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Review Paper

# Research progress and development prospects on critical challenges in deepwater riserless drill string dynamics

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ABSTRACT

With the ongoing expansion of oil and gas drilling into deeper waters, riserless drilling technology has shown prominent advantages in deepwater drilling applications. The structural design and operational mechanism of riserless drilling make drill strings more vulnerable to stochastic ocean loads, requiring thorough investigation of critical factors influencing drill string dynamics in deepwater riserless operations to maintain drilling stability. Accordingly, this work initially synthesizes computational approaches for drill string external loads, elucidating how multiphysics-coupled loading mechanisms impact both drilling safety and operational efficiency. Furthermore, this work investigates fundamental challenges in drill string dynamics, including riser vortex-induced vibrations (VIV) in water columns and nonlinear drill string vibrations in formation sections, establishing connections between oceanic loads and traditional drilling dynamics. Moreover, this work systematically evaluates both active and passive vibration mitigation techniques, including VIV suppression for marine riser segments and formation vibration control methodologies. This work concludes by examining next-generation drilling control systems that feature intelligent data transmission, data-driven modeling, and smart control technologies. These elements collectively form a "perception-modeling-control" closed-loop system to overcome the time-delay limitations of traditional methods. The findings establish a theoretical foundation for deepwater drilling parameter optimization, safety risk mitigation, and efficiency improvement.


## 1. Introduction

The sea serves as a critical repository of resources and strategic domain for national development. Studies indicate that marine petroleum resources represent approximately 25% of China's crude oil reserves, and natural gas resources exceed 25% of the total reserves (Du, 2022). As the demand for hydrocarbon resources grows annually, offshore oil and gas extraction is advancing into deeper regions. Yet, influenced by factors such as the intricate marine environment and subsurface geological conditions, China's deepwater exploration encounters significant challenges. Consequently, China's reliance on imported crude oil and natural gas remains substantial, posing serious threats to its energy security (Li, 2022).

Riserless drilling technology, as an emerging method, demonstrates notable benefits in deepwater drilling. It resolves challenges such as tight formation pressure windows, accelerates well construction, minimizes drilling incidents, and removes reliance on conventional riser components, thereby reducing costs. It stands as a secure and high-performance innovation in drilling practices (Chen et al., 2023). The riserless drilling system can be divided into the seawater section and the formation section based on drill string position. Unlike conventional systems, it forgoes traditional risers in the seawater section, instead using dedicated conduits for mud return. A mud-lift pump transports formation mud to the drilling platform, where processed drilling fluid is recycled, enabling efficient subsea mud recovery (Li et al., 2021). Nevertheless, significant limitations persist for deepwater deployment of this technology. Key restricting factors are: increased complexity and cost of downhole pressure control and pumping systems due to the extended return path; more arduous and time-consuming operations for deploying and retrieving the pipe string in deepwater, with greater susceptibility to weather

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**Abbreviations**

| | |
|---|---|
| ADRC | Active disturbance rejection control |
| ASM | Along-string measurement |
| BHA | Bottom hole assembly |
| CFD | Computational fluid dynamics |
| DOF | Degree of freedom |
| FSI | Fluid–structure interaction |
| HCC | Hydraulic clutch controller |
| LQR | Linear quadratic regulator |
| MPC | Model predictive control |
| PDC | Polycrystalline diamond compact |
| PID | Proportional integral derivative |
| *Re* | Reynolds number |
| ROP | Rate of penetration |
| RPM | Revolutions per minute |
| VIV | Vortex-induced vibration |
| WOB | Weight on bit |

conditions; and a substantial increase in the return line's self-weight with water depth, which places exceptionally stringent requirements on the rig's tension and compensation system. Schematic diagrams of riserless drilling system and conventional drilling system are shown in Fig. 1.

In contrast to conventional drilling, riserless drilling systems demonstrate higher vulnerability to coupled influences from marine environmental loads, internal mud flow, and inherent high length-to-diameter ratios. This predisposition triggers various dysfunctions including drill string destabilization, VIV in marine segments, stick-slip oscillations, whirl motions, and bit bounce phenomena, potentially resulting in catastrophic failures like structural buckling, drill pipe sticking, and fatigue-induced fractures. Performing nonlinear dynamical assessments of riserless drilling configurations contributes to improved force management and operational security. The deep-sea riserless drilling assembly comprises two distinct domains: the seawater interval and formation interval. The hydrodynamic loads acting on the marine portion and the geomechanical stresses in the formation portion exhibit analogous characteristics to conventional drilling's riser and bottomhole assembly dynamics correspondingly. Dynamic analysis of conventional drilling risers and drill strings facilitates the prevention and mitigation of detrimental vibrations in riserless drilling systems, thereby extending tool life. Furthermore, it offers fundamental principles for engineering riserless systems resilient to harsh oceanic conditions, boosting process reliability and achieving cost efficiencies.

The preceding analysis reveals that riserless drill strings experience multifaceted loading conditions (encompassing wave forces, ocean currents, platform displacement, and self-induced whirling motion), leading to extraordinarily complex dynamic behaviors and stress profiles. With increasing water depth and rotational speed, the drill string demonstrates heightened susceptibility to significant deflection, kinetic instability, and catastrophic failure, compounded by the persistent issue of coupled axial-lateral-torsional nonlinear vibrations. Traditional mechanical modeling approaches and human-operated control systems prove inadequate for real-time management of such dynamic intricacies, exhibiting fundamental limitations in handling substantial phase lag, control overshoot, and stochastic environmental variations. Implementing cutting-edge solutions including intelligent telemetry, data-derived modeling frameworks, and adaptive control algorithms demonstrates significant potential for vibration suppression, cost optimization, and operational safety/efficiency improvements.

In light of the aforementioned challenges and needs, this review aims to systematically synthesize the research progress in this field and clarify future directions. The entire article unfolds according to the following logical framework.

Section 2 reviews the computational methods and current state of development for calculating the external loads acting on deepwater riserless drill strings. Section 3 then focuses on two critical dynamic issues: VIV of risers in the seawater section and the nonlinear coupled vibrations of drill strings in the formation section, analyzing their respective mechanisms and research frontiers. Section 4 systematically reviews existing active and passive control technologies and their application limitations in addressing the vibration problems of deepwater riserless drill

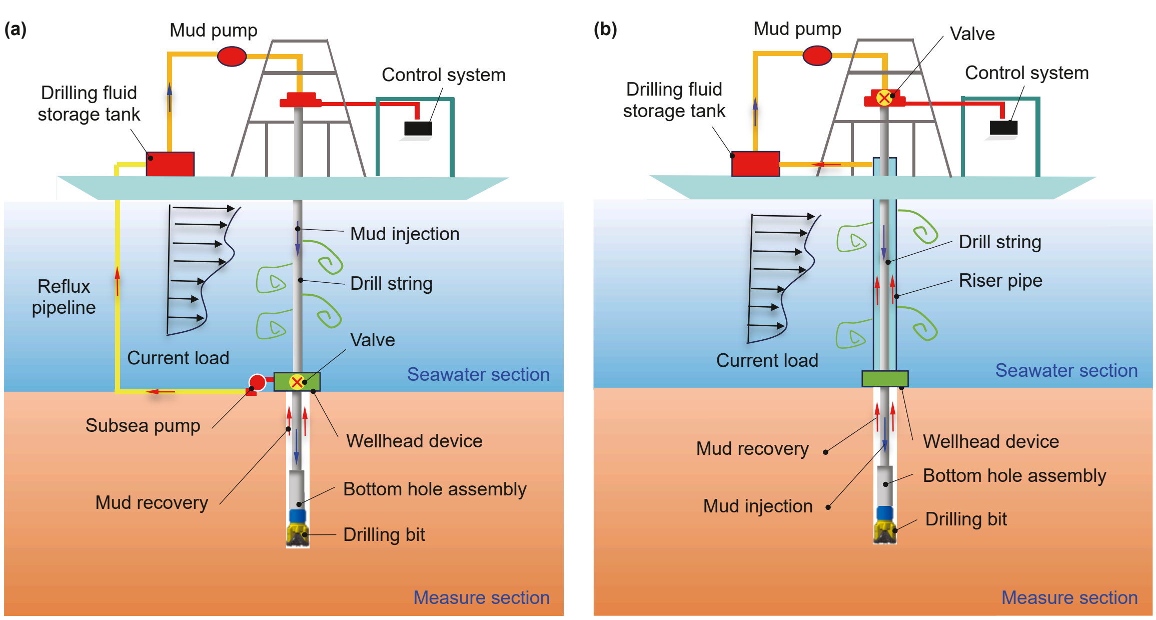


**Fig. 1.** Schematic diagram of deepwater oil and gas drilling. **(a)** Riserless drilling; **(b)** Riser pipe drilling (Liu et al., 2023a; Chen et al., 2022).

strings. Finally, it prospects emerging control technologies for drilling systems centered on intelligent data transmission, data-driven modeling, and intelligent control, discussing their potential to construct a closed-loop “perception-modeling-control” system, the technology roadmap of which is shown in Fig. 2.

## 2. Calculation method of external load of drill string

During riserless drilling operations, drill strings experience intricate multi-physics coupled dynamic loading in marine and geological segments, critically influencing wellbore integrity, equipment durability, and process efficiency. Investigating the action mechanisms of external loads on drill strings provides a theoretical basis for guiding drilling parameter optimization, tool selection, and safety risk prevention, ultimately enhancing drilling efficiency and economic performance.

### 2.1. Viscous damping of drilling fluid

Drilling mud, as a specialized fluid in hydrocarbon exploration, serves crucial roles such as tool lubrication/cooling, cuttings removal, and borehole wall stabilization. Drilling fluid damping attenuates oscillation energy via viscous mechanisms, thereby critically governing string dynamic stability, vibrational magnitude, and kinematic path. These factors ultimately determine operational efficiency and safety.

Initial investigations recognized drilling fluid viscous damping as a crucial factor in drill string dynamics. Dareing et al. (Dareing and Livesay, 1968; Huang and Dareing, 1968) pioneered the inclusion of drilling fluid damping in the analysis of axial-torsional vibrations in deviated wells. Building upon continuous technological advancements, contemporary studies have progressively established more refined models to accurately quantify the influence of drilling fluid viscous damping. Lin and Wang (1991) developed a single-degree-of-freedom torsional pendulum model of the drill string to analyze how drilling fluid viscous damping and other factors affect bottomhole assembly vibrations. Zhu and Liu (2008) incorporated drilling fluid viscous damping in developing solution methods for nonlinear drill string systems with uncertainties and dynamic boundaries. Sun et al. (2020) identified the drilling fluid viscous damping coefficient as a critical factor affecting torque transfer in ultra-deep directional wells during slide drilling, subsequently proposing engineering recommendations to improve efficiency. Di et al. (2024a) compared Rayleigh, Caughey and Clough models, demonstrating that the Rayleigh model effectively captures drilling fluid damping effects with vibration predictions matching field observations.

Drilling fluid damping offers significant advantages in reducing vibration amplitudes and enhancing drilling efficiency. However, its damping coefficient is influenced by the coupling of multiple factors such as fluid properties, wellbore geometry, and drilling speed. How to efficiently and accurately represent the mechanism of viscous damping in full-wellbore, multidimensional coupled models constitutes one of the current research priorities.

### 2.2. Wellbore friction and collision

Riserless systems lack the protection and guidance of risers, making the formation-section drill string prone to wellbore collisions that exacerbate fatigue damage. Particularly in horizontal and deep wells, gravitational forces press the drill string against wellbore walls, intensifying frictional and impact forces. This not only causes energy loss (reducing effective weight on bit, WOB, and bit torque) but may also trigger wall spalling, collapse, or even stuck pipe incidents. Furthermore, sustained impact and friction aggravate both drill string wear and wellbore damage, while increasing risks of string whirl and stick-slip vibration, as shown in Fig. 3. Consequently, minimizing wall contact interactions constitutes a critical factor in enhancing drilling safety, operational efficiency, and bottomhole assembly service life.

In early research, Johancsik et al. (1984) simplified the drill string as a stiffness-free cable, assuming coincidence between the drill string axis and wellbore, then derived a contact force model through axial forces and self-weight, ultimately establishing a friction torque simulation model incorporating friction coefficients. The experimental setup developed by Westerman's team (Westermann et al., 2015) systematically investigated wall contact effects on drill string dynamics, particularly vibration modes, stick-slip oscillations, and whirling behavior in horizontal wells. The comprehensive 3D modeling framework by Zhu et al.

