ADVANCEMENTS IN SUPERSONIC FLIGHT CONTROL: REVIEW OF CAVITY FLOW IMPACT AND INTEGRATION OF ACTIVE AND PASSIVE CONTROL MECHANISMS

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ABSTRACT

This review paper explores the challenges of supersonic flight, specifically focusing on the impact of cavities on flight dynamics and the effectiveness of various control mechanisms. The paper addresses three primary objectives: understanding cavity-induced effects during supersonic flight, evaluating the effectiveness of active and passive cavity flow control techniques, and exploring the integration of both approaches for optimized control. Cavities, or recessed areas on aircraft surfaces, can cause complex shock-wave patterns during supersonic flight, leading to problems like increased drag, reduced controllability, and heightened acoustic emissions. The paper aims to highlight the mechanisms underlying these cavity-induced phenomena by analysing existing research and shedding light on their effects on flight dynamics. The effectiveness of two distinct control strategies, active and passive, in managing cavity-related issues is investigated. Active control involves real-time adjustments using technologies like jets and feedback loops, while passive methods alter flow behaviour through design features. The review examines the outcomes of research studies that have employed these techniques, providing an assessment of their individual merits and limitations. The paper also emphasizes the potential benefits of integrating active and passive control approaches to achieve a comprehensive solution for cavity-induced instabilities. By combining the strengths of both methods, this integrated approach promises improved stability, reduced drag, and enhanced overall flight performance. The review synthesizes findings from existing research, facilitating a comparison of outcomes, and offering a guide for future investigations into the synergistic application of active and passive controllers.

KEYWORDS

Supersonic; Cavity flow; Active control; Passive control;

INTRODUCTION

Supersonic flight represents the pinnacle of human technological achievement, enabling rapid global travel and a host of military applications. However, this extraordinary mode of travel is accompanied by intricate aerodynamic challenges that demand innovative solutions to ensure safety, efficiency, and optimal performance. Among these challenges, the effects of cavities on supersonic flight dynamics stand as a formidable hurdle that can significantly impact both aircraft stability and overall mission success [1-2]. This review paper delves into the complex interplay between cavity-induced flow instabilities, the utilization of active and passive flow control mechanisms, and the integration of these approaches to achieve effective supersonic flight control.

Cavity flow is when air passes over a hollow silhouette on the surface of an object. Cavities, defined as recessed areas on aircraft surfaces, can manifest during the design or operation of high-speed vehicles due to various structural, aerodynamic, and propulsion requirements such as at the weapon bay, cargo compartment, landing gear bay, intake duct and even the engine nozzle area. In the context of supersonic flight, these cavities have been observed to create intricate shock-wave patterns, generate unsteady flow phenomena, and trigger significant aerodynamic disturbances [3-7]. Cavity flows can cause pressure oscillations up to 160 dB in the weapon bay of a fighter jet aircraft [8]. These effects, ranging from increased drag and compromised control to heightened noise emissions, underscore the importance of comprehending and managing cavity-induced phenomena.

To address these challenges, the field of supersonic flight control has witnessed the development of active and passive flow control techniques to disrupt the feedback loop that is caused inside the cavity. Active control strategies leverage real-time adjustments using technologies such as microjets, plasma actuators, and pulsed blowing, enabling the aircraft to adapt to rapidly changing flight conditions [9]. In contrast, passive control methods such as the sawtooth spoilers, aft wall slopes, ramps etc. involve permanent alterations to the aircraft's geometry or surface properties, providing inherent flow alteration and stabilization [10-11]. Each approach has demonstrated merits in specific contexts, prompting an ongoing exploration of their potential to manage cavity-induced instabilities.
However, the potential for even greater success lies in the integration of active and passive control methodologies [12]. This integrated approach seeks to combine the benefits of real-time adaptability with the inherent flow-altering properties of passive measures. The integration could lead to synergistic effects, minimizing the limitations of each method and yielding more comprehensive and robust solutions to cavity-induced flow issues.

This review paper aims to provide a comprehensive overview of the intricate relationships between cavity-induced flow instabilities and supersonic flight control mechanisms. By addressing the impact of cavities on flight dynamics, evaluating the individual effectiveness of active and passive control techniques, and exploring the potential for an integrated approach, this paper contributes to a deeper understanding of the challenges and opportunities in the realm of supersonic flight control. Ultimately, the insights garnered from this exploration are poised to influence future research, development, and innovation in the pursuit of safer, more efficient, and more controlled supersonic travel.

METHODOLOGY

This review paper follows a systematic approach to fulfil its objectives of comprehensively examining the impact of cavities on supersonic flight dynamics, evaluating active and passive cavity flow control techniques, and exploring the integration of these strategies for effective flow management. The methodology involves a thorough literature review, analysis of relevant research papers, and a critical synthesis of findings from the selected studies between 1964 to 2023.

Literature Review

A comprehensive search was conducted in reputable databases such as ScienceDirect, Google Scholar, and Web of Science using relevant keywords. These keywords included "supersonic flight control," "cavity flow dynamics," "active control mechanisms," "passive control strategies," "integrated flