

Review

From Geometric Regulation to Intelligent Design: A Review on Performance Improvement of Dual-Feedback Fluidic Oscillators

Ye Chu ^{1,2}, Henghui Liao ^{1,2}, Guo Tang ^{1,2} and Hao Chang ^{1,2,*}

¹ National Research Center of Pumps, Jiangsu University, Zhenjiang 212013, China; 3230212161@stmail.ujs.edu.cn (Y.C.); 3230212288@stmail.ujs.edu.cn (H.L.); 2222311043@stmail.ujs.edu.cn (G.T.)

² School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, China

* Correspondence: changhao@ujs.edu.cn; Tel.: +86-182-5258-5609

Abstract

Fluidic oscillators (FOs) are self-excited jet-generating devices without moving parts that convert steady fluid supply into oscillatory jets through inherent flow instabilities. Among various FO configurations, dual-feedback fluidic oscillators (DFFOs) have attracted extensive attention due to their simple structure, high reliability, stable oscillation characteristics, and broad applications in active flow control, heat transfer enhancement, and fluid mixing. However, conventional trial-and-error-based optimization methods are limited by strong parameter coupling and trade-offs among multiple performance objectives, such as oscillation frequency, jet deflection angle, and energy efficiency. This review systematically summarizes recent advances in performance enhancement strategies for DFFOs from the perspective of “from geometric control to intelligent design”. The effects of multi-scale geometric regulation, including macroscopic structures, internal microstructures, and manufacturing-related factors, are discussed. Advanced optimization approaches, including active control, novel configurations, inverse design, and data-driven methods, are further reviewed. Particular attention is given to additive manufacturing challenges and DFFO performance under multiphase flow conditions, including erosion, particle deposition, atomization, and mass transfer. Finally, future perspectives are proposed regarding multi-physical coupling, intelligent optimization, and engineering applications. This review provides a comprehensive reference for the cross-scale performance enhancement and intelligent design of DFFOs.

Keywords: fluidic oscillator; sweeping jet; performance enhancement; multi-scale structural design; intelligent optimization; multiphase flow; additive manufacturing

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1. Introduction

A fluidic oscillator (FO) is a functional device capable of converting a steady fluid supply into a self-excited oscillatory jet through inherent flow instabilities within the device [1]. As a fluidic actuator with no moving parts, the FO has attracted extensive attention over the past five decades owing to its self-excited and self-sustained oscillation characteristics, as well as its inherent advantages of structural simplicity, high reliability, and low maintenance requirements [2,3]. Since the beginning of the twenty-first century, with

the rapid development of active flow control (AFC), the FO has been increasingly employed as a fluidic actuator in a wide range of applications, including airfoil lift enhancement, heat transfer enhancement, and fuel-air mixing promotion [4,5].

FOs can be categorized according to their underlying oscillation mechanisms and feedback configurations. As illustrated in Figure 1, different FO designs originate from various flow instability mechanisms, including feedback interactions, shear-layer instabilities, jet impingement, and vortex dynamics [6]. Based on whether external feedback channels (FCs) are involved in sustaining the oscillation process, FOs can be broadly classified into feedback-type and feedback-free oscillators. Feedback-type oscillators generate periodic jet oscillations through the transmission of pressure disturbances via FCs and the subsequent interaction between feedback flows and the primary jet. This category mainly includes dual-feedback fluidic oscillators (DFFOs) and single-feedback fluidic oscillators. The Warren single-loop oscillator is a representative example of single-feedback configurations, where a single feedback loop is employed to induce periodic jet switching [7]. In contrast, feedback-free oscillators do not require external FCs to maintain self-excited oscillations; their oscillatory behaviors are driven by intrinsic flow instabilities and the periodic evolution of unsteady flow structures, such as shear-layer instabilities, jet impingement interactions, and large-scale vortical structures formed within the oscillation chamber. The Von Kármán chamber oscillator is a typical representative of this category, in which oscillations arise from the periodic generation and evolution of chamber-scale vortices [6]. Among various FO configurations, DFFOs have attracted the most extensive research attention due to their simple geometry, stable oscillation characteristics, and wide range of applications. Therefore, this review primarily focuses on performance enhancement strategies for DFFOs. Unless otherwise specified, the term “FO” used throughout the following sections refers specifically to DFFOs.

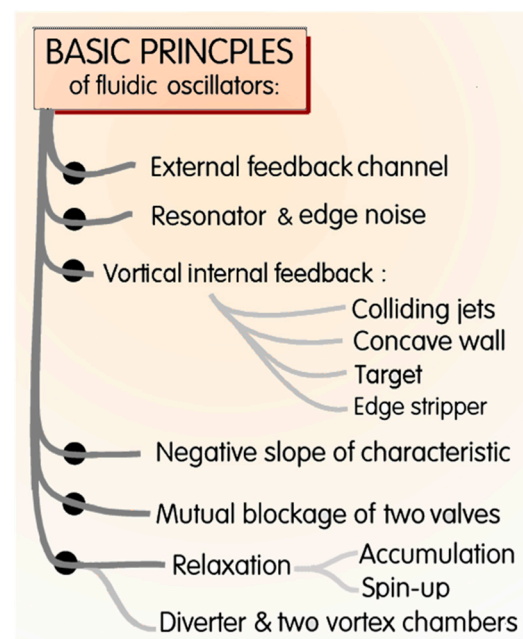


Figure 1. Taxonomic tree of fluidic oscillators (FOs) arranged on the basis of operation mechanism principles [6].

To provide a fundamental understanding of the configuration and oscillation mechanism investigated in this review, the typical structure and working principle of a DFFO are introduced below. As illustrated in Figure 2, a typical DFFO consists of a power nozzle, a mixing chamber (MC), two symmetric FCs, and an outlet structure [8,9]. During operation, the primary jet issued from the power nozzle interacts with the feedback flows

and internal vortical structures, resulting in periodic jet attachment, deflection, and switching within the MC. These coupled flow interactions govern the oscillation characteristics and determine the behavior of the generated sweeping jet.

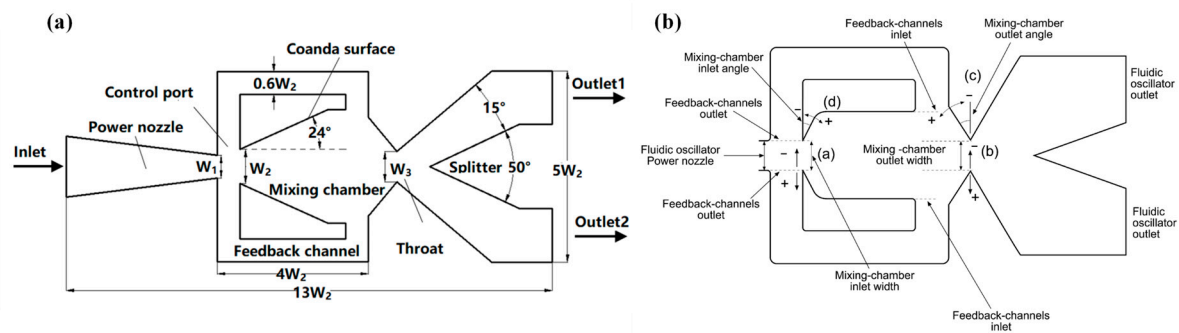


Figure 2. Different geometric parameters of a dual-feedback fluidic oscillator (DFFO): (a) Sang et al. [8]; (b) Baghaei and Bergada [9].

The traditional FO design has primarily relied on trial-and-error-based geometric parameter tuning. Performance indicators such as oscillation frequency, jet deflection angle (the instantaneous deviation of the jet from the oscillator centerline), and mixing effectiveness have conventionally been improved through iterative adjustments of geometric parameters, including the FC length, MC width, and outlet throat dimensions [10,11]. However, this approach is often inefficient, computationally expensive, and incapable of accurately identifying optimal designs within a high-dimensional parameter space [12]. Moreover, existing studies have demonstrated that improvements in a specific performance metric achieved through modification of macroscopic geometric parameters are frequently accompanied by deterioration in other critical performance indicators, highlighting the inherent trade-offs among multiple design objectives.

To overcome the limitations of conventional geometric parameter optimization, recent studies have explored performance enhancement strategies from both structural and methodological perspectives. From a structural perspective, micro-scale structures such as ribs and backward-facing steps have been introduced to manipulate the evolution of recirculation bubbles within the MC, thereby regulating oscillatory behavior. In addition, novel configurations and active control strategies, such as master–slave structures, have been proposed to alter jet stability and switching dynamics [13,14]. From a methodological perspective, advanced optimization techniques, including the Taguchi Method and adjoint shape optimization, have been adopted to achieve multi-objective optimization of oscillation frequency, jet deflection angle, and pressure drop [15,16]. Furthermore, Duan et al. [17] integrated adaptive sampling, deep Infinite mixed Gaussian process, and genetic algorithm techniques to realize synergistic optimization of energy efficiency and operational safety. Henry et al. [18] developed a surrogate model based on the Fourier neural operator (FNO), achieving more than a fiftyfold acceleration in simulation speed and providing a promising framework for the design and optimization of large-scale FO arrays.

To objectively characterize the development trends of the FO research field, a bibliometric analysis was conducted based on published literature. On 15 July 2026, a literature search was performed using the Web of Science Core Collection (WoSCC) database with “fluidic oscillator” as the topic keyword, resulting in a total of 549 relevant publications. The bibliographic information and analytical data provided by WoSCC were further processed, and Figure 3 was generated using Origin software (version 10.2.0.188). Figure 3a presents the global distribution of publications in the FO field, indicating that China currently has the highest number of publications worldwide. Figure 3b summarizes the

annual publication output and cumulative citation frequency from January 2002 to December 2025, revealing a significant increase in global research activity on FO technologies in recent years. Subsequently, keyword co-occurrence analysis was performed using VOSviewer (version 1.6.20.0) based on the retrieved publications (Figure 4). The analysis further demonstrates that FO research has primarily focused on flow control and sweeping jet technologies. High-frequency keywords, including “flow”, “jet”, “frequency” and “performance” highlight the central research themes of this field. Meanwhile, heat transfer enhancement has emerged as another major application-oriented research direction, reflecting the increasing interest in utilizing FO-induced oscillatory flows for thermal management applications. It should be noted that Figures 3 and 4 characterize the overall development trends of the broader FO research field rather than specifically focusing on DFFOs. These analyses are intended to provide a macroscopic overview of the evolution and research landscape of FO technologies.

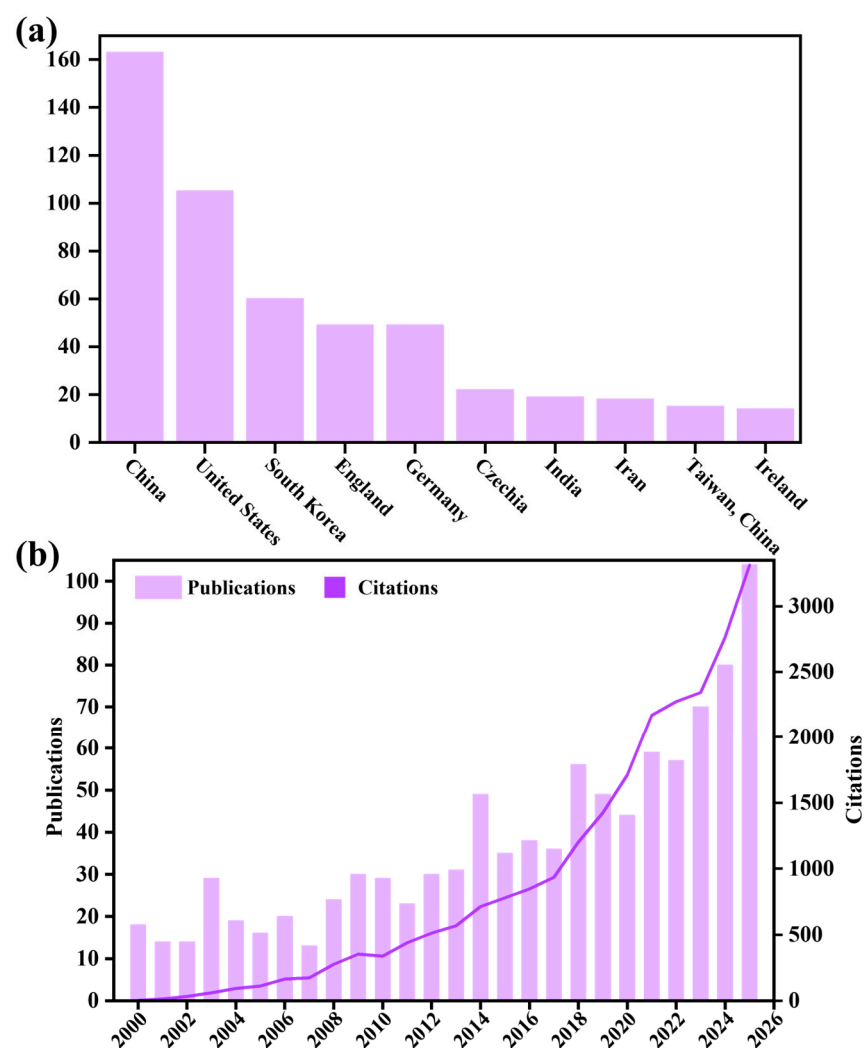


Figure 3. Geographical distribution and annual publication trends in FO research: (a) comparison of publication outputs among major countries; (b) annual numbers of publications and citations since 2002.

Table 1. Comparison of existing review articles on FO.

Year	Researchers	Main Research Content
2013	Gregory & Tomac. [7]	The historical evolution of FO from the 1960s to the present and its applications in flow control, including separation control and drag reduction The renewed interest in FO as a zero-moving-part actuator in modern flow control systems
2019	Ghanami & Farhadi. [2]	Introduction, classification, and physical mechanisms of various traditional FOs Numerical and experimental studies on the FO and existing correlation methods
2022	Hussain & Khan. [19]	The FO design improvement Recent research advances in enhancing the thermohydraulic characteristics of impact sweeping Variation in heat transfer and hydraulic performance of impinging jet on target surfaces of different shapes
2023	Wu et al. [20]	Established a systematic classification of seven oscillatory jet excitation methods, including microjet, mechanical, and feedback-based approaches The operating principles and oscillatory jet characteristics of different excitation strategies The challenges, industrial limitations, and future development directions of oscillatory jet technologies
2026	Zhang et al. [1]	Emerging interest in sweeping jet FOs in heat transfer applications--sweeping jet impingement heat transfer, sweeping jet film cooling, and sweeping jet combined cooling

2. Basic Fluid Dynamic Performance Indicators

The performance and engineering applicability of the FO is fundamentally governed by its fluid dynamic performance indicators. These parameters not only reflect the intrinsic flow characteristics within the oscillator but also determine its effectiveness and energy efficiency in practical applications, such as AFC, heat transfer enhancement, and fluid mixing. Therefore, a comprehensive understanding of these key performance indicators is essential for the design, optimization, and application of the FO. In this section, the principal fluid dynamic performance indicators of the FO are reviewed and discussed.

Performance evaluation indicators for FOs can be classified into two categories. The first category consists of general parameters used to characterize the intrinsic oscillation characteristics and energy efficiency of the oscillator, including oscillation frequency, Strouhal number (St), and Euler number (Eu). The second category includes application-specific performance indicators, such as the Sauter mean diameter (SMD) used for evaluating atomization and microbubble generation performance.

2.1. Oscillation Frequency and Strouhal Number

The oscillation frequency and St are two fundamental parameters used to characterize the oscillatory behavior of the sweeping jet generated by the FO. The St is defined as $St = f \cdot h / U$, where h and U denote the characteristic length of the oscillator and the inlet velocity of flow, respectively, and f represents the oscillation frequency. These parameters are primarily governed by the geometric design of the FO and the inlet flow conditions [1,21]. For incompressible flows, the St generally remains nearly constant over a wide range of the Reynolds number (Re), indicating that the oscillatory behavior is predominantly controlled by the fluid convection timescale. As the flow transitions from the low- Re laminar regime to the high-subsonic compressible regime, the oscillation mechanism of the FO undergoes significant changes. To investigate the sweeping jet characteristics and oscillation mechanisms in the low- Re laminar flow regime, Sarwar et al. [22] performed numerical simulations using the spectral element method. Their results demonstrated that the St decreases significantly with increasing Re , whereas the jet deflection angle exhibits a larger oscillation amplitude as the Re increases. In the high-subsonic compressible flow regime, Lai et al. [23] examined the external flow characteristics and velocity distributions of the FO using Schlieren visualization and Schlieren image

velocimetry (SIV). Their findings revealed that, with increasing inlet pressure and outlet Mach number (Ma_{outlet}), the oscillation frequency of the sweeping jet initially increases rapidly and subsequently approaches a plateau. These observations indicate that oscillation frequency and St are key parameters governing the unsteady flow characteristics of FOs and play a critical role in determining their flow-control effectiveness and engineering performance.

