction regime, while Wang et al. (2017) analyzed a fully passive flapping foil. These studies reinforce the broader principle that periodic fluid forcing can be transformed into mechanical energy through appropriately designed oscillatory structures.

Wind-energy literature provides a complementary

theoretical basis for understanding the conversion of fluid kinetic energy into useful mechanical and electrical power. Manwell et al. (2011), Burton et al. (2011), and Wilson et al. (1976) describe the fundamental relationship between fluid velocity, aerodynamic loading, and energy extraction. Although conventional wind turbines employ rotational motion, the underlying energy-balance principle remains applicable to vibration-based systems.

A particularly important experimental foundation is provided by Zhao et al. (2018), whose investigation of a rotating circular cylinder demonstrates that changes in flow-induced loading can produce significant variations in structural response. This reinforces the need to treat fluid forcing and structural motion as a coupled dynamic process rather than independent design variables.

Despite substantial progress, a research gap remains in integrating these individual findings into a unified efficiency-oriented vibration framework. Existing studies frequently concentrate on specific geometries, damping conditions, or flow configurations. A more comprehensive approach should instead optimize the entire chain from vortex generation to structural oscillation and finally to energy extraction.

3. Methodology

3.1 Dynamic System Representation

The proposed framework represents the vibration energy harvester as a coupled fluid–structure–converter system. For a simplified single-degree-of-freedom oscillator, structural motion can be represented by

$$my^{¨} + cy^{˙} + ky = FL(t), m\ddot{y} + c\dot{y} + ky = F_L(t),$$

where mm is effective structural mass, cc represents damping, kk is structural stiffness, yy is vibration displacement, and FL(t)F_L(t) is the unsteady fluid force.

The damping term should be separated conceptually into inherent structural damping and harvesting-related damping. Therefore,

$$c = cs + ch, c = c_s + c_h,$$

where csc_s represents structural losses and chc_h represents the effective damping associated with energy extraction.

This distinction is central to the proposed methodology. If chc_h is too small, the system may produce substantial oscillations but extract only a limited portion of the available mechanical energy. If chc_h is excessively large, the oscillation amplitude can be substantially reduced. The optimum therefore exists between the two extremes.

3.2 Fluid Excitation and Vortex Synchronization

For a bluff body, vortex shedding generates alternating fluid forces. The characteristic shedding frequency can be related to flow velocity through the Strouhal relationship,

$$fs = StUD, f_s = St\frac{U}{D},$$

where StSt is the Strouhal number, UU is free-stream velocity, and DD is a characteristic body dimension.

The structural natural frequency is

$$fn = 12\pi km. f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

High-response conditions occur when the fluid excitation frequency approaches the structural natural frequency. This synchronization mechanism is a central component of vortex-induced vibration and has been observed across different cylinder geometries and operating conditions (Khalak and Williamson, 1996; Zhao et al., 2019).

The proposed system therefore seeks to maintain an appropriate relationship between fsf_s and fnf_n across the intended operating velocity range.

3.3 Energy Conversion Model

The mechanical power available to an energy converter can be expressed in simplified form as

$$Ph = chy^{˙}2. P_h = c_h\dot{y}^{\,2}.$$

The average harvested power becomes

$$Ph^{-} = chy^{˙}2^{-}.\overline{P_h} = c_h\overline{\dot{y}^{\,2}}.$$

This formulation illustrates an important design trade-off. Increasing harvesting damping increases the instantaneous power dissipation coefficient, but it can simultaneously decrease the vibration velocity. Consequently, maximizing chc_h alone is not an appropriate optimization strategy.

A dimensionless conversion efficiency can be defined as

$$\eta = Ph^{-}Pfluid, \eta = \frac{\overline{P_h}}{P_{\mathrm{fluid}}},$$

where PfluidP_{\mathrm{fluid}} represents the kinetic power available in the intercepted fluid stream.

The framework consequently defines the design objective as maximizing η\eta, rather than simply maximizing vibration amplitude.

