The Aeronautical Journal (2026), 1–43
doi:10.1017/aer.2026.10212

ROYAL AERONAUTICAL SOCIETY

SURVEY PAPER

Recent advances in active flutter suppression: a comprehensive review

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Received: 22 December 2025 UTC; **Revised:** 26 June 2026 UTC; **Accepted:** 30 June 2026 UTC

Keywords: active flutter suppression; control algorithms; flight mechanics; flight control systems; morphing wing

Abstract

Active flutter suppression (AFS) is currently one of the most prolific areas of research within the aeroelasticity domain, driven by advances in computational capabilities and the increasing importance of weight reduction in the aerospace industry. The rapid progress of AFS, coupled with the growing need for flutter control in non-conventional aircraft, underscores the need for an up-to-date review in this field. This paper presents a systematic review of recent AFS advances, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure traceability and updatability. The review reveals two dominant research trends: the development of increasingly sophisticated control algorithms for conventional control-surface-based AFS, and the application of technologically mature algorithms to alternative control strategies, including morphing technologies and flow- and vibration-based solutions. A comprehensive classification of AFS algorithms is proposed to support the selection of suitable control approaches for different applications, and the advantages and limitations of alternative control strategies are critically discussed. The analysis identifies the synthesis of novel algorithms tailored to non-traditional control strategies, the exploration of multi-actuated and spanwise-deformable morphing wings and the extension of AFS studies to transonic, supersonic and hypersonic flight regimes as key research gaps. The need for full-aircraft models, experimental validation and the development of reference test cases for objective algorithm comparison is also highlighted.

Nomenclature

ADP	adaptive dynamic programming
ADRC	active disturbance rejection control
ADVA	active dynamic vibration absorber
AFS	active flutter suppression
AFSMC	adaptive fuzzy SMC
BFF	body freedom flutter
BWB	blended wing body
CC	circulation control
CeRAS	central reference aircraft data system
CFO	compensator with full-order observer
CIC-ONNC	optimal neural network control with control input constraints
CSF	control surface flutter
DDPG-TD3	twin delayed deep deterministic policy gradient
DRL	deep reinforcement learning
DVFB	direct velocity feedback
GS-fPID	gain scheduled filtered PID
GS-PID	gain scheduled PID

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I&I	immersion and invariance
ILAF	identically located acceleration and force
INDI	incremental nonlinear dynamic inversion
IRM	implicit reference model
LCO	limit cycle oscillations
LEB	leading edge blowing
LHS-GA	Latin hypercube sampling – genetic algorithm
LMPC	Laguerre orthonormal function-based MPC
LPV	linear parameter-varying
LQG	linear quadratic Gaussian
LQR	linear quadratic regulator
LSA	light sport aircraft
LS-SVM	least-squares support vector machine
MFC	Macro Fiber Composite
MFRL	model-free reinforcement learning
MHE	moving horizon estimation
MIDAAS	modal isolation and damping for adaptive aeroelastic suppression
MIMO	multiple-input-multiple-output
MPC	model predictive control
MR	Magneto-rheological
MRAC	model reference adaptive control
NDO	nonlinear disturbance observer
NMI	nonlinear model inversion
NN	neural network
PDSO	population decline swarm optimisation
PID	proportional-integral-derivative
PIS	piezoelectrically induced stress
PPF-FxLMS	positive position feedback – filtered-X least mean square
PRISMA	preferred reporting of items for systematic reviews and meta-analyses
RISE	robust integral of the sign of error
RL	reinforcement learning
SAC	single adaptive control
SISO	single-input-single-output
SMC	sliding mode control
UDE	uncertainty and disturbance estimation
WOS	Web of Science

1.0 Introduction

Flutter is a form of self-excited vibration in which a flexible structure extracts energy from the airflow [1]. Below a certain airspeed, the extracted energy remains below the critical value that the system can dissipate, resulting in damped oscillations. However, when the critical flutter speed is reached, the extracted and dissipated energies are equal, leading to constant-amplitude oscillations. For airspeeds over this critical value, the extracted energy cannot be completely dissipated, and oscillations are amplified, which can result in fatigue damage or structural failure [2]. Thus, the theoretical study of the flutter phenomenon and the development of methods to guarantee aircraft safety and extend the flutter boundary have been central topics among aeroelastic researchers from the inception of aeronautics to the present day [3].

The first flutter suppression mechanisms were based on increasing structural stiffness [4, 5] and adding counterweights to control surfaces [6]. Such was the case of the Handley Page O/400, a WWI bomber that experienced antisymmetric vibrations in the fuselage and elevator when it reached

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110 km/h. This is considered the first registered flutter occurrence [7], and it was resolved by Lanchester by adding a torque tube connecting both elevators to increase their torsional stiffness [4].

The problem of flutter control has become particularly significant in recent times. The growing importance of environmental concerns [8] and the slowness of the transition towards alternative energy sources producing less greenhouse-effect emissions have put the focus on technological improvements to increase aircraft efficiency, such as reducing aircraft weight, in order to reduce fuel consumption [9–11]. In line with this, aeronautical developers seek to increase structural flexibility, which results in flutter being an even more limiting constraint to the flight envelope [12].

Therefore, passive flutter suppression, based on increasing structural stiffness, has given way to active flutter suppression (AFS), which suppresses flutter by means of control laws applied to actuated control surfaces or other solutions, such as morphing technologies or flow control devices [13, 14]. This has the advantage that aircraft weight can be reduced at the same time that flight performance is improved.

Recent developments in active flutter control technologies can be classified into two main areas of innovation: the synthesis of more complex and efficient control algorithms, and the introduction of new actuators and devices. Regarding control algorithms, classical methods, notably the proportional-integral-derivative control theory (PID), were used in the first AFS systems designed in the 1970s [15, 16]. The invention of linear quadratic Gaussian (LQG) control in 1980, as an extension of the linear quadratic regulator (LQR) [17], was the starting point for the implementation of optimal control methods in AFS, which include the H_∞ controller [18, 19]. More recently, modern control methods, such as sliding mode control (SMC) [20], and robust control methods, like active disturbance rejection control (ADRC) [21] have been developed with the aim to provide enhanced AFS systems, which are robust to uncertainties and disturbances, and which do not rely on accurate plant models [22]. As control algorithms continue to be synthesised and perfected, it is crucial to keep reviewing the most recent contributions, in order to provide a concise update of the state of the art and to guide future research.

On the topic of the control devices used to achieve flutter suppression, control surfaces have been the most widely used solution since the introduction of AFS. However, in recent years, many researchers have put the focus on using morphing technology, i.e. the modification of the wing shape during flight [23], to suppress flutter [24]. Morphing flaps constitute the most mature solution [25, 26]. They are similar to traditional control surfaces but enable continuous deformations without hinges, and they are actuated by means of piezoelectric materials or kinematic mechanisms [27]. Other potential morphing solutions include wing deformation control using masses that move along the span to modify the dihedral angle [28]; telescopic span, which can suppress flutter by retracting the wingtip, which results in a wing stiffness increase [29]; and surface morphing [30]. In addition to morphing, other novel technologies include the use of smart materials, such as embedded shape memory alloys [31] and flow control, using plasma actuators [32] or blowing [33].

However, in spite of the tangible advances in both algorithms and control devices, substantial research effort is still needed to reach a maturity level that would allow the widespread implementation of AFS systems in military and commercial aviation [14].

Due to the accelerated pace at which novel AFS systems and methodologies are developed, it is of paramount importance to provide a specific and detailed review of the most recent advances in the field. In this work, with the aim of providing a systematic and updatable review, the Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology has been used [34, 35]. This methodology has already been implemented for recent reviews in the field of aeroelasticity [36] and in other areas of aeronautical research [37–40]. Seventy-three articles covering the most recent contributions to AFS and dating between January 2017 and December 2024 have been selected following the search procedure explained hereafter in the Methods section. The target period has been selected in order to cover the advances not gathered in the works by Livne [14] and Chai et al. [13], which cover the previous advances on AFS and whose included articles and findings have been taken into consideration in the Discussion and Conclusions. Thus, the present review aims to: i) summarise the most relevant contributions in the literature in the topic of AFS in the past eight years; ii) determine the current trends in terms of control devices and actuators and of control algorithms and compare their performances and

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possible applications; and iii) draw the most promising lines of research and the current knowledge gaps to better direct future research.

2.0 Methods

This review has been performed following the PRISMA statement in its 2020-updated version [35]. The included articles were selected using two different strategies. First, a systematic database search was conducted, followed by a complementary search based on the snowballing technique [41], i.e. examining the references of the included articles (backward snowballing) [42], as well as more recent articles citing those included works (forward snowballing) [43].

Three databases were used to perform the initial search, which was conducted in January 2025: Scopus, Web of Science (WOS) and Dimensions, as they are the most widely used databases for peer-reviewed articles [44]. First, a preliminary search using the keyword 'active flutter control' was performed in order to determine the keyword combinations to be used for the systematic search. Analysis of the additional keywords used in the most relevant papers and their cited sources provided the following insight: both the terms 'control' and 'suppression' are used interchangeably to refer to the technology studied in this review. Additionally, some articles referring to active methods of flutter control do not explicitly include the term 'active', opting for more precise terminology characterising the particular method used. As a result, and aiming to avoid missing relevant studies, keywords were divided into three groups: the first group was formed by 'control' and 'suppression', the second group comprised 'active', 'flexible wing', 'morphing' and 'adaptive', and the third group included exclusively the term 'flutter'. Thus, the systematic search in all three databases was performed for every possible combination of one keyword from each group.

All filters used for each database are specified below, in order of application:

Scopus:

Search within Article title, Abstract, Keywords: 'keyword 1' AND 'keyword 2' AND 'flutter'. **Year:** 2017–2024. **Document type:** Article. **Source type:** Journal. **Language:** English. **Subject area:** Engineering.

WOS:

Database: Web of Science Core Collection. **Search Topic (includes title, abstract and keywords):** 'keyword 1' AND 'keyword 2' AND 'flutter'. **Publication years:** 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024. **Document type:** Article. **Language:** English.

Dimensions:

Search in Title and abstract: 'keyword 1' AND 'keyword 2' AND 'flutter'. **Publication year:** 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024. **Publication type:** Article.

Next, a quick scan of keywords and abstracts was performed to eliminate works that were out of scope. All eligible works were incorporated into a *Zotero* [45] bibliography, so that duplicated entries could be identified and removed. Finally, remaining records were assessed for eligibility after careful examination of their full content. Three exclusion criteria were applied:

1. **Out of scope:** For articles only briefly mentioning AFS and focusing on other topics.
2. **Low impact:** For articles not adding relevant information or focusing on widely established technology.
3. **Superseded records:** For articles regarding a line of research for which more recent articles by the same authors that mention the previously extracted conclusions had already been included in the review.