2.2. Euler Number

While the oscillation frequency and St characterize the flow-control capability of a FO, its energy utilization efficiency is commonly evaluated using the Eu , which reflects the pressure loss associated with fluid passage through the device. The Eu represents the ratio between pressure forces and inertial forces and is defined as: $Eu = 2\Delta P / (\rho U^2)$, where ΔP represents the pressure loss across the FO, ρ is the density of the working fluid, and U denotes the inlet velocity of flow [21]. The Eu provides insight into the energy consumption characteristics of the FO under varying inlet flow conditions. For a given St , a lower Eu indicates that self-excited oscillation can be sustained with lower energy input, corresponding to higher energy utilization efficiency [24,25]. Various configurations of FOs illustrated in Figure 5 are compared in terms of pressure loss in Figure 6. Since the inertial force term is normalized in the definition of the Eu , the magnitude of the pressure loss directly reflects the variation in Eu . The approximately linear relationship between pressure loss and Re shown in Figure 6 indicates that the single backward-facing step fluidic oscillator (BFSFO) exhibits the highest Eu among the investigated configurations and therefore suffers the greatest energy loss [24]. Consequently, the Eu serves as a fundamental performance indicator for evaluating and comparing the energy efficiency of different FO designs.

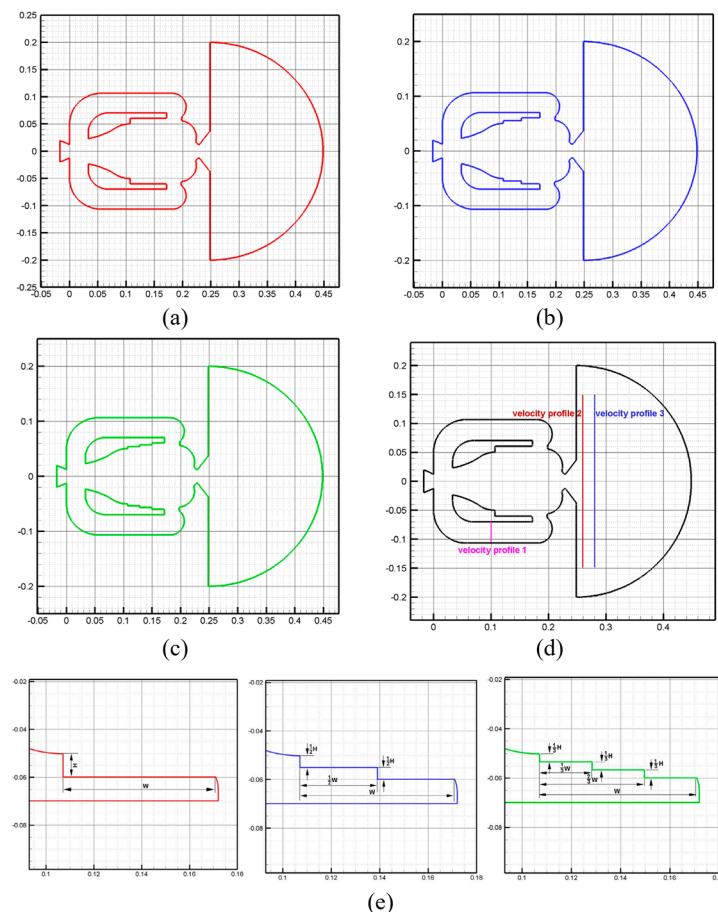


Figure 5. FO geometric model (x and y coordinates are expressed in m). (a) single BFS FO; (b) double BFS FO; (c) triple BFS FO; (d) velocity profile extraction location; (e) BFS details in the mixing chamber [24].

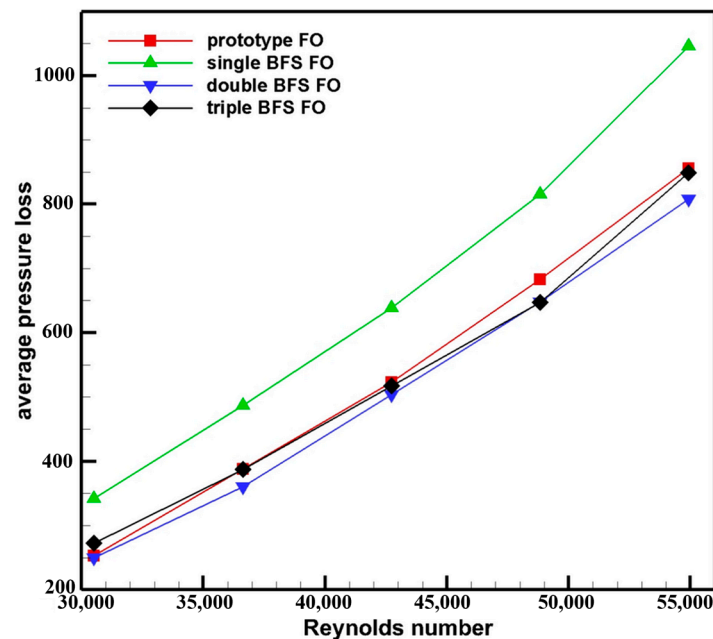


Figure 6. Pressure loss of various FO models (prototype, single, double, triple-layer backward step FO) (ΔP expressed in Pa) [24].

2.3. Sauter Mean Diameter

In gas–liquid two-phase mixing and atomization applications, the SMD is a key parameter used to evaluate atomization quality [26]. It is defined as the diameter of a droplet having the same volume-to-surface-area ratio as the entire droplet population and can be expressed as: $D_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2}$, where (n_i) and (d_i) represent the number and diameter of droplets within a given size class, respectively [27]. In recent years, SMD has increasingly been adopted as an important performance indicator in the optimization of FOs [28]. For FO-based atomization systems, SMD not only reflects atomization fineness but is also closely associated with turbulence intensity and gas–liquid momentum exchange within the MC. Consequently, it has become a critical parameter influencing the oscillatory behavior and overall performance of multiphase sweeping jets [29,30].

The regulation of SMD is strongly affected by both the internal structure and operating conditions of the FO. Increasing the gas-to-liquid mass flow rate ratio enhances secondary droplet breakup and generally leads to a reduction in SMD [31,32]. In addition, Zhai et al. [33] reported that increasing temperature significantly decreases SMD under low air-fuel ratio (AFR) conditions (10–50%). At an AFR of 20%, a temperature increase of 100 K resulted in an SMD reduction of up to 65 μm . These findings indicate that atomization performance can be effectively tailored through simultaneous adjustment of the gas–liquid flow ratio and operating temperature. Nevertheless, it should be noted that a smaller SMD does not necessarily correspond to superior overall performance. Although finer droplets are generally beneficial for interfacial heat transfer and cooling enhancement in FO-based systems [34–38], excessively small droplets may reduce the momentum of the primary jet and compromise jet stability. Moreover, increased gas pressure may elevate the risk of cavitation, thereby adversely affecting system performance [39–41]. Therefore, optimization of SMD should aim to achieve an appropriate balance between atomization quality and jet stability rather than simply minimizing droplet size.

3. Multi-Scale Structural Design

It should be noted that, depending on the form of the outlet jet, DFFOs can be further classified into two typical configurations: sweeping-jet FOs and pulsed-jet FOs. The former generates large-scale flow manipulation through the periodic spatial oscillation of a single outlet jet, whereas the latter produces periodic momentum input through alternating jets from two outlets. Although these two configurations share similarities in their oscillation mechanisms and the effects of certain structural parameters, their distinct outlet flow behaviors and engineering objectives result in different performance evaluation criteria. Therefore, the subsequent discussions on structural optimization and performance enhancement in this review primarily focus on the sweeping-jet FO, which has received broader research attention and wider practical applications.

To improve the performance of sweeping-jet FOs, it is essential to understand the influence of structural parameters on their internal unsteady flow dynamics and overall performance. Previous studies have demonstrated that FO performance is governed not only by macroscopic geometric parameters, such as FCs and MCs, but also by microscale features and manufacturing-related factors, including the modification of separation bubble characteristics by backward-facing steps and the effects of surface properties and dimensional accuracy introduced by additive manufacturing (AM). Accordingly, this chapter systematically reviews FO performance optimization strategies from multiple scales, including macroscopic structural design, microscale flow regulation, and manufacturing considerations.

3.1. Basic Macroscopic Structural Parameters

The macroscopic geometric configuration plays a critical role in governing the oscillatory behavior and overall performance of FOs. Key structural components, including FCs, MCs, and inlet/outlet configurations, regulate internal flow evolution and consequently affect essential performance metrics such as oscillation frequency, diffusion angle (the spatial expansion of the discharged jet after exiting the oscillator), and pressure loss. This section reviews the influence of geometric control on the internal flow mechanisms of FOs, analyses the effects of representative structural parameters on oscillation characteristics, and summarizes general design principles for performance-oriented FO optimization.

3.1.1. Feedback Channel

Numerous studies have demonstrated that the geometry of the dual FCs, particularly their length and width, plays a crucial role in regulating the oscillation characteristics of FOs by modifying the feedback delay, pressure interaction, and vortex evolution within the oscillator. These effects are mainly reflected in variations in jet oscillation frequency, maximum jet deflection angle, and oscillation stability.

Park et al. [42] combined the Taguchi Method and response surface methodology to investigate the influence of internal geometric parameters on the performance of a supersonic FO. Their results showed that the overall oscillator length and the gap between the internal blocks were the dominant factors affecting sweeping jet performance. Specifically, the oscillation frequency decreased with increasing oscillator length and increased with increasing gap width, whereas the maximum jet deflection angle exhibited the opposite trend. In contrast, geometric variables associated with the FC shape exerted only a limited influence on sweeping jet performance. Yu et al. [43] experimentally investigated the influence of FC width on the cooling performance of oscillating jets. Their results indicated that shortening the FC increased the oscillation frequency and strengthened the dynamic sweeping motion, thereby effectively suppressing the intrusion of the high-temperature

mainstream into the near-wall region. However, excessive shortening of the FC resulted in distortion of the pressure pulse signal. This phenomenon was attributed to the reduction in the phase delay associated with feedback propagation, causing the jet oscillation to become synchronized with the turbulence spectrum of the mainstream flow. Using the $k - \omega$ turbulence model to solve the Reynolds-averaged Navier–Stokes (RANS) equations, Wang et al. [44] numerically investigated oscillating jets generated by symmetric and asymmetric nozzles and analyzed the effects of FC length and width on flow and heat transfer characteristics. For asymmetric nozzles, the oscillation frequency increased as the FC length and width decreased, whereas the maximum jet deflection angle exhibited the opposite trend. Pronounced asymmetry was also observed in both the pressure distribution and jet deflection behavior on either side of the nozzle, accompanied by an extended duration of peak pressure on the switching side. Regarding heat transfer performance, reducing the FC width increased the time-averaged Nusselt number (Nu). In contrast, variations in FC length altered the oscillation frequency and deflection asymmetry but produced only minor changes in overall heat transfer performance. Song et al. [45] experimentally examined the influence of FC inlet width on the flow mechanism of an FO. Their results revealed that the recirculation bubble within the MC and the feedback flow jointly govern the formation of both internal and external sweeping jets. The inlet width of the FC directly affects the feedback flow rate and the size of the recirculation bubble, thereby influencing key flow characteristics such as oscillation frequency and diffusion angle. Furthermore, widening the FC increased the time-averaged pressure difference, indicating enhanced feedback flow intensity. However, the oscillation frequency decreased simultaneously due to increased jet switching delay and greater flow dissipation. Using three-dimensional (3D) direct numerical simulation, Bergadà et al. [46] investigated the influence of FC length on FO performance under compressible subsonic flow conditions. The results showed that increasing the FC length reduced the oscillation frequency of the outlet mass flow rate. When the channel became excessively long, the original dominant oscillation mode was suppressed, causing the MC jet to transition into a high-frequency pulsation state. Beyond a critical threshold, self-sustained oscillation ceased completely. Gui et al. [47] further explored the influence of FC length on oscillation characteristics and mode-switching behavior through numerical simulation. Their results demonstrated that when the FC length reached approximately 1.5 times that of the baseline configuration, the FO exhibited intermittent transitions between a low-frequency, high-amplitude (LF-HA) mode and a high-frequency, low-amplitude (HF-LA) mode. This mode switching was induced by variations in the FC pressure gradient arising from unsteady flow structures within the MC. Specifically, elongation of the FC increased flow resistance and pressure loss, resulting in an unstable feedback supply and increased uncertainty in jet attachment. Moreover, a coupling effect among oscillation mode, inlet velocity, and FC length was identified. For a fixed geometry, controlled transitions between LF-HA and HF-LA modes could be achieved by adjusting the inlet velocity. D’Angelo et al. [48,49] investigated the effect of the minimum FC width on sweeping jet impingement heat transfer, using the outlet throat width for non-dimensionalization. Their results showed that reducing the FC width decreased the jet spreading on the impingement surface owing to a reduction in oscillation amplitude accompanied by an increase in oscillation frequency. Duan et al. [50] combined numerical simulation and experimental measurements to compare the performance of an angled fluidic oscillator (AFO) and a curved fluidic oscillator (CFO). The effects of several FC design parameters, including the inlet and outlet angles, the distance between the FC and the MC, and the channel thickness, were investigated. The results indicated that modifications to the FC geometry of the AFO exerted only a minor influence on the sweeping jet velocity field, whereas channel thickness significantly affected the uniformity of the time-averaged velocity distribution. In contrast, the outlet

flow field of the CFO was relatively insensitive to channel thickness in terms of velocity uniformity, while the jet deflection angle exhibited a much stronger sensitivity.

In addition to conventional geometric optimization, researchers have explored innovative FC configurations to further improve FO performance. Gärtlein et al. [51] combined high-speed particle image velocimetry (PIV) with time-resolved pressure measurements and demonstrated experimentally that rectangular FCs are susceptible to flow separation and vortex formation, resulting in increased pressure loss and delayed jet switching. To mitigate these effects, they proposed streamlined FCs, which were shown to reduce flow losses while improving both oscillation frequency and overall efficiency. Yan et al. [52] proposed a novel FO configuration incorporating a movable and adjustable feedback loop and resonator, as illustrated in Figure 7. This design enables tunable jet oscillation frequencies by modifying the effective feedback loop length. The proposed FO exhibited a decreasing total pressure loss coefficient with increasing normal jet velocity, while maintaining a lower pressure loss compared with the original baseline configuration. Numerical results further revealed that the displacement of the FC could regulate the coupling strength between the feedback loop and the resonator, thereby inducing different orders of jet oscillation frequencies. However, for FOs consisting of both an MC and FCs, achieving effective control of jet sweeping frequency solely by adjusting the FC length remains challenging. As shown in Figure 8, Loe et al. [53] proposed a novel FO design strategy by incorporating elastic structures around the oscillator. Elastic structures were respectively installed around different regions of the oscillator, including the FC (Figure 8a) and the MC (Figure 8b), providing an additional degree of freedom for actively regulating the oscillatory flow behavior. By applying external periodic excitation (f_s) to the elastic boundaries, the structural deformation interacts with the intrinsic oscillation of the internal flow field. Experimental and numerical results demonstrated that the weak periodic excitation generated by the elastic structures could synchronize with the internal flow dynamics, leading to a coordinated oscillation state. This synchronization effect reduced pressure loss and enhanced lateral momentum transport, thereby improving mixing performance without disrupting the inherent oscillatory characteristics of the FO. Martinke et al. [54] developed a modified FO that eliminated the dual-feedback channel configuration. In this design, jet switching was achieved through an external fast-opening valve, allowing independent control of the primary mass flow rate, feedback flow rate, and oscillation frequency. The device was capable of generating multiple oscillation modes. As the valve mass flow rate was gradually reduced, the oscillation state transitioned sequentially from continuous oscillation to intermittent oscillation and finally to a non-oscillatory state. Hussain et al. [55] introduced a bleed-feed channel (D) on the Coanda surface (Figure 9) and investigated the influence of its width on the performance of the FO. As shown in Figure 10, compared with the conventional smooth configuration, the FO with a bleed-feed channel width of $0.3D$ exhibited the most significant performance enhancement. This improvement can be attributed to the enhanced feedback flow induced by the additional channel. A wider bleed-feed channel allows a larger amount of fluid to be redirected into the feedback loop, thereby accelerating jet switching and resulting in a higher oscillation frequency (Figure 10a). Meanwhile, the bleed-feed channel provides an alternative flow path that diverts fluid away from the high-resistance regions within the main chamber, effectively reducing energy dissipation and suppressing pressure losses (Figure 10b).

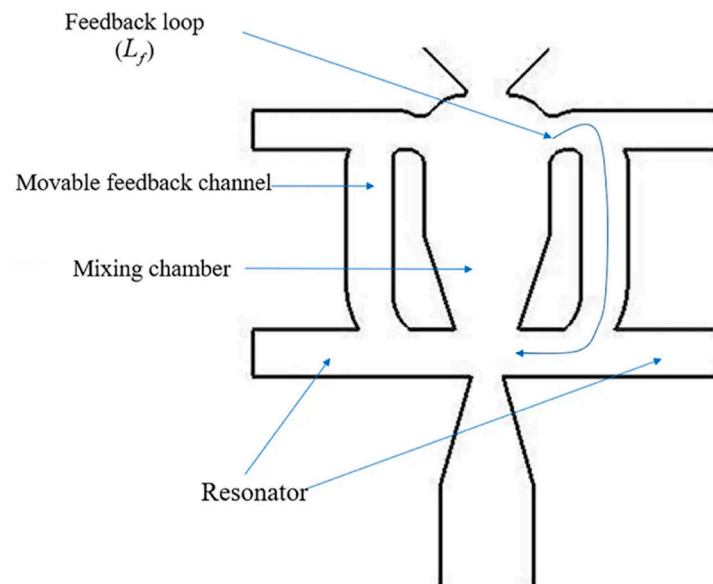


Figure 7. New FO with movable feedback channel (FC) and resonator [52].