3.4 Structural and Geometric Optimization

The system can be optimized through several coupled

variables: mass ratio, damping ratio, stiffness, cylinder geometry, surface attachments, spacing between multiple bodies, and rotational conditions.

Multiple-cylinder configurations provide one route for improving the excitation environment. Kim and Bernitsas (2016) showed the relevance of cylinder synergy to hydrokinetic conversion. Similarly, rod attachments have been investigated as a means of modifying vortex-induced vibration characteristics (Wang et al., 2020).

Geometry optimization should therefore focus on wake organization and fluid-force generation rather than solely on minimizing structural mass. Elliptical and square-cylinder investigations indicate that changes in body shape and orientation can substantially modify fluid–structure interaction (Zhao et al., 2014; Zhao et al., 2019).

3.5 Controlled Damping Strategy

The proposed methodology treats harvesting damping as an active design variable. A practical converter could adjust its electromechanical loading according to the instantaneous or average vibration response.

At low flow velocity, excessive loading should be avoided because it may prevent the structure from entering an effective oscillatory regime. Near synchronization, the harvesting load can be increased to capture a larger fraction of mechanical energy. At higher flow velocities, the control system should prevent excessive structural response and maintain operation within safe limits.

This concept follows the broader conclusion that damping is simultaneously a loss mechanism and an energy-conversion mechanism (Soti et al., 2018). The optimal damping state is therefore dynamic rather than universally constant.

3.6 System-Level Configuration

A complete vibration-based energy harvesting system can be represented by five functional stages: fluid excitation, vortex or wake formation, structural oscillation, mechanical-to-electrical conversion, and electrical conditioning.

The first stage determines the kinetic energy available to the device. The second determines the periodicity and magnitude of fluid excitation. The third converts fluid forcing into mechanical oscillation. The fourth extracts energy through an electromechanical interface, while the fifth conditions the resulting electrical output.

The experimental findings associated with rotating-cylinder flow-induced vibration further indicate that the excitation mechanism can be modified by controlling body rotation and flow interaction (Zhao et al., 2018). Such control could therefore become an additional parameter within an adaptive vibration-energy system.

4. Results / Findings

The analytical synthesis indicates that high-efficiency fluid-flow energy extraction depends primarily on dynamic matching, rather than on vibration amplitude alone. The first major finding is that synchronization between fluid excitation and structural natural frequency represents the central mechanism governing large oscillatory response. When the excitation frequency approaches the structural frequency, energy transfer from the fluid to the structure becomes more effective. This theoretical interpretation is consistent with the hydroelastic-cylinder behavior reported by Khalak and Williamson (1996) and subsequent investigations of elliptical and other cylinder geometries.

The second finding concerns damping. The available literature indicates that damping produces a non-monotonic relationship between structural response and harvested power. Increasing harvesting damping initially increases the fraction of mechanical energy removed from the structure, but excessive damping reduces oscillation amplitude and velocity. Therefore, maximum power is expected at an intermediate effective damping level rather than at either zero damping or maximum damping. This finding is particularly important because vibration systems designed solely for maximum amplitude may not deliver maximum electrical output. The damping–power relationship identified by Soti et al. (2018) provides strong theoretical support for this interpretation.

The third finding is that geometric modification can serve as an excitation-enhancement mechanism. Multiple-cylinder arrangements, rod attachments, and alternative body shapes can modify vortex formation and wake interaction. Kim and Bernitsas (2016) demonstrated the relevance of multiple-cylinder synergy, while Wang et al. (2020) demonstrated the potential of rod attachments for enhancing vibration. These approaches suggest that structural geometry should be optimized together with dynamic properties.

A fourth finding is that controlled excitation can expand the operating range. Rotation, turbulence control, and geometry modification provide mechanisms for influencing fluid forcing rather than allowing the device to operate solely according to naturally occurring vortex shedding. Experimental observations of rotating-cylinder vibration provide evidence that flow-induced response can be substantially affected by rotational conditions (Zhao et al., 2018).

Finally, comparison across cylindrical and foil-based

systems indicates that vibration energy harvesting is not limited to a single converter architecture. Oscillating airfoils and passive flapping foils demonstrate that fluid-induced periodic motion can be exploited through different structural mechanisms (Kinsey and Dumas, 2008; Wang et al., 2017). The resulting framework therefore supports a generalized design philosophy: maximize the time-averaged conversion of fluid-induced mechanical motion while controlling structural loading, rather than optimizing one isolated parameter.

5. Discussion

The findings establish that vibration-based energy extraction should be considered a coupled optimization problem involving hydrodynamics, structural mechanics, and energy-conversion loading. This interpretation differs from approaches that treat vibration amplitude as the primary indicator of performance. A structure may exhibit very large oscillations while transferring relatively little usable energy to the electrical subsystem if the harvesting load is poorly matched to the structural response.

The most important theoretical implication is the dual role of damping. Conventional structural damping is undesirable because it dissipates mechanical energy without producing useful output. Harvesting damping, by contrast, intentionally removes energy from the oscillating structure. The distinction means that an efficient system should minimize parasitic damping while controlling the conversion-related damping. The literature on damping effects supports this distinction and indicates that the optimum depends on the dynamic state of the system (Soti et al., 2018).

The framework also reveals an important trade-off between structural compliance and durability. Lower stiffness can facilitate larger oscillations, but excessive structural flexibility can increase fatigue loading and mechanical instability. Conversely, a very stiff structure may remain below the vibration regime necessary for efficient energy transfer. Consequently, stiffness should be selected according to the expected flow-velocity range rather than optimized independently.

Geometric modification provides another important design opportunity. Multiple-cylinder synergy can enhance the interaction among wakes, while rod attachments can modify vortex formation. These methods may increase excitation without requiring proportionally larger structural dimensions (Kim and Bernitsas, 2016; Wang et al., 2020). However, increased geometric complexity can introduce additional manufacturing, maintenance, and hydrodynamic uncertainties.

The comparison with oscillating foils also suggests that no single geometry is universally optimal. Foil-based systems can exploit lift-driven oscillation, whereas bluff-body systems rely strongly on vortex shedding. Kinsey and Dumas (2008) demonstrated that oscillating airfoils can operate in power-extraction regimes, while Wang et al. (2017) showed the feasibility of passive flapping configurations. These findings broaden the possible architecture of vibration-based converters.

A major practical limitation is the variability of environmental flow velocity. Because vortex-shedding frequency changes with velocity, a fixed natural frequency may only provide optimum synchronization within a limited operating range. Adaptive stiffness, damping, or geometric control could potentially address this limitation. Rotational control provides another possible route, as demonstrated by studies of rotating-cylinder flow-induced vibration (Zhao et al., 2018).

The principal limitation of the present study is methodological: it is a literature-grounded analytical framework rather than a new experimental investigation. Consequently, the reported findings should not be interpreted as measured efficiency improvements. Experimental validation involving controlled flow velocity, structural properties, damping coefficients, displacement, velocity, and electrical output would be required to quantify the performance of a specific device.

Nevertheless, the synthesis provides a useful basis for future research because it integrates hydrodynamic excitation and energy-conversion loading into one optimization problem. The most promising direction is therefore not simply to maximize vibration, but to maximize useful energy transfer under dynamically controlled conditions.

6. Conclusion

This paper developed a dynamic vibration-based framework for high-efficiency energy extraction from fluid flows using only the supplied literature. The analysis establishes that effective conversion depends on coordinated interaction among vortex excitation, structural dynamics, damping, geometry, and energy-conversion loading.

The central conclusion is that maximum vibration amplitude and maximum harvested power are not necessarily equivalent. Efficient energy extraction requires an optimized harvesting-damping condition that removes substantial mechanical energy while maintaining sufficient structural oscillation. Synchronization between fluid excitation and structural dynamics is consequently a fundamental design requirement.

The literature further demonstrates that geometric and hydrodynamic modifications—including multiple-cylinder arrangements, rod attachments, passive

turbulence control, rotating bodies, and oscillating foils—can alter the excitation mechanism and potentially improve energy extraction. These approaches support the development of adaptive vibration converters capable of operating over broader flow conditions.

Future investigations should combine computational fluid dynamics, structural dynamic modeling, controlled experiments, and adaptive energy-conversion control. Particular attention should be given to variable-flow environments, fatigue resistance, nonlinear structural behavior, and real-time damping optimization. Such developments could move vibration-based energy harvesting from isolated laboratory configurations toward robust renewable-energy systems capable of extracting useful power from naturally occurring water and air flows.

References

1. Burton T, Jenkins N, Sharpe D, Bossanyi E. Wind energy handbook. John Wiley & Sons; 2011.
2. Chang C-C, Bernitsas MM. Hydrokinetic energy harnessing using the VIVACE converter with passive turbulence control. In: International conference on offshore mechanics and arctic engineering, vol. 44373. 2011, p. 899–908.
3. Khalak A, Williamson C. Dynamics of a hydroelastic cylinder with very low mass and damping. J Fluids Struct 1996;10(5):455–72.
4. Kim ES, Bernitsas MM. Performance prediction of horizontal hydrokinetic energy converter using multiple-cylinder synergy in flow induced motion. Appl Energy 2016;170:92–100.
5. Kinsey T, Dumas G. Parametric study of an oscillating airfoil in a power-extraction regime. Am Inst Aeronaut Astronaut J 2008;46(6):1318–30.
6. Lee J, Bernitsas M. High-damping, high-Reynolds VIV tests for energy harnessing using the VIVACE converter. Ocean Eng 2011;38(16):1697–712.
7. Lo JCC, Hourigan K, Thompson MC, Zhao J. The effect of structural damping on flow-induced vibration of a thin elliptical cylinder. J Fluid Mech 2023;974:A5.
8. Manwell JF, McGowan JG, Rogers AL. Wind energy explained: theory, design and application. 2nd ed. John Wiley & Sons; 2011, p. 137.
9. Shi G, Tan T, Hu S, Yan Z. Hydrodynamic piezoelectric energy harvesting with topological strong vortex by forced separation. Int J Mech Sci 2022;223:107261.
10. Soti AK, Zhao J, Thompson MC, Sheridan J, Bhardwaj R. Damping effects on vortex-induced vibration of a circular cylinder and implications for power extraction. J Fluids Struct 2018;81:289–308.
11. Sumer BM, et al. Hydrodynamics around cylindrical structures. In: Advanced series on ocean engineering, vol. 26, World Scientific; 2006.
12. Wang J, Zhao W, Su Z, Zhang G, Li P, Yurchenko D. Enhancing vortex-induced vibrations of a cylinder with rod attachments for hydrokinetic power generation. Mech Syst Signal Process 2020;145:106912.
13. Wang J-S, Fan D, Lin K. A review on flow-induced vibration of offshore circular cylinders. J Hydrodyn 2020;32(3):415–40.
14. Wang Z, Du L, Zhao J, Sun X. Structural response and energy extraction of a fully passive flapping foil. J Fluids Struct 2017;72:96–113.
15. Wilson R, Lissaman P, Walker S. Aerodynamic performance of wind turbines. Tech. rep., Corvallis (USA): Oregon State Univ.; 1976.
16. Zhao J, Hourigan K, Thompson MC. Dynamic response of elliptical cylinders undergoing transverse flow-induced vibration. J Fluids Struct 2019;89:123–31.
17. Zhao J, Hourigan K, Thompson M. Flow-induced vibration of D-section cylinders: an afterbody is not essential for vortex-induced vibration. J Fluid Mech 2018;851:317–43.
18. Zhao J, Leontini JS, Lo Jacono D, Sheridan J. Fluid–structure interaction of a square cylinder at different angles of attack. J Fluid Mech 2014;747:688–721.
19. Zhao J, Lo Jacono D, Sheridan J, Hourigan K, Thompson MC. Experimental investigation of in-line flow-induced vibration of a rotating circular cylinder. J Fluid Mech 2018;847:664–99.