After this step, the snowballing technique was applied to all selected articles, and the additional records identified were filtered using the same exclusion criteria.

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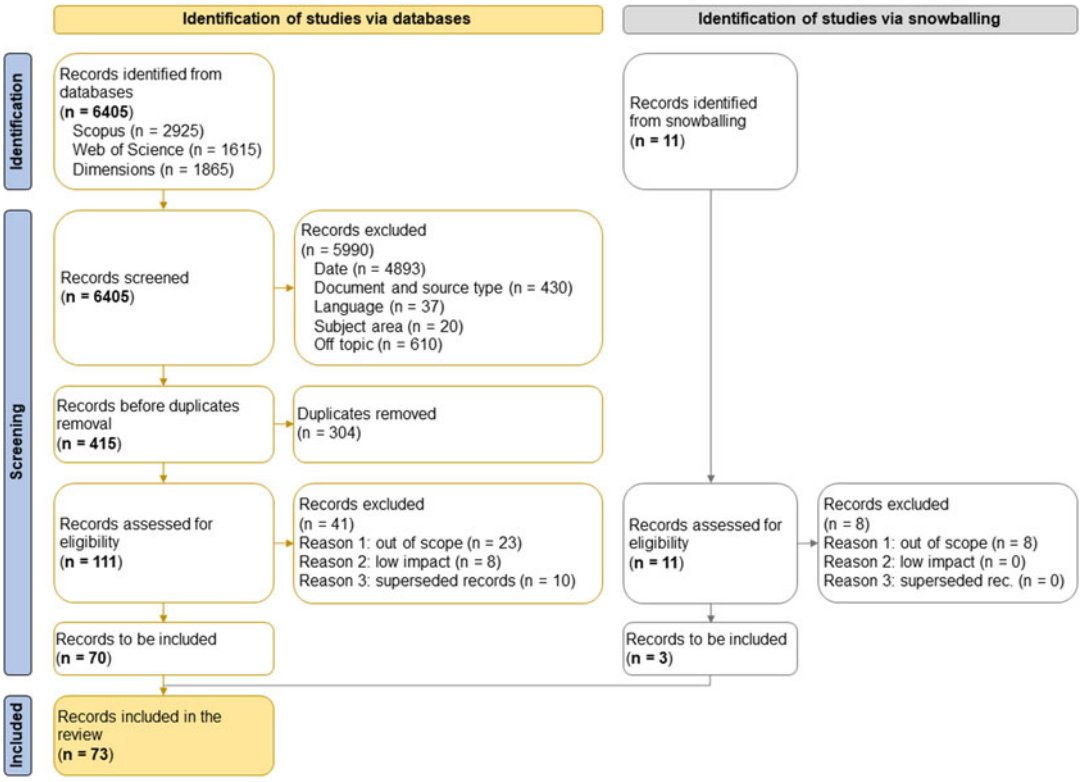


Figure 1. *Study search and selection process. Based on the PRISMA 2020 flow diagram [46].*

Once the final set of articles had been selected, the information of interest was retrieved using a customised table including the following items: authors, year, title, country, research objectives, implementation, control strategy, algorithm, aircraft part, flutter type, flight condition, main findings, limitations and observations. Finally, the retrieved information was carefully studied and compared to provide the analysis included in the Results section and to elaborate on the dissertation included in the Discussion section.

3.0 Results

3.1 Study selection

The PRISMA-based study selection process, which begins with all papers identified through the database search and snowballing technique described in the Methods section and culminates in the identification of the relevant articles for inclusion in the review, is schematically illustrated in the flowchart presented in Fig. 1.

A total of 6,405 articles were identified by introducing the mentioned keyword combinations in all three databases. After applying the date, type, language and subject area filters (depending on their availability in each database search engine) and scanning keywords and abstracts to verify alignment with the topic, the number of eligible records was reduced to 415. Only 4,893 articles were discarded after selecting the date filter, which evidences the current relevance of AFS, as roughly 25% of the initially identified articles had been published in the last 8 years. This observation further underscores the need for an updated review of AFS. In the following step, 304 articles were removed since they were duplicates, showing a high degree of commonality both between databases and between keyword

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combinations. Finally, the 111 candidate records were assessed for eligibility according to the three exclusion criteria defined in the Methods section. Forty-one records were excluded, of which 23 were considered to be out of scope, 8 were assessed to have low impact, and 10 were superseded by more recent publications on the same project that were already included in the review. As a result, 70 articles were finally selected through the database search process.

Application of the snowballing technique to these 70 documents yielded only 11 potential records, which is an indication of the adequacy of the keyword choice and the thoroughness of the database search. Of these, eight articles were excluded after being considered out of scope, which led to three articles being finally added through the snowballing procedure. This led to a total of 73 records included in the review.

3.2 Features of the selected studies

The main features of the selected articles are presented in Table 1, in order to provide a quick overview of the conditions of each study, as well as the main findings highlighted in each article. Six features were considered to fully describe the research, and their incidence was analysed to provide an outline of the most frequently addressed AFS subjects, while also identifying potential gaps in the existing research. These features are: (i) the research implementation or methodological approach – numerical or experimental; (ii) the aircraft part modeled or tested; (iii) the flight condition; (iv) the flutter type targeted for control; (v) the control strategy, defined as the physical element actuated by the control system and (vi) the implemented algorithm. The analysis of the main findings is presented in the Discussion section.

3.2.1 Methodological approaches

Concerning the methodological approaches, 61 articles are purely numerical, while 9 are purely experimental. Of the experimental studies, eight feature wind-tunnel tests, and the remaining one reports tests performed in free flight. Additionally, three articles combine numerical and experimental approaches, using experimental tests to validate the results of preceding numerical analyses. Of these combined studies, two involved a wind tunnel, while the remaining one was conducted in free flight. This predominance of numerical approaches is largely attributed to their lower development costs, with many authors proposing experimental tests as part of their future work to further validate the proposed systems.

3.2.2 Aircraft parts

Regarding the aircraft parts modeled or tested, 31 articles focus on an aerofoil or a two-dimensional wing, 30 articles on a three-dimensional wing – including the engines in two cases, the fuel tanks in one case and an external store in another – and 12 articles on the entire aircraft. Among these, six consider a conventional aircraft – including one featuring a fuselage-tail ensemble for a light sport aircraft (LSA) – five address a flying wing, and one investigates a blended wing body (BWB). Once again, the main reason for aerofoil and wing models being more frequent than full aircraft models is the lower cost associated with analysing the problem at a smaller scale. Moreover, it is worth noting that out of the 12 full aircraft models, 6 feature unconventional configurations, highlighting the heightened interest in controlling flutter in these aircraft. This is particularly relevant, as flying wings and BWBs are prone to body-freedom flutter, which arises from the interaction between a flight dynamic mode and a low-frequency structural mode [120].

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Table 1. *Main features of the included studies.*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[47]	Exp. (wind-tunnel)	Aerofoil	Subs.	Lifting surface flutter	Vibr. control	Classical (PI)	The flutter boundary is extended by applying a PI controller to an MFC ADVA. Experimental data are used to balance the MFC hysteresis and to eliminate resulting nonlinearities.
[48]	Exp. (Free flight)	Aircraft	Subs.	BFF	Control surface	Classical (PI)	The PI controller increases flutter speed by 46%. However, when the gains are chosen with a genetic algorithm, it is increased twofold. Moreover, BFF ceases being the flutter form.
[49]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Classical (PD)	Including viscoelastic materials as a passive strategy results in a 25% higher flutter speed. Adding an active controller on top of this increases it by 7% more, showing the interest of hybrid techniques.
[50]	Num.	Aerofoil	Subs.	Stall flutter	Morph. flap	Classical (PD)	The PD controller with no delay excites stall flutter. Thus, including a time delay is beneficial to suppress flutter, a 0.1 s delay providing the best results in the simulations.
[51]	Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Flow control (LEB and CC)	Classical (PID)	Open-loop leading edge blowing (LEB) and CC are shown to extend the flutter boundary. However, PID control is shown to be more efficient, increasing flutter speed an additional 53% and reducing the necessary airflow by 90%.

Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[52]	Num.	Wing	Subs.	LCO	Vibr. control	Classical (DVFB)	DVFB is especially effective when actuator and sensor are collocated. In addition, piezoelectric materials are embedded both to harvest energy and to perform AFS. Significant part of the control effort is required while the harvested energy exceeds the consumed amount, resulting in energy savings.
[53]	Num.	Wing	Subs.	Lifting surface flutter	Vibr. Control	Classical (negative velocity feedback)	Twist speed feedback control enhances flutter speed in weakly coupled wings, while strongly coupled ones require feedback of both twist and flapwise bending speeds and a more complex controller.
[54]	Num.	Aerofoil	Subs. (Inc.)	Lifting surface flutter	Vibr. control	Classical (negative feedback)	Flutter speed is increased compared with the use of a passive dynamic absorber alone. The controller is robust to parameter variations and detuning. Feeding pitch and plunge into the controller results in better performance than feeding a single state, with pitch feedback outperforming plunge feedback.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[55]	Num.	Wing	Subs.	Lifting surface flutter	Vibr. control	Classical (negative feedback)	Piezoelectrically induced stress (PIS) control shows similar flutter suppression capabilities to conventional active control and remains reliable when control surfaces would get saturated. However, it is considerably more energy-intensive, so its use may be relegated to emergency equipment.
[56]	Num.	Aircraft	Subs.	CSF	Control surface	Classical (negative feedback)	An AFS method, specifically designed for LSA, is introduced, representing the first of its kind for this category. Flutter can be suppressed using only a portion of the control surface, with 50% of the elevator span being optimal, while coverage below 44% is insufficient.
[57]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Optimal (LQR)	A control surface layout optimisation algorithm is presented. The resulting layout enables effective flutter suppression with an LQR controller without complementing with passive methods. Furthermore, the required number of actuators increases as control cost is taken into consideration.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[58]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Optimal (original LQR-based controller)	The sub-optimal controller designed using the most influential states identified through second-order sensitivity performs nearly as well as the optimal one. Additionally, neglecting time delay during algorithm synthesis leads to instability. However, the proposed method successfully mitigates its effects.
[59]	Num.	Wing	Subs.	LCO	Vibr. control	Optimal (LQR (SFC, CFO))	This active controller is proven to be more effective than a passive damper. In addition, the SFC outperforms the compensator with full-order observer (CFO).
[60]	Num.	Aerofoil & Wing	Subs.	Lifting surface flutter	Control Surface	Optimal (LQR)	The use of a modal approach when synthesising the LQG controller avoids obtaining the time domain form of the unsteady aerodynamic forces, which typically requires approximations.
[61]	Num.	Aerofoil	Subs.	Lifting surface flutter	Morph. flap	Optimal (LQR)	The morphing flap enables effective flutter suppression.
[62]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Optimal (LQR), state-space (pole placement)	The LQR controller is robust and predictable regarding critical time delay, which decreases with airspeed. However, the critical delay is more sensitive to pole placement tuning, reducing its reliability.
[63]	Num.	Aircraft	Subs.	Whirl flutter	Control surface	Optimal (LQR)	Whirl flutter speed is increased by 18%.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[64]	Num.	Wing	Subs., Trans.	Lifting surface flutter	Control surface	Optimal (LQR)	The flutter speed with a hybrid control strategy is 35% and 7% higher than obtained with only passive and only active control, respectively. In addition, hybrid strategies reduce control cost.
[65]	Num.	Wing-Engine System	Subs.	Lifting surface flutter	Vibr. control	Optimal (LQG)	AFS can be achieved by means of a piezoelectric plate situated on the upper part of the wing box. Performance is improved by placing the actuator closer to the root and with a 75° angle.
[66]	Num.	Aerofoil	Subs., trans.	Lifting surface flutter	Morph. flap	Optimal (LQG)	The morphing flap is proven to provide better AFS performance than a conventional flap, showing both a more extended flutter boundary and reduced deflection commands.
[67]	Num.	Wing-Engine System	Subs.	Lifting surface flutter	Vibr. control	Optimal (LQG)	Active control using piezocomposite actuators results in a 25% higher flutter speed when compared to passive control methods, but it entails more complexity and weight.
[68]	Num.	Wing	Trans.	Lifting surface flutter	Control surface	Optimal (H_2, H_∞)	Actuator saturation negatively affects controller performance, with rate saturation being more critical than amplitude limitations. Moreover, incorporating the parameters proposed in the paper into the design analysis helps identify controllers that may appear effective in a linear framework but perform inadequately in practice.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[69]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Optimal (LQG, H_∞)	Both controllers increase flutter speed by 90%. Whereas the LQG algorithm is more efficient in terms of control cost, requiring smaller surface deflections, the H_∞ is more effective, as it balances disturbances better.
[70]	Num.	Aircraft	Subs.	Lifting surface flutter	Control surface	Optimal (H_∞)	By damping the first vibration modes, both symmetric and antisymmetric, this algorithm consisting of three local airspeed H_∞ controllers increases the flutter speed.
[71]	Num.	Aerofoil	Subs., trans., supers.	Lifting surface flutter	Control surface	Optimal (LQR, H_∞), state-space (pole placement)	H_∞ is shown to be the optimal control algorithm across all flow regimes in terms of robustness and cost when compared with pole placement and LQR.
[72]	Num.	Aircraft	Subs.	BFF	Control surface	Optimal (LPV H_∞)	Both flutter suppression and flight path control are achieved using an LPV H_∞ robust controller that operates reliably for all airspeeds.
[73]	Num.	Wing	Trans.	Lifting surface flutter	Control surface	Optimal (original controller)	The study concludes that a nonlinear approach is needed to synthesise a flutter control system in the transonic regime. The best strategy to generate preliminary controllers is to combine doublet lattice aerodynamics and the Padé approximant of order zero.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[74]	Num. & Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Control surface	Robust (μ-Synthesis)	A single-input-single-output (SISO) and a MIMO (multiple-input-multiple-output) μ-Synthesis controller were designed for AFS of a wing. Both managed to increase the flutter speed, yet only slightly, with the MIMO raising it from 36.5 to 38 m/s and the SISO reaching 39 m/s. Therefore, the less costly SISO controller is more suitable for this system.
[75]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Robust (LPV μ-Synthesis)	A μ-Synthesis controller considering airspeed as the model uncertainty is applied to a morphing folding wing flying at different folding angles. It expands the flutter boundary more effectively at smaller angles, 30% at 30° vs. 7% at 90°, with varying critical modes based on the angle.
[76]	Num.	Aircraft	Subs.	Lifting surface flutter	Control surface	Robust (loop shaping)	Flutter speed is increased by 27%. The controller is robust to backlash and rate limits, and it does not reach actuator saturation.
[77]	Num.	Wing	Trans.	Lifting surface flutter	Control surface	Robust (ADRC)	The ADRC controller effectively controls flutter in the transonic regime, even in the presence of measurement noise and computational delay, demonstrating its suitability for real systems.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[78]	Num.	Aerofoil	Hypers.	Lifting surface flutter	Control surface	Robust (ADRC)	The addition of a least-squares support vector machine (LS-SVM) to the ADRC, with the aim to predict and counterbalance partial disturbances, results in better flutter control performance and robustness compared with standard ADRC.
[79]	Num.	Wing (+ Tanks)	Subs.	Lifting surface flutter	Control surface	Robust (linear ADRC (LADRC))	The ADRC controller is more robust and adaptive than a PID, and it manages to suppress adverse effects of fuel sloshing on flutter.
[80]	Num.	Aircraft	Subs.	BFF	control surface	Robust (LPV + anti-wind-up compens.)	The LPV controller fails to control BFF when synthesised without accounting for actuator saturation. However, the inclusion of an anti-wind-up compensator results in successful flutter suppression.
[81]	Num.	Aircraft	Subs.	Lifting surface flutter	Control surface	Robust (LPV observer-based SFC)	The flutter speed is increased by 17% with a controller that is robust to sensor noise and delay. In addition, actuators do not reach saturation.
[82]	Num.	Aerofoil	Subs., Trans.	Lifting surface flutter	Control surface	Robust (original controller)	The designed robust controller can extend the flutter boundary. However, adaptive control shows greater potential, particularly in the transonic regime, because the performance of robust control is limited as it is designed balancing different conditions.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[83]	Num.	Aircraft	Subs.	BFF	control surface	Robust (robust H_∞)	The controller increases the flutter speed by 47% and is robust to external disturbances.
[84]	Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Control surface	Robust (robust H_∞), optimal (LQG, LQG/LTR, standard H_∞)	All studied techniques can suppress flutter when the control synthesis and the model are compatible. However, H_∞ is shown to be optimal.
[85]	Num.	Aerofoil	Subs.	LCO	control surface	Adaptive (L_1 adaptive control)	The controller suppresses flutter in a variety of situations while being robust to disturbances and system nonlinearities. However, its application may be restricted due to the high control effort required.
[86]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Adaptive (SAC)	An SAC strategy adaptive to airspeed and air density is developed by combining a PD adaptive law with an implicit reference model (IRM). The controller includes a module to balance the wind-up effect.
[87]	Num.	Aerofoil	Subs.	LCO	Control surface	Adaptive (GS-PID)	A GS-PID controller using airspeed and pitch angle as scheduling signals is investigated, and it is shown that the introduction of the pitch angle in the algorithm synthesis prevents performance degradation.
[88]	Num.	Aerofoil	Subs. (Inc.)	Lifting surface flutter	Control surface	Adaptive (GS-fPID, SAC)	Comparison between SAC and GS-fPID controllers shows that SAC is more robust to uncertainties and has superior control performance. Moreover, it is better suited to piezoelectric actuators.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[89]	Num.	Aircraft	Supers.	Lifting surface flutter	Control surface	Adaptive (PPF-FxLMS)	This hybrid adaptive algorithm can increase the flutter speed, providing better performance than a simple FxLMS controller.
[90]	Num.	Wing	Supers.	CSF	Control surface	Adaptive (I&I), classical (PID)	A novel AFS method for nonlinear fin–actuator systems without supplementary control surfaces is introduced. It effectively suppresses flutter, increasing the flutter speed beyond that of linear systems. Moreover, it demonstrates robustness against noise and external disturbances.
[91]	Num.	Aerofoil	Subs.	LCO	Control surface	Adaptive (LHS-GA), optimal (H_∞, LQR)	The LHS-GA controller can be synthesised offline, thereby avoiding the need for cost-inducing real-time computations. In addition, it outperforms the H_∞ and LQR algorithms, particularly in terms of robustness and performance against uncertainties.
[92]	Num.	Aerofoil	Subs. (Inc.)	Lifting surface flutter	Control surface	Adaptive (velocity-adaptive PID)	In the subsonic range, the integral gain of the PID controller is shown to have almost no contribution. Thus, the heuristic optimisation leads to a PD controller which increases the flutter speed by 47%.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[93]	Num.	Aerofoil	Subs.	LCO	Control surface	Adaptive (composite adaptive control)	Both flutter suppression and exact parameter estimation are accomplished by this original composite adaptive controller, which is robust to unknown actuator behaviour and time-varying nonlinearities.
[94]	Num.	Aerofoil	Hypers.	Lifting surface flutter	Control surface	Adaptive (adaptive fault-tolerant control)	An original adaptive and fault-tolerant flutter suppression algorithm is developed, which shows great robustness to actuator and sensor faults and external disturbances. The controller does not require state measurements, since it relies on dynamic output feedback.
[95]	Num.	Aerofoil	Subs.	CSF	Control surface	Intelligent (NN/RL), optimal (H_∞)	While H_∞ control struggles to suppress highly nonlinear vibrations, the NN/RL algorithm is effective. However, a suitable NN topology and RL procedure have to be chosen. For instance, a backpropagation strategy is effective, whereas simple gradient is not.
[96]	Exp. (Wind tunnel)	Aerofoil	Subs.	Lifting surface flutter	Control surface	Intelligent (neural networks (CIC-ONNC))	The novel optimal neural network control with control input constraints (CIC-ONNC) algorithm is velocity-adaptive and optimal when considering control-input constraints. Besides, it is computationally efficient across all case studies, unlike the LPV-LQR controller used for comparison.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[97]	Num.	Aircraft	Subs.	BFF	Control surface	Intelligent (RL)	The RL controller increases the flutter speed by 37%, showing enhanced robustness with respect to a conventional H_∞ controller. Moreover, its synthesis process is considerably faster than the H_∞ manual tuning.
[98]	Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Flow control (trailing edge CC)	Intelligent (MFRL (DDPG-TD3))	Jet intensity is chosen by the twin-delayed deep deterministic policy gradient (DDPG-TD3) controller based on the real-time wing state. Thus, successful flutter control is achieved with 37% less air consumption with respect to steady circulation control (CC).
[99]	Num.	Aerofoil	Trans.	LCO	Flow control (synthetic jets)	Intelligent (DRL)	The robust DRL algorithm manages to control LCOs in a broader range of airspeeds with respect to the control law trained in a single environment. Additionally, it increases the flutter speed by approximately 83%.
[100]	Num.	Aerofoil	Subs.	LCO	Control surface	Intelligent (ADP)	The data-driven ADP algorithm can suppress flutter without a system model, relying solely on input constraints. This controller is more efficient and less costly than an LQR, showing reduced oscillations.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[101]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	Modern (MPC)	A controller based on moving horizon estimation (MHE) and MPC employs two strategies for active flutter control: conventional surface deflection and increasing wing deformation to avoid unstable conditions. This approach, based on nonlinear models that predict stability regions based on the wing deformation, outperforms linearisation-based methods.
[102]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Modern (LMPC)	Unconstrained Laguerre orthonormal function-based MPC (LMPC) requires highly demanding actuator inputs, which renders it unfeasible. By contrast, constrained LMPC shows comparable performance to that of classical MPC with notably lower computational cost.
[103]	Num.	Aerofoil	Subs.	Lifting surface flutter	Morph. flap	Modern (Koopman-MPC)	High-frequency nonlinear pulses are difficult to balance using conventional controllers. This limitation is addressed by employing an MPC strategy using the Koopman operator as a state estimator.
[104]	Num.	Wing	Subs.	Lifting surface flutter	Vibr. control	Modern (SMC)	The actuator and control method combination manages to suppress flutter considering time delay. Time delay is found to be more constraining when it is smaller.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[105]	Num.	Aerofoil	Subs.	LCO	Control surface	Modern (AFSMC)	The controller can suppress flutter without a system model, by measuring the state variables, even in the presence of disturbances. Moreover, compared with a classical SMC, the adaptive fuzzy SMC (AFSMC) converges better and does not experience chattering.
[106]	Num.	Aerofoil	Subs.	Stall flutter	Control surface	Modern (SMC)	Stall flutter suppression is achieved even in the presence of unmatched disturbances derived from actuator dynamics, owing to a nonlinear disturbance observer (NDO)-based SMC.
[107]	Exp. (Wind-tunnel)	Aerofoil	Subs.	Lifting surface flutter	Control surface	Modern (INDI)	The controller achieves both gust load alleviation and a 15% increase in flutter speed with the same control parameters.
[108]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Modern (RISE-based partial feedback linearised controller)	The controller, which does not need a system model, increases the flutter speed by 48% while being robust to airspeed variation, uncertainties and external disturbances. Moreover, its performance surpasses that of conventional SMC and uncertainty and disturbance estimation (UDE)-SMC controllers.
[109]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Modern (ridge regression)	The data-driven ridge regression controller outperforms LQR controllers at higher airspeeds, exhibits fewer saturation issues, and is less costly due to the absence of a system model.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[110]	Num.	Aerofoil	Subs.	Stall flutter	Morph. flap	Modern (NMI), classical (PID)	The NMI controller effectively suppresses stall flutter, while the PID only reduces its amplitude by a factor of four. In addition, the morphing flap AFS mechanism is identified as a counteracting trailing-edge vortex that offsets the naturally occurring leading-edge vortex.
[111]	Num. & Exp. (Free flight)	Aircraft	Subs.	BFF	Control surface	Modern (MIDAAS, ILAF), Robust (Robust H_∞)	Although the ILAF and H_∞ methods show bigger stability margins at the design point, the H_∞ controller shows a lower flutter speed than the MIDAAS and ILAF strategies. The flutter mechanism reached with each controller is different.
[112]	Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Vibr. control	State-space (pole placement)	The self-sensing approach based on MFC actuators mitigates feedforward interference and prevents bridge imbalance from affecting the pole placement controller.
[113]	Num.	Wing	Subs.	Lifting surface flutter	Control surface	State-space (pole placement)	The pole assignment algorithm based on output feedback control results in successful flutter control even with some unavailable measurements, provided that acceleration measurements are added to the displacement and velocity ones. Furthermore, control effort can be minimised by optimising the selection of measured variables and the placement of the corresponding sensors.
[114]	Num. & Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Control surface	State-space (pole placement)	The frequency-based MIMO controller does not require modelling of the structural matrices or the aerodynamics. The tests show that the best way to expand the flutter boundary is to further damp the torsion mode.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[115]	Num.	Wing (+ Stores)	Subs.	Lifting surface flutter	Vibr. control	Hybrid (original adaptive-robust controller)	A hybrid adaptive-robust algorithm is designed to control flutter in a wing-store ensemble by using a piezoelectric wafer strut incorporated into the pylon as the actuator. The resulting controller demonstrates robustness in terms of disturbances and uncertainties.
[116]	Num.	Wing	Subs.	Lifting surface flutter	Vibr. control	Hybrid (adaptive LQR)	A multifunctional wing that integrates piezoelectric materials and lithium-ion battery cells is designed to achieve both AFS and energy harvesting. The algorithm enables variation of the number and position of actuators to optimise vibration alleviation under stochastic gust disturbances. Unused elements automatically switch to energy harvesting, creating a partially self-sustained system that recycles stored energy.
[117]	Exp. (Wind-tunnel)	Wing	Subs.	Lifting surface flutter	Vibr. control	Hybrid (original adaptive-pole placement controller)	Three pole placement switching controllers are synthesised to manage AFS over a wide airspeed range. Controller stability is ensured using the Lyapunov method, and experimental results confirm its performance.