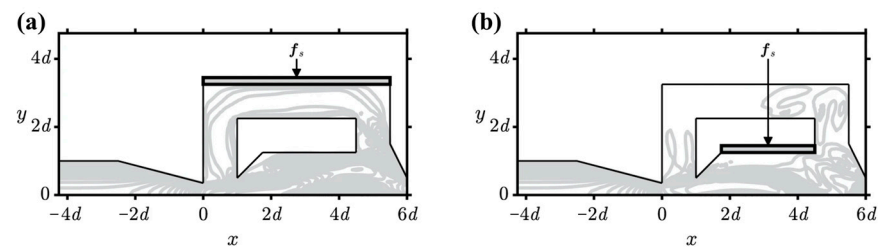


Figure 8. Arrangement of elastic structures. (a) First structure: arranged around the FC; (b) Second structure: arranged around the mixing chamber (MC). f_s represents the external excitation applied to the boundary of the elastic structure, and the arrows indicate the location of excitation application. The grey lines represent the streamlines [53].

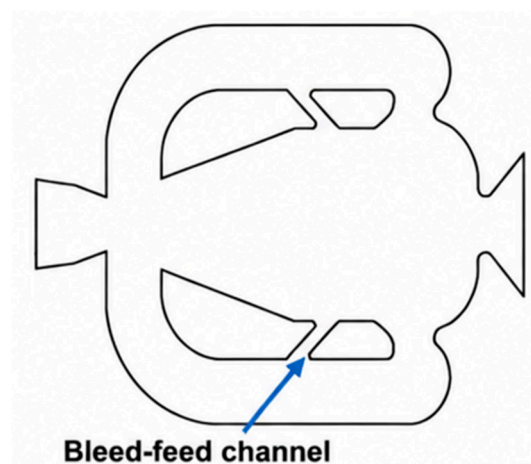


Figure 9. FO with gas venting and feed channels [55].

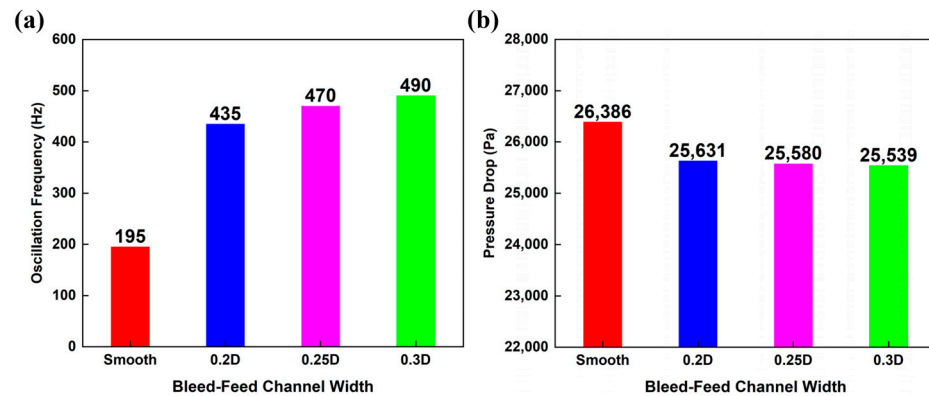


Figure 10. (a) Oscillation frequency of oscillators with different vent-feeding channel widths; (b) Pressure drop of oscillators with different vent-feeding channel widths (“Smooth” represents the baseline oscillator without a bleed-feed channel. D corresponds to the throat diameter of the FO’s exit nozzle) [55].

3.1.2. Mixing Chamber

The MC is the core region where the primary jet interacts intensely with the feedback flows from both sides, leading to the generation, evolution, and breakdown of vortical structures. As a result, its geometric configuration plays a critical role in determining the oscillation frequency, oscillation amplitude, and overall flow behavior of the FO [56]. Through experimental investigations, Song et al. [45] demonstrated that increasing the inlet wedge width (W_w) increases the proportion of the primary flow entering the MC and strengthens the feedback flow intensity. Consequently, both the internal jet deflection amplitude and the external diffusion angle increase, accompanied by a corresponding rise in oscillation frequency. Chen et al. [57] combined numerical simulations and experimental measurements to investigate the sweeping jet characteristics of a CFO with a 10 mm outlet throat under varying effective MC lengths. The results revealed that deviations of the effective MC length from the design value caused the oscillation frequency to depart from the expected linear relationship. This behavior was primarily attributed to the weakening of the separation vortex and the displacement of the jet attachment point from its optimal location. DeAngelo et al. [48] reported the existence of a critical MC length when normalized by the outlet throat width. When the normalized length exceeded this critical threshold, stable sweeping oscillations were generated, and a dual-jet structure was formed. In contrast, when the normalized length fell below the threshold, self-sustained oscillation could not be established, and the flow remained in a single-jet state. Using PIV to characterize both the internal and external flow fields of an FO, Wen et al. [11] further performed proper orthogonal decomposition (POD) analysis to investigate the underlying flow dynamics. Their results showed that W_w regulates the feedback flow and consequently controls the recirculation bubble structure within the MC. A critical inlet wedge width was identified, below which sweeping jet oscillation could not be sustained. In addition, the width of the MC primarily governs the size of the recirculation bubble and exhibits a strong proportional influence on the diffusion angle. Baghaei [9] employed 3D computational fluid dynamics (CFD) simulations to investigate the influence of MC geometric parameters on the dynamic characteristics of oscillating jets. The study revealed that the feedback flow within the FCs is predominantly controlled by W_w , and that reducing W_w increases the oscillation amplitude. The pressure level within the MC was found to be primarily determined by the outlet width; a narrower outlet significantly increased the chamber pressure, thereby strengthening outlet recirculation and enhancing oscillation amplitude. Furthermore, the outlet inclination angle substantially altered the dynamic pressure distribution within the FCs. Increasing the outlet inclination angle weakened

both stagnation pressure and pressure-wave transmission efficiency, leading to reduced oscillation intensity. In contrast, the inlet inclination angle exerted only a minor influence on the Coanda effect and therefore had a limited impact on the overall flow and oscillation characteristics.

3.1.3. Exit Section and Entrance Section

Apart from the FCs and MC, the inlet and outlet geometries also play essential roles in determining the flow behavior of FOs. These geometric features regulate the inlet momentum distribution, outlet jet expansion, and Coanda-induced attachment characteristics, thereby affecting the internal oscillation mechanism and external jet behavior. As a result, inlet and outlet geometries have a direct impact on key performance metrics, including oscillation frequency, jet deflection angle, pressure loss, and mixing efficiency. Optimizing these geometric parameters is therefore crucial for achieving stable oscillation, effective jet coverage, and improved energy efficiency.

Yu et al. [43] experimentally investigated the effects of outlet angle and outlet throat width on the cooling performance of oscillating jets. Their results indicated that an excessively large outlet throat width substantially reduces the momentum flux at the jet exit. A moderate reduction in the outlet angle was found to strengthen the Coanda effect and expand the lateral cooling coverage. However, excessive reduction in the outlet angle promoted flow separation, thereby degrading flow performance. Zhai et al. [10] combined experimental measurements and numerical simulations to investigate the airflow and oscillation characteristics of ideal air flowing through FOs with different outlet throat widths and channel thicknesses. The results showed that increasing the channel thickness enhanced both the outlet tangential velocity and jet deflection angle while reducing the oscillation frequency. In contrast, increasing the outlet throat width resulted in simultaneous reductions in tangential velocity, jet deflection angle, and oscillation frequency. Wen et al. [11] reported that the outlet throat width exerts a non-monotonic influence on both the diffusion angle and oscillation frequency. Stable sweeping behavior could be maintained even when the outlet throat width was substantially increased, while the outlet blockage effect was significantly reduced. Conversely, reducing the outlet throat width suppressed the diffusion angle of the external sweeping jet and increased its oscillation frequency. This behavior was attributed to the obstruction caused by the narrower outlet throat, which diverted a larger proportion of the primary flow into the FCs and accelerated the growth of the recirculation bubble within the MC. In contrast, a wider outlet throat promoted a more uniform and concentrated distribution of jet momentum. Wang et al. [44] also investigated the influence of outlet throat width and outlet angle on the oscillating jet characteristics of an asymmetric nozzle. Their results indicated that the oscillation frequency remained largely insensitive to variations in these geometric parameters. However, the maximum jet deflection angle decreased as the outlet throat width and outlet angle were reduced, while the jet deflection exhibited pronounced asymmetry between the two sides of the nozzle. To investigate the external flow mechanism of high-subsonic sweeping jets, Lai et al. [23] examined FOs with inlet throat widths of 2 mm and 3 mm using geometrically scaled models. Their results demonstrated that increasing the inlet throat width enhanced the visibility of the external flow structures and intensified the associated acoustic waves. Kim et al. [58] investigated the oscillation characteristics of a FO with a curved exit nozzle under quiescent external flow conditions, where the curvature angle of the nozzle was defined as β (Figure 11). For cases involving external cross-flow, the installation configuration of the FO is illustrated in Figure 12. Since the pitch angle of the FO coincides with the nozzle curvature angle, both angles are represented by β . As shown in Figure 13, under high mass flow rate conditions, the oscillation frequency

increased with increasing nozzle bending angle. However, when the bending angle reached 40° , jet oscillation ceased completely for the mass flow rates larger than 0.3 g/s.

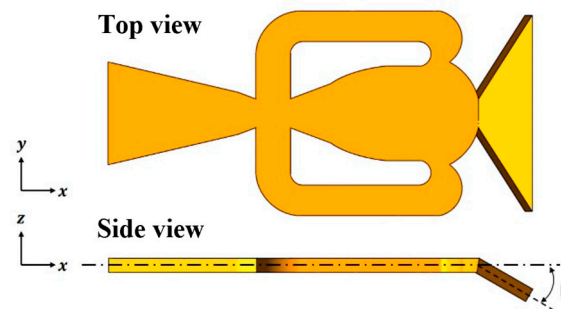


Figure 11. FO model with a bent outlet nozzle [58].

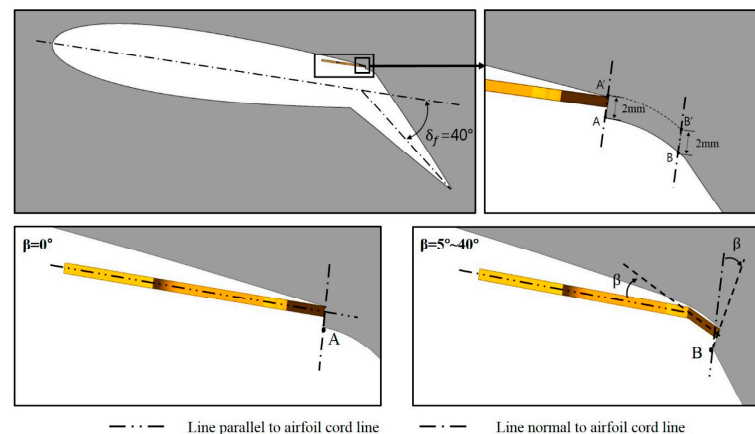


Figure 12. Installation conditions of FOs. A–A' and B–B' represent the initial and translated downstream mounting planes, point A and B is the rotation pivot, and β denotes the deflection bending angle [58].

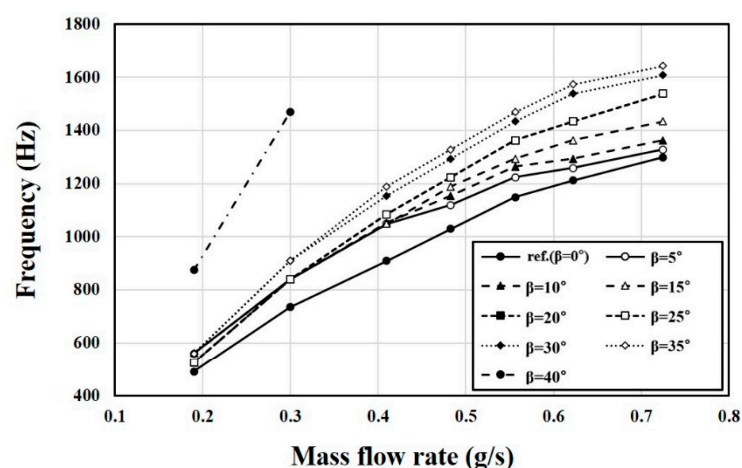


Figure 13. Frequency variations with mass flow rate for various bending angles (β) [58].

3.2. Internal Microstructure

Building upon macroscopic geometric optimization, the introduction of micro-scale structures has emerged as an effective approach for overcoming the performance trade-offs inherent in conventional FO designs. By incorporating microstructures, such as ribs and backward-facing steps, on the Coanda surface or within the MC, the near-wall flow

field and the evolution of recirculation bubbles can be actively manipulated. Consequently, key performance parameters, including oscillation frequency, jet deflection angle, and pressure drop, can be optimized in a more decoupled manner.

3.2.1. Coanda Surface Ribbing

In the performance optimization of FOs, the geometric topology of the Coanda surface plays a crucial role in determining jet attachment behavior and switching efficiency. As a result, the introduction of rib structures on the Coanda surface has attracted increasing attention as a means of manipulating near-wall flow dynamics and enhancing oscillator performance.

Regarding the fundamental characteristics of ribbed Coanda surfaces, Hussain et al. [13] numerically investigated the influence of rectangular ribs on the oscillation characteristics of a FO. Their results showed that introducing ribs onto the Coanda surface reduced the internal pressure drop of the oscillator. Furthermore, increasing the aspect ratio of the rectangular ribs, defined as the ratio of rib height to rib base width, increased the oscillation frequency while reducing the jet deflection angle. These effects were attributed to the influence of the ribs on the formation and evolution of recirculation bubbles within the MC. Subsequently, Hussain et al. [59] further investigated the influence of rib location on FO performance through numerical simulations. Three rib configurations, namely full-rib configuration (Rib 1), upper-half rib configuration (Rib 2), and lower-half rib configuration (Rib 3) (Figure 14), were compared with the smooth Coanda surface (dashed line) to evaluate their effects on jet deflection characteristics and overall performance. As shown in Figure 15a, the smooth configuration exhibited the highest jet deflection angle, reaching a maximum value of 53.3° . Among the ribbed configurations, the arrangement with ribs positioned on the upper half of the Coanda surface achieved the largest jet deflection angle and demonstrated a significant improvement in the comprehensive performance indicator, namely the frequency-jet deflection angle-pressure ratio (FDPR, dimensionless) (Figure 15b). Besides that, Hussain et al. [60] also numerically examined the effect of the number of ribs (ranging from one to six) on FO performance. The results indicated that the introduction of ribs generally reduced the jet deflection angle, while the deflection angle increased with increasing rib number, reaching a maximum value of 37.1° with four ribs. Moreover, the four-rib configuration exhibited the optimal performance in terms of FDPR, achieving an 87.7% improvement compared with the smooth Coanda surface without ribs.

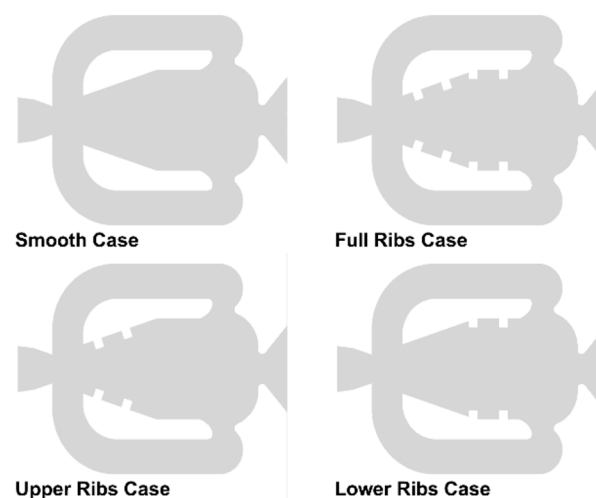


Figure 14. Schematic diagrams of different rib arrangements on the Coanda surface of the fluidic oscillator [59].

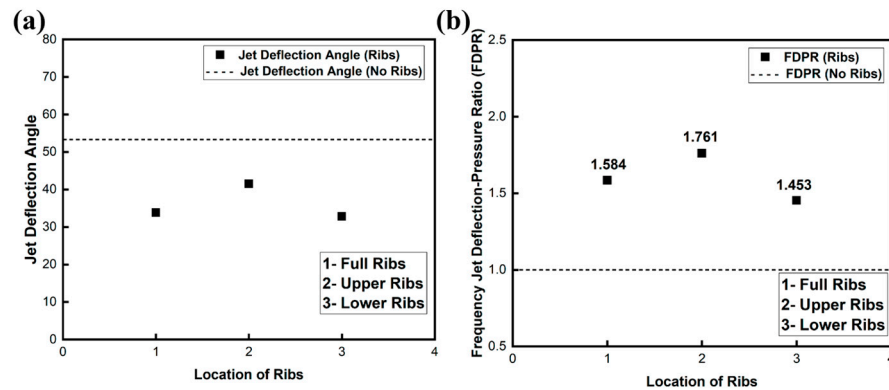


Figure 15. (a) Jet deflection angle at different rib positions and (b) Frequency-jet deflection angle-pressure ratio (FDPR) at different rib positions [59].

Building upon these single-factor investigations, Hussain et al. [15] employed CFD combined with Taguchi-grey relational analysis (GRA) to perform multi-objective optimization of FO performance. Three design variables, namely rib aspect ratio, rib number, and rib angle, were considered. GRA and analysis of variance revealed that rib number exerted the strongest influence on oscillation frequency, rib angle predominantly affected the jet deflection angle, and rib aspect ratio played a major role in reducing pressure loss. Compared with the baseline configuration, the optimized design increased oscillation frequency by 19.9%, increased jet deflection angle by 39.7%, and reduced pressure drop by 17.6%. In a related study, Hussain et al. [16] applied the Taguchi Method to optimize the thermal-hydraulic performance of FOs by varying the rib aspect ratio, rib number, and rib angle on the Coanda surface. The optimized design achieved an approximately 20% increase in oscillation frequency, a 40% increase in jet deflection angle, and a 24.3% enhancement in the Nu . Furthermore, the comprehensive performance evaluation criterion (PEC) reached a value of 1.252, indicating substantial improvement in overall thermal-hydraulic performance.

The underlying physical mechanism responsible for these performance enhancements can be traced to the influence of surface roughness (Sa) on near-wall flow behavior. Hossain et al. [61] were the first to demonstrate that wall roughness affects oscillation frequency by altering the effective aspect ratio of the flow passage. However, excessive roughness within the main MC was found to suppress oscillation and potentially lead to oscillation failure. This finding provided important guidance for the subsequent design of micro-rib structures. More recently, Tajik et al. [56] experimentally demonstrated that modifications to the Coanda surface can significantly alter the morphology of recirculation bubbles, thereby directly affecting oscillation frequency and jet deflection angle. These observations further support the conclusion that the performance improvements associated with ribbed Coanda surfaces originate from their ability to manipulate near-wall flow structures and control recirculation bubble evolution. Overall, conventional FO designs are often constrained by the inherent trade-off between oscillation frequency and pressure loss. The introduction of micro-rib structures provides an effective means of overcoming this limitation by modifying the near-wall flow field and regulating recirculation bubble dynamics, thereby enabling more decoupled optimization of oscillation frequency, jet deflection angle, and energy efficiency.

3.2.2. Backward-Facing Steps

In addition to ribbed Coanda surfaces, the introduction of backward-facing steps within the MC has also emerged as an effective microstructural modification strategy. By altering the formation and evolution of recirculation bubbles, backward-facing steps can

further improve the oscillation characteristics of FOs. Although research in this area remains relatively limited, existing studies have demonstrated the considerable potential of this approach for performance enhancement.

As early as 2007, Yang et al. [21] proposed a novel FO incorporating a stepped attachment wall and an acute-angle splitter. Using PIV, flow visualization, and pressure measurements, they compared its pressure spectra, pressure loss, and flow field structures with those of a conventional planar-wall oscillator. The results showed that the stepped configuration significantly broadened the stable operating range, extending operation to flow rates as low as 5 L/min. In addition, the stability of the recirculation vortex oscillation was substantially enhanced. At a flow rate of 65 L/min, the signal-to-noise ratio was approximately 17 times greater than that of the planar-wall configuration. Furthermore, the oscillation frequency was higher and exhibited a linear relationship with flow rate, highlighting the potential of stepped-wall designs for oscillator performance enhancement. Building upon this concept, Iskandar et al. [62] investigated a BFSFO, as illustrated in Figure 16, and optimized its performance through simultaneous adjustment of the length ratio (LR) and height ratio (HR) of the backward-facing step geometry. As shown in Figure 17a, the configuration with LR = 0.402 and HR = 0.4 consistently exhibited higher oscillation frequencies than both the conventional oscillator and the reference stepped configuration. Moreover, the oscillation frequency maintained a linear positive correlation with Re , demonstrating excellent operational stability. Across the entire Re range investigated, the average pressure drop of the optimized configuration remained comparable to that of the conventional oscillator and significantly lower than that of the reference stepped design (Figure 17b). These results confirmed that the configuration with LR = 0.402 and HR = 0.4 achieved the best overall performance under varying operating conditions. The superior performance of the optimized backward-facing step configuration was attributed to its ability to enhance fluid momentum within the FCs while simultaneously reducing the size of the recirculation bubbles in the MC. This modification promoted more effective feedback-flow transmission and improved jet-switching dynamics, thereby achieving a favorable balance between oscillation frequency and pressure loss.

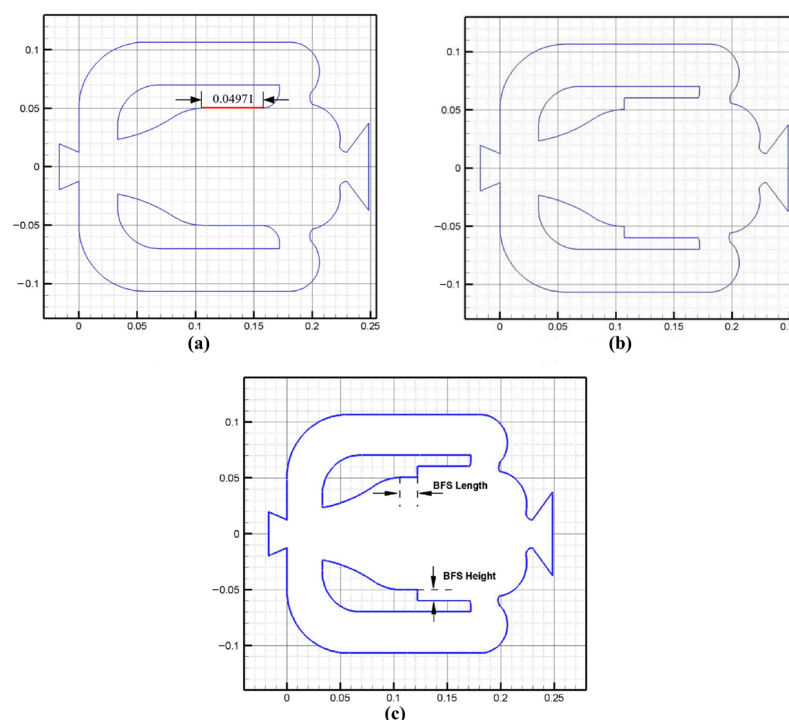


Figure 16. Schematic diagram of the geometric configuration evolution of backward-facing step fluidic oscillator (BFSFO). (a) clean FO; (b) BFSFO baseline; (c) BFSFO with length ratio (LR) and height ratio (HR) variations [62].

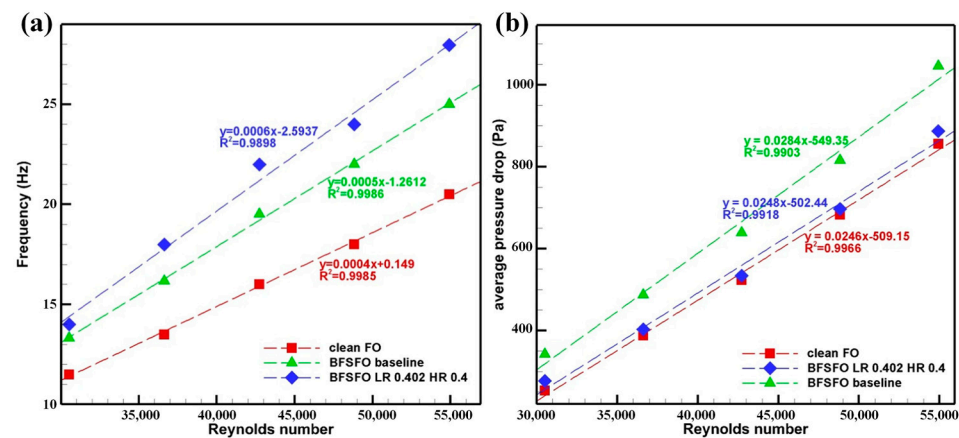


Figure 17. Variation in FO flow performance with Re for different configurations: (a) Effect of Re on FO frequency; (b) Effect of Re on FO pressure drop [62].

3.3. Structural Design Constraints and Optimization for Additive Manufacturing

Early studies on FOs primarily relied on traditional milling processes [63–66] and laser cutting techniques [67,68] for device fabrication. However, these manufacturing methods are generally suitable only for the small-batch production of laboratory prototypes and are limited in their ability to fabricate complex internal flow passages. Furthermore, the long production cycles and high manufacturing costs associated with conventional processes restrict their applicability to large-scale production. With the rapid advancement of AM technologies, various 3D printing techniques have been increasingly adopted for the fabrication of FOs, including both the main oscillator body and the cover plate [69–72]. Compared with conventional manufacturing methods, AM offers two major advantages. First, it enables the integrated fabrication of complex geometries, thereby reducing manufacturing time and assembly requirements. Second, it facilitates the production of fluidic actuators with sharp geometric features that are difficult to achieve using traditional machining methods. Nevertheless, AM also introduces process-related constraints, such as Sa , printing orientation, and dimensional deviations, all of which can significantly influence the performance of FOs.

3.3.1. Surface Roughness

AM processes inherently generate complex surface morphologies, a phenomenon that has been extensively documented in the literature [73]. The resulting Sa and texture directly influence the flow behavior and hydraulic performance of fluid systems [74–78]. Consequently, understanding and controlling Sa has become an important aspect of AM-based FO design. Tajik et al. [79] compared the performance of FOs fabricated using AM and conventional machining under different Sa conditions characterized by the arithmetic mean Sa . Their results indicated that when Sa was below $20\text{ }\mu\text{m}$, the internal flow structures remained largely unchanged. However, increasing Sa reduced the diffusion angle while increasing the oscillation frequency. Based on these observations, they further developed a linear model to predict the relationship between jet spreading characteristics and Sa . The influence of AM-induced roughness has also been reported in other fluid engineering applications. For example, Ilya Fedorov et al. [80] investigated the cooling performance of hot turbine guide vanes fabricated using metal AM and found that the high Sa of the internal flow passages generated local pressure peaks and non-uniform flow

distributions, thereby affecting cooling performance. To systematically investigate the influence of roughness location on FO performance, Hossain et al. [61] artificially introduced controlled roughness into three regions of a FO: the upper and lower walls, the FCs, and the main MC. Their study demonstrated that the effects of roughness are highly location-dependent. Roughness can alter the development of near-wall flow structures, modify feedback-flow transmission, and affect the evolution of recirculation bubbles, ultimately influencing oscillation frequency, jet switching behavior, and pressure loss. These findings highlight the importance of considering Sa not merely as a manufacturing imperfection but also as a design parameter that can substantially affect the operational characteristics of FOs.

3.3.2. Grating Angle

Among the various AM technologies, fused deposition modeling (FDM) is one of the most widely adopted methods for fabricating prototypes and functional components from engineering thermoplastics [81]. In FDM printing, the quality and performance of the manufactured component are strongly influenced by several process parameters, including raster angle, printing orientation, and raster width [82]. These parameters affect not only the dimensional accuracy of the printed part but also its surface morphology and flow-channel characteristics, which are particularly important for FOs. Tajik et al. [83] experimentally investigated the influence of raster orientation in FDM 3D printing on the jet performance of FOs. By comparing three commercially printed oscillators with different raster angles (0° , 45° , and 90°) and a milled oscillator, the authors demonstrated that raster orientation significantly affected the dimensionless maximum jet deflection angle, required supply pressure, St , and jet switching mass k (Figure 18). Among all tested printed samples, the oscillator fabricated with a 0° raster angle exhibited overall performance closest to that of the milled counterpart, whereas the 45° raster configuration generally showed the poorest performance and was therefore considered unsuitable for FO fabrication. Notably, although the P₃ printer (MakerBot Replicator+) produced relatively high surface roughness ($Sa = 12.4\text{--}22.3\ \mu\text{m}$), its surface texture exhibited no pronounced directional raster pattern. As a result, the corresponding oscillator achieved even better jet switching quality than the smooth milled sample. Moreover, all FOs fabricated by FDM printing required lower operating supply pressures compared with the milled baseline configuration. These findings suggest that surface morphology anisotropy may have a more critical influence on actuator performance than the absolute magnitude of surface roughness. This insight provides important guidance for optimizing FDM fabrication parameters of FOs: post-processing methods aimed at eliminating directional surface textures may significantly improve device performance without substantially increasing manufacturing costs. The detailed results are presented in Figure 18.

To mitigate the process-related constraints associated with AM, particularly those arising from Sa and printing-induced geometric deviations, several optimization strategies can be adopted. First, process-level optimization can be implemented by selecting appropriate FDM printing parameters, such as a 0° raster angle, to improve jet performance. Second, post-processing techniques, including chemical polishing and abrasive flow machining, can be employed to reduce flow-channel Sa and improve flow quality. Third, geometric compensation can be incorporated during the design stage, whereby the anticipated effects of manufacturing-induced roughness are accounted for through predictive models, enabling pre-correction of geometric features and reducing performance degradation after fabrication. Collectively, these approaches provide practical pathways for improving the performance and reliability of additively manufactured FOs.

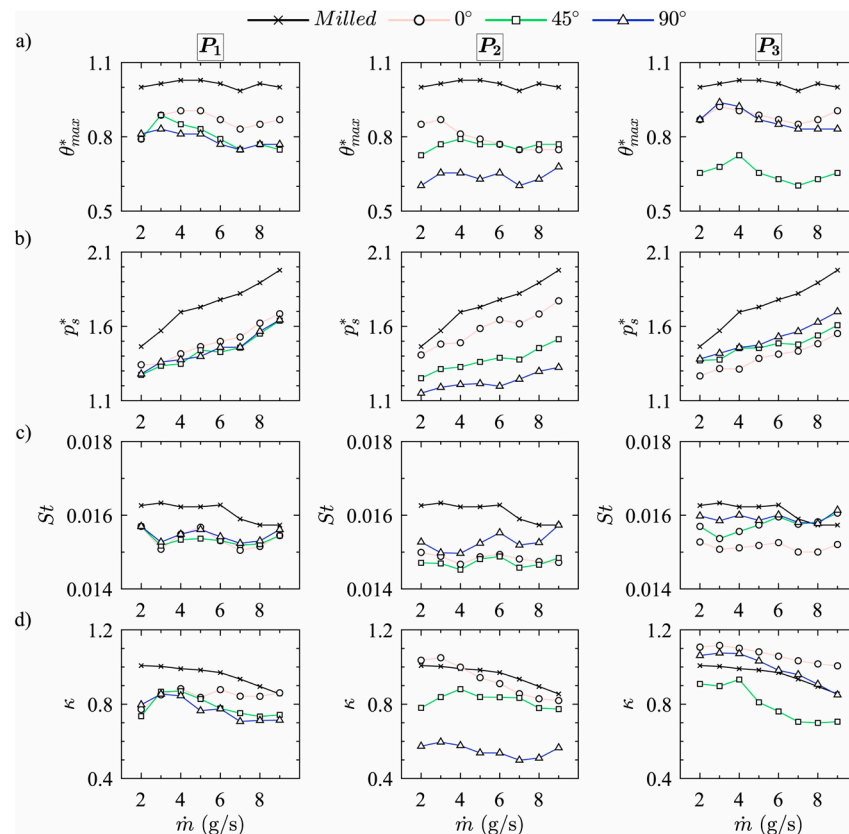


Figure 18. The variation in the flow characteristics of the actuators produced by printers P_1 , P_2 , and P_3 with the inlet mass flow rate $\dot{m}$ when the grating angles are 0° , 45° , and 90° : (a) dimensionless maximum jet deflection angle; (b) dimensionless required supply pressure; (c) St ; (d) jet switching mass k [83].

3.4. Multi-Physical Parameter Coupling Control Mechanism

In practical applications, the FO is often subjected to complex flow environments in which its performance is governed not only by geometric characteristics but also by the coupled effects of multiple physical parameters, including flow rate, velocity ratio, Re , and fluid properties. These coupled parameters collectively regulate the key performance characteristics of FOs, including oscillation stability, oscillation frequency, and jet evolution behavior, through their interactions with the internal flow dynamics. Therefore, understanding the complex interplay among external flow conditions, working fluid properties, and geometric parameters is crucial for achieving coordinated control and optimized performance of FOs.

Hu et al. [84] experimentally investigated the interaction and mixing characteristics of oscillating jets generated by a five-element FO array under crossflow conditions using planar and stereoscopic PIV in a low-speed wind tunnel. Their results showed that no phase synchronization occurred among the oscillators within the array. Under high-flow-rate conditions, strong interactions developed between adjacent jets, leading to the formation of localized velocity-enhancement regions. Furthermore, the velocity ratio between the jet and crossflow was identified as the dominant parameter controlling flow-field morphology, with increasingly complex flow structures observed at higher velocity ratios. In contrast, Duan et al. [85] focused on the characteristics of a single sweeping jet FO operating under co-flow conditions. Their results indicated that Re and oscillator size exerted only minor influences on the overall flow structure. Similar flow patterns were observed at identical velocity ratios, whereas higher flow velocities increased both the intensity and spatial extent of the vortex cores. To investigate the external flow

characteristics of high-subsonic sweeping jets, Lai et al. [23] examined the effects of throat width, inlet pressure, Ma_{outlet} , and outlet temperature on the jet deflection angle and oscillation frequency. The results demonstrated that increasing inlet pressure or Ma_{outlet} initially increased the jet deflection angle, followed by a subsequent decrease. In contrast, the oscillation frequency increased rapidly at first and then gradually approached a plateau. Moreover, higher outlet temperatures consistently resulted in higher oscillation frequencies. To minimize total pressure loss while maintaining sufficient axial force in drilling applications, Duan et al. [17] investigated the multi-objective optimization of a dual-vortex fluidic oscillator (DVFO). Through sensitivity analysis, channel thickness, shunt channel width, offset distance, and FC width were identified as the most influential design parameters. The study revealed that wider shunt channels, increased channel thickness, and reduced offset collectively decreased the number and intensity of vortical structures, thereby reducing pressure loss and improving energy efficiency. Spens et al. [86] systematically evaluated the influence of mass flow rate, hydraulic diameter, aspect ratio, curvature radius, Sa , inlet orientation, and non-uniform curvature on the performance of a novel out-of-plane bending FO. Oscillation behavior was characterized using the St , flow coefficient, diffusion angle, and oscillation angle. Three distinct operating regimes were identified. In the first regime, the oscillator exhibited oscillation frequencies and oscillation angles comparable to those of conventional planar oscillators. In the second regime, the oscillation frequency increased slightly while the oscillation angle decreased. In the third regime, no dominant oscillation frequency could be detected, indicating the complete loss of self-sustained oscillation. These findings suggest that under strong multi-parameter coupling, FOs may deviate substantially from their typical operating modes and even lose their oscillatory behavior. In addition to flow conditions, the multiphase composition of the working medium represents another important source of coupled effects. Li et al. [87] investigated the erosion behavior of FOs operating in particle-laden drilling fluids and quantitatively evaluated the effects of flow rate, particle concentration, and particle size on erosion characteristics. Their results demonstrated that optimizing the solid-phase composition of the drilling fluid can effectively mitigate erosion damage and thereby extend the service life of the oscillator.

3.5. Summary of Structure–Performance Relationships

To provide a concise overview of the structural optimization strategies discussed in Section 3, Table 2 summarizes the representative geometric features, corresponding design parameters, key findings and their limitations. Based on the aforementioned parametric studies, several common trends and trade-off relationships can be identified.

Macroscopic geometric parameters provide the fundamental basis for determining oscillation frequency and sweeping characteristics; however, their effects are often non-monotonic and exhibit critical threshold behaviors. For instance, the FC generally possesses an optimal length range: an excessively short channel may result in insufficient feedback signal development, whereas an excessively long channel can suppress oscillation or even lead to complete oscillation failure [43,46]. Similarly, the MC length exhibits a critical value, below which the jet is unable to sustain self-excited oscillation [48]. These nonlinear responses indicate that geometric optimization should initially ensure that the oscillator operates within a stable and effective oscillation regime.

Microstructural modifications provide an effective approach to overcoming inherent trade-offs among macroscopic design parameters. Although the introduction of ribs may reduce the jet deflection angle, it can simultaneously enhance oscillation frequency and reduce pressure loss, thereby enabling partial decoupling among multiple performance metrics [13]. Moreover, multi-objective optimization methods, such as the Taguchi approach, have demonstrated the potential to simultaneously improve oscillation frequency,

deflection angle, and pressure characteristics [15,16]. Similarly, backward-facing steps can increase oscillation frequency by reducing the size of separation bubbles while maintaining relatively low pressure losses [62]. The underlying mechanism of such microscale regulation lies in the modification of near-wall flow structures and the evolution pathways of flow separation regions.

The influence of AM constraints on FO performance should not be overlooked. In particular, surface morphology anisotropy may have a greater impact on actuator performance than the absolute magnitude of surface roughness itself [83]. This finding provides a new perspective for post-processing optimization, suggesting that eliminating directional surface textures may be more effective than simply reducing surface roughness.

In practical applications, structural parameters interact strongly with multiphysics operating conditions, potentially triggering transitions between different oscillation modes or even causing oscillation failure [86]. Nevertheless, the stability boundaries of FO systems under such multi-parameter coupling conditions remain insufficiently understood. Future studies should therefore incorporate data-driven approaches to advance FO design from empirical parameter correlation toward coordinated and intelligent performance regulation.

Table 2. Overview of multi-scale structural design strategies and their influence on key performance characteristics of FO.

Structure/Parameters	Influencing Factors	Key Findings	Limitations/Trade-Offs	References
Feedback channel (FC)	Length, width, entrance width, shape	The frequency decreases as the length increases and increases as the width increases Streamlined channels can reduce pressure loss and improve efficiency	A feedback path that is too short causes signal distortion, while one that is too long suppresses oscillation	[42–55]
Mixing chamber (MC)	Inlet wedge width, MC length, outlet width, inclination angle	Increasing the inlet wedge width enhances feedback intensity and diffusion angle The exit width and tilt angle significantly affect recirculation and oscillation amplitude	There is a critical length for the MC, which affects oscillation stability	[9,11,45,48,57]
Exit section and entry section	Outlet throat width, outlet angle, inlet throat width	An appropriate exit angle can enhance the Coanda effect The inlet throat width affects the flow structure and sound wave intensity	An overly wide exit will weaken momentum, while an overly narrow one will inhibit sweeping	[10,11,23,43,44,58]
Coanda surface ribbing	Rib width-to-height ratio, number, position, angle	Ribs can reduce pressure drop and increase frequency The angle of the ribs primarily governs the deflection angle, while the quantity primarily governs the frequency	The strut may reduce the jet deflection angle 4 ribs have the best overall performance; too many or too few are not ideal	[13,15,16,56,59–61]
Backward step	Length ratio (LR), height ratio (HR)	Optimizing LR = 0.402, HR = 0.4 can increase frequency and maintain low pressure drop Reduce the size of the circulating bubbles and enhance feedback momentum	There are few relevant studies, and the optimal configuration has only been verified under specific conditions	[21,62]
Surface roughness (Sa)	Roughness Sa value	Sa < 20 μm has little effect; if too large, increase frequency and reduce diffusion angle. A linear model can be established to predict the relationship between diffusivity and roughness.	Excessive roughness in the main mixing channel can lead to oscillation failure	[61,79,80]

Raster angle	0°, 45°, 90°	0° grating angle printing enables wider diffusion and lower supply pressure	The performance of the 45° grating angle is the worst and should be avoided	[83]
Flow parameters	Velocity ratio, Re, inlet pressure, outlet temperature	The speed is greater than the jet forming in the dominant crossflow Increasing temperature raises the oscillation frequency	At high subsonic speeds, the sweeping angle first increases and then decreases	[17,23,84–86]
Multiphase medium	Solid phase particle concentration, particle size, flow rate	Particle concentration and size affect erosion behavior, requiring optimization of solid phase control	Solid-phase control needs to be optimized to reduce device erosion and extend lifespan	[87]
System coupling	Multi-parameter interaction	Multi-parameter coupling may cause oscillation failure or mode switching, requiring data-driven methods to achieve coordinated control	Current research on critical performance in systems is still relatively weak	[86]

4. Advanced Design Methodologies

In the performance optimization of the FO, passive regulation through geometric parameters establishes the fundamental operating mode, but it remains difficult to actively tune oscillation characteristics such as oscillation frequency. To overcome this limitation, research has progressively shifted from purely geometric design toward the integration of dynamic control strategies and intelligent optimization methods. Concurrently, advances in design methodologies have increased the demand for more efficient mathematical optimization algorithms and data-driven modeling approaches. This chapter reviews recent progress in performance enhancement from geometric control to intelligent design, focusing on active control strategies, array synchronization design, novel vortex-oscillator configurations, inverse shape optimization, and data-driven surrogate models. It should be noted that when novel configurations such as non-feedback vortex type, master–slave type, synthetic jet-driven type and array type are mentioned in this chapter, the term “FO” is adopted as a generic term. It refers to oscillator devices that generate periodic flow output relying on hydrodynamic instabilities, rather than specifically denoting dual-feedback FO structures. The specific structural categories are clearly distinguished and discussed in the corresponding sections.

4.1. Active Control Strategies

In addition to passive structural regulation, actively controlling fluid oscillatory behavior has become an important research direction. Representative approaches include master–slave structural design and synthetic jet actuation, both of which modify the stability and deflection path of the primary jet through flow redistribution or external perturbations.

4.1.1. Master–Slave Structural Design

The diffusion angle is a key parameter for evaluating FO performance, as a larger diffusion angle corresponds to a wider sweeping jet range. However, in conventional designs, the diffusion angle is strongly coupled with the volumetric flow rate and internal geometric parameters, making independent and active regulation difficult. To address this issue, To overcome this issue, Wen et al. [88] proposed a non-dual-feedback master–slave FO (Figure 19a), which is capable of generating sweeping impinging jets with tunable diffusion angles. The configuration consists of a master layer and a slave layer, where V_{master} and V_{slave} denote the inlet velocities of the master and slave layers, respectively.

The master layer inherits a similar oscillation mechanism to that of conventional sweeping jets, whereas the slave layer functions as a stable jet passage. By adjusting the master flow rate ratio (MFR) from 0 to 1, the diffusion angle can be continuously regulated from 0° to over 100° . Here, MFR represents the fraction of the total inlet flow supplied to the master layer. When $\text{MFR} = 0$, the entire flow passes through the slave layer, resulting in a nearly steady straight jet due to the absence of oscillatory control from the master layer. Conversely, when $\text{MFR} = 1$, the entire flow enters the master layer, enabling full utilization of the sweeping oscillation mechanism and achieving the maximum diffusion angle. This configuration therefore provides an effective approach for continuously controlling different jet patterns. Building on this concept, Li et al. [89] developed an improved master–slave FO to further decouple the diffusion angle from the volumetric flow rate and investigated its internal and external flow characteristics as well as oscillation mechanisms. Compared with the configuration in Figure 19a, Figure 19b introduces a long gourd-shaped interaction chamber into the exit channel of the secondary layer to enhance flow instability. This modification significantly strengthened the influence of the primary layer on jet deflection. Moreover, even without inflow in the primary layer, the additional chamber induced pronounced jet oscillation, demonstrating improved momentum distribution uniformity and vortex entrainment capability in fluid mixing and flow-control applications.

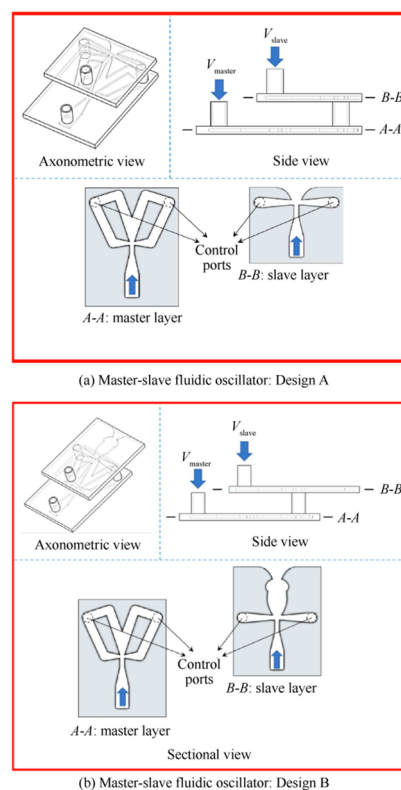


Figure 19. Schematic illustrations of non-dual-feedback master–slave FOs. (a) Design A consisting of a master layer for generating sweeping oscillations and a slave layer for providing a stable flow path; (b) Design B with a long gourd-shaped interaction chamber introduced in the slave-layer outlet channel to improve jet oscillation control. V_{master} and V_{slave} denote the inlet velocities of the master and slave layers, respectively [89]. Both subfigures (a) and (b) are reproduced from Ref. [89], which is an open-access article distributed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

4.1.2. Synthetic Jet Actuation

Another important active-control approach is synthetic jet actuation. Zhao et al. [90] developed a novel FO by replacing the conventional FCs with periodic synthetic jets, which enabled different oscillation frequencies to be achieved at the same velocity ratio, effectively decoupling the oscillation frequency from the velocity ratio. Subsequently, they applied this FO to flow separation control over a hump airfoil under three different forcing frequencies. Numerical results demonstrated that all three forcing frequencies were capable of suppressing flow separation. Furthermore, Zhao et al. [91] extended the application of this FO to flow control of a high-lift airfoil and investigated the influence of oscillation frequency on lift enhancement. The underlying mechanism revealed that low-frequency actuation enhanced chordwise momentum exchange through periodic amplification of turbulent kinetic energy and Reynolds shear stress, while effectively synchronizing the shedding frequency of separation vortices with the actuation frequency. As a result, low-frequency control achieved the most effective suppression of flow separation and the greatest lift enhancement, providing important theoretical guidance for frequency-based optimization of AFC strategies. The configuration of this novel FO is illustrated in Figure 20. In addition, Onofrio et al. [92] developed a device employing two out-of-phase synthetic jets to control a stable primary jet issued from a square nozzle, thereby generating a sweeping jet. Their results showed that increasing the momentum coefficient enlarged the sweeping angle (total angular range covered by the oscillating jet during one cycle) of the primary jet and improved heat-transfer performance at small impingement distances. Because the synthetic jets operate independently of the stable primary jet, the amplitude and frequency of the sweeping motion can be adjusted autonomously through the synthetic-jet parameters without changing the device geometry or the primary jet velocity. As shown in Figure 21, the dimensions of the device are expressed in terms of a reference length, namely the side of the square exit nozzle throat, $D = 10$ mm.

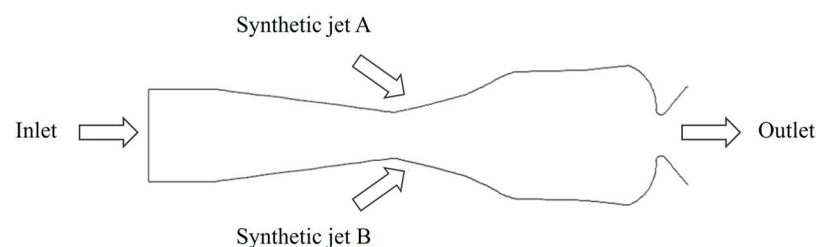


Figure 20. Schematic diagram of the novel feedback-free FO [91].

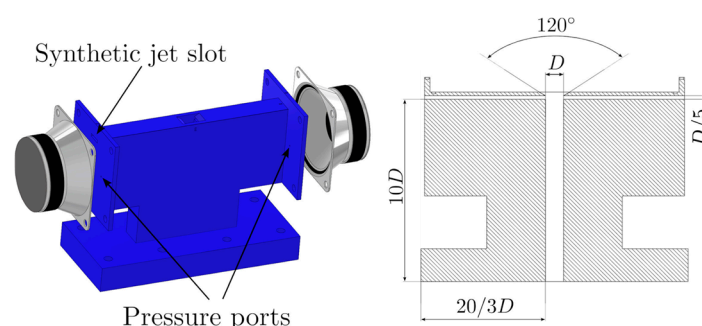


Figure 21. 3D schematic (left) and sectional view (right) of the synthetic jet FO [92].

4.2. Fluidic Oscillator Array Design

As the application requirements of FOs continue to expand from localized flow manipulation toward large-area flow control and heat-transfer enhancement, a single oscillator is often insufficient to provide adequate spatial coverage and momentum input.

Therefore, arranging multiple FOs into an array configuration has become an effective strategy for enlarging the control area, improving flow uniformity, and enhancing overall system performance. FO arrays have shown considerable potential in applications such as AFC, drag reduction, and impingement cooling [93–96]. Aram et al. [97] investigated the synchronized control of swept-jet arrays on wall-mounted hump surface separation flows, demonstrating that setting jet phases at 0° , 60° , and 180° significantly improves separation control compared to steady jets. Khodkameh et al. [98] conducted a comparative analysis of flow and heat transfer for synchronized and non-synchronized FO swept impinging jets arranged in parallel on a flat plate, in comparison with conventional steady jets. The results indicated that synchronized FO arrays consistently outperform non-synchronized oscillators and steady jets in average heat transfer performance. Conversely, non-synchronized FO arrays tend to form fluid retention zones between jets, reducing local heat transfer on heated surfaces. Shigeta et al. [99] highlighted that in turbulent separated cavity flows, synchronized oscillation is critical for effective cavity noise suppression. Therefore, FO arrays generally require synchronized oscillation to achieve optimal performance.

To achieve coordinated flow control and improve heat-transfer uniformity, considerable effort has been devoted to the development of phase-control strategies for FO arrays [84,100,101]. In parallel, researchers have proposed innovative configurations in which two oscillators are connected either side-by-side or in stacked arrangements to generate synchronized oscillating jets. The dual-sweeping-jet oscillator (DSJO) developed by Zubair [102] and Wen et al. [66] (Figure 22) is capable of producing two synchronized sweeping jets, particularly at low Re . However, Wen et al. [66] observed that the two jets gradually became asynchronous as the Re increased. To address this issue, Zubair et al. [102] investigated the influence of oscillator aspect ratio and demonstrated that reducing the aspect ratio effectively suppresses asynchronous behavior at high Re . Oscillators with an aspect ratio greater than or equal to unity were found to deviate from symmetric and synchronized oscillation. To evaluate the thermal performance of different dual-jet configurations, Zubair et al. [103] experimentally compared dual sweeping jet (DSJ), double sweeping jet (DbSJ), and double circular jet (DbCJ). Their results showed that DSJ provided the best heat-transfer performance at small jet spacings and high Re , whereas DbSJ performed optimally at moderate spacings and low Re , and DbCJ exhibited superior performance at moderate spacings and intermediate Re . Sang et al. [3] designed a combined FO system incorporating two distinct oscillation mechanisms, enabling either synchronous or asynchronous jet operation. Experimental results revealed that both synchronous and asynchronous sweeping jets produced a more uniform Nu distribution on the impingement surface than steady jets, with the improvement becoming increasingly pronounced as the nozzle-to-surface distance increased. Tomac et al. [104] proposed a counter-flow dual-oscillator configuration incorporating a shared FC. Experimental and numerical investigations demonstrated that this arrangement achieved a high degree of synchronization over a broad Re range, with cross-correlation coefficients exceeding 0.88. The synchronization mechanism was attributed to pressure equalization through the common FC. Similarly, Wang et al. [105] achieved synchronization of two bistable FOs through two different feedback-loop interconnection configurations, as illustrated in Figure 23. In Configuration 1, the feedback loops of the two oscillators are directly interconnected, enabling rapid transmission of pressure disturbances between the oscillators and facilitating synchronized jet switching. Under this configuration, the oscillation frequency remains close to that of an individual oscillator operating independently, while the two jets exhibit an approximately anti-phase pulsation behavior. In contrast, Configuration 2 adopts a different feedback-loop coupling strategy, where the jet switching process is additionally affected by the feedback response time. Consequently, the oscillation period is

jointly determined by the propagation time of pressure disturbances and the jet deflection dynamics, resulting in a significantly lower jet oscillation frequency and a phase difference of approximately one-quarter of the oscillation period. To further improve synchronization performance, Tomac et al. [106] developed a vertically stacked oscillator configuration in which adjacent oscillators were coupled through a quasi-rectangular synchronization channel. Hot-wire measurements showed that synchronized jets maintained cross-correlation coefficients greater than 0.94 over a total flow-rate range of 10–30 standard liters per minute. The authors further noted that stacked oscillators could be interconnected using a variety of coupling approaches, including pipes and synchronization channels with different geometries, dimensions, and quantities. More recently, Sundström et al. [107] investigated a novel back-to-back counter-flow oscillator pair through both experiments and numerical simulations. Owing to the presence of a shared FC, pressure fluctuations and flow momentum on both sides of the system remained balanced and in phase, resulting in the generation of two highly synchronized oscillating outlet jets.

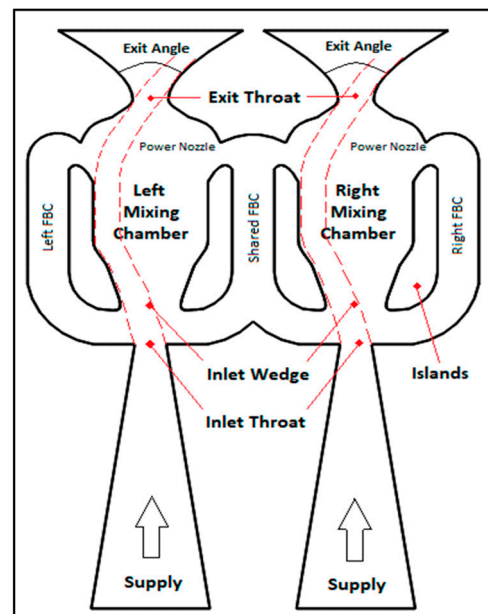


Figure 22. Schematic illustration of the dual sweeping jet (DSJ) FO configuration. The red dashed lines represent the trajectories of the primary oscillating jets inside the oscillator [102].

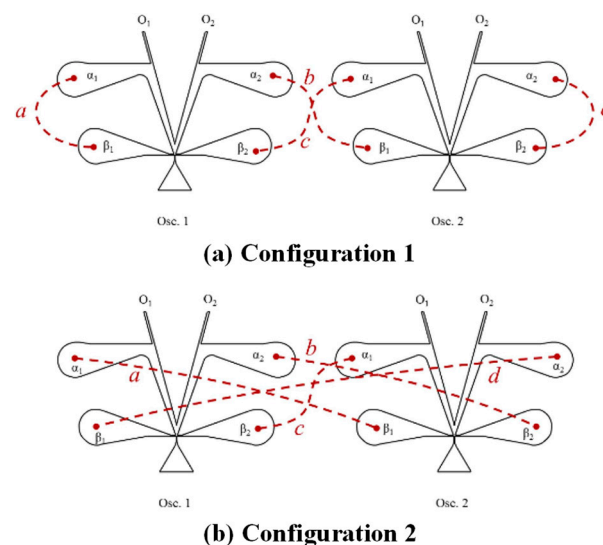


Figure 23. Schematic illustrations of two feedback-loop interconnection configurations for synchronizing two bistable FOs. The red dashed lines (a, b, c, d) denote the coupling pathways between the FCs of the two oscillators. The symbols α and β represent the upper and lower feedback connectors, respectively, with subscripts 1 and 2 indicating the left and right oscillators, O represents the outlet of FO. (a) Configuration 1: a combined direct and cross-coupled interconnection topology. (b) Configuration 2: a fully cross-coupled interconnection topology [105].

4.3. Design of Novel Fluidic Oscillators

The Coanda effect, referring to the tendency of a fluid jet to attach itself to a nearby curved or inclined surface due to the entrainment of surrounding fluid and pressure imbalance, plays a fundamental role in the operation of conventional FOs [108,109]. In traditional FO configurations, the jet initially adheres to one sidewall through the Coanda effect and is subsequently switched to the opposite side by the pressure feedback generated within the FCs, producing self-sustained oscillation [110]. This mechanism enables simple passive control of jet oscillation without moving components and has been widely employed in practical applications such as separation control, heat transfer enhancement, and mixing enhancement [111–117]. Nevertheless, the working principle based on the Coanda effect and feedback-channel flow dynamics inevitably imposes intrinsic limitations. The large cavity volume and substantial jet deflection required in conventional FOs lead to considerable momentum dissipation of the primary jet and induce significant pressure losses inside the oscillator [118].

To improve oscillation characteristics and operational efficiency, researchers have explored feedback-free or alternative FO designs. Kim et al. [119] proposed a feedback-free fluidic oscillator (FFO) with a stabilizing cavity; its feedback-free sweeping jet (FFSJ) achieves higher oscillation frequency and smaller sweeping angles than conventional feedback jets, enhancing impingement heat transfer. Nili Ahmadabadi et al. [118] proposed a novel vortex-based feedback fluidic oscillator (VFFO). As shown in Figure 24a, the proposed oscillator adopts a dual MC configuration consisting of a main chamber and a secondary chamber, which are separated by an intermediate throat and interconnected through two FCs. Figure 24b illustrates the asymmetric growth and shrinkage of the two pairs of vortices at different instants within one oscillation cycle, which induces a sinusoidal oscillation pattern of the internal jet. It can be observed that, unlike conventional Coanda-effect-based FOs where the jet primarily impinges on the chamber walls, the jet in the proposed oscillator mainly interacts with the vortex structures. This feature effectively reduces jet momentum dissipation and decreases the pressure loss inside the oscillator compared with traditional FO configurations. Subsequently, Rezaei et al. [120] numerically investigated the heat transfer performance of sweeping impinging jets generated by vortex-based and conventional FOs on a concave surface. The average Nusselt number (Nu) was adopted as a quantitative indicator to evaluate the cooling enhancement capability of different jet configurations. As shown in Figure 25, under a Reynolds number of 30,000, the vortex-based oscillator consistently achieved higher average Nusselt numbers than both the conventional FO and classical impinging jet over the entire range of normalized jet-to-surface distances (X/D). This result indicates that the vortex-driven oscillation mechanism can effectively enhance jet disturbance and interfacial heat transfer, thereby improving the overall impingement cooling performance. Subsequent studies [121–126] further explored their heat transfer enhancement characteristics. Karimzadegan et al. [127] proposed a novel FO configuration featuring a wide and short FC (Figure 26). This design reduces the influence of pressure propagation delay within the conventional long and narrow FCs on the oscillation process, thereby enhancing the capability of feedback flow to regulate the deflection of the primary jet. Consequently, the output oscillation frequency exhibits a strong linear relationship with the inlet Reynolds number.

The traditional FO flow path is complex, and the mechanisms governing pressure-drop amplitude remain insufficiently understood. Introducing a vortex diode has been shown to improve pressure-drop characteristics, prompting researchers to explore novel FO structures incorporating vortex diodes. Yang et al. [128] proposed a sweeping-vortex fluidic oscillator (SVFO) that integrates a vortex diode, operating on a fundamentally different principle from the conventional FO. Traditional oscillators rely on the Coanda effect to attach the jet to the wall, achieving delay and switching through the flow rate and length of the same-side FC, which complicates stable operation at low frequencies [129]. In contrast, the SVFO employs an upper-lower coupled configuration of a sweeping cavity and a vortex cavity, using contralateral fluid feedback and the growth-dissipation delay of trapped vortices to drive oscillation. This mechanism enables the main jet to achieve two continuous deflections within the cavity, imparting robust low-frequency characteristics suitable for applications such as hydraulic shock absorbers and axial vibration tools [130–135]. Similarly, Zhang et al. [136] proposed a simplified dynamic-compliance fluidic oscillator (DCFO) integrated with a vortex diode, which enhances pressure retention and output pressure-drop amplitude relative to the traditional FO, allowing stable regulation of both oscillation frequency and pressure drop.

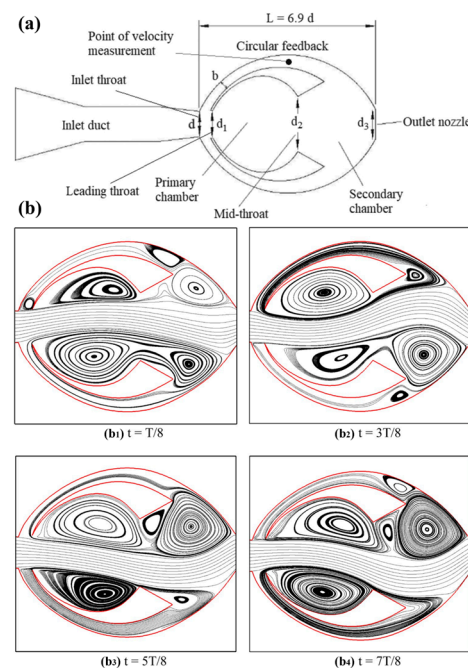


Figure 24. Vortex-based feedback fluidic oscillator (VFFO). (a) Design dimension schematic (d : reference width of inlet throat; d_1 : width of leading throat; d_2 : width of mid-throat; d_3 : width of outlet nozzle; b : flow width of circular FC; L : total axial length of the oscillator); (b) Streamlines inside the oscillator at 4 equal intervals of a time period after forming the harmonic oscillations at ($Re = 60,000$) [118].

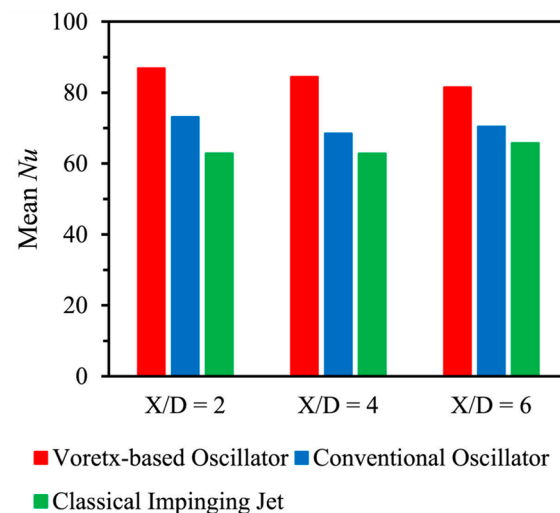


Figure 25. Comparison of average Nusselt numbers for classical impinging jets, conventional FOs, and vortex-based FOs at different normalized jet-to-surface distances (X/D) under $Re = 30,000$ [120].

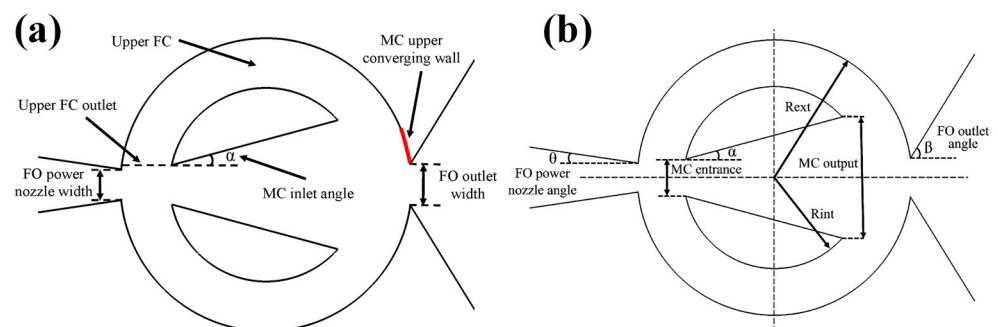


Figure 26. Schematic diagram of the new FO structure: (a) Main configuration of MC and FCs; (b) Main internal dimensions [127].

4.4. Optimized Design Methods

Under the multi-objective design requirements of the FO, a key challenge is to simultaneously enhance oscillation frequency and jet sweeping angle while minimizing total pressure losses arising from manufacturing-induced Sa , flow separation, and abrupt channel turns. In recent years, inverse-design approaches, particularly gradient-based adjoint shape optimization and the statistical Taguchi orthogonal design method, have demonstrated considerable potential for addressing this challenge. Adjoint optimization is a gradient-based design methodology that efficiently evaluates the sensitivity of an objective function to geometric variations throughout the computational domain by solving the adjoint form of the governing flow equations [137]. In contrast, the Taguchi method employs orthogonal experimental design in combination with signal-to-noise ratio analysis and analysis of variance to rapidly identify the geometric parameters that exert the greatest influence on flow behavior. By revealing the dominant factors governing the formation and evolution of recirculation zones and separation bubbles, the method facilitates efficient multi-objective optimization of macroscopic performance characteristics [15,138,139].

4.4.1. Adjoint Optimization Methods

To enhance the heat-transfer performance of sweeping-jet impingement systems, Tang et al. [137,140] employed adjoint optimization to improve the structural design of the FO. A calibrated generalized $k-\omega$ turbulence model was adopted for flow-field

simulations, with the objective of minimizing the average wall temperature. The numerical results demonstrated that micrometer-scale, sensitivity-guided modifications to the internal walls of a conventional FO significantly altered the flow structure within the MC. The optimized configuration exhibited weaker recirculation, a reduced jet sweeping angle, a more concentrated velocity distribution, and lower flow dissipation. These changes promoted the outward migration of near-wall vortical structures along the concave surface, thereby enhancing convective heat transfer and improving overall thermal performance. In another application of adjoint optimization aimed at reducing energy consumption, Jabbari et al. [12] performed gradient-based sensitivity analysis to optimize the geometry of the Coanda surface and FCs in a VFFO. The results showed that sensitivity-guided geometric modifications substantially improved the internal vortex dynamics and overall oscillator performance. In particular, increasing the Coanda surface angle by 12° resulted in an approximately 70% increase in oscillation frequency while simultaneously reducing internal pressure loss by about 18% compared with the baseline design.

4.4.2. Taguchi Orthogonal Method

Compared with gradient-based optimization techniques, the Taguchi method offers outstanding practicality for the multi-objective optimization of discrete geometric parameters. Park et al. [42] combined Taguchi experimental design with response surface methodology and employed high-speed Schlieren imaging together with dynamic pressure measurements to investigate the effects of internal geometric parameters on the performance of a supersonic FO. Their results revealed that the oscillator length and the spacing between internal blocks are the dominant design variables governing sweeping-jet behavior. A clear trade-off was observed between the effects of these two parameters, whereas geometric variables associated with the feedback-channel shape exerted only a minor influence on the overall flow-field characteristics. Hussain et al. [15] further applied an integrated CFD-Taguchi-GRA framework to optimize an FO incorporating ribbed Coanda surfaces. Three geometric parameters, namely the rib height-to-width ratio, rib number, and rib inclination angle, were evaluated at three levels through numerical simulations and orthogonal experimental design. The results indicated that the rib number primarily controls oscillation frequency, the rib inclination angle governs the jet sweeping angle, and the rib height-to-width ratio predominantly affects pressure loss. Based on these relationships, an optimal rib configuration was identified that simultaneously achieved high oscillation frequency, large jet sweeping angle, and low pressure drop. Subsequently, Hussain et al. [16] applied the optimized oscillator to sweeping-jet impingement heat-transfer enhancement. The optimized design increased the average Nu on the target surface by up to 24.3% and achieved the PEC of 1.252. These results demonstrate that the ribbed structure systematically optimized through the Taguchi method can effectively alleviate the traditional coupling constraint between frequency enhancement and pressure loss, thereby significantly improving heat-transfer performance while maintaining relatively low energy consumption.