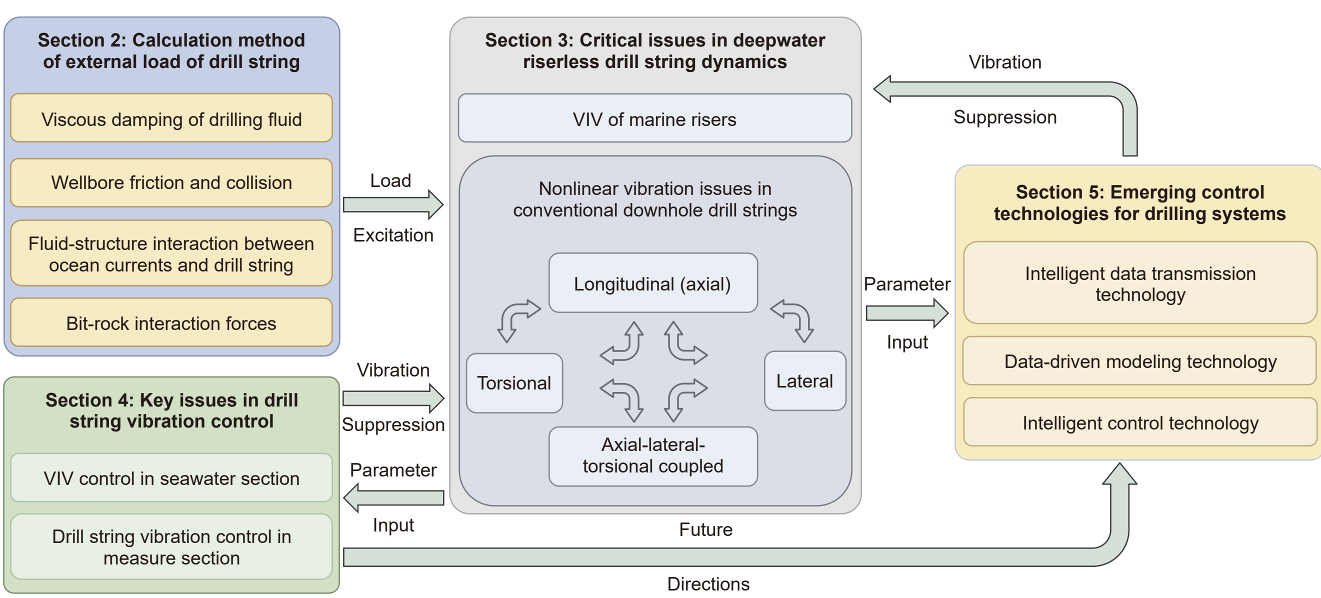


**Fig. 2.** Technology roadmap.

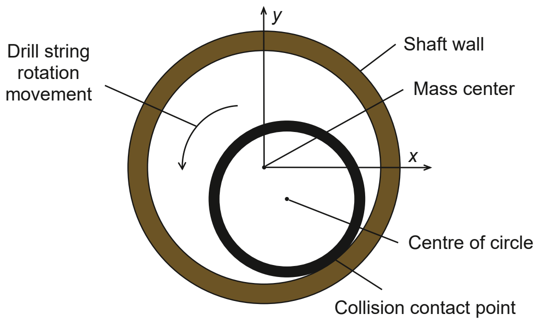


**Fig. 3.** Illustration of drill pipe and borehole wall interaction.

(2015) accurately simulated torque/drag dynamics in high-angle wells, fully incorporating both frictional and impact interactions between drill strings and wellbores across complex 3D trajectories. Wu et al. (2023) established a horizontal well drilling model incorporating drill string–wellbore impact contacts and other critical factors. Their findings revealed that increasing hook load (within critical limits) could effectively reduce drill string–wellbore contact forces. Wang W.C. et al. (2024) employed a stochastic general contact model to characterize drill string-wellbore interactions, combining with actual well trajectories to compute full-string dynamic characteristics in ultra-deep wells. Di et al. (2024b) established collision criteria and developed a corresponding impact model between drill strings and wellbores to enable dynamic simulation in extra-deep wells. Results indicated that drill string whirling becomes most severe at the neutral point position.

Friction and impact with the wellbore wall represent a major source of external excitation for drill string vibrations. Parameters critical to collision dynamics, such as contact force geometry, friction coefficient, annular clearance, and hook load, should be integrated into the drilling parameter optimization process.

### 2.3. Fluid–structure interaction between ocean currents and drill string

In deepwater riserless drilling, the drill string is directly exposed to marine environments and subjected to complex dynamic loads from ocean currents and waves, generating significant fluid–structure interaction effects. This induces nonlinear drill string vibrations (lateral, axial, and torsional), subsequently destabilizing wellbore pressure fields and potentially causing severe incidents like lost circulation, blowouts, or tubular failures. This has driven extensive research on current-drill string fluid–structure interaction (FSI) computational methods to precisely forecast dynamic behavior, determine safe operating envelopes, and establish mechanical design criteria.

Wang (2017) developed both lateral vibration and transient VIV models for rotating riserless drill strings, systematically investigating the influence of operational parameters (hook load, platform displacement) and environmental loads (currents, waves) on vibration characteristics. Gao et al. (2017) incorporated both marine environmental loads and seabed soil interactions to develop a mechanical model for riserless sampling drill strings, finding that increased current velocity and drag coefficient amplify bending deformation and moment. Guo et al. (2022) established a full-wellbore axial-lateral-torsional coupled nonlinear vibration model for the drill string system. This model accounts for factors such as wellbore constraint effects, bit–rock interaction forces, and drilling fluid viscosity. Their research indicates that, provided other operational criteria are not adversely affected, raising the rotary table speed and extending the bottom hole assembly (BHA) length can significantly improve drilling efficiency. Qian's group (Qian et al., 2025) innovated a proper orthogonal decomposition and Gaussian process hybrid surrogate modeling framework for FSI analysis, leveraging particle-based computations to efficiently resolve complex marine current–structure interactions with parametric adaptability. Liu et al. (2023b) employed Hamilton's principle to develop a nonlinear dynamics model incorporating current loads, bit–rock interaction, and wall contacts, investigating how drill string vibrations affect wellbore pressure fields in deepwater riserless systems. The study revealed current-induced vibration amplification across all modes, particularly demonstrating enhanced high-frequency torsional harmonics and nonlinear chaos at upper string segments proximate to floating platforms.

Evidently, the fluid–structure interaction between ocean currents and the drill string provides substantial excitation to its vibrations. The intensity of this coupling is primarily governed by factors such as current velocity, wave properties, platform offset, and BHA configuration.

### 2.4. Bit–rock interaction forces

Bit-induced reaction forces during rock destruction transmit along the drill string, altering stress profiles, accelerating fatigue

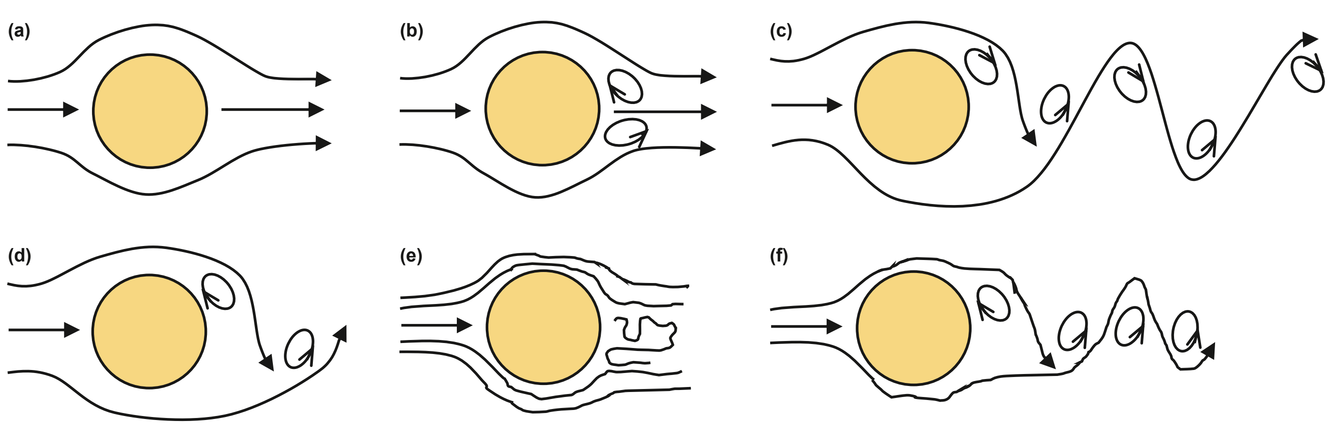


**Fig. 4.** Correlation of *Re* with wake regimes behind bluff bodies. **(a)** $Re < 5$, no separation phenomenon occurs; **(b)** $5–15 < Re < 40$, a pair of fixed small vortices appear behind the cylinder; **(c)** $40 < Re < 150$, periodically alternating laminar vortices are generated; **(d)** $150 < Re < 300$, in the subcritical regime, periodically alternating turbulent vortex shedding occurs; **(e)** $3 \times 10^5 < Re < 3.5 \times 10^7$, in the transition section, the drag force is significantly reduced; **(f)** $Re > 3.5 \times 10^7$, supercritical stage.

accumulation, and increasing buckling potential. Accurate quantification of bit–rock interface dynamics facilitates operational parameter optimization (WOB and revolutions per minute, RPM), mitigating non-productive vibrations and energy dissipation to enhance both penetration rates and BHA durability. Integrated analysis with formation properties also provides diagnostic capabilities for lithology changes and bit wear prediction, enabling process optimization that enhances borehole integrity, reduces safety risks, and minimizes non-productive time and expenditures.

Zhu's team (Zhu et al., 2007) formulated an axial dynamics model accounting for triaxial loading conditions (WOB, rock reaction forces, and inertial effects) at the bit–rock interface, enabling comprehensive drill string response analysis. Liu (2015) regarded the equivalent bit–rock contact process as friction and established a coupling model of WOB and torque. Combined with the whole well drill string model considering the actual drilling trajectory and the BHA, the simulation calculation of the dynamic characteristics of the drill string in the highly deviated well under different well depths was performed. Mao et al. (2023a) developed and validated a nonlinear polycrystalline diamond compact (PDC) cutter–rock engagement model as string model boundary conditions, systematically evaluating parametric influences (WOB, rotary speed, rock strength) on system dynamics. Xing et al. (2023) incorporated bit–rock interactions into a torsional vibration model, revealing how formation types affect stick-slip behavior: higher drillability formations generate milder stick-slip. Wang (2019) combined numerical and experimental methods to study PDC cutter interactions with varied bottomhole geometries, finding: Rock-breaking stress decreases with increasing outer cone curvature radius, but increases in inner cone regions. Panayirci (2022) conducted full-scale PDC–bit limestone drilling tests with precision equipment, demonstrating WOB's critical role in steering stability through parametric analysis of bit dynamics. Hu et al. (2017) developed a coupled drill string–bit–rock model incorporating axial-lateral-torsional vibrations and bit–rock contacts, simulating fragmentation dynamics to reveal strongly nonlinear, stochastic vibration characteristics. To overcome the inability of traditional dynamics models to concurrently simulate the rock-breaking process at the bit and the motion of the drill string, Huang et al. (2024) established a comprehensive integrated model. This model incorporates the drill string, bit, formation, and wellbore, facilitating the coupled study of rock fragmentation mechanics and drill string dynamics.

The analysis of drill bit–rock interaction forces has progressed from initial simplified models to sophisticated system models featuring multi-degree-of-freedom coupling and experimental validation, thereby achieving accurate wellbore trajectory prediction and tool lifespan evaluation.

In actual drilling environments, the external loads on the drill string are often the result of multi-factor coupling and dynamically vary with well depth, geological conditions, and drilling parameters. Consequently, future studies should place greater emphasis on systematic analyses of multi-load interactions to improve both the adaptability to complex downhole conditions and the predictive accuracy of the models.

## 3. Critical issues in deepwater riserless drill string dynamics

The dynamics of drilling systems represents a cornerstone in applied drilling theory and a critical technological factor governing productive oil/gas well construction. As China's hydrocarbon exploration progresses into deepwater domains with escalating drilling activities, marine environmental loads on drilling systems become increasingly complex. Precise characterization of drilling system dynamics forms the theoretical foundation and technical crux for ensuring successful ultra-deep drilling, enhancing quality/efficiency, and reducing costs—representing one of the most pressing challenges in current hydrocarbon exploration (Liu et al., 2009).

As the fundamental load-bearing element in well construction, the drill string simultaneously performs torque transmission, mud circulation, and axial force application. Consequently, maintaining string mechanical reliability represents the prerequisite for efficient drilling execution. The combined rotational and axial motions subject drill strings to multi-physics loads encompassing cutter–rock engagement, borehole wall tribology, and downhole vibration tool dynamics. These factors induce severe vibrations that damage tools and compromise efficiency (Di et al., 2024c).

With the constraint and isolation effect of the riser system absent, dynamic responses from the seawater-section drill string are transmitted to the formation section, markedly influencing bit–rock interaction; the reverse is also true. While the isolated analysis of drill strings in the seawater and formation sections can respectively utilize the established theoretical frameworks from marine riser and conventional drilling studies, the riserless drill string system itself constitutes a nonlinearly coupled system. Unraveling its integrated behavior necessitates, first and foremost, a clear understanding of its basic attribute distinctions from marine risers, detailed in Table 1.

Building on these distinctions, marine riser VIV theory can serve as a qualitative guide for basic dynamic analysis of the seawater–conduit drill string in riserless operations under the following conditions.

(1) The drill string rotation effect is neglected.
(2) The inline and cross-flow VIV mechanisms under uniform ocean currents are investigated.
(3) The influences of drill string arrangement modes (e.g., side-by-side, tandem or staggered layouts) on flow–induced vibration trends are analyzed.

Nevertheless, significant errors may arise from directly extrapolating marine riser VIV findings to situations involving these working conditions:

The continuous high-speed rotation of the drill string during operation, where torsional vibration couples with VIV; The continuous flow of drilling fluid inside the drill string and its coupling effects with the external flow field; The bidirectional coupling between vibrations of the seawater-section and formation-section drill strings, and the feedback effect from bit–rock interaction.

### 3.1. VIV of marine risers

Due to the high slenderness ratio of riserless drill strings in the seawater section, they are more susceptible to wind, wave, and current loads in complex marine environments compared to conventional systems, leading to VIV that compromises system stability.

As vital subsea-to-surface pathways, marine risers link offshore floating structures with underwater production systems while conveying oil/gas from seafloor to platform. In the complex marine environment, the marine riser not only bears its own weight and top tension, but also is susceptible to wind, wave, current and other loads. The main constraints of the riser structure exist in the seabed facilities and sea-level platforms, which are prone to VIV (Yin et al., 2022). This can induce severe riser oscillations, fatigue damage accumulation, and potentially catastrophic structural failures. The hydrodynamic loading on riserless drill strings in

**Table 1**
Comparison of characteristics between marine risers and riserless drill strings.

| Characteristic | Marine riser | Riserless drill string |
|---|---|---|
| State differences in rotation | Low-amplitude torsion (usually ignored) | Continuous high-speed rotation driven by sustained torque from the drilling platform |
| Diameter | Single riser: 50.8–254 mm<br>Multi–riser system: 30.5–91.4 mm | Typically available in three sizes: 88.9, 114.3, and 127.0 mm |
| Inherent characteristics | Constructed from high-strength steel. Typical surface roughness Ra ≤1.6 μm, with precision requirements Ra ≤0.8 μm. Wall thickness 30–40 mm (X65 steel) | Steel pipe body. Inner surface roughness Ra ≤1.6 μm, outer surface Ra ≤3.2 μm. Wall thickness 9–11 mm |
| Internal flow regime | Drilling mode: flowing drilling fluid carrying cuttings<br>Production/completion mode: static completion fluid | Drilling mode: single-phase drilling fluid inside the drill string; liquid–solid two-phase drilling fluid in the annulus |
| Mass | The mass per unit length is comparatively large owing to its greater diameter and wall thickness | Mass per unit length is relatively low |
| Structural damping ratio | 0.003 | 0.025–0.03 |
| Axial tension boundary | Top tension is relatively stable | Dynamically varies with well depth and WOB |

seawater sections resembles that on conventional drilling risers. Consequently, investigating riser VIV mechanisms offers fundamental insights for controlling destructive oscillations in riserless operations and optimizing drilling performance.

As fluid approaches a cylindrical structure, it bifurcates and travels along dual circumferential paths around the obstruction. The obstruction causes simultaneous pressure and velocity variations, creating velocity differentials behind the cylinder that generate continuously forming and dissipating vortices. Periodically alternating lift forces in the cross-flow direction excite structural oscillations, constituting the VIV phenomenon. The Reynolds number (*Re*) typically characterizes wake flow regimes and vortex street formation/shedding patterns behind bluff bodies, as shown in Fig. 4.

Currently, studies on VIV of marine risers are conducted across several directions, with a detailed analysis of the current status as follows:

**Vibration issues of risers under external flow effects:** The complex topography of deep-sea environments causes drastic variations in flow velocity, presence of turbulence/vortices, and non-uniform flow distribution. These complex flow fields (including shear flow, internal wave currents, multi-riser interference) significantly alter VIV characteristics and riser dynamic responses.

Mathelin and Langre (2005) proposed the wake oscillator model, combining shear flow with VIV for the first time, and investigated the effect of flow field non-uniformity on vortex shedding frequency. Chaplin and King (2018) studied the influence mechanism of two inflow directions—upstream anchoring at the tank bottom and downstream anchoring at the water surface—on the VIV of catenary risers with high curvature and low bending stiffness. Chen et al. (2011) established a multi-mode lock-in model for shear flows caused by internal waves, demonstrating that oceanic risers display higher-order, multi-mode VIV behaviors owing to heterogeneous flow fields and densely spaced low-frequency structural modes. Xu et al. (2017) constructed a hydrodynamic force model for flexible cylinder VIV, analyzed the characteristics of hydrodynamic coefficients under varying inflow angles and shear flows via towing tank experiments, and delineated the energy input and output regions of the structure. Gao et al. (2018) formulated a coupled oscillator model (structure–wake) for flexible cylinders, evaluating VIV responses—including wavelength, displacement, and frequency—across varying shear conditions. Bearman (2011) examined the effect of *Re* on isolated cylinder dynamics, emphasizing mutual interference in tandem cylinder configurations, offering solutions for VIV in multi-riser systems. Li et al. (2017) and Ji et al. (2018a, 2018b) performed three-dimensional numerical modeling of VIVs in flexible cylinders subjected to uniform, shear, and oblique flows, examining vibrational frequencies, drag coefficients, energy exchange, and standing/traveling wave responses. Zhou et al. (2022) revealed the amplitude and frequency response characteristics of VIV for marine risers under bidirectional shear flow through model tests. The experiments demonstrated that the dominant (VIV) frequency of the riser model under bidirectional shear flow depends exclusively on its natural frequency, while the mean drag coefficient shows little variation across different flow velocities.

**Vibration issues of risers under coupled internal–external flow interactions:** During offshore hydrocarbon extraction, subsea risers convey multiphase media including crude oil, natural gas, and solid particulates. The internal flow of these media frequently generates liquid–solid multiphase flow. This, when coupled with external shear flows, excites flow-induced vibrational responses and may lead to fatigue failure.

The multiphase flow transported in deep-sea riser pipelines can readily cause blockages in ultra-long risers, thereby inducing detrimental vibrations. Consequently, flow-induced vibration and VIV problems caused by internal riser flow represent one of the key research focuses.

Païdoussis and Issid (1974) investigated the hydrodynamic properties of internal flow and stability issues in risers, further elucidating the influence of internal flow on riser vibration behavior. Huera-Huarte et al. (2014) examined the effect of fluid velocity on VIV in isolated long flexible cylindrical pipes through dynamic response experiments, results demonstrated that increasing fluid velocity induces dynamic responses in risers, potentially leading to dynamic instability. Kim and O'Reilly (2019) and Nguyen et al. (2013) formulated riser VIV equations incorporating internal flow effects, analyzing its impact on VIV response. Results indicated that internal flow velocity effectively suppresses natural frequency, while centrifugal and Coriolis forces from internal flow moderately affect riser vibrations. Li (2014) employed the immersed boundary method for numerical simulation of flexible risers with bidirectional VIV, examining VIV characteristics under first three modal shapes while considering internal flow velocity and mass ratio. Results revealed that in-line bending vibrations amplify cross-flow amplitudes compared to cross-flow-only models, with internal flow increasing participating vibration modes. Thorsen et al. (2019) proposed a novel coupled internal flow-riser model to investigate VIV response in marine risers with steady internal flow, analyzing the mechanistic effects of flow velocity and density on VIV modes, frequency and displacement.

With technological advancements, many researchers have increasingly investigated how coupled internal and external flows influence offshore riser VIV characteristics. Guo and Lou (2007) conducted experimental studies on flexible riser vibration responses under coupled internal–external flow conditions, considering both static and dynamic water flow scenarios, results demonstrated that increasing internal flow velocity amplifies riser vibration amplitude while reducing oscillation frequency. Zhu et al. (2019, 2024) employed high-speed imaging non-invasive techniques to simultaneously capture vibration displacement and internal flow conditions, with the experimental setup shown in Fig. 5. The study analyzed the coupled VIV response of flexible catenary risers subjected to internal slug flow/liquid–solid two-phase flow and external shear flow.

Duan et al. (2021a) developed a predictive model for VIV of marine risers under coupled shear and internal flows, investigating the cross-flow VIV characteristics of top-tensioned risers at varying internal flow velocities and densities. Gao et al. (2024) experimentally studied the vibration response of catenary flexible risers with coupled single-phase internal flow and nonlinear shear external flow. By systematically varying the external flow reduced velocity and internal flow rate, they analyzed how internal flow affects the riser's vibrational response. Duan et al. (2021b) established a coupled internal–external flow numerical model to examine the effects of internal flow velocity and fluid density on flexible riser VIV. Results showed that increasing either internal flow velocity or density amplifies vibration amplitudes, while density variations also modify the riser's vibration modes.

**Structural vibration characteristics of riser arrays:** As the demand for hydrocarbon resources grows, multi-riser configurations are increasingly employed in deepwater drilling. In multi-riser clusters, marine risers are typically arranged in configurations such as "tandem", "side-by-side", "staggered" dual risers, triple risers at varying inflow angles, and riser arrays (Feng et al., 2021), as shown in Fig. 6. Compared to isolated risers, the interstitial flow between multiple risers leads to more complex VIV responses.

Dual risers are the fundamental units of riser cluster systems. Research on their VIV primarily focuses on analyzing the effects of spacing ratio, reduced velocity, and other factors on VIV characteristics. Zdravkovich (1985) demonstrated that the arrangement of dual cylinders significantly affects oscillations induced by vortex shedding. They classified the fluid–elastic responses of two cylinders with identical properties, providing a theoretical foundation for subsequent VIV research. Zhang et al. (2022) investigated the effects of spacing ratio, inflow angle, and reduced velocity on the VIV characteristics of staggered dual cylinders. Gu (2024) established a dual-cylinder geometric model and analyzed the effects of reduced velocity, spacing ratio, and diameter ratio on the VIV response characteristics of tandem cylinders using a two-way fluid–structure interaction numerical method. Liu et al. (2024) explored how the interplay of mass ratio, spacing ratio, and *Re* governs VIV-induced collisions between side-by-side cylinders.

Compared to dual-riser systems, the interactions between pipes in triple-riser systems make the VIV response more complex. In recent years, many scholars have conducted further research on VIV in triple-riser systems. Han et al. (2018) numerically simulated VIV of rigid cylinders in equilateral triangular arrays at various attack angles. The results showed that inflow attack angle significantly affects vortex shedding between arrays, and they identified the optimal inflow angle for suppressing cylinder vibrations. Zhang et al. (2021) observed that for equilateral triangular cylinder arrays under increasing reduced velocity, the vibration responses at different spacing ratios can be classified into initial branch, lower branch, and desynchronization region. Zhang et al. (2019) examined how reduced flow velocity and spacing ratio influence VIV behavior in triangular marine riser configurations. Tu et al. (2019) numerically investigated the effects of shear rate, natural frequency ratio, and reduced velocity on flow-induced force responses and flow field characteristics in tandem triple cylinders under shear flow.

As the number of risers increases, the VIV response becomes significantly more complex, rendering studies on four-riser and larger configurations particularly difficult. Consequently, existing research on multi-riser VIV systems remains scarce, with most studies limited to four or five riser arrangements. Yao and Deng (2023) investigated four risers in tandem arrangement, demonstrating that flow-mediated interference effects in stepped currents substantially modify the vibrational behavior of individual risers. Feng et al. (2021) arranged five risers side-by-side with equal spacing and analyzed the VIV patterns of the riser cluster under coupled interference effects. Gao et al. (2019) arranged four cylinders in a square pattern and simulated the effects of incident angle and reduced velocity changes on the cylinders' vortex-induced responses.

Current research on riser clusters mainly focuses on dual or triple riser systems. Therefore, further theoretical and experimental studies on VIV of multiple riser clusters in deep-sea drilling systems are needed to provide a theoretical basis for riser arrangement and collision avoidance under different working conditions.

### *3.2. Nonlinear vibration issues in conventional downhole drill strings*

As a critical component of drilling systems, the drill string undergoes complex rotational and drilling motions during operations in vertical, horizontal, and directional wells. It is subjected to multiple forces including bit–rock interaction, friction contact between the drill string and wellbore, and specific motions of downhole acceleration tools. These combined effects generate severe vibrations that may cause equipment damage and compromise drilling performance.

The nonlinear vibration issues of drill strings in formation sections primarily manifest as axial, lateral, and torsional vibrations and their coupling effects induced by drill string–formation interaction. These vibrations readily cause phenomena such as bit bouncing, whirling, and stick-slip, reducing drilling efficiency, increasing operational costs, and potentially leading to premature tool failure. A schematic of the three primary vibration modes is provided in Fig. 7.

**Longitudinal (axial) vibration:** The impact loads generated during drilling operations react on the drill string, inducing high-frequency longitudinal vibrations. When the vibration frequency matches the natural frequency or its harmonics of the drill string, it tends to cause bit bounce phenomenon, leading to fatigue failure. Such vibration effects are especially severe in geologically complex environments (Yan et al., 2006; Zhang, 2019).

Nandakumar and Wiercigroch (2013a, 2013b) refined the discrete dynamics model for drill strings, accounting for both axial stiffness and damping characteristics, with solutions obtained through Galerkin projection techniques. Linear stability analysis of this model yielded the parameter range for stable drill string motion. Li et al. (2024) developed a nonlinear dynamic model for horizontal well drill strings incorporating coupled dynamic responses and system energy transfer, analyzing buckling behavior under axially movable constraints. Results demonstrated absence of helical buckling in non-horizontal sections, with significant lateral vibrations occurring near the bit during extended horizontal drilling. Gao et al. (2024) established a longitudinal motion model incorporating vibration tools in horizontal wells, investigating the influence mechanism of tool frequency and drill string–wellbore friction on forced vibrations. Tengesdal et al. (2023) constructed a coupled model for directional well drill strings, validating steady-state motion and convergence in both longitudinal and lateral directions.

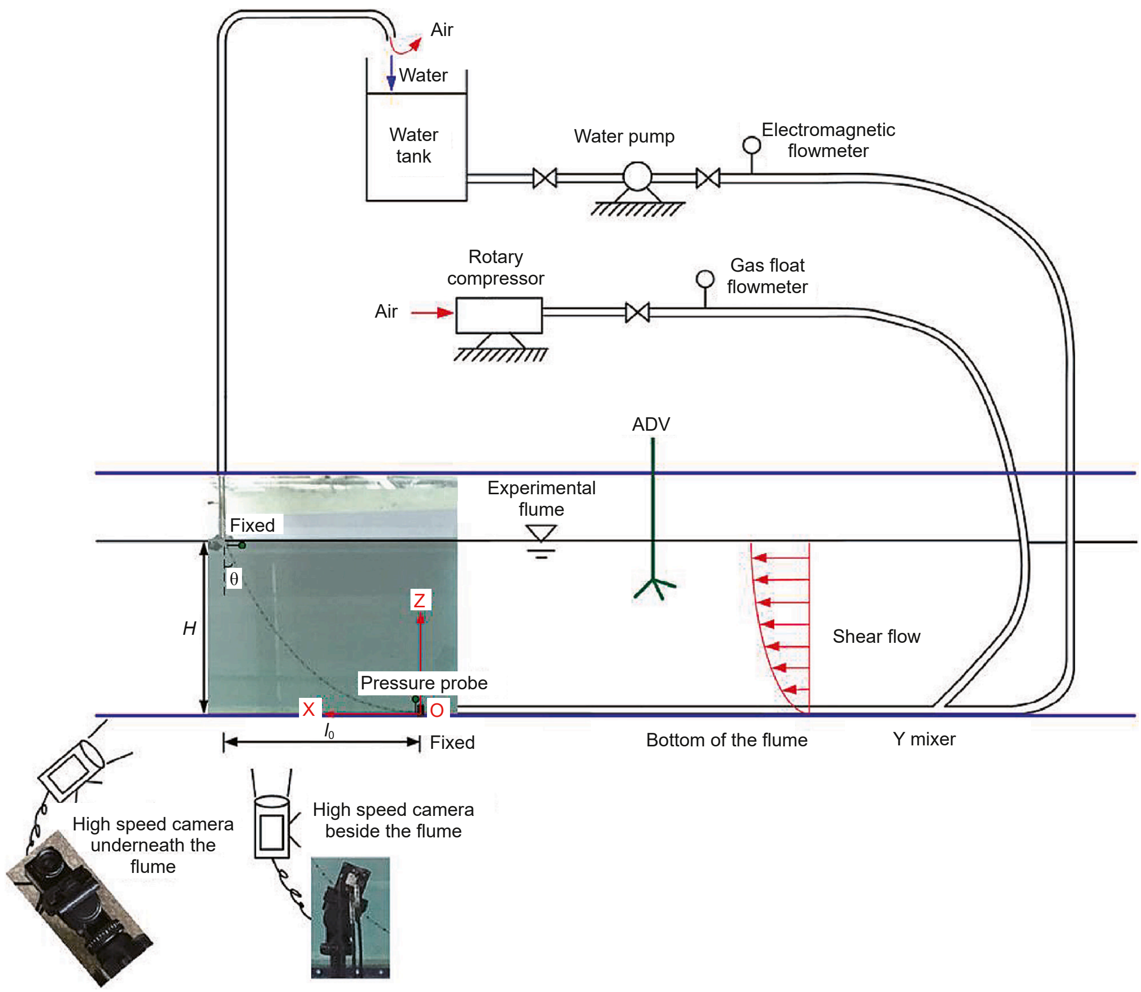


**Fig. 5.** Schematic diagram of the experimental setup.

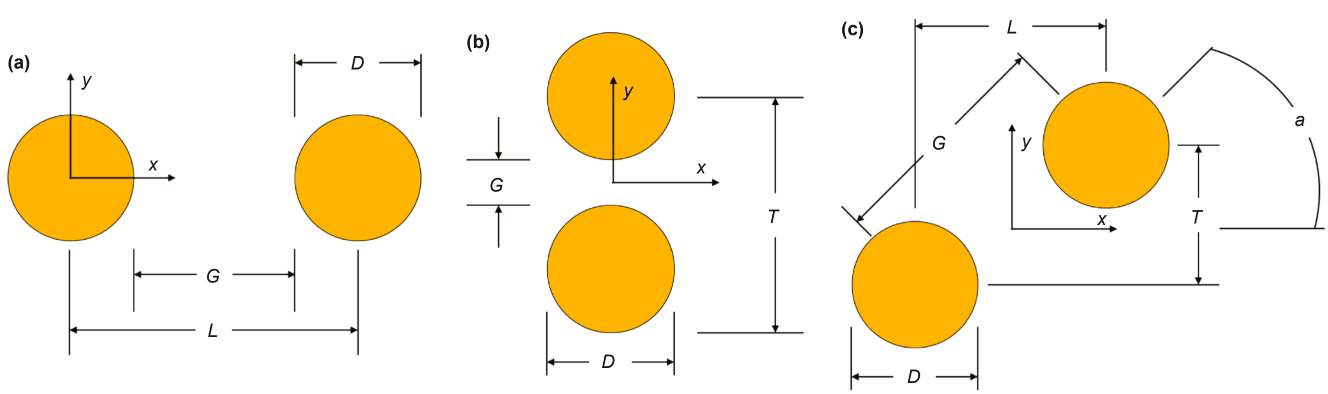


**Fig. 6.** Illustration of the configuration for two cylinders of identical diameter. **(a)** Serial distribution; **(b)** Parallel distribution; **(c)** Mosaic distribution.

**Lateral vibration:** Lateral vibrations primarily occur in the BHA section. Due to the narrow clearance between BHA and wellbore, and the multiple forces acting during drilling including centrifugal forces and frictional forces, these combined forces inevitably cause BHA contact with wellbore walls, resulting in whirling motion that compromises operational safety. Consequently, BHA whirling—as a critical vibration phenomenon—remains a primary concern in drilling dynamics research.

Kapitaniak et al. (2018) systematically investigated the characteristics of forward and backward whirl in BHA across different operational parameters. Experimental analysis revealed the coexistence of forward and backward whirl in BHAs, with model parameters subsequently calibrated based on experimental results. Vijayan et al. (2017) examined BHA–wellbore interactions by developing a discrete mass-spring system model, analyzing how rotational speed and axial forces affect backward whirl to mitigate

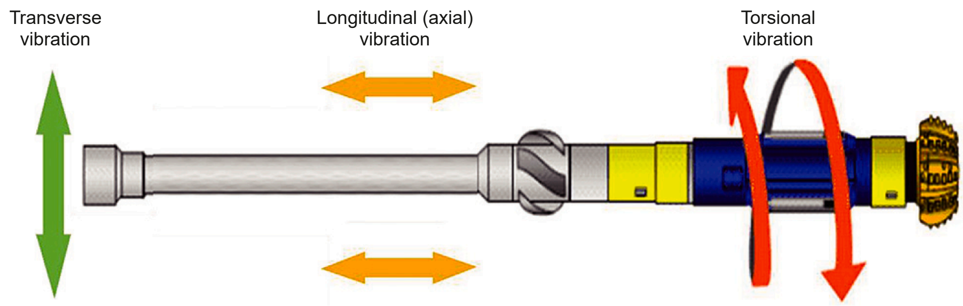


**Fig. 7.** Three forms of drill string vibration.

drill string fatigue. Zhu et al. (2021) employed a lumped-mass torsional model (Fig. 8) to investigate stick-slip vibrations in horizontal wells under varied conditions without WOB, revealing how nonlinear wall friction triggers these oscillations. Results demonstrated that nonlinear drill string–wellbore friction induces periodic stick-slip vibrations.

Mohammadzadeh et al. (2022) incorporated initial deformation-induced drill string–wellbore contact, bit–rock interaction, and geometric stiffening effects to establish full-order nonlinear equations for composite drill strings, analyzing how initial deformation affects their dynamic behavior. Liao (2022) converted conventional rock mechanics parameters into HJC constitutive model parameters, establishing dynamic models for drill string–wall collisions during drilling to quantify impacts on wellbore instability, casing deformation, and cement sheath failure. Di et al. (2024d) proposed a "pipe-in-pipe" coupled system model for deepwater riser–drill string interactions to understand their relative motion, reduce mutual contact, and ensure operational safety. By analyzing displacements and contact forces between risers and drill strings, they established coupled dynamic simulations for deepwater drilling operations. Tian et al. (2023) investigated the stochastic effects of wall collisions and frictional variability on drill string buckling characteristics in horizontal wellbores. To mitigate the damaging effects of lateral vibrations on the drill string, Ni et al. (2025) employed numerical simulation methods to investigate the stress characteristics of the drill string under various lateral motion states, validating the results with field data. Their findings reveal that although torque rises with increasing rotary speed, the correlation between bending moment and rotational speed is contingent upon the particular dynamic state of the drill string.

**Torsional vibration:** Stick-slip vibration represents the most significant manifestation of drill string torsional vibration, primarily occurring during bit–rock interaction. Extensive research has been conducted on bit–rock interaction dynamics to suppress or eliminate stick-slip vibrations in drill strings.

In 1982, Belokobyl'skii and Prokopov (1982) conducted research on the characteristics and influencing factors of stick-slip vibration in drill strings, and derived the bit–rock interaction principle that bit torque decreases as rotational speed increases. Kovalyshen (2014) performed linear stability analysis of coupled axial-torsional vibrations to investigate stick-slip causes, revealing that bit cutting action and wear flat/rock interaction are primary contributors. Gupta and Wahi (2016) utilized a lumped-parameter axial-torsional model with linear cutting force theory, incorporating bit bounce and stick-slip to analyze global BHA dynamics during rotary drilling. Bai et al. (2023) proposed a rate-of-penetration enhancement technology through adaptive bit–rock energy matching, applicable to deep, ultra-deep and complex formations, achieving 83% ROP improvement over conventional methods. Zhang (2019) established a bit–rock interaction model based on bit motion trajectory and developed a bit excitation model suitable for finite element analysis of drill string dynamics, and analyzed how structural parameters, WOB, RPM, and drilling fluid-induced added mass affect BHA lateral vibrations. It also investigated stick-slip and whirling behaviors in ultra-deep wells and proposed mitigation strategies. Results showed that while increasing RPM suppresses stick-slip, it amplifies BHA whirling. Adjusting WOB can effectively eliminate stick-slip vibrations. Kuang et al. (2024) designed a scaled experimental rig (Fig. 9) simulating horizontal well drill string dynamics using micro-bit, drill string, and rock samples. The setup incorporated segmented casing to constrain the drill string and a miniature PDC bit for rock cutting. Experiments investigated coupled vibrations and RPM/WOB effects on system dynamics.

Mao et al. (2023b) formulated a mathematical model for nonlinear dynamic characteristics of horizontal well drill strings by integrating 3D well trajectory, drilling parameters, and drill string–wellbore contact. They analyzed WOB, RPM, and stabilizer effects on lateral vibrations. The results show that during the drilling process, the closer to the bit or the greater the WOB, the greater the lateral vibration of the drill string in the deflecting section and the horizontal section, while the drill string in the vertical section is less affected by the WOB. Luo et al. (2023) established an axial-torsional coupled vibration model for deep well drill strings, validated and analyzed using a 5200 m case well. Analysis demonstrated that stick-slip vibrations can be mitigated by either reducing WOB or increasing bit blade count. Zhang et al. (2025) aiming to investigate the mechanism by which compound impact loads influence the stick-slip vibration of PDC bits, employed an experimental rock-breaking impact system. They analyzed the evolution of stick-slip vibration during the rock-breaking process of a PDC bit and, by applying axial-torsional compound impact loads, systematically examined the regulatory effect and influence characteristics of such loading conditions on the stick-slip vibration behavior during PDC bit rock fragmentation. Huang et al. (2025) investigated the relationship between stick-slip vibration and ROP using a combination of laboratory experiments and numerical simulations. Their findings indicate that increasing the WOB and reducing the drill string's torsional stiffness progressively intensifies the bit's torsional vibrations, culminating in the onset of stick-slip motion. Nonetheless, the ROP did not exhibit a significant change corresponding to the increase in torsional vibration intensity.

**Axial-lateral-torsional coupled vibrations:** During operation of deepwater riserless drilling systems, combined effects of external ocean loads in the seawater section, drilling fluid flow characteristics in formation sections, and nonlinear drill string vibrations readily induce coupled axial-transverse-torsional

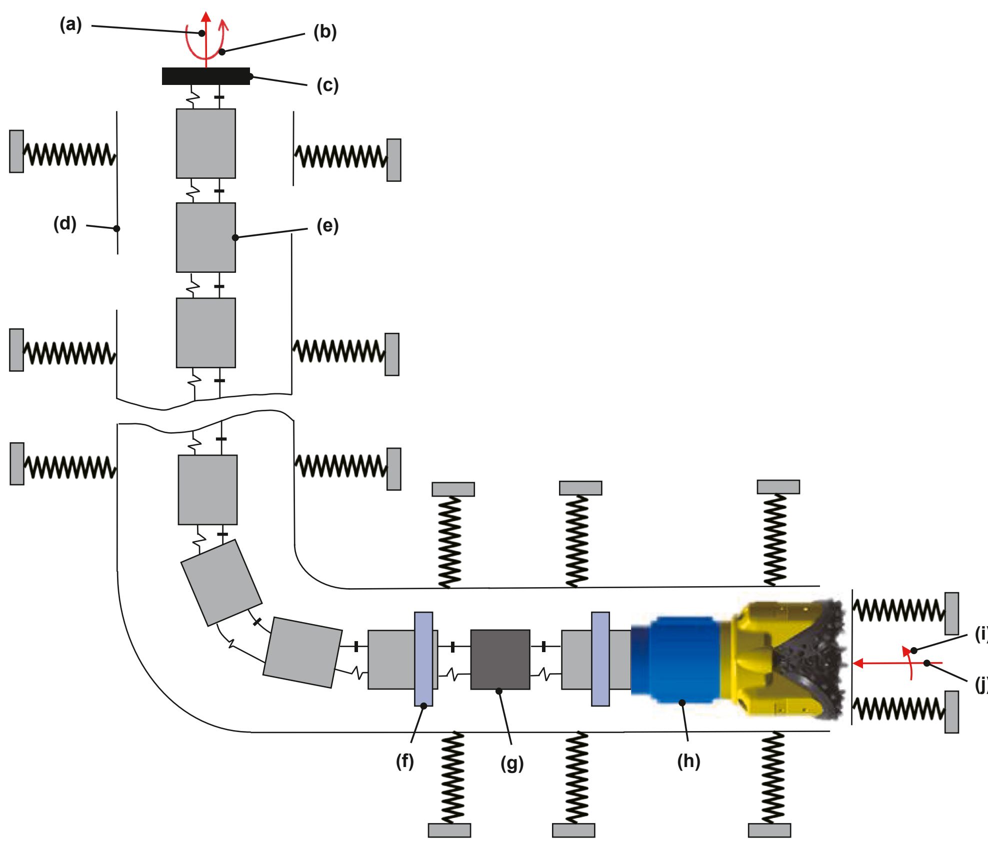


**Fig. 8.** Dynamic model of horizontal well drill string system. (a) Hook load; (b) Rotating speed; (c) Drill plate; (d) Shaft wall; (e) Drill pipe; (f) Centralizer; (g) Drill collar; (h) Drill bit; (i) Drill torque; (j) Drilling pressure.

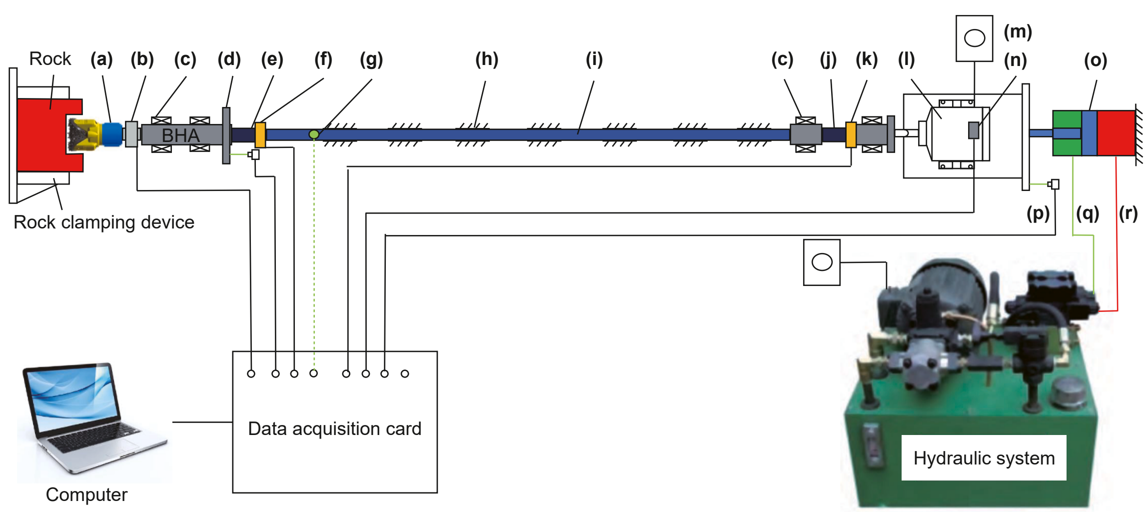


**Fig. 9.** Small-scale horizontal well test bench schematic. (a) Micro drill; (b) Speed encoder 1; (c) Ball bearings; (d) Displacement encoder 1; (e) Test joint 1; (f) Conductive slip ring 1; (g) Sensors; (h) Discrete casing; (i) Drill pipe; (j) Test connector 2; (k) Conductive slip ring 2; (l) Variable frequency motor; (m) Inverter; (n) Speed encoder 2; (o) Hydraulic cylinder; (p) Displacement encoder 2; (q) Oil return port; (r) Oil inlet.

vibrations. This leads to drill string wear and fatigue failure, compromising service life.

Feng et al. (2017) developed a coupled axial-lateral-torsional vibration model incorporating BHA eccentricity, drilling fluid damping, and bit–rock interaction, investigating WOB, RPM, and BHA eccentricity effects on drill string dynamics. Yang et al. (2018) established a coupled axial-transverse-torsional vibration model for extended-reach drilling, analyzing the mechanistic effects of WOB and RPM on drill string coupled vibrations. Results demonstrated that higher WOB increases vibration frequency/amplitude, while greater RPM reduces vibration period. Moraes and Savi (2019) analyzed coupled axial-lateral-torsional vibration characteristics considering bit–rock interaction, string–wall contact, drill string eccentricity and drilling fluid forces, examining effects of string length and RPM on coupled vibrations.

Current research on drill string axial-lateral-torsional coupled vibrations primarily focuses on formation segments, with insufficient coupled dynamic analysis of seawater and formation sections. Therefore, investigation is warranted for riserless drill string systems under combined seawater and formation loading conditions.

Liu et al. (2022) established separate axial, lateral, and torsional vibration models for deepwater riserless drill strings, accounting for seawater current, drilling fluid flow velocity, and drill string–wellbore collisions. They obtained the influence mechanisms of *Re*, velocity ratio, fluctuating WOB, and rotation speed on drill string vibrations. In 2023, Liu et al. (2023c) extended this work by incorporating bit–rock interaction and seawater–formation coupling effects, establishing a full-well coupled axial-lateral-torsional nonlinear vibration model for riserless drilling. Experimental validation confirmed the model's effectiveness.

The coupling mechanisms between the oceanic load characteristics that induce VIV in the seawater section and the downhole nonlinear vibrations in the formation section represent critical issues urgently requiring resolution in deepwater riserless drill string dynamics. While sharing some commonalities with standard systems, the distinctive features of deepwater riserless operations— including the fully exposed drill string in the water column and the extreme deepwater pressure—exacerbate dynamic hazards. This necessitates more refined modeling and rigorous experimental verification for accurate dynamic analysis of such drill strings.

## 4. Key issues in drill string vibration control

The preceding sections have separately analyzed the multiple external loads acting on deepwater riserless drill strings and the key dynamic problems they excite (VIV in the seawater section and nonlinear vibration in the formation section). Suppressing these deleterious vibrations is essential for ensuring safe and efficient drilling operations. Present vibration mitigation strategies are largely based on two principal technical routes: active and passive control. Their implementation is intrinsically linked to the specific vibration mode and its location of occurrence.

### *4.1. VIV control in seawater section*

To mitigate or eliminate VIV-induced damage and extend service life of seawater-exposed drill strings, effective VIV suppression remains a critical challenge in riserless drilling systems (Fan, 2023). The mitigation of VIV in the seawater-section drill string is mainly accomplished via passive control strategies, either by altering the surrounding flow field or through the direct application of opposing forces.

#### *4.1.1. Active vibration control*

This method primarily employs controllers to identify real-time drill string data and implement control actions. Through this process, it achieves the suppression or elimination of harmful vibrations. The method demonstrates good adaptability with precise and efficient control performance, but requires higher technical expertise and incurs greater costs than passive control.