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Table 1. *(Continued)*

Ref.	Approach	Aircraft part	Flight cond.	Flutter type	Control strategy	Algorithm	Main findings
[118]	Num.	Aerofoil	Hypers.	Lifting surface flutter	Control surface	Hybrid (H_∞ adaptive fault-tolerant)	The combination of H_∞, adaptive fault-tolerant, and neural network control enables flutter suppression when control delays and actuator faults are taken into account.
[119]	Num.	Aerofoil	Subs.	Lifting surface flutter	Control surface	Hybrid (PD, adaptive in velocity)	Linear interpolation of PD parameters tuned for different airspeeds using population decline swarm optimisation (PDSO) results in a controller that effectively handles speed variations and potential nonlinearities. Moreover, this optimisation method is proven to be less computationally expensive than standard particle swarm optimisation.

3.2.3 Flight conditions

With regard to the flight conditions studied in each paper, most works focus exclusively on AFS systems for the subsonic regime (60 articles), while only four, two and three studies address the transonic, supersonic and hypersonic regimes, respectively. Additionally, four studies consider more than one regime, with Ref. [82] standing out in this regard. Its objective was to design a robust controller capable of demonstrating adequate performance in both the subsonic and transonic regimes. However, this approach required a trade-off between the two regimes, whereas adaptive algorithms show greater potential. The higher incidence of subsonic studies can be attributed to the fact that most commercial aircraft operate in this regime. Two of the transonic studies also target commercial aircraft, analysing three-dimensional elastic swept-back wings [73, 77], whereas the remaining two feature a generic rectangular wing [68] and a generic aerofoil [99]. In contrast, the two supersonic studies apply to a missile fin [89, 90], while two of the hypersonic studies focus on reentry vehicles [94, 118], and the remaining hypersonic study concerns a generic double-wedge aerofoil [78].

3.2.4 Flutter types

Concerning the flutter types targeted by the AFS system, six main flutter mechanisms have been identified:

1. Lifting surface flutter: This phenomenon is triggered by the dynamic coupling between two or more structural modes associated with lifting surfaces. It includes the classical wing torsion-bending flutter as well as other couplings such as wing–fuel tanks, wing–engines or horizontal stabiliser–vertical stabiliser. Lifting surface flutter is addressed in 51 articles, making it the most studied flutter type in the sample.
2. Control surface flutter (CSF): This is the earliest identified flutter phenomenon [7]. It involves control surface deflection as one of the degrees of freedom whose coupling leads to flutter. Only three articles address this flutter type, likely because passive flutter control solutions, such as mass balancing, and improved hinge and actuator stiffness, which have low impact on the aircraft weight in the case of control surfaces [121], are commonly used. One of the three articles focuses on hysteresis nonlinearity in a wing–aileron system [95], another models the fuselage and tail of an LSA [56], and the remaining study investigates CSF suppression in a missile fin–actuator system [90].
3. Stall flutter: It arises from nonlinear dynamic coupling between the structural modes of a lifting surface and the unsteady aerodynamic forces generated by periodic flow separation and reattachment at high angles of attack. Three articles study this phenomenon [50, 106, 110].
4. Whirl flutter: It appears in rotor systems, due to the coupling between the elastic deformation of the rotor support (wing, engine nacelle or pylon) and the rotor itself. Gyroscopic torques acting on the rotor induce changes in its orientation with respect to the airflow, thereby modifying aerodynamic loads and potentially leading to increasing amplitude oscillations. One article addressing whirl flutter has been included in the review. This work analyses a tiltrotor aircraft – defined as an aircraft with rotors mounted on rotating shafts capable of producing thrust, lift or a combination of both – in which the flutter mechanism results from the coupling between the aerodynamic forces induced by blade flapping and the bending and torsional deformation of the flexible wing [63].
5. Body freedom flutter (BFF): This flutter type involves the coupling of a rigid-body mode of the aircraft with other dynamic modes [122, 123]. All six articles featuring BFF correspond to the works where either a flying wing or a BWB is analysed, due to the tendency of these aircraft to experience BFF caused by the coupling between the wing bending mode and the short period mode.

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6. Limit cycle oscillations (LCO): This phenomenon consists of non-attenuated oscillations whose amplitude remains bounded as airspeed increases [1]. Unlike linear flutter, for which oscillation amplitudes grow indefinitely, LCOs arise due to the presence of aerodynamic and/or structural nonlinearities. Nine articles focus on this phenomenon.

In summary, six distinct flutter mechanisms, arising from different combinations of flight conditions and aircraft types, are studied in the articles included in this review. This underscores the complexity of designing AFS systems, as tailored analyses and control strategies are required for different aircraft configurations and operational regimes, discussed further in the Algorithms subsection.

3.2.5 Control strategies

The different active solutions employed by the control system to suppress flutter can be classified into four categories based on their physical mechanisms:

1. Control surface: Flutter is suppressed through the deflection of a control surface governed by a deflection law defined by the AFS system. This is the most technologically mature AFS strategy [14]. Accordingly, research activity in the 52 articles employing this approach mainly focuses on the development, analysis and performance comparison of novel and less technologically mature algorithms, or on the application of classical and optimal control algorithms to suppress flutter in unconventional aircraft.
2. Morphing technology: As mentioned in the Introduction section, this technology involves altering the wing's external surface during flight. Although a wide variety of morphing concepts – including in-plane, out-of-plane and aerofoil morphing – have been proposed by many authors to adapt the wing's aerodynamic performance to different flight conditions [124], the five articles implementing morphing technology reviewed here exclusively use camber morphing. These articles explore so-called morphing flaps, which modify the wing camber in the trailing-edge section. This solution achieves a similar effect to that of a conventional trailing-edge flap, but without a hinge, as the surface deformation is continuous. All five works are numerical. In two cases [66, 103], the morphing behaviour is investigated at a theoretical level, since no real actuator is modeled. In Ref. [61], aerofoil deformation is achieved by means of a tendon-spooling pulley connected to two tendons attached to the upper and lower wing surfaces near the trailing edge, while Refs [50, 110] use the Fish Bone Active Camber structure proposed in Ref. [125]. Moreover, the five articles focus on studying the interest in using morphing technologies for AFS. As a result, three of them use classical and optimal algorithms to simplify the study. In contrast, Ref. [110] uses a nonlinear model inversion (NMI) controller to extend the investigation of the morphing aerofoil previously studied in Ref. [50] using a PD controller, while Ref. [103] employs a model predictive control (MPC) approach. Additionally, active surface morphing is proposed as a potential AFS solution in another article [30] by the authors of Refs [50, 110]. These authors investigated the benefits of inducing harmonic oscillations of the wing's flexible surface for stall flutter suppression. However, this concept has so far only been implemented using an open-loop strategy.
3. Flow control: Two experimental studies aimed at assessing the AFS capabilities of two flow control strategies through wind-tunnel tests are included in the review. In Ref. [98], trailing-edge circulation control is achieved by incorporating two blowing slots on the upper and lower wing surfaces. In Ref. [51], two additional leading-edge blowing slots are added to the previous configuration. Furthermore, one numerical study employs two zero-mass synthetic jets on the upper and lower surfaces, where the total flux of both jets is zero, thereby eliminating the need for additional air sources [99]. In all three studies, control algorithms adjust jet intensity to suppress flutter.