4.5. Data-Driven Surrogate Models and Artificial Intelligence

As FO applications continue to expand into areas such as fuel injection and mixing in supersonic combustors, solid–liquid mixing in continuous crystallization processes, and high-temperature film cooling of transonic turbine blades, the associated flow fields exhibit increasingly complex characteristics, including strong nonlinearity, multi-scale interactions, and multiphysics coupling [141–144]. To reduce the computational cost of high-fidelity numerical simulations under complex operating conditions, data-driven machine learning surrogate models have been increasingly introduced into the performance prediction and optimization of FOs. By learning flow characteristics from existing

experimental or numerical databases, these approaches can achieve rapid performance prediction and parameter optimization to some extent. However, their predictive accuracy remains highly dependent on the quality and coverage of the training datasets [145–150].

Currently, data-driven studies in the field of FOs are primarily concentrated on established approaches, such as surrogate modeling, reduced-order reconstruction, and optimization-assisted methods. Henry and Maulik [18] employed FNOs and other data-driven dimensionality reduction techniques to extract dominant frequencies and dynamic features from high-dimensional spatiotemporal flow field datasets, thereby developing an efficient surrogate modeling framework based on boundary condition representation. The proposed framework was capable of accurately capturing the nonlinear time–frequency characteristics of jet switching and the relationship between oscillation behavior and supply conditions, while significantly reducing the computational cost compared with conventional high-fidelity simulations. For the spatiotemporal filtering of highly dynamic temperature fields and impinging sweeping jets, Castellanos et al. [151] combined POD with Gaussian and Savitzky–Golay filtering methods to effectively separate high-frequency experimental noise while preserving key thermal topological features. Furthermore, a data-driven surrogate model constructed using manifold learning enabled rapid prediction of heat transfer responses under various flow conditions. For the optimization of DVFOs under liquid-phase operating conditions, Duan et al. [17] integrated adaptive sampling, deep infinite mixture Gaussian process (DIM-GP) surrogate modeling, and genetic algorithms to establish a multi-objective optimization framework, overcoming the limitations of conventional gradient-based methods in complex design spaces. Beyond performance optimization, reduced-order and data-driven models have also been applied to rapidly reconstruct unsteady flow fields around turbine blade leading edges subjected to sweeping jet impingement, providing insights into transient heat transfer mechanisms [152], as well as to investigate the effects of microscopic parameters on particle agglomeration behavior in gas–solid two-phase flows [145].

Although data-driven approaches have demonstrated considerable potential in the performance prediction and parameter optimization of FOs, their further development still faces several challenges. First, machine learning models generally rely on high-quality, large-scale, and representative training datasets, whereas the acquisition of complex 3D unsteady flow data still requires substantial computational resources for high-fidelity simulations or extensive experimental efforts. Second, the reliability of data-driven models beyond the training data distribution requires further validation, as their generalization capability and uncertainty quantification remain critical limitations for practical engineering applications. Moreover, numerical simulation errors, experimental measurement uncertainties, and model selection strategies may all influence the optimization outcomes. Therefore, the integration of experimental validation and physical constraints remains essential for improving model reliability and interpretability. In the future, emerging intelligent approaches, such as physics-informed neural networks (PINNs), reinforcement learning, and autonomous design frameworks, are expected to further integrate flow physics with data-driven capabilities, enabling more efficient design optimization of FOs. However, these approaches are currently still in the exploratory stage, and their large-scale application in the field of FOs requires further investigation.

Overall, the enhancement of FO performance has evolved from conventional trial-and-error approaches based on geometric parameter adjustment to a multidimensional design paradigm integrating active control, inverse optimization, and data-driven intelligence. Master–slave configurations and synthetic-jet actuation strategies enable independent regulation of jet oscillation characteristics, while synchronized oscillator arrays improve the uniformity of AFC. In parallel, vortex-based oscillators have demonstrated

significant advantages in simultaneously reducing pressure loss and increasing oscillation frequency, thereby extending the applicability of the FO to confined-space flow control and multi-jet collaborative systems. Meanwhile, adjoint optimization and Taguchi-based design methods provide complementary advantages in sensitivity analysis and discrete-parameter optimization, respectively, offering both theoretical optimality and strong engineering practicality. Data-driven approaches based on FNOs, POD, and Gaussian-process models have further reduced the computational cost associated with complex flow simulations, enabling rapid prediction and optimization under challenging operating conditions such as fuel-air mixing in supersonic combustors and turbine-blade film cooling. With the continued integration of machine learning, high-fidelity numerical simulation, and advanced optimization techniques, FO design is expected to transition from experience-based development to intelligent optimization, thereby accelerating the deployment of the FO in AFC, enhanced heat transfer, and other advanced engineering applications.

5. Multiphase Flow Conditions

Most existing studies characterize FO performance using single-phase working media, including gases (e.g., air) and liquids (e.g., water and aviation kerosene). However, practical industrial applications frequently involve complex multiphase flow environments, such as drilling fluids containing solid particles, gas–solid particulate flows, and gas–liquid mixed fuels. Compared with single-phase systems, the flow behavior and performance characteristics of the FO under multiphase conditions remain insufficiently understood. Therefore, this section reviews the fundamental issues, recent research progress, and performance enhancement strategies associated with solid–liquid, gas–solid, and gas–liquid two-phase flows, with the aim of providing theoretical guidance for the engineering application of the FO in multiphase environments.

5.1. Solid–Liquid Two-Phase Flow

In industrial processes such as oil and gas drilling, mineral extraction, and chemical crystallization, the FO often operates in solid–liquid two-phase flows containing suspended particles. The presence of a solid phase not only alters the hydrodynamic characteristics of the flow field but also introduces challenges such as erosion, particle deposition, and changes in residence-time distribution, all of which directly influence equipment durability and process efficiency.

In oil and gas drilling applications, the FO is widely employed in fluid-hammer systems, including rotary percussive drilling tools, friction-reduction vibration tools for extended-reach wells, and coiled-tubing drilling tools [153–156]. Under downhole operating conditions, drilling fluids containing abrasive particles are accelerated through the FO nozzle to form high-velocity jets, resulting in severe wall erosion. The erosion rate increases markedly with increasing flow rate and may eventually lead to fluid-hammer failure [157–159].

To address particle-induced erosion in the FO, extensive investigations have been conducted in recent years. Tang et al. [160] examined the erosion characteristics of a vertical-feedback oscillator (V-FO) and a curved-feedback oscillator (C-FO) using transient CFD simulations. Their results demonstrated that erosion exhibits periodic behavior associated with jet oscillation, with the erosion rate remaining nearly constant within each oscillation cycle. Severe erosion was primarily concentrated near the nozzle, splitter, and vent regions, while the erosion rates at the splitter and vents fluctuated periodically. Comparative analysis further revealed that the oscillating jet in the V-FO was less stable than that in the C-FO, resulting in additional erosion during the start-up stage. However, the study neglected the influence of impactor motion on jet dynamics, which introduced discrepancies between the numerical predictions and actual operating conditions. To

overcome this limitation, Li et al. [87] coupled impactor motion with the internal flow field for the first time and investigated the dynamic erosion mechanism of an FO operating with drilling fluid using a CFD-discrete phase model (DPM) combined with dynamic mesh techniques. The results indicated that the primary erosion regions were located at the splitter, connecting wall, control nozzle, and cover plate. The cumulative erosion mass per unit area increased approximately linearly with particle concentration throughout each operating cycle. Owing to differences between the forward and return stroke durations, erosion patterns in the geometrically symmetric FO exhibited pronounced asymmetry. Furthermore, the degree of asymmetry increased with particle size and stabilized when the particle diameter exceeded 100 μm . To alleviate friction-related problems in extended-reach wells, Tang et al. [161] proposed a reverse-feedback oscillation tool (RFOT), as illustrated in Figure 27. Using a Lagrangian particle-tracking approach, the authors numerically investigated the effects of fluid properties, particle characteristics, and jet-switching behavior on internal erosion. As shown in Figure 28, erosion at the nozzle initially increased and subsequently decreased with increasing particle size. Larger particles possess greater kinetic energy and therefore induce more severe erosion; however, beyond a critical particle size, the fluid carrying capacity decreases, resulting in reduced particle velocity and erosion intensity. In addition, erosion rates at all locations increased exponentially with flow velocity. Particle accumulation caused by the concave splitter geometry led to an initial increase followed by a gradual decrease in splitter erosion, eventually approaching zero. Since each side of the splitter is exposed to the oscillating jet only once every two oscillation cycles, the fluctuation period of splitter erosion was found to be twice the jet oscillation period. From a materials perspective, Li et al. [162] replaced conventional tungsten carbide with polycrystalline diamond composite (PDC) materials to improve erosion resistance. Using an improved submerged abrasive water-jet apparatus, the authors systematically investigated the erosion behavior of PDC materials under different particle-size conditions. The results showed that the erosion resistance of PDC was significantly superior to that of tungsten carbide. At a jet velocity of 100 m s^{-1} , the erosion rate of PDC was only 1/192–1/43 that of tungsten carbide. Moreover, fine-grained PDC grades (except those with grain sizes of 2–3 μm) exhibited even greater resistance to impact erosion. These findings demonstrate the suitability of PDC materials for local reinforcement of erosion-prone regions within the FO.

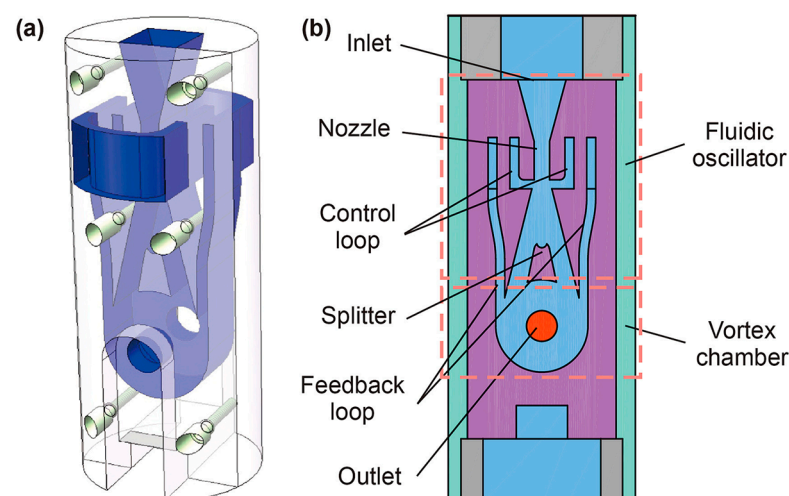


Figure 27. Schematic of reverse-feedback oscillation tool (RFOT) (a) 3D model of RFOT (b) Cross-sectional view of RFOT [161].

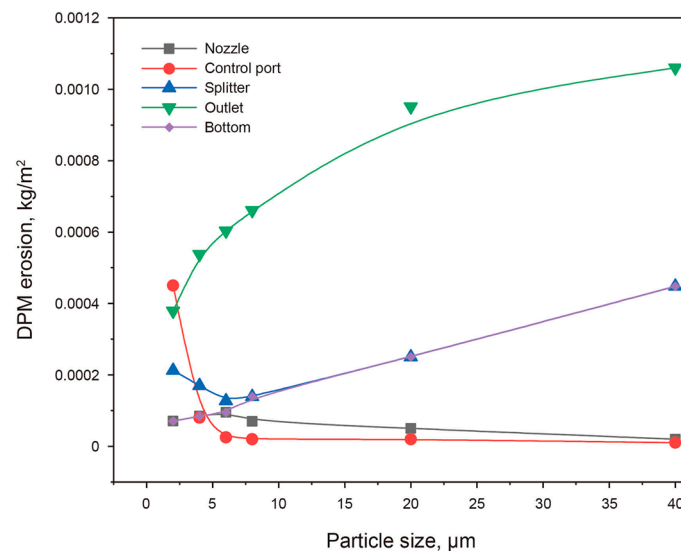


Figure 28. Effect of particle size on erosion behavior [161].

In chemical process intensification applications, the FO is frequently employed in continuous crystallisers, where the solid phase represents the desired product. Nevertheless, the influence of suspended solids on FO flow and mixing characteristics remains insufficiently investigated. Madane [142] examined the effects of solid volume fraction and particle size on FO flow dynamics through combined experimental and numerical studies. A laser Doppler anemometer (LDA) was employed for the first time to characterize FO flow behavior and validate the numerical models. The results indicated that, within the investigated range (up to 175 μm paracetamol particles and 5% solid loading), neither particle size nor solids concentration significantly affected the jet oscillation frequency or the overall flow structure. However, fine particles experienced extended residence times due to recirculation within secondary flow regions. This study provides valuable insight into the application of the FO in solid-containing processes such as continuous crystallization.

Under solid–liquid two-phase flow conditions, erosion resistance is a critical factor governing the service life and operational reliability of the FO. Consequently, erosion mitigation strategies should focus on material selection and structural optimization of regions subjected to severe particle impact, particularly the splitter, which is typically the most vulnerable component. In drilling-related applications, additional measures such as optimizing the solids-control system, reducing particle concentration and particle size in drilling fluids, and appropriately lowering the flow rate while maintaining fluid-hammer performance can effectively alleviate particle-induced erosion and extend the service life of the FO.

5.2. Gas–Solid Two-Phase Flow

Research on the FO operating under gas–solid two-phase flow conditions remains limited, yet these systems demonstrate significant potential for particle dispersion and enhanced gas–solid mixing. Morris et al. [163] investigated the dynamics of air and solid particles (21 μm and 54 μm glass microspheres) in an FO oscillating jet using laser Doppler velocimetry. Their results indicate that, compared with steady jets, oscillating jets substantially enhance transverse diffusion of the working medium, with larger diffusion angles corresponding to stronger transverse velocity components. At an oscillation frequency of 50 Hz, the gas and solid phases exhibited a phase lag of up to 40°. This study confirms that fluidic oscillating nozzles can effectively disperse particles at the outlet via the sweeping jet, making the FO a promising device for two-phase mixing and aerosol

generation. Liu et al. [145] numerically examined the influence of FO mixing-chamber dimensions—specifically inlet width (W_1), cavity width (W_2), and outlet width (W_3)—on the gas–solid flow field. The results show that W_1 controls the formation and orientation of recirculation zones, thereby influencing the sweeping motion of the jet. W_2 primarily adjusts the expansion angle of the jet by modulating recirculation bubble size, exerting minor influence on oscillation frequency; however, larger W_2 values increase the diffusion angle and the risk of particle agglomeration due to elevated particle concentrations in the FC and main jet. Increasing W_3 reduces outlet constraints on jet sweeping, leading to higher oscillation frequency and expansion angle while simultaneously enhancing the shear-induced particle agglomeration effect through dissipative vortices.

The presence of solid particles in gas–solid two-phase flows affects both oscillation performance and flow-channel phenomena such as deposition and agglomeration. Optimization of internal FO geometry, including mixing-chamber dimensions, allows regulation of oscillation frequency and jet expansion angle, thereby improving mixing efficiency while mitigating particle clustering. In numerical studies, population balance models are often employed to describe the evolution of particle-size distribution, enabling quantification of particle collision, aggregation, and breakage dynamics [145,164–166].

In gas turbines and other power-generation systems, the FO is frequently used as cooling-hole devices for jet-film cooling of turbine blades [125,167–169]. Under harsh operating conditions, entrained dust and combustion byproducts form particle-laden flows that deposit on high-temperature surfaces, reducing film-cooling performance [170,171]. In such environments, FO nozzles with sweeping jets can actively manipulate the near-wall gas–solid flow, thereby limiting deposition, protecting cooling holes, and extending component service life. Zhou et al. [172] introduced a shaped sweeping jet design that simultaneously achieves effective film cooling and particle-deposition mitigation. Using pressure-sensitive paint for adiabatic cooling measurements and multi-perspective scanning to quantify 3D particle-deposition morphology, the study demonstrated that SSJ holes increased cooling efficiency by up to 70% and reduced maximum deposition height by 28% relative to conventional designs. At low blowing ratios, SSJ holes showed a pronounced anti-deposition effect; however, at high blowing ratios ($M = 2.0$), the increased oscillation frequency decreased wall shear stress, reducing particle-removal effectiveness to levels comparable with 777-shaped holes. This reduction is attributed to the momentum loss of oscillating jets at higher frequencies, which limits wall-shear forces required to dislodge particles. Zhang et al. [173] further compared SSJ and 777-shaped holes in flat-plate film-cooling experiments and numerical simulations, revealing 5–14% lower deposition roughness for SSJ holes. The improved performance results from unique vortex structures and elevated periodic wall-shear stress near the hole exit. Subsequent engine-like simulations by Zhang et al. [174] on nozzle-guide vanes confirmed that SSJ designs expand deposition-free zones and reduce area-averaged deposition rates under high blowing ratios ($M = 2.0$), demonstrating their practical applicability for gas–solid flow environments.

5.3. Gas–Liquid Two-Phase Flow

Under gas–liquid two-phase flow conditions, the significant differences in physical properties between the gas and liquid phases, together with complex interfacial interactions, provide new opportunities for regulating the performance of FOs. The coupling between the two phases not only alters the internal flow structures and unsteady oscillation characteristics of FOs but also further regulates droplet atomization and bubble generation processes by affecting jet shear, interfacial breakup, and energy transfer mechanisms. Therefore, the optimization of gas–liquid flow mechanisms and structural design has become an important approach for enhancing the atomization efficiency, microbubble generation capability, and gas–liquid mass transfer performance of FOs.