Baz and Ro (1991) designed a direct-drive feedback controller to suppress multi-modal VIV in flexible cylindrical structures. Results indicated that the suppression efficiency could reach 40%. Song et al. (2021) considered shear flow-induced bending moments and designed a linear quadratic regulator (LQR) optimal controller, effectively suppressing multi-modal vibrations in risers. The results showed that the suppression efficiency could reach 71%–89% compared to the original system. Xiros and Aktosun (2022) utilized neural networks to forecast fluid forces arising from VIVs in a cylindrical structure. The derived neural network approximator was then integrated into the dynamic model by adjusting the compensator's linear stiffness and damping. This approach successfully mitigated VIVs in the cylinder. Hasheminejad and Fallahi (2023) designed a self-tuning fuzzy proportional integral derivative control method, which achieved effective two-degree-of-freedom (2DOF) VIV control for an elastically mounted cylinder. The proposed method exhibited superior efficiency relative to alternative control approaches. Zhao et al. (2017) accounted for the effects of coupled internal flow dynamics, developing a boundary control system and disturbance observer for effective vibration mitigation in flexible risers. Zhang et al. (2022) focused on a flexible marine riser system with top tension constraints, and proposed an output feedback controller to suppress riser vibrations, where the riser's dynamic behavior was represented by partial differential equations. Zhou et al. (2025) designed an adaptive fuzzy backstepping control algorithm to effectively suppress vibrations in marine flexible riser systems with uncertain parameters. Numerical simulation results demonstrated that this algorithm outperforms both PID control and robust adaptive control in suppressing flexible riser vibrations. Yu et al. (2022) proposed an adaptive neural network-based boundary control method to suppress vibrations in flexible marine riser systems with unknown nonlinear disturbances and output constraints.

#### *4.1.2. Passive vibration control*

Through changes to the structural surface morphology or installation of additional devices to modify the near-field flow characteristics, the vortex generation, evolution, and detachment processes can be controlled. The predominant vibration mitigation devices in current applications include helical strakes and fairing (Dong et al., 2016; Yang et al., 2023). Its principal configuration is illustrated in Fig. 10.

**Helical strakes:** The working principle of helical strakes is to disrupt the fluid symmetry around the riser through spiral blades (similar to threads), interfering with vortex formation and thereby reducing the amplitude of VIVs.

Trim et al. (2005) used a riser model with a slenderness ratio of 1400 to simulate VIVs of marine risers in both uniform and shear flows. The study evaluated VIV suppression performance of helical strakes with two distinct pitch-to-height ratios at varying coverage lengths. Quen et al. (2014) investigated the effectiveness of strakes in suppressing VIV of long flexible cylinders by varying the spacing ($p$) and height ($h$) of the strakes. Results showed that increasing strake height narrowed the lock-in region and provided optimal vibration suppression. Nevertheless, significant drag loss persisted at higher reduced velocities. Holland et al. (2017) conducted numerical simulations to study vortex-induced motions of a semi-submersible platform equipped with helical strakes. The results demonstrated significant sway motion reduction but revealed non-negligible increases in total inline drag resistance. Xu et al. (2018) performed experimental investigations of VIV suppression for flexible cylinders characterized by large length-to-diameter ratios, small mass ratios and significant inclination angles in a laboratory towing basin, evaluating the VIV suppression performance of helical strakes and further examining the vibration response features of inclined cylinders. Yang et al. (2024) considered both in-line and cross-flow vibrations of the VIV suppression device, established a fluid–structure interaction dynamic model

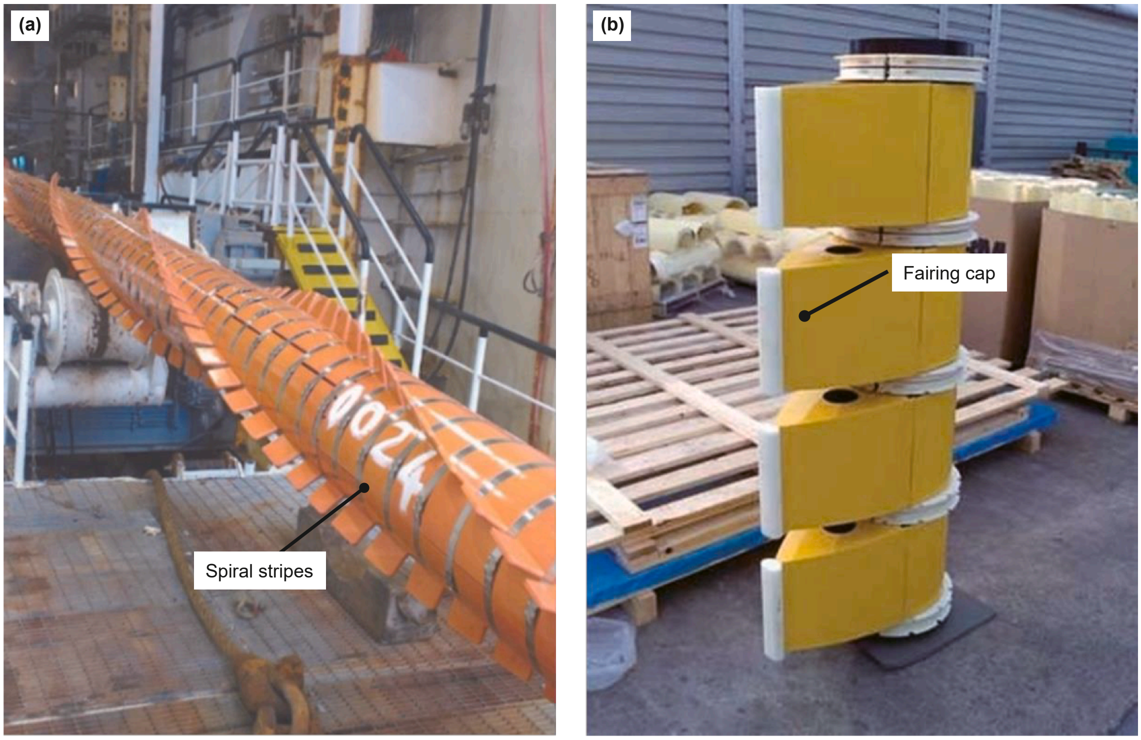


**Fig. 10.** Schematic diagram of vibration suppression device. **(a)** Helical strakes (De Wilde, 2020); **(b)** Fairing cap (Zhao, 2011).

for the VIV suppression device, and predicted and validated the suppression effectiveness of helical strake VIV suppression devices on marine riser VIV.

Although helical strakes are simple to install and require no complex maintenance, the helical grooves are prone to marine biofouling and sediment accumulation, which may degrade performance over time, necessitating periodic cleaning to ensure optimal performance.

**Fairing cap:** The working principle of fairing cap is to optimize the flow field around the riser through streamlined outer casings (such as teardrop or airfoil shapes), delaying flow separation and suppressing vortex generation.

Xie et al. (2015) performed numerical modeling of the vibrational behavior and surrounding flow fields for a cylinder fitted with freely-rotating U-shaped fairing cap under transverse flow conditions within a defined *Re* regime, evaluating the VIV mitigation performance of three distinct fairing geometries. Wang et al. (2015) employed teardrop-shaped fairings to control cylinder wake flow and suppress Kármán vortex street formation, and quantitatively evaluated the results using high-precision computational fluid dynamics (CFD) techniques. Results showed that when the fairing trailing-edge angle was between 30° and 45°, both lift coefficient and mean drag coefficient were significantly reduced. Zhao (2019) combined fairings with splitter plate suppression devices, evaluating the VIV suppression effectiveness of short-tail fairings under both low and subcritical *Re* conditions. Xia et al. (2021) investigated galloping phenomena resulting from high rotational friction coefficients in fairing systems, developing a two-dimensional mass-spring-damper analytical model. They numerically studied the galloping mechanism, two-degree-of-freedom galloping characteristics, and the influence of in-line to cross-flow natural frequency ratios on galloping. Using numerical methods, they examined the galloping generation mechanism, 2DOF galloping behavior, and the effect of in-line/cross-flow natural frequency ratios on galloping response. Zhang (2022) conducted numerical simulations of riser VIV using a simulation platform, and results demonstrated that 45° trailing-edge fairings could effectively reduce vibration amplitudes in the lock-in region.

Compared to helical strakes, fairings contribute less additional structural weight and have broader applicability. Nevertheless, stuck of the rotational mechanism could potentially amplify vibrational responses, thus requiring segmented assembly and high-precision installation in deep-sea applications.

### 4.2. Drill string vibration control in measure section

For complex vibrations in the formation-section drill string (such as stick-slip, whirling, and coupled vibrations), control focuses on active methods to regulate system input or dissipate vibrational energy.

**Active control:** The active control of drill strings is achieved by real-time monitoring of various drilling parameters, followed by applying targeted disturbances or open-loop control inputs to either the drill string itself or its surrounding flow field as needed, thereby achieving vibration suppression (Li et al., 2024). Based on the control type and scope of active control methods, existing research can be summarized as follows.

Torsional vibration control: As the most typical and detrimental manifestation of torsional vibration, stick-slip vibration is a primary focus of control research (Zhang et al., 2025). Liu et al. (2021) established a dynamic model for drill string stick-slip vibration and derived the general patterns governing this phenomenon. They employed an active disturbance rejection control (ADRC) method to suppress stick-slip vibration. Experimental results demonstrated that this method can eliminate stick-slip vibration by reducing motor torque fluctuations, thereby achieving compliant torque control of the drill string. Su et al. (2023) employed a machine learning algorithm to optimize the parameters of a fractional-order PID controller designed to suppress drill string stick-slip vibration. The results indicated that the optimized

FOPID controller performs effectively in suppressing mild stick-slip vibration, but shows limited efficacy when the drill string experiences severe stick-slip (sticking). Zhang and Wu (2018) established dynamic models for the drill string rotary system and hoisting system, along with their load models, and designed a state feedback controller based on a LQR control strategy. Simulation results showed that the use of the LQR controller reduces fluctuations in WOB, torque, and axial displacement, effectively suppressing drill string stick-slip vibration and bit bounce. Kabziński (2017) developed a nonlinear adaptive controller incorporating command-filtering techniques for the suppression of torsional vibrations in drilling systems. Farhangfar (2022) devised a robust model predictive controller utilizing an observer to mitigate stick-slip vibration in drill strings. It features automatic parameter tuning in response to real-time operational conditions, resulting in effective vibration suppression. Tian et al. (2022) proposed a hydraulic clutch controller (HCC) suitable for directional drilling. Compared to a controller-free drilling system, the HCC can effectively reduce friction and suppress stick-slip vibration.

Control of axial and lateral vibrations: In contrast to torsional vibration, which is primarily localized at the bit, axial and lateral vibrations encompass drill string–wellbore interactions and the global dynamic behavior of the drilling assembly. Sassi et al. (2021) conducted experimental research on suppressing periodic drill string vibrations using controllers that manage vibration transmissibility in different directions, and validated the feasibility of this approach through a laboratory prototype. The validation results indicated that this controller can improve the dynamic behavior of the drill string, manage its longitudinal and axial vibrations, and significantly reduce vibration amplitudes within a specific frequency range. Zhu (2025) taking into account the influence of drill string lateral vibration, systematically analyzed the effects of parameters such as lateral acceleration, rotary speed, and WOB on wellbore instability, and proposed bit arrangement and structural design methods that significantly suppress lateral vibrations.

Coupled vibration control: In practical drilling operations, drill string vibrations frequently manifest as the coupling of multiple modes. Some researchers (Rajabali et al., 2020; Barjini et al., 2024) formulated coupled axial-torsional vibration equations for the horizontal section of horizontal wells to study the stability of horizontal drill strings. They designed a nonlinear sliding mode controller that effectively suppressed the coupled axial-torsional vibrations and developed an extended Kalman filter to estimate all state variables in the model, thereby addressing the issue of sensors being unable to record all state variables. Li et al. (2025) conducted a simulation study on the effectiveness of LQR control in suppressing both axial and torsional vibrations of the drill string, aiming to effectively address the failure issues induced by coupled axial-torsional vibrations. Boussaada et al. (2013) established a coupled axial-torsional vibration model for the drill string that incorporates both feedback delay and state delay, and discussed the vibration suppression effectiveness of PID control.