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4. Vibration control: The remaining 13 articles propose different strategies aimed at suppressing flutter by controlling the structural vibrations of the aerofoil or wing. In Ref. [47], an innovative approach based on an active dynamic vibration absorber (ADVA) is introduced. This concept extends a traditional mass–spring–damper system by incorporating an active component that applies a control force to the mass, guided by feedback signals derived from the response of the aeroelastic system. The ADVA was constructed using a Macro Fiber Composite (MFC) actuator driving a mass located at the tip of a cantilever beam, and it was subsequently tested in a wind-tunnel. In Ref. [54], this strategy is further explored, complementing the initial tests with numerical studies. In addition, in Ref. [115], a piezoceramic wafer strut is incorporated in the pylon to suppress flutter in a wing–store ensemble. Other researchers have also employed piezoelectric actuators to suppress wing vibrations, placing them either on the wing box [65, 67], on the wing surface [116] or on a cantilevered beam simulating the wing [52, 53, 55, 104, 112, 117]. A remarkable asset of piezoelectric actuators is their energy harvesting capacity, as they can retrieve energy from wing vibrations while simultaneously controlling flutter. This feature has the potential to reduce the energetic cost of vibration control AFS systems, as investigated in Refs [52, 116]. Finally, in Ref. [59], flutter suppression is achieved using an external store equipped with a magneto-rheological (MR) damper at its attachment to the wing. This MR damper relies on a fluid whose viscosity varies in response to an applied magnetic field, enabling real-time tuning of the damping force to suppress vibrations effectively. As in the case of morphing technologies, articles featuring vibration control strategies primarily focus on the strategy itself and therefore tend to employ classical and optimal control algorithms.

The analysis of the control strategies explored in the articles included in this review reveals a clear relationship between control strategies and algorithms. Studies on technologically mature solutions – such as control surface deflections – tend to focus on developing novel and complex algorithms, while those addressing less mature technologies prioritise the technology itself, often relying on more conventional algorithms. A notable exception is the case of flow control, for which two of the three reviewed studies employ reinforcement learning techniques, and whose positive results demonstrate the potential of artificial intelligence-based algorithms for this control strategy.

Finally, the distribution of the reviewed control strategies is illustrated in Fig. 2. Nearly three-quarters of the studies employ traditional control surfaces for AFS, reflecting their technological maturity and suitability for advanced algorithm development. In contrast, only 21 articles explore non-conventional control methods, among which vibration control is the most common. Morphing flaps are addressed in five studies, while flow control is investigated in three.

3.2.6 Algorithms

The study of the control algorithms employed in the papers included in this review has enabled the development of an exhaustive classification of algorithms used for AFS. This classification encompasses both well-established methods – such as PID – and more recent approaches, including those based on artificial intelligence. The classification, summarised in Fig. 3, is accompanied by a brief note on each algorithm's operation, properties and most suitable applications, which is included below. This classification constitutes one of the main contributions of the present review, and it is intended to support future AFS researchers in selecting the most appropriate algorithm for their specific applications.

Classical control: These methods were used in the earliest AFS systems, dating back to the 1970s [15, 16]. They are characterised by being simple and intuitive, as they are based on feedback loops. Consequently, they represent a suitable option for simple systems that are not significantly affected by uncertainties or external disturbances. However, they are less suited for complex systems.

- PID: It is a simple form of feedback control, consisting of three feedback loops with their corresponding gains – proportional, integral and derivative – aiming to correct the error between

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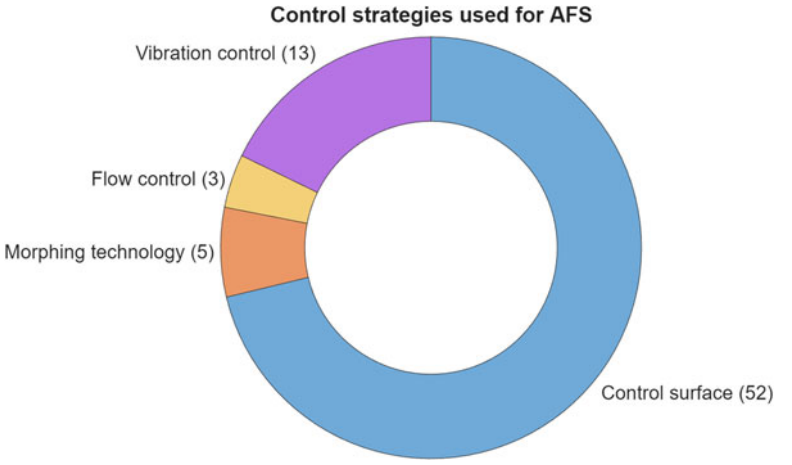


Figure 2. *Frequency of control strategies in the reviewed works.*

the desired and the actual output of the system [126]. For AFS purposes, it may be insufficient when the system's complexity is moderate to high. Therefore, it is sometimes combined with other algorithms within hybrid control strategies.

- Direct velocity feedback (DVFB): It constitutes an even simpler form of feedback control when compared to PID, as it relies on a single derivative term. Its main advantage lies in its low control cost, but in most cases, it is insufficient to suppress flutter.

Optimal control: These methods are based on optimising a performance function defined by the programmer. As a result, they are best suited for applications in which the minimisation of the energetic cost is a key requirement. In addition, they have the advantage of being able to handle disturbances and uncertainties. Optimal control approaches have been used for AFS purposes since the 1980s [17], and, together with the classical methods, they represent the most widely implemented and technologically mature class of AFS algorithms.

- LQR: It is based on the minimisation of a quadratic cost function designed to provide the best balance between control effort and performance. It is used for linear systems.
- LQG: It extends the LQR algorithm by incorporating a Kalman filter, which enables state estimation in the presence of measurement noise [17]. Therefore, it is well suited for stochastic systems.
- H_2 control: It is based on minimising the H_2 norm of the transfer function, which measures the root-mean-square (RMS) of the system output in response to a unit energy input [127]. This makes it a natural choice for optimising performance in terms of energy efficiency or disturbance attenuation.
- H_∞ control: It minimises the H_∞ norm, which represents the maximum gain of the system transfer function over all frequencies [18]. Consequently, it provides guaranteed performance in the worst-case scenario, making it a well-suited algorithm for systems subject to disturbances and model uncertainties.

Robust control: These methods have as their main advantage their ability to guarantee stability and performance in the presence of uncertainties and parameter variations. Therefore, they are used when the system is required to operate under a wide range of conditions. Consequently, they are well suited for the design of AFS systems capable of operating across different flight regimes.

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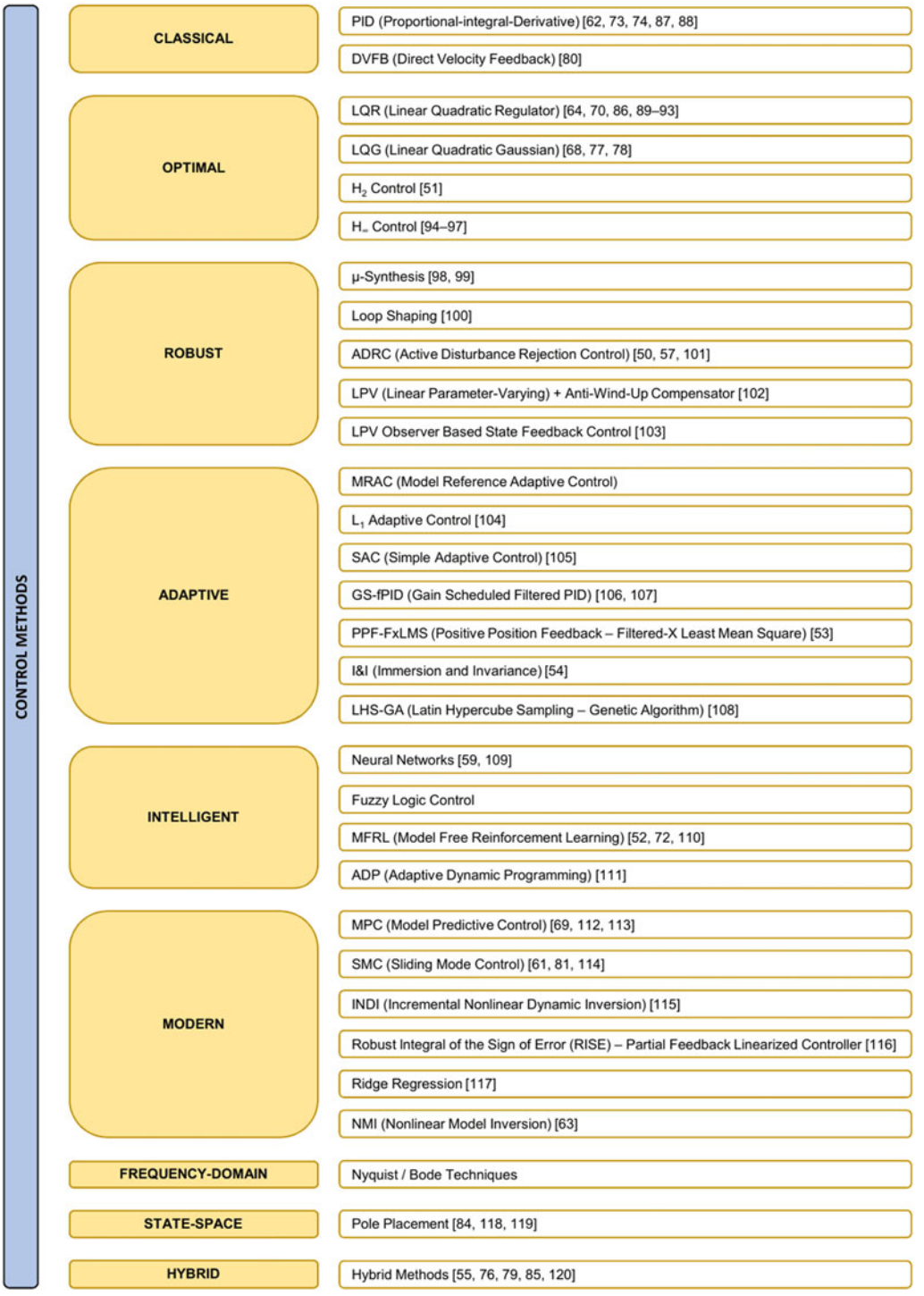