FOs can serve as injection devices producing self-excited sweeping jets of liquid fuel, offering enhanced atomisation performance. However, under high thermal-load conditions, continuous backflow of fuel within the nozzle can lead to oxidative coking. To mitigate this, researchers have proposed premixing high-temperature air with fuel prior to injection to reduce in-nozzle residence time. Zhai et al. [175] combined numerical simulations and experiments to study the oscillation characteristics and atomisation performance of a self-excited oscillating nozzle under gas–liquid premixed intake. The study demonstrated that the Coanda effect sustains self-excited oscillation, with oscillation frequency exhibiting higher sensitivity to the gas-phase velocity. The primary oscillation frequency was consistent between single-phase air and gas–liquid two-phase cases, while secondary frequency components became more pronounced under two-phase conditions. Increasing the AFR and premix gas temperature reduced the SMD and narrowed the spray cone angle. Low fuel flow rates or large initial droplets resulted in higher SMD and wider exit cone angles due to the shorter residence time of larger droplets in the nozzle. Subsequently, Zhai et al. [33] used range analysis of orthogonal experiments to identify the main factors affecting atomisation performance. AFR emerged as the primary influencing factor, followed by fuel flow rate. The study also highlighted the critical role of nozzle size: for smaller nozzles (D1.8, H1.8, with both throat diameter and height of 1.8 mm), increasing AFR significantly elevated oscillation frequency, enhancing shear forces at the nozzle exit and improving droplet atomisation. Ma et al. [176] employed two-dimensional gas–liquid multiphase numerical simulations to investigate the flow characteristics at the outlet of a self-excited sweeping nozzle under stationary atmospheric conditions. The results revealed that high-frequency liquid-column oscillations generate localized high-speed gas regions with velocities up to three times that of the liquid, thereby enhancing gas–liquid shear interactions—the primary mechanism for improved atomisation.

In summary, under gas–liquid two-phase premixed injection conditions, the atomization performance of FO-based nozzles is jointly governed by the gas–liquid ratio, fuel flow rate, nozzle geometric dimensions, and premixing chamber configuration [33]. Among these factors, the AFR regulates the momentum exchange between the gas and liquid phases and serves as the dominant parameter affecting atomization performance. Meanwhile, the nozzle dimensions and internal structural design further optimize the droplet breakup process by modifying the oscillation frequency and shear intensity. Therefore, through the synergistic regulation of gas–liquid two-phase coupling and structural optimization, the enhancement effect of the unsteady oscillating jet generated by FO on fuel atomization can be fully exploited.

In gas–liquid two-phase flow applications, FOs not only regulate gas–liquid mixing processes but also provide a novel approach for efficient microbubble generation through their periodic oscillating jets. Conventional porous diffusers are limited by the wetting force during bubble growth, buoyancy-driven detachment mechanisms, and bubble coalescence. Even with microscale pore structures, it remains difficult to generate microbubbles with sizes comparable to the pore diameter. In contrast, FOs utilize periodic flow pulsations to induce bubble detachment while the bubbles are still in the hemispherical cap stage, enabling bubble size control by the pore scale rather than by buoyancy effects. This mechanism allows the generation of microbubbles with low energy consumption and a narrow size distribution [177].

Zimmerman et al. [178] further extended this concept to efficient nanobubble generation. They demonstrated that the size regulation of bubbles induced by fluidic oscillation is essentially attributed to the restriction of bubble growth time scales by oscillatory pulses, enabling the generated bubbles to be controlled within the range of 20–100 μm . This mechanism significantly increases the gas–liquid interfacial area, thereby enhancing gas–liquid exchange efficiency in oxygen transfer, ozone mass transfer, and biological

reaction processes. Based on this concept, Liu et al. [179] further investigated the bubble breakup mechanisms in FO under gas–liquid two-phase coupling conditions using high-speed imaging and PIV techniques. Their results revealed that the liquid-phase velocity is the dominant factor governing bubble evolution behavior. Furthermore, Zheng et al. [180] found that the microbubble jet generated by FO exhibits a pronounced periodic sweeping characteristic, which originates from the periodic interaction between gas–liquid separation vortices and the primary jet inside the oscillator. This unsteady flow environment promotes the synergistic development of multi-scale bubble breakup mechanisms within the FO, causing bubbles to undergo continuous fragmentation, refinement, and interface renewal during transportation. Consequently, the gas–liquid contact area is effectively increased, leading to enhanced mass transfer efficiency between the two phases. To further overcome the limitations of single oscillation mechanisms in achieving uniform bubble size distribution, Yang et al. [181] proposed a swirl–oscillation coupled microbubble generation strategy. In this approach, the swirl structure first generates strong shear effects to achieve the preliminary breakup of gas–liquid phases, followed by the periodic oscillating jet induced by the FO to further promote secondary bubble breakup and interface renewal. Experimental results demonstrated that, compared with conventional swirl jets, this coupled configuration can produce a more uniform microbubble population.

In summary, the key advantage of FO-based microbubble generation does not solely rely on high-speed jet shear, but rather on its ability to actively regulate bubble formation, detachment, breakup, and migration processes through periodic oscillations. This enables the synergistic optimization of bubble size, spatial distribution, and interfacial renewal efficiency. In the future, the integration of multi-scale structural designs and external enhancement strategies, such as swirling flows and jet impingement, with the intrinsic oscillation characteristics of FOs is expected to further improve microbubble generation efficiency, providing new technical solutions for enhanced gas–liquid mass transfer, fuel atomization, and environmental engineering applications.

6. Challenges and Future Perspectives

Although significant progress has been achieved in FO performance enhancement through geometric regulation, manufacturing-constrained design, data-driven optimization, and multiphase-flow applications, several fundamental challenges still limit their further development toward practical engineering applications. These challenges are not only associated with individual design strategies but also arise from the lack of unified evaluation criteria, insufficient understanding of complex flow mechanisms, and limitations in prediction and validation methods. Therefore, this section summarizes the major challenges identified from previous studies and discusses potential future directions.

6.1. Advancing Active Regulation Mechanisms

Currently, FO design is gradually evolving from passive regulation based on fixed geometric parameters toward active control strategies. Previous studies have demonstrated that approaches such as master–slave configurations and synthetic-jet-driven actuation provide new pathways for manipulating jet oscillation behaviors. However, achieving real-time, wide-range, and independent control of key performance parameters, such as oscillation frequency and jet deflection angle, while preserving the inherent advantages of FOs, including the absence of moving components and high operational reliability, remains a critical challenge and an important direction for future active control research.

Future research directions may include:

- Introducing auxiliary jets through control ports to dynamically manipulate the pressure distribution and recirculation-bubble evolution within the MC, thereby enabling decoupled control of oscillation frequency and jet sweeping amplitude [90].
- Integrating smart materials, such as shape-memory alloys and piezoelectric ceramics, into FO structures. By exploiting externally induced deformation or stiffness variation in critical components, including Coanda surfaces and feedback-channel walls, the oscillator itself could acquire active self-regulation capabilities. For example, Loe et al. [53] demonstrated that incorporating elastic structures around the oscillator can effectively modify and optimize oscillation behavior.
- Combining active-control strategies with closed-loop sensing and feedback systems. Real-time flow or thermal signals could be used to adaptively adjust control parameters through intelligent algorithms, enabling optimal performance under dynamically varying operating conditions.

6.2. Coupled Effects of Multiple Physical Parameters

FO performance optimization involves multi-scale parameters, including geometric configurations, microscale features, manufacturing-related factors, operating conditions, and working fluid properties. The interactions among these parameters determine the balance between oscillation characteristics and energy dissipation. For instance, structural modifications aimed at enhancing oscillation frequency may simultaneously increase pressure loss or distort pressure pulse signals [43,62]. At present, the underlying coupling mechanisms among these parameters remain insufficiently understood, and the lack of unified performance evaluation criteria capable of guiding high-performance FO design represents a critical challenge that requires further investigation.

Future studies should focus on the following aspects:

- Developing integrated research frameworks that combine high-fidelity numerical simulations with advanced experimental diagnostics to systematically investigate the coupling mechanisms among key dimensionless parameters, including the Re , St , and Eu , and to identify the dominant factors controlling FO performance.
- Establishing standardized performance-testing and evaluation protocols to facilitate quantitative comparisons among different studies and oscillator configurations, thereby providing a unified basis for high-performance FO design and optimization.

6.3. Transforming Additive-Manufacturing Constraints into Design Opportunities

AM has emerged as a key enabling technology for the fabrication of geometrically complex FOs. However, manufacturing-induced features such as Sa , layer texture, and geometric imperfections are generally regarded as detrimental factors that degrade oscillation performance [79]. Future research should move beyond the conventional approach of merely minimizing these effects and instead explore opportunities to exploit them as functional design elements.

A particularly promising research direction is:

- Investigating how characteristic surface textures generated by different AM process parameters, such as raster orientation, layer thickness, and printing strategy, influence near-wall flow structures, separation-bubble dynamics, and boundary-layer transition. Such studies may reveal opportunities to transform manufacturing constraints into performance-enhancement mechanisms, thereby establishing a new design paradigm in which fabrication-induced features are intentionally tailored to improve FO performance rather than being treated solely as manufacturing defects.

6.4. Design Optimization Under Complex Multiphase Flow Conditions

With the expanding applications of FOs in energy systems, mass transfer enhancement, and complex fluid processing, reliable operation under multiphase flow conditions has become an important research direction for future engineering applications. Due to the complex interactions between multiphase media and unsteady oscillating jets, future studies should further focus on elucidating multiphase flow mechanisms and developing optimized structural designs

Future research should focus on the following aspects:

- Developing high-fidelity fluid-particle and fluid–structure interaction models capable of accurately predicting particle trajectories, impact locations, and collision energies within oscillatory flow fields. Such models would facilitate a deeper understanding of how oscillation characteristics influence the spatial and temporal evolution of erosion and deposition processes.
- Optimizing critical structural components, particularly the MC and splitter, through advanced design approaches such as concurrent optimization and topology optimization. By tailoring local flow structures and particle transport pathways, it may be possible to guide particles through the oscillator more smoothly and reduce high-energy particle impacts on vulnerable surfaces.
- Exploring the local application of advanced wear-resistant materials and surface-engineering technologies in erosion-prone regions. For example, Li et al. [162] demonstrated that replacing conventional tungsten carbide with PDC materials can substantially improve the erosion resistance of critical FO components.

In addition, identifying the structural parameter combinations required to achieve stable jet switching and periodic pressure-pulse generation remains a major challenge. Current design practices still rely heavily on empirical knowledge and repeated trial-and-error procedures, resulting in substantial development time and cost. Future studies should therefore investigate the integration of machine-learning-assisted design methodologies, enabling rapid prediction of feasible geometric configurations and accelerating the development of high-performance FO [145,161].

6.5. Development of Artificial-Intelligence-Integrated Design Theories and Tools

As discussed in Section 4.5, data-driven approaches have demonstrated considerable potential for accelerating numerical simulations, reconstructing complex flow fields, and predicting FO performance. However, current applications remain largely task-specific and fragmented. Future research should move towards the establishment of a comprehensive intelligent design framework capable of supporting the entire FO development process.

Key research directions include:

- Developing physics-informed deep learning models that incorporate governing fluid-dynamics principles into the training process. Such approaches could enable high-accuracy flow-field reconstruction and performance prediction even when experimental or simulation data are sparse, noisy, or incomplete.
- Establishing reinforcement-learning-based autonomous design frameworks that integrate parametric geometry generation, CFD solvers, performance-evaluation modules, and optimization algorithms such as genetic algorithms and Bayesian optimization. Such frameworks would enable artificial intelligence systems to autonomously explore and identify high-performance FO configurations beyond the limits of conventional human-driven design strategies.

7. Conclusions

This review systematically summarizes recent advances in performance enhancement of FOs following the central theme of “from geometric regulation to intelligent design”. The key developments and emerging trends in structural optimization, manufacturing technologies, intelligent design, and multiphase flow applications are discussed. The main conclusions are summarized as follows:

- Geometric regulation remains the fundamental approach for improving FO performance. Macroscopic geometric parameters, including FCs, MCs, and throat configurations, primarily determine the oscillation modes and global flow characteristics of FOs. Meanwhile, microscale structures, such as Coanda surface modifications and local flow-disturbing features, provide additional strategies for regulating vortex evolution and jet deflection behavior. These multi-scale structural designs contribute to overcoming the inherent coupling constraints among oscillation frequency, pressure loss, and flow characteristics.
- Advanced manufacturing technologies and intelligent optimization are driving new paradigms in FO design. AM techniques have expanded the design space of FOs by enabling the fabrication of complex internal flow structures beyond the limitations of conventional manufacturing methods. However, process-related factors, such as surface roughness and fabrication-induced geometric deviations, have also emerged as important design considerations. Meanwhile, the development of optimization algorithms, statistical approaches, and data-driven models is gradually transforming FO design from empirical trial-and-error strategies toward intelligent and multi-objective optimization frameworks.
- Novel configurations and multiphase flow applications have further expanded the engineering potential of FOs. Emerging designs, including vortex-based oscillators, arrayed configurations, and actively controlled structures, have broadened the application scenarios of FOs in areas such as heat transfer enhancement and flow control. Moreover, multiphase flow studies have demonstrated the capability of FOs to manipulate droplets, particles, and bubbles through unsteady jet dynamics, providing new opportunities for applications involving fuel atomization, microbubble generation, and gas–liquid mass transfer enhancement. Nevertheless, their long-term reliability, complex flow mechanisms, and adaptability under multiphase operating conditions require further investigation.

Despite significant progress in FO performance optimization, several challenges remain. First, considerable differences exist among various FO configurations in terms of structural characteristics, operating mechanisms, and working conditions, making direct comparison between studies difficult. A unified performance evaluation system and standardized parameter framework are still lacking. Second, the development of data-driven design methods is constrained by the limited availability of high-quality experimental and numerical datasets, which restricts the generalization capability of intelligent models for complex design optimization. Furthermore, multiphase flow applications remain relatively fragmented, and systematic understanding of issues such as erosion, interface evolution, and long-term operational stability has not yet been fully established.

Future research on FOs should focus on integrating multi-scale structural design, multiphysics analysis, advanced manufacturing technologies, and artificial intelligence-based optimization methods to establish standardized performance evaluation criteria and reliable data-driven design frameworks. Meanwhile, more comprehensive experimental validation and theoretical modeling under complex multiphase conditions are needed to promote the transition of FOs from conventional flow control components

toward high-performance and intelligent fluidic devices for applications in heat transfer enhancement, spray cooling, energy systems, and aerospace engineering.

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Abbreviations

The following abbreviations are used in this manuscript:

FO	Fluidic Oscillator
AFC	Active Flow Control
DFFO	Dual-Feedback Fluidic Oscillator
SIV	Schlieren Image Velocimetry
SMD	Sauter Mean Diameter
AFR	Air-Fuel Ratio
BFSFO	Backward-Facing Step Fluidic Oscillator
LR	Length Ratio
HR	Height Ratio
RANS	Reynolds-averaged Navier–Stokes
LF-HA	Low-frequency, High-amplitude
HF-LA	High-frequency, Low-amplitude
AFO	Angled Fluidic Oscillator
CFO	Curved Fluidic Oscillator
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
CFD	Computational Fluid Dynamics
FDPR	Frequency-Jet Deflection Angle-Pressure Ratio
PEC	Performance Evaluation Criterion
AM	Additive Manufacturing
3D	Three-Dimensional
FDM	Fused Deposition Modeling
DVFO	Dual-Vortex Fluidic Oscillator
DSJO	Dual-Sweeping-Jet Oscillator
DSJ	Dual Sweeping Jet
DbSJ	Double Sweeping Jet
DbCJ	Double Circular Jet
FFO	Feedback-Free Fluidic Oscillator
FFSJ	Feedback-Free Sweeping Jet
VFFO	Vortex-Based Feedback Fluidic Oscillator
FC	Feedback Channel
MC	Mixing Chamber
SVFO	Sweeping-Vortex Fluidic Oscillator
DCFO	Dynamic-Compliance Fluidic Oscillator
GRA	Grey Relational Analysis
FNO	Fourier Neural Operator
DIM-GP	Deep Infinite Mixture Gaussian Process
V-FO	Vertical-Feedback Oscillator
C-FO	Curved-Feedback Oscillator

DPM	Discrete Phase Model
RFOT	Reverse-Feedback Oscillation Tool
PDC	Polycrystalline Diamond Composite
LDA	Laser Doppler Anemometer
PINN	physics-informed neural networks

Nomenclature

f	Oscillation frequency
St	Strouhal number
h	Characteristic length of the oscillator
U	The Inlet velocity of flow
Re	Reynolds number
Ma_{outlet}	Outlet Mach number
Eu	Euler number
ΔP	Pressure drop
ρ	Fluid density
n_i	The number of droplets
d_i	The diameter of droplets
D_{32}	Sauter mean diameter
W_w	Inlet wedge width
Sa	Surface roughness
W_1	Inlet width
W_2	Cavity width
W_3	Outlet width
Nu	Nusselt number

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