Passive control: Passive control of drill strings refers to structural modifications of certain components within the drill string system to alter its dynamic characteristics. As an energy-independent control method, its control capability stems from passive deformation of control devices induced by structural vibrations, thus making the control process immune to structural responses and external disturbances (Li et al., 2024).

Bailey and Remmert (2010) improved a novel BHA design by removing the near-bit stabilizer and relocating the roller reamer from the drill collar position to the heavyweight drill pipe, This modification effectively controlled drill string resonance and stick-slip vibrations. Selnes et al. (2009) developed a circumferential vibration absorber that converts torsional forces into circumferential spring compression energy, thereby reducing drill string torsional vibrations. Lv (2020) designed a cylindrical LWD tool vibration absorber based on the impact of drill string vibrations on logging-while-drilling instruments, which can effectively suppress lateral vibrations in the drill string system and reduce rotational speed effects on vibrations. Hu et al. (2022) investigated vibration dampener effects on both upper drill string and bit by treating the dynamic bit–rock interaction process as a bottomhole boundary condition. Radford et al. (2009) designed a concentric expandable reamer. When expanded, it contacts the wellbore wall to minimize bending moments in the drill string, thereby providing vibration damping. McCarthy et al. (2012) designed a V-shaped stabilizer. Based on the principle that the centripetal force will be generated when the drill string rotates, the stabilizer can interfere with the propagation of the vibration mode transmitted to the stabilizer. Gong et al. (2025) formulated an enhanced mechanical specific energy model for complex directional drilling operations, and optimized key parameters based on this model to improve drilling efficiency. Mi (2022) investigated the mechanistic effects of vibration damping tools and well deviation angle on drill string effective vibration length in directional drilling. Results showed that within a certain range, the effective vibration length increases with greater distance from the bit, but stabilizes when the distance becomes too large.

### 4.3. Correlation between loads and control methods

The previous sections of this work have systematically categorized the external loads experienced by deepwater riserless drill strings during operations, covering influences from both the seawater column and the subsurface formation, such as drilling fluid dynamics and bit–rock engagement. These loads differ significantly in their action mechanisms, consequently inducing various types of vibration phenomena, such as VIV, stick-slip vibration, coupled axial-lateral-torsional vibration, and parametrically excited resonance.

Conversely, available vibration mitigation strategies vary considerably in their fundamental design and suitable operating regimes. The choice of control method must be aligned with the specific vibration type generated by a given load. Therefore, building upon a summary of the control techniques, it is essential to develop a mapping between the external loads, the resulting vibration instability modes, and appropriate control methodologies. This provides a systematic framework for identifying more suitable and efficient control approaches under varying load scenarios. Based on the aforementioned load analysis and review of control methods, this paper summarizes different external loads and the vibration forms they induce, linking them to the most relevant control methods. This correspondence is presented in Table 2.

Synthesizing the preceding separate discussions on control technologies for VIV in the seawater section and drill string vibrations in the formation section, passive control and active control, as two fundamental technical approaches, exhibit significant differences in their core characteristics and applicable conditions. To clearly present a systematic comparison between the two across key dimensions such as suppression effectiveness, cost, and risk, the typical characteristics of both technologies are summarized in Table 3.

In conjunction with the content of Table 3, to achieve optimal control and ensure safe, stable, and efficient drilling operations, the technological development path for vibration control in deepwater riserless drilling should focus on constructing a hybrid control architecture characterized by “a passive control foundation enhanced by active intelligent optimization". At key locations highly sensitive to drill string vibrations, adaptively analyzed and improved passive vibration dampening devices should be deployed. Simultaneously, based on key drilling data collected on-site and integrated with optimized intelligent algorithms, global dynamic regulation of drilling parameters and top-drive operating modes should be implemented to achieve system-level vibration suppression and improve drilling efficiency.

## 5. Emerging control technologies for drilling systems

The reliable and high-performance operation of drilling systems is essential for exploiting deep-sea mineral resources during riserless drilling operations in deepwater environments. As previously discussed, deepwater riserless drilling systems confront significant dynamic complexities, notably triaxial (axial-lateral-torsional) coupled nonlinear vibrations and high-frequency stick-slip oscillations in drill strings. Conventional control methods are limited by data acquisition delays and slow control model updates, making real-time dynamic behavior regulation difficult to achieve. With the advancement of intelligent drilling technology, closed-loop systems integrating smart data transmission, data-driven modeling and intelligent control ("data sensing—modeling analysis—decision control") are becoming the core solution for deepwater drill string dynamics problems.

### 5.1. Intelligent data transmission technology

Time delays and discontinuity in drilling data transmission constrain the intelligentization of drilling processes. As Zhang (2014) demonstrated, mud pulse channels exhibit time-space frequency variation characteristics, long latency, and lismited feedback capacity. Meanwhile, with the development of technologies such as imaging logging, the amount of downhole data has surged (such as high-resolution geological parameters), and the original transmission methods can no longer meet the demand for real-time transmission of large amounts of data. Research on emerging data transmission technologies can break through the bottlenecks of traditional transmission technologies, achieve highly reliable, low-latency, and adaptive data transmission, thereby supporting real-time closed-loop control.

Currently, measurement-while-drilling systems both domestically and internationally generally use drilling fluid pulses to transmit measurement data. This technology cannot work normally in gas or aerated drilling fluid environments; meanwhile, the signal transmission rate of drilling fluid pulses is low, making it difficult to achieve bidirectional communication of downhole and surface data. The emergence of electromagnetic (EM) transmission technology has solved this problem well. Its transmission process is basically not affected by the drilling fluid medium, solving the problem of low real-time data transmission efficiency (Li et al., 2009), and it is widely used in oil exploration processes.

NOV Corporation implemented non-contact toroidal antennas in downhole short-range wireless systems, achieving short-distance electromagnetic transmission within oil/gas pipes (Liu et al., 2023). Raytheo company accomplished bidirectional surface-to-downhole communication by combining low-frequency EM waves with mud pulse transmission (Fan et al., 2016). Wang et al. (2016) investigated the influence mechanisms of parameters such as formation resistivity, annular drilling media, and surface environmental conditions on the electromagnetic signals of electromagnetic measurement-while-drilling systems. Results showed effective data transmission during foam drilling with minimal drilling fluid dependence. Li et al. (2022) developed a downhole wireless monitoring system for shale gas well production dynamics based on technologies such as electromagnetic wave transmission. This system can collect real-time dynamic data such as fluid temperature, flow rate, and pressure in the wellbore, and directly upload them to the surface system through an electromagnetic wave transmitter. DEMETER company has realized long-distance data transmission of low-frequency electromagnetic waves through the leakage current loop between the outer wall of the casing and the formation (Deng, 2022). Jiang (2022) adopted ultra-low frequency electromagnetic waves as the transmission carrier and communication mechanism, and loaded the collected temperature and pressure signals into the downhole closed oscillation circuit, thereby effectively enhancing the wireless transmission performance of downhole data in the drilling process.

### 5.2. Data-driven modeling technology

Data-driven drilling technology utilizes sensors and automated equipment to collect, analyze, and apply real-time drilling data for parameter optimization, efficiency improvement, and safety

**Table 2**
Table of correlation between primary loads and control methods.

| Load type | Induced vibration form | Primary control method | Method advantage | Limitation |
|---|---|---|---|---|
| Marine environmental loads | VIV | Passive control: helical strakes, fairings. | It disrupts vortex shedding through geometric design, offering high reliability. | Its performance is static, potentially increases drag, and lacks adaptability to varying downhole conditions. |
| Bit–rock interaction forces | Stick-slip vibration | Active control: PID, ADRC, MPC-based top-drive torque/RPM algorithms | It directly regulates system energy input, responds rapidly, and fundamentally suppresses torsional instability. | It highly depends on precise speed/torque measurement and fast actuators. |
| Drill string–wellbore contact/collision | Whirling, lateral vibration | Passive control: optimized BHA design, stabilizers, lateral dampers | It suppresses vibration by altering contact conditions or increasing system damping. | Its design is experience-dependent and poorly adapts to unforeseen formation changes. |
| Coupled multi-load interactions | Parametric resonance, coupled axial-lateral-torsional vibration | Intelligent coordinated control: multi-source data-driven MPC, adaptive coordination algorithms | It handles multi-variable, strongly coupled system dynamics for global optimization. | The algorithms are complex and demand high model accuracy, computational resources, and real-time data. |

**Table 3**
Comparison of active and passive control technologies for riser/measure-section drill strings.

| Control mechanism | Marine riser vibration control | | Measure-section drill string vibration control | |
|---|---|---|---|---|
| Control type | Passive control | Active control | Passive control | Active control |
| Core control parameters | It controls the flow separation point and vortex shedding pattern around the riser by designing its geometry to disturb the flow. | Sensors are employed to detect and regulate the riser's modal response or boundary forces for real-time vibration counteraction. | Vibrational energy is passively dissipated or isolated by modifying the drill string system's stiffness, damping properties, or contact state. | It suppresses vibrations by algorithmically controlling the top-drive torque and speed, or adjusting downhole tool states. |
| Typical technical methods | Helical strakes, Fairings | Optimal control, Adaptive/intelligent control. | Axial/torsional dampers, BHA design optimization | PID control, ADRC, MPC |
| Test/operational conditions | Helical strakes: A pitch length/strake height of 17.5 D/0.25 D yields better suppression (Xu et al., 2018); Fairings: A vertex angle of 60° yields superior suppression performance (Zhao, 2011). | Control input: Requires input parameters like flow velocity, displacement. | System excitation: typically bit–rock impacts, random wellbore friction, etc. Key parameters: damping coefficient and stiffness coefficient of the damper. | Primary control target: Top-drive motor (torque, speed); Control objective: Fluctuation of bit speed/torque |
| Performance efficacy | Helical strakes can reduce VIV amplitude by over 90%, fairings by over 80%; | Simulation results indicate LQR control achieves 71% to 89% suppression efficiency for multi-mode VIV. | Axial dampers can reduce vibration amplitude by 30%–50%; Torsional dampers can reduce torque vibration by 40%–60%. | Optimization algorithms considering vibration constraints can improve ROP by over 20%. |
| Cost and risk | Helical strakes may increase the drag coefficient by 20%–40%; Fairings may experience “galloping” phenomenon. | Reliance on dense sensor arrays leads to high cost; model mismatch or sensor failure can easily cause control failure. | Control performance faces harsh environmental challenges such as high temperature, high pressure, and material degradation. | Reliant on accurate downhole or surface measurement signals, significantly affected by delay or noise. |
| Applicability evaluation for riserless drill strings | Applicability rating: Medium–Low. Control algorithms must account for boundary excitation from the formation section in the model. | | Applicability rating: Medium–High. Active control algorithms need to account for additional disturbances introduced by seawater-section VIV. | |

enhancement. This approach not only elevates drilling intelligence but also substantially reduces operational costs and risks.

Li et al. (2024) proposed a data-driven model for predicting erosion rates in downhole compressed air storage strings. They established a CFD model coupling discrete and continuous phases to investigate how gas velocity, pipe bending angle, diameter, sand particle size, and mass flow rate affect erosion rates. Using this dataset, they created an extreme learning machine-based data-driven model for rapid erosion rate prediction. Keshavarz et al. (2024) integrated surface drilling parameters (flow rate, RPM, string length) with hook load, pressure, and torque measurements during wellbore conditioning to predict additional surface sensor data. Zhang et al. (2023) combined conventional hydraulic models with AI methods to create a measured-data-based cuttings distribution technique, advancing hole cleaning research through pressure-derived flow characteristics and introducing along-string measurement (ASM) data for quantitative cuttings distribution assessment. Results demonstrated accurate real-time evaluation of cuttings distribution and hole cleaning status, effectively addressing insufficient cleaning in extended-reach and horizontal wells. Magnus et al. (2021) implemented an extremum seeking data-driven optimization approach to automatically minimize mechanical specific energy in real-time, achieving more efficient and safer drilling. The method conducts small-scale tests of WOB and rotation speed (RPM) during drilling to gather downhole condition data, then automatically implements optimizations based on test results. Simulation results showed the ES method can track optimal WOB-RPM variations corresponding to formation changes, with ROP improvements ranging 20%–170%.