Figure 3. *Classification of the algorithms used for AFS.*

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- μ-synthesis: It explicitly accounts for structured uncertainties, optimising system performance under the worst-case scenario associated with these uncertainties [128].
- Loop shaping: It consists of designing the frequency-domain closed-loop gain of the system so that it verifies the control requirements. The controller transfer function is subsequently obtained, taking into account the plant transfer function and the desired closed-loop gain [129].
- ADRC: It compensates both external and internal disturbances in real time. Moreover, it does not require a precise system model, which makes it adaptable to different systems [22].
- Linear parameter-varying (LPV) + anti-wind-up compensator: LPV control is specifically designed for systems whose dynamics vary smoothly depending on certain scheduling parameters. Thus, it is well suited for representing parameter variations across the flight envelope [130], allowing automatic gain scheduling as a function of these varying parameters, thereby improving robustness [131]. In this algorithm combination, the LPV formulation allows the controller to work under varying conditions, while the anti-wind-up compensator prevents actuator saturation, which could appear when implementing a basic LPV controller [80].
- LPV observer-based state feedback control: The system state is estimated by the LPV observer and subsequently used in the feedback control strategy [81].

Adaptive control: This category includes all the algorithms whose distinctive feature is the ability to adjust their parameters according to real-time changes in either the environment or the system itself. Therefore, they are used to guarantee performance in systems with time-varying parameters, which is particularly relevant for AFS applications.

- Model reference adaptive control (MRAC): It consists of controlling a system subject to uncertainties and disturbances by tracking the behaviour of a desired reference model. The controller parameters and gains are tuned in real time using the tracking error [132].
- L_1 adaptive control: Similar to MRAC, it is based on determining the system dynamics by tracking the desired reference model [132]. However, it handles control and state estimation as separate tasks. Thus, its adaptability with respect to parameter variations is enhanced, making it better suited to fast-changing systems.
- Simple adaptive control (SAC): It is a simplified adaptive algorithm conceived to guarantee and formally prove stability while keeping the qualities of classical MRAC [133].
- Gain scheduled filtered PID (GS-fPID): It is an improvement of conventional PID, incorporating both a filtering stage to reduce measurement noise and gain scheduling capabilities to tune the gain values according to varying conditions [88]. Its unfiltered version is denominated GS-PID (gain scheduled PID) [87].
- Positive position feedback – filtered-X least mean square (PPF-FxLMS): In this algorithm, positive position feedback is enhanced by the use of an adaptive filter that minimises error by modifying the control action in response to changing conditions [89].
- Immersion and invariance (I&I): This method is based on immersing the system into a lower-dimensional manifold and ensuring that the system state remains invariant within it. This approach allows for adaptive control with strong stability properties, even in the presence of model uncertainties and external disturbances, and it is particularly well suited for nonlinear systems [90].
- Latin hypercube sampling – genetic algorithm (LHS-GA): This approach integrates Latin hypercube sampling for an efficient representation of the design space, combined with genetic algorithms for optimisation. It is particularly effective for control problems requiring robust solutions under uncertain or fluctuating conditions, striking a balance between exploring different possibilities and exploiting known solutions to optimise control parameters [91].

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Intelligent control: These methods are based on the use of artificial intelligence, being specifically appropriate for complex systems that are difficult to model. They rely on analysing the available data and learning from it, and therefore do not need a precise model of the system subject to control.

- Neural networks: This control strategy can be applied in cases where the availability of complete control data is not guaranteed, as the control law is learned using available data while predicting unavailable information [134]. It is best suited for complex and nonlinear systems.
- Fuzzy logic control: It is based on the use of fuzzy set theory to learn a control strategy that must be robust in the presence of uncertainties. It is best suited for systems characterised by vague input data, such as incomplete, delayed or time-varying systems, as it does not require a precise model of the system [135].
- Model-free reinforcement learning (MFRL): The data used by this algorithm to design the control laws are obtained directly from the interaction with the environment. Thus, no explicit model of the controlled system is required [136]. Deep reinforcement learning (DRL) is a subtype of MFRL that employs deep neural networks to approximate policies or value functions. DRL extends the capabilities of MFRL by enabling the agent to handle high-dimensional input spaces. As a result, more complex behaviours can be learned through its neural network-based architecture [99].
- Adaptive dynamic programming (ADP): It approximates an optimal control law by using artificial intelligence and dynamic programming, without requiring an explicit model of the controlled system [100].

Modern control: These methods involve nonlinear control strategies, predictive models, and state estimation techniques to address complex systems that cannot be controlled using simpler alternatives.

- MPC: It is based on predicting the future states of a dynamic plant model and optimising the control law that leads the model from the initial state to the desired state. The resulting law is then applied to the actual plant [103].
- SMC: It relies on switching between different control laws depending on the conditions [104]. As a result, it is well suited for systems subject to disturbances and for aircraft flying across different regimes.
- Incremental nonlinear dynamic inversion (INDI): It handles nonlinear systems by linearising the dynamics around the desired trajectory and then adjusting them with incremental changes [107]. Therefore, it is used when an exact linearisation of the system is computationally expensive.
- Robust integral of the sign of error (RISE)-based partial feedback linearised controller: The use of the RISE formulation allows this algorithm to better reject nonlinearities and disturbances [108].
- Ridge regression: This algorithm is based on minimising the sum of squared errors by adding a penalty proportional to the coefficients. It has the advantage of being able to be implemented on a model-free controller [109].
- Nonlinear model inversion (NMI): This control strategy directly inverts the nonlinear system dynamics to compute the required control inputs, effectively transforming a nonlinear system into an approximately linear one. It is best suited for applications in which nonlinearities significantly affect performance. However, a major limitation of this method is the need for an accurate system model, as any discrepancies in the model can lead to suboptimal control performance [110].

Frequency-domain control: These methods are based on analysing the frequency-domain behaviour of the system, and they are usually applied to linear systems.

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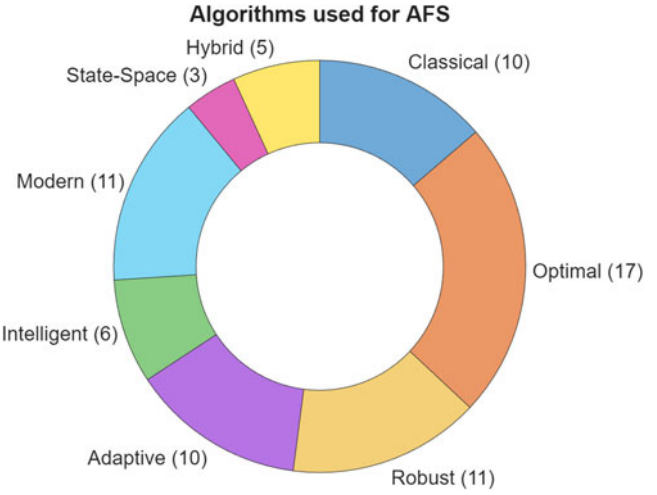


Figure 4. *Frequency of algorithm types in the reviewed works.*

- Nyquist and Bode techniques: The desired system performance is achieved by establishing the necessary stability margins. Their limited robustness and adaptability make them generally not well suited for AFS purposes.

State-space control: These algorithms represent system dynamics in a multidimensional state-space model. They are mainly used for multi-variable or complex systems.

- Pole placement: It consists of placing the closed-loop system poles at the desired locations by using a state feedback strategy. Therefore, it allows selecting the desired response speed and stability. Different methods can be selected to place the poles. Among these, the receptance method is particularly suitable for AFS systems, as it determines the pole placement gains by using the relationship between the system's inputs and outputs, thereby eliminating the need for explicit knowledge of the system model [114].

Hybrid control: These algorithms combine two or more of the previously mentioned strategies, in order to enhance the flexibility and robustness of the control system.

Furthermore, the incidence of the aforementioned algorithm types is represented in Fig. 4 with the aim of studying the relevance of each category in current research. In the cases where the articles aim to compare the performance of different algorithms, the most complex one has been considered for classification purposes, since simpler algorithms are generally included as benchmarks or reference methods in such comparisons.

First, it is remarkable that none of the reviewed works employ frequency-domain strategies, even though they constitute one of the most basic techniques to design control systems. This absence is likely related to their inability to adapt to changes or disturbances, which constitutes an important drawback for AFS applications.

By contrast, optimal algorithms form the most frequent category, with almost 25% of the articles employing one of these strategies. Moreover, when classical and optimal algorithms are considered together, this proportion increases to nearly 40%. It has previously been mentioned that these algorithms, which are the most technologically mature, are employed in works focusing on studying new control strategies differing from the deflection of aerodynamic surfaces. However, this explanation alone does not account for all papers employing classical and optimal methods, as fewer than 30% of the articles deal with alternative control strategies. The remaining works, concerning the use of technologically mature algorithms applied to control surfaces, focus on specific cases of application, comparisons with

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other methods, and particular properties of the algorithms to make their contribution to the state of the art. For instance, concerning specific cases of application, Refs [68, 73] focus on the application of optimal control in the transonic regime, while Ref. [71] considers the subsonic, transonic and supersonic regimes. Additionally, Refs [48, 72] cover BFF, while Ref. [50] studies stall flutter, Ref. [63] discusses whirl flutter and Ref. [56] covers CSF. Concerning comparisons with other methods, Refs [49, 64] compare the performance of passive control methods alone against hybrid methods combining those passive methods with a classical or optimal active strategy, respectively. Finally, regarding particular properties of the algorithms, Ref. [62] studies the critical time delay, Ref. [60] focuses on the use of a modal approach to synthesise the optimal controller, Ref. [58] studies the reduction in the number of states in the plant to design a sub-optimal controller and Ref. [68] discusses the performance loss due to actuator saturation.

Robust controllers form the next group in terms of algorithm maturity. All 11 articles featuring one of these algorithms apply them to the deflection of control surfaces. However, while some focus exclusively on the algorithms themselves by considering the baseline case of lifting surface flutter in the subsonic regime, others apply the algorithms to different conditions in order to better test their robustness. In line with this, Refs [77, 82] apply them to the transonic regime, while Ref. [78] considers the hypersonic regime. In addition, Refs [80, 83] focus on controlling BFF, while Ref. [79] applies the algorithm to a system comprising both wings and fuel tanks.

Adaptive algorithms are featured in ten works, mainly focusing on testing the AFS capabilities of the algorithms, as they are applied to control surfaces in the subsonic regime. An exception is Ref. [94], which analyses the application of an adaptive fault-tolerant controller to a reentry vehicle in the hypersonic regime.

Intelligent algorithms are relatively less represented in the reviewed literature, with only six articles addressing this category. This limited presence is likely attributed to the emerging stage of this kind of technology. However, as mentioned later in the Discussion section, results are highly promising in terms of performance and cost. Refs. [98, 99] apply MFRL and DRL, respectively, to suppress flutter using flow control; Ref. [97] applies reinforcement learning (RL) to control BFF; and Ref. [95] uses both neural network (NN) and RL to suppress CSF.

Concerning the 11 articles featuring modern algorithms, 6 focus on their application to the baseline case, while the remaining ones extend their study to particular flutter mechanisms and alternative control technologies. Regarding the suppression of particular flutter phenomena, Ref. [106] applies SMC to control stall flutter, while Ref. [111] compares the performance of both modal isolation and damping for adaptive aeroelastic suppression (MIDAAS) and identically located acceleration and force (ILAF) algorithms to that of robust H_∞ when suppressing BFF. Regarding alternative control technologies, Ref. [103] designs an MPC strategy for a morphing flap, while Ref. [104] applies SMC to vibration control. Additionally, combining both of the aforementioned purposes, Ref. [110] synthesises an NMI controller to suppress stall flutter using a morphing flap and compares its performance with that of a PID controller.

Moreover, only three articles focus on state-space algorithms. This is likely due to two main reasons. First, the pole placement strategy is not well suited for AFS purposes due to its lack of adaptability and robustness. Second, the technology is well studied, so new research can only focus either on refining the method to place the poles in order to improve controller performance or on studying the control strategy itself. Concerning the first research focus, Refs [113, 114] investigate the receptance method, which has the advantage of not requiring a precise model of the system. In contrast, Ref. [112] aligns with the second research focus, presenting an improved self-sensing circuit manufactured using MFC.

Finally, five articles employ hybrid strategies. The low number of works opting for this line of research is due to the higher complexity of hybrid controller synthesis and the need to properly study the properties and performance of the integrating algorithms separately beforehand. However, the promising results shown in Refs. [118, 119] indicate that this research path needs to be extensively explored in the near future. Moreover, it is remarkable that three of the articles featuring hybrid algorithms apply them

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to vibration control strategies, even if the complexity of such controllers may hinder the evaluation of the control strategy performance [115–117].

In summary, with the exception of state-space, frequency-domain and hybrid control, all categories are well represented in the reviewed literature, highlighting their research interest in the field of AFS. The absence of works on frequency-domain algorithms and the scarcity of works featuring state-space solutions are justified by their inability to adapt to disturbances, uncertainties and changes in the conditions, which is a key aspect of AFS system performance. By contrast, the low number of works featuring hybrid algorithms is due to the complexity of this solution, although their positive results indicate that hybrid algorithms constitute a promising area of research. Classical and optimal algorithms remain well represented in the sample, mainly due to their use in studies testing alternative control strategies. Finally, intelligent algorithms are featured less often than other solutions due to their novelty. However, their results are also promising, showing better performance and lower energetic cost when compared with more traditional solutions.

3.2.7 Tabular summary of features and findings

To conclude the Results section, Table 1 provides a consolidated summary of the main features and findings of the 73 articles included in this review. The works are organised according to the taxonomy introduced in Fig. 3.

4.0 Discussion

As mentioned above, recent research efforts in the field of AFS have focused on two main areas of innovation: the development of new strategies and devices to control flutter, and the synthesis of increasingly complex and better performing algorithms. The study of the features of the included studies, presented in Section 3.2., allows the identification of a clear relationship between algorithms and control devices. In general, works studying alternative control devices to traditional aerodynamic surfaces tend to employ technologically mature algorithms, so that the research focus is placed on the device itself. Conversely, innovative algorithms are mainly studied in conventional control surface configurations. This separation enables the advances introduced in each of these innovation areas to be analysed independently. Therefore, the present Discussion section is divided into two parts, in order to better reflect on the advances introduced by the works included in this review.

4.1 Advances in control strategies

The various control devices explored in the reviewed works are discussed in Section 3.2.5. In contrast, the present section aims to summarise and analyse the main findings and advances associated with these technologies.

Regarding morphing technologies, two key findings can be highlighted. First, when integrated within an LQG framework, morphing flaps show better AFS capabilities than plain flaps, both in terms of increasing the flutter speed and reducing the amplitude of the deflection commands [66]. Second, it has been found that introducing a time delay in a morphing flap-actuated controller can be beneficial to control flutter. Specifically, in Ref. [50], a PD controller without delay actually induced stall flutter, whereas the best performance was achieved with a delay of 0.1 s. These results underline the importance of continuing research on morphing solutions for AFS, as they can offer enhanced performance over conventional control surfaces, and they involve unique challenges that must be addressed in order to design optimised controllers.

With regard to flow control, the results reported in Refs [51, 98, 99] indicate a promising future for this strategy in the field of AFS. However, further research is required to reduce the size and complexity of the systems used in these studies in order to ensure their feasibility for implementation on actual aircraft. Additionally, trailing-edge circulation control achieved significantly better performance than

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leading-edge blowing. Moreover, although open-loop flow control proved effective in managing flutter, incorporating a control algorithm into the system further increased the flutter speed and significantly reduced the required airflow. Finally, two additional potential uses of flow control for AFS have been identified. Notwithstanding, the corresponding articles have not been included in this review because they are yet to be modeled and tested. In particular, Ref. [137] proposes the use of any kind of active flow control to eliminate the leading-edge separation bubble so as to prevent the controlled system from experiencing flutter, while Ref. [138] proposes using a mini-tab or flow fence to avoid vortex formation and thus prevent whirl flutter.

With respect to the vibration control strategies examined in the included articles, the ADVA has demonstrated significant potential for AFS, as it achieves higher flutter speeds compared to its passive counterpart [54]. Its associated drawbacks, such as MFC hysteresis and the resulting nonlinearities, can be balanced by incorporating experimental data into the design process [47]. Similarly, MR dampers have been shown to suppress flutter oscillations in wing-store systems more rapidly than passive dampers, demonstrating their potential for AFS [59]. Finally, regarding the use of piezoelectric actuators, several noteworthy observations can be highlighted. These actuators have demonstrated superior performance compared to passive methods, achieving a flutter speed increase of 25% [67]. Moreover, they exhibit comparable AFS capabilities to conventional control surfaces, with the added advantage of remaining operational in scenarios where control saturation may occur [55]. Additionally, embedded piezoelectric materials can serve a dual purpose, as they can both harvest energy and suppress flutter. This approach has shown great potential for energy savings, as a significant portion of the control effort is required while the retrieved energy surpasses the energy cost, thus resulting in a net energy surplus [52]. Consequently, a combination of piezoelectric actuators and thin-film battery cells would allow storing the energy output while the AFS system is not operating for its reuse when needed, resulting in a system with partial self-sufficiency, akin to hybrid vehicles [116]. Furthermore, piezoelectric actuators have demonstrated the ability to control flutter effectively even when accounting for time delays. As observed with morphing flaps [50], a certain time delay can enhance performance [104]. By contrast, some limitations of this strategy have been identified. In particular, these actuators tend to be heavier and more complex than passive methods [67]. Additionally, they are significantly more energy-intensive than control surfaces, therefore being best suited to serve as a backup for emergency situations [55].

In addition, it is noteworthy that the use of shape memory alloys for AFS, proposed in previous works cited in Ref. [13] and identified as promising in Ref. [139], has not been implemented or further explored in the years covered by this review.

In conclusion, all the examined strategies have demonstrated their capability to suppress flutter, with morphing flaps and vibration control devices demonstrating superior performance compared to traditional control surfaces. This justifies the sustained research interest in these alternative solutions. On the downside, piezoelectric actuators have been shown to be energetically demanding, which can be resolved by exploiting their energy harvesting capabilities. Moreover, the potential of multi-actuated wings or morphing wings that are continuously deformable along the span remains largely unexplored, as prior works have only considered up to two control surfaces for AFS [140]. In line with this, Ref. [74] further investigates the two-surface configuration introduced in Ref. [140], while Ref. [57] presents a study optimising the control surface layout for AFS based on an initial configuration of 20 control surfaces. However, this study only considers flutter control at the design point, instead of assessing controller performance over the full flight envelope. As a result, this approach, which could benefit from the adaptability resulting from control surface multiplicity, represents a significant knowledge gap to be explored in future works.

4.2 Advances in algorithms

Following the same structure as the previous section, the advances related to the algorithms presented in Section 3.2.6 are discussed in the following paragraphs.

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Regarding classical algorithms, their inherent simplicity offers limited scope for improvement, with their only area of research being the exploration of new gain selection methods. In this context, the use of genetic algorithms to select PI gains has been shown to double the increase in flutter speed compared to manual gain selection [48]. This result highlights the value of incorporating optimisation procedures into the gain scheduling process, as they not only enhance controller performance but also reduce design workload by automating tasks.

Concerning optimal algorithms, studies comparing LQR, H_∞ and pole placement (state-space) techniques consistently identify H_∞ as the most effective and robust option [69, 71]. However, there is no consensus among authors regarding whether H_∞ or LQR yields lower costs in terms of surface deflection, highlighting the need for further research to thoroughly evaluate this aspect. In addition, pole placement demonstrates lower performance in handling time delays compared to LQR [62]. Several alternatives to improve optimal algorithms are explored in the reviewed literature, including: (i) the adoption of an LPV strategy to enhance the robustness of an H_∞ controller and enable effective operation across different airspeeds [72]; (ii) the combination with passive flutter control mechanisms, which simultaneously increases flutter speed and reduces control effort [64]; (iii) the use of a nonlinear approach to develop a controller capable of suppressing flutter in the transonic regime [73]; and (iv) the identification of two parameters capable of revealing controllers that appear effective under linear assumptions but perform inadequately in real situations [68]. Another noteworthy advancement is the application of a modal approach to design an LQG controller [60]. This approach eliminates the need for the time-domain form of unsteady aerodynamic forces, thereby removing a significant source of approximations. Additionally, the cost efficiency of LQR algorithms can be improved through the synthesis of a sub-optimal controller with a reduced state dimension, achieving performance levels close to those of the optimal controller [58].