### 5.3. Intelligent control technology

Intelligent control technology is currently in a phase of rapid development with broad application prospects. Although research applying neural networks and artificial intelligence technologies to drilling control remains in its infancy, it has emerged as a new research direction in drilling. Current intelligent control of drilling systems primarily divides into holistic system control and critical component (drill string) control.

**Holistic control:** Tang (2024) upgraded the well control equipment pressure testing system by integrating pneumatic relief valves, proportional servo valves, control cabinets, and control software. The system enables remote control, intelligent pressure ramp-rate adjustment, automatic pressure relief, and smart test report uploading to databases. The upgrade significantly improved automation, reduced operator workload, and substantially lowered operational risks. Hao et al. (2024) developed a model-free online learning adaptive decision strategy for intelligent wellbore adjustment and toolface stabilization in both slide-steering and rotary-steerable systems under complex downhole conditions. They created reward functions incorporating expert operational experience to learn directional strategies from driller corrections. Additionally, a priority-based experience replay mechanism was implemented to enhance online learning efficiency. Li (2024) investigated four key smart sensing technologies (formation, tools, fluids, equipment) for offshore drilling/completion, developing an intelligent monitoring system covering the entire well lifecycle. Wang (2020) developed a complete hydraulic disc brake auto-driller control system for precise downhole WOB control. A novel fuzzy-mmune PID controller was implemented, with online proportional gain adjustment via fuzzy-immune control and real-time integral/derivative tuning through adaptive fuzzy logic. To tackle the challenges of slow drilling speed, accelerated bit wear, and inefficient rock fragmentation in hot dry rock formations, Jiao (2025) optimized PDC bit operational parameters. This work established an intelligent decision-making framework for drilling optimization by leveraging digital twin and deep learning techniques. As the conventional driller-dominated drilling parameter regulation mode fails to achieve adaptive optimal regulation, Zhao et al. (2024) constructed an adaptive control system architecture for drilling parameters relying on digital twin technology and systematically clarified its operating mechanism. Hu (2025) noting that traditional wellbore and reservoir models fail to fully capture the complex nonlinear dynamic changes within the wellbore, proposed a machine learning-based digital twin model to dynamically calculate the liquid loading risk in gas wells over long-term production. Zhang (2025) confronting the problem that existing drilling risk early-warning methods struggle to achieve accurate identification and timely alerts in the early stages of risk, proposed a drilling risk warning method that integrates knowledge graph and deep learning technologies, thereby reducing drilling risk incidence and improving operational efficiency.

The holistic control of the drill string system pursues global optimization and coordination, thereby enabling multi-objective collaborative decision-making such as intelligent optimization of drilling parameters and precise navigation of the wellbore trajectory (Zeng et al., 2024). The core advantage of holistic control lies in its ability to transcend the boundaries of subsystems, consequently enhancing drilling efficiency while reducing operational costs and risks. Nevertheless, significant challenges remain prominent: the inherent complexity of certain drilling systems means that holistic control could lead to a considerable rise in drilling costs, while constraints like restricted offshore/downhole communications may adversely affect the stability and responsiveness of the control system.

**Critical component control:** Laib and Gharib (2024) developed a cascade feedforward neuro-fuzzy PID controller for multi-degree-of-freedom drill string systems under torsional vibration. Compared to conventional PID controllers, it demonstrates superior performance in handling variations of WOB and desired bit speed. Sharifinasab et al. (2023) conducted ROP prediction research using neural networks and AI methods with field data, developing effective intelligent prediction approaches validated through field cases. Wang H.G. et al. (2024) noted that advancing data acquisition, processing, and multi-source data integration enables machine learning to significantly improve vibration identification/prediction accuracy and reliability through optimized algorithms. Hegde et al. (2019) proposed an optimization algorithm combining ROP enhancement with machine-learning-based vibration modeling, incorporating extreme vibration modes as constraints to ensure parameter optimization increases ROP without excessive vibrations. Feng (2019) developed a top drive controller based on directional drilling models (top drive/drawworks, drill string–wellbore contact, and bit–rock interaction) to control drill string vibrations, along with a genetic algorithm to optimize BHA stabilizer placement for vibration suppression. Zhang et al. (2020) addressed drilling data noise interference using quality control algorithms for drilling sequence data, developing a conjugate gradient-optimized neural network for accurate formation identification. Guo et al. (2025) addressing the issues of low efficiency, high cost, and poor stability in measuring drilling fluid rheological properties during experiments, proposed a drilling fluid rheological property prediction method based on generative adversarial networks within a digital twin environment. In response to the challenge of applying standard machine learning to real-time drilling torque prediction, Bai et al. (2025) developed a just-in-time learning framework and a localized machine learning model utilizing digital twin technology. Mamoori et al. (2025) addressed the issue of traditional detection methods being prone to delays and human errors by proposing an anomaly diagnosis method based on a deep learning autoencoder to enhance the accuracy of stuck pipe incident detection.

Control strategies targeting critical drill string components are dedicated to the optimization of particular performance indicators, such as mitigating vibrations or enhancing the mechanical drilling speed. Its advantages lie in the highly targeted nature of the control strategy (e.g., the previously designed cascade neural fuzzy PID controller) and high flexibility (it can be developed and tested as an independent module without altering the entire drilling system architecture, facilitating implementation and iteration). A potential drawback is the risk of achieving only a “local optimum”. Optimization focused on a single objective may compromise global performance if not properly synchronized with other critical subsystems, such as wellpath control and drilling fluid hydraulics.

For a systematic comparison of the advanced control methods discussed above, Table 4 summarizes their technical features and practical suitability for drilling based on key criteria: control principle, required measurement, actuation option, implementation difficulty, latency sensitivity, and energy limit.

Based on the preceding discussion, intelligent control of drilling systems can be divided into two major categories according to their control objects and core objectives: overall drilling system control and key component control of the drill string. The two exhibit systematic differences in control scope, technical approaches, and engineering challenges. For a clear comparison of their features, a summary of the two control approaches is provided in Table 5.

**Table 4**
Comparison of emerging control method characteristics.

| Control method | Control principle | Required measurement | Actuation option | Implemen-tation difficulty | Latency sensitivity | Energy limits |
|---|---|---|---|---|---|---|
| PID | Linear error feedback using proportional, integral, and derivative terms | Single output (e.g., speed, pressure, torque) | Motor torque/speed, valve opening | Low | Medium | Not explicitly considered |
| LQR | Optimal state feedback minimizing quadratic cost | Full state or state observer | Motor torque, actuator force | Medium–High | High | Explicit energy weighting |
| ADRC | Disturbance estimation and compensation | Single output | Motor torque/speed, valve opening | Medium | Medium–High | Implicitly considered |
| MPC | Rolling-horizon optimization under constraints | Multi-variable states or outputs | Multi-actuator coordinated control | High | Very high | Explicitly considered |
| SMC | Enforcing system motion on a designed sliding surface | State or error variables | Force/torque actuators | Medium–High | Medium | Implicitly considered |
| HCC | Hydraulic torque modulation and dissipation | Speed difference, pressure, torque | Hydraulic valves and clutch mechanisms | High | Low–Medium | Physically constrained |

**Table 5**
Comparison of holistic control and critical component control methods.

| Comparison dimension | Holistic control | Critical component control |
|---|---|---|
| Core control scope | Coordination of multiple subsystems and global optimization of the drilling process | Dynamic behavior and stability of the drill string itself |
| Primary control objectives | System stability, operational safety, drilling efficiency | Vibration suppression, fatigue reduction, instability avoidance |
| Typical technical methods | Data-driven modeling and optimization<br>Digital twin and simulation<br>Intelligent decision-making systems | Vibration-specific algorithms<br>Adaptive and robust control<br>Vibration-based condition monitoring |
| Advantages | Capable of integrating multi-source loads and system coupling effects | High specificity and fast response speed |
| Limitations | Complex models, high parameter uncertainty, stringent real-time requirements | Difficulty in reflecting system-level coupling and boundary condition variations |

The synergistic integration of three novel technologies—intelligent data transmission, data-driven modeling, and intelligent control—establishes a framework for dynamics optimization: Electromagnetic transmission breaks physical data constraints to enable real-time dynamics monitoring; data-driven methods construct dynamic models from real-time sensor data to inform control decisions; while intelligent control algorithms execute closed-loop vibration suppression and trajectory optimization. Together they form a “sense-decide-act” loop, representing a paradigm shift from reactive to predictive drilling control.

## 6. Prospects

Regarding seawater section pipe dynamics theory: Current riser cluster research primarily focuses on dual or triple riser configurations, while VIV control for quad-riser and larger clusters remains challenging with limited studies. Future work should integrate data-driven approaches to investigate multi-riser interactions and their VIV mechanisms through combined theoretical/experimental studies. For instance, data-driven techniques could develop real-time FSI models accounting for multiphase flows and riser arrangements, offering novel VIV suppression solutions.

Regarding riserless drill string dynamics: Current research lacks effective analysis that integrates the coupled dynamics of both the seawater and formation sections across the entire well. Existing studies have developed triaxial coupled vibration models incorporating vessel motion, wind/wave currents, wall contacts, and bit–rock interactions, their treatment of seawater-formation coupling mechanisms requires refinement. Future research needs to consider the combined action of loads in the seawater section and the formation section, construct a full-well multi-scale coupled dynamics model, focus on analyzing the mechanism of environmental load-structural response-fluid action, and provide theoretical support and intelligent control schemes for the safe and efficient operation of riserless drilling.

Regarding emerging control technologies: Current EM transmission still suffers from severe signal attenuation (especially in complex formations), low data rates, and sensitivity to downhole high temperature and high pressure conditions. Moreover, data acquisition systems struggle to capture key parameters like bit displacement/acceleration, requiring stringent quality standards and advanced collection techniques. Future improvements should enhance EM systems’ anti-interference capability and transmission range in deepwater environments. Concurrently, precise downhole dynamics monitoring (such as annular pressure and string bending stress) need be improved to address data scarcity, acquisition challenges, and model input distortions.

## 7. Conclusions

In terms of external load calculations for drill strings, existing methods can already analyze the mechanisms of complex loads such as drilling fluid, wellbore walls, ocean currents, and bit–rock interactions from a multiphysics coupling perspective, laying the foundation for drill string dynamics analysis. However, the coupled load models for extreme deep-sea environments still require refinement.

Regarding critical dynamics issues, the fluid–structure interaction characteristics of marine riser VIVs and the complexity of downhole drill string axial-lateral–torsional coupled nonlinear vibrations have become research focal points. Most analyses on the longitudinal–transverse–torsional coupled vibration of drill strings are limited to the formation section, and there is a lack of research on the full-well coupled dynamics of the seawater section and the formation section. The hydrodynamic properties of the seawater segment differ greatly from the geomechanical properties of the formation segment. The manner in which their interaction influences the vibration response of the drill string has not been fully elucidated, making it difficult for the prediction accuracy of the drill string’s dynamic response under multi–factor coupling to meet practical engineering requirements.

In the field of vibration control, active–passive control technologies have demonstrated certain effectiveness in suppressing vibrations for both risers in the seawater section and drill strings in the formation section. Nevertheless, given the complex and variable operating conditions of deep-sea drilling, a single active or passive control technology is usually insufficient to handle all scenarios. Hybrid active–passive control systems integrate the real-time responsiveness of active control with the inherent stability of passive approaches, potentially offering a breakthrough solution to existing vibration control challenges.

In emerging control technologies, the closed-loop “sensing-decision-execution” system constructed by intelligent data transmission, data-driven modeling and intelligent control technologies provides new approaches for real-time regulation of drill string dynamics issues. Nevertheless, extreme deep-sea environmental factors such as high pressure, low temperature and strong electromagnetic interference seriously threaten system stability and reliability. Issues such as signal attenuation and distortion during data transmission, and failure risks of intelligent control algorithms under complex working conditions, all constrain the practical application effectiveness of these emerging technologies.

## CRediT authorship contribution statement

**Rong-Jie Wu:** Writing – original draft, Investigation, Formal analysis, Data curation. **Xiao-Qiang Guo:** Writing – review & editing, Supervision, Conceptualization. **Xin-Ye Li:** Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Liang He:** Software, Investigation. **Yue-Chao Liu:** Software, Investigation. **Chao-Qun Xia:** Writing – review & editing.

## Data availability statement

The data used to support the findings of this study are included within the article.

## Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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