When extending the comparative studies to robust controllers, these demonstrate superior performance and adaptability relative to optimal [84] and classical [79] controllers. However, robust algorithms also exhibit certain limitations. For instance, while ADRC can successfully suppress flutter in the transonic regime [77], other solutions, such as adaptive algorithms, are better suited for this purpose due to the challenges robust control faces in balancing varying conditions [82]. Furthermore, although some robust controllers can suppress flutter while accounting for noise, delays, backlash and rate limits without reaching actuator saturation [76, 81], others remain susceptible to saturation effects. This limitation can be addressed by incorporating an anti-wind-up compensator [80]. Another important breakthrough is the enhancement of the ADRC algorithm through the integration of an LS-SVM, enabling it to predict and counterbalance partial disturbances [78].

Regarding adaptive algorithms, their robustness against actuator faults, system nonlinearities and external disturbances has been demonstrated under various conditions [85, 93], including hypersonic regimes [94]. Studies comparing their performance with that of simpler algorithms also demonstrate this superiority, as is the case of I&I control relative to PID [90] and of LHS-GA controllers when compared to H_∞ and LQR [91]. In the latter case, the enhanced robustness and performance of the LHS-GA controller against uncertainties are highlighted. Moreover, actuator saturation can be mitigated through the incorporation of an anti-wind-up module [86]. Nevertheless, the high control effort associated with adaptive controllers may limit their practical applications [85]. Furthermore, comparisons between SAC and GS-fPID controllers indicate that SAC offers superior robustness, increased performance and better compatibility with piezoelectric actuators [88].

Studies on intelligent algorithms compare their performance to that of optimal algorithms – notably LQR and H_∞, highlighting several advantages: (i) higher computational efficiency [96], (ii) enhanced robustness [97], (iii) reduced oscillations [100], (iv) faster synthesis process [97], (v) greater effectiveness against highly nonlinear vibrations [95] and (vi) elimination of the need for a system model [100]. Furthermore, the importance of selecting an appropriate strategy for RL is emphasised, as backpropagation has proven effective, whereas simpler gradient-based approaches have not [95]. Finally, the potential of DRL for transonic flutter suppression due to its robustness across a wide range of flutter speeds has also been demonstrated [99].

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Similarly, performance comparisons between modern and optimal algorithms confirm the superiority of modern controllers in terms of effectiveness, as they achieve higher flutter speeds [109, 111]. Analogously, in the case of the comparison between NMI and PID for stall flutter suppression, while the PID controller only reduced the oscillation amplitude by a factor of four, the NMI controller eliminated it completely [110]. Additionally, they are less prone to control saturation and, in model-free formulations – such as ridge regression algorithms – their implementation cost is lower [109]. Another key advantage of modern control – particularly MPC – is its ability to manage high-frequency nonlinear pulses, which pose challenges for more conventional controllers [103]. Furthermore, one of the most prominent areas of research in modern control is the improvement of baseline modern algorithms to develop higher-performance solutions. For instance, SMC algorithms, which require a system model, can be replaced by model-free and disturbance-robust alternatives, such as AFSMC [105] and RISE-based partial feedback linearised controllers [108]. Similarly, constrained Laguerre orthonormal function-based MPC (LMPC) variants offer performance comparable to classical MPC at substantially reduced computational cost, whereas unconstrained LMPC formulations are impractical due to excessive actuator demands [102].

Despite their limitations when applied to complex systems with uncertainties and disturbances, state-space algorithms have also demonstrated their applicability to baseline control surface-lifting surface flutter problems. The main advances in this area are the development of a model-free pole placement algorithm by using a frequency-based approach [114] and the possibility to handle certain unavailable measurements by including acceleration feedback alongside position and velocity signals [113]. Pole placement has also been employed in a vibration control AFS study to focus on improving the control strategy itself [112]. Indeed, after the vibration control strategy was studied, the algorithm was upgraded to a hybrid version in a subsequent article by the same authors, in which an adaptive strategy is adopted by designing three pole placement switching controllers that can be selected according to the flight condition [117].

Finally, regarding hybrid algorithms, they have been shown to effectively handle actuator faults, control delays, speed variations, nonlinearities, disturbances and uncertainties, while also delivering enhanced performance relative to the basic algorithms used in their composition [115, 118, 119].

In summary, current lines of research in AFS algorithms pursue two complementary objectives: (i) improving classical and optimal algorithms, taking advantage of their simplicity and optimisation potential, and (ii) developing advanced algorithms that offer superior performance, adaptability and cost effectiveness. Robust algorithms demonstrate strong adaptability but face challenges in balancing varying conditions and preventing actuator saturation, which can be mitigated with solutions such as anti-wind-up compensators. Adaptive algorithms excel in handling actuator faults, nonlinearities and disturbances, although their high control effort may limit their applicability. Intelligent algorithms stand out for their computational efficiency and ability to address complex nonlinear scenarios without requiring a system model. Similarly, modern algorithms achieve notable improvements in terms of performance and system adaptability, often at a reduced computational cost. Finally, hybrid algorithms effectively integrate the strengths of various approaches to manage multiple challenges simultaneously, highlighting the potential of multi-faceted strategies in advancing AFS technology.

Furthermore, it is important to note that algorithm-focused studies typically explore the advantages of a specific algorithm or compare it against a limited set of technologically mature algorithms. Therefore, a comprehensive study comparing a broader range of algorithms would provide more accurate performance assessments and help identify the most suitable algorithm category for each specific application.

4.3 Discussion of methodological approaches

As noted in Refs. [13, 14], the use of wind-tunnel tests and, in particular, flight tests, to validate the mathematical and numerical aeroservoelastic models designed for AFS is of utmost relevance to ensure their practical applicability and adequate performance in operational aircraft. However, as presented in

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Section 3.2.1, the majority of the works reviewed rely exclusively on numerical tests, with only 12 articles supported by experimental tests. Furthermore, only two of these studies include flight tests [48, 111], showing the need to further invest in flight test campaigns capable of validating the advantages of implementing AFS systems in aircraft and demonstrating compliance with safety requirements, which is an essential step towards AFS system certification.

In line with this, several large-scale AFS flight test programmes were conducted prior to the time span addressed in this review [14]. From Boeing's B-52CCV in the early 1970s [141] to Lockheed Martin Skunk Works' X-56 in the 2010s [142] – passing through European AFS flight test programme in the 1970s [143], NASA's DAST UAV in the late 1970s and early 1980s [144], and Boeing's AFS systems implemented in the B-747-8 and B-787-10 in the 2000s and 2010s [14] – these programmes have significantly advanced the state of the art in AFS.

Notwithstanding, during the past eight years, the only open-access large-scale AFS flight test programme to have continued operation is the Lockheed Martin X-56, with the X-56A MUTT having successfully extended its flutter boundary after controlling its BFF, which appeared due to the coupling between the first symmetric wing bending and the short-period modes [145]. However, this does not preclude the possibility that private companies may have continued investigating the practical implementation of AFS systems without publicly disclosing their results. Moreover, two smaller-scale flight test programmes for AFS development and validation are currently in progress. These include an unmanned demonstrator aircraft developed by DLR, SZTAKI, and the University of Bristol within the EU-funded FLEXOP project [81, 146], as well as another EU-funded project, FliPASED [147], developed by SZTAKI, TUM, DLR and ONERA. Both projects have successfully demonstrated the implementation of AFS controllers in flight.

In addition, no advances have been reported on the development of reference test cases intended to verify results and compare the performance of different algorithms and strategies, which was mentioned by Livne [14] as a highly beneficial step towards building the required confidence level for AFS system certification. The establishment of common reference cases and shared data repositories to facilitate collaboration among researchers has also been proposed in other aviation fields – such as the use of ontologies for aircraft design [148] – and implemented, as seen in the Central Reference Aircraft data System (CeRAS) database for aircraft conceptual design [149]. Furthermore, it would be of great value to establish clear performance and cost comparisons between algorithms, helping to determine the optimal solution for each specific application.

5.0 Conclusions

This article presents a comprehensive review of the advances in the field of AFS published between 2017 and 2024. The PRISMA methodology has been employed to provide a systematic and updatable review, and the article search and selection process has been detailed in the Methods section both to facilitate future updates of this review and to serve as an example of the application of the PRISMA methodology within the aerospace domain. The analysis presented in the Results section has enabled the development of a comprehensive classification of the algorithms currently used for AFS, including their main advantages and most suitable applications. This classification aims to assist researchers in selecting the most appropriate algorithm for their projects and constitutes one of the main contributions of this work. The principal findings drawn from the Results and Discussion sections can be summarised as follows:

1. Current research on AFS can be broadly classified into two separate categories: (i) the study of alternative control strategies, relying on technologically mature algorithms, and (ii) the application of advanced algorithms to traditional control surfaces. As a result, the application of novel algorithms to alternative control strategies remains largely unexplored.

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2. Most reviewed studies implement AFS systems on either aerofoils or wings using numerical approaches. Thus, it is deemed necessary to extend these investigations to full-aircraft configurations and to complement them with experimental tests in order to further validate the practical applicability of the proposed controllers. This need is particularly relevant for non-conventional aircraft configurations, which correspond to half of the full-aircraft studies reviewed. In this regard, continued development of AFS flight test programmes is of paramount importance to validate the numerical results and advance towards AFS system certification.
3. Very few articles explore the synthesis of AFS systems for the transonic, supersonic and hypersonic regimes, which remains a promising area of research.
4. Similarly, the design of AFS systems specifically conceived for stall, whirl and body-freedom flutter suppression has recently attracted more research interest.
5. Alternative control strategies, such as morphing technologies as well as flow and vibration control, demonstrate significant potential for AFS, as their performance exceeds that of control surfaces. Consequently, they continue to offer significant interest for future study. Nevertheless, the potential of multi-actuated wings and spanwise deformable morphing wings for AFS is yet to be explored.
6. Classical and optimal algorithms retain relevance due to the improvements effectuated by recent studies, while more advanced algorithms demonstrate higher performance, robustness, adaptability and cost-efficiency. A comprehensive comparative study encompassing a broader range of algorithms would enable a more accurate assessment of their relative performance and facilitate the selection of the most suitable algorithm for specific applications.
7. In line with this, the development of reference test cases for their use within the research community would help to validate results and compare algorithm performances.
8. Finally, the study of uncertainties, disturbances and algorithm performances under failure conditions, which was deemed of paramount importance in previous reviews, has considerably progressed. The same conclusion can be extracted with respect to the modeling of high-order and multiple degree-of-freedom systems to account for more complex phenomena.

Competing interests. The authors declare none.

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Cite this article: Cobo-González Á., Rodríguez-Robles R. and Cuerno-Rejado C. Recent advances in active flutter suppression: a comprehensive review. *The Aeronautical Journal*, https://doi.org/10.1017/aer.2026.10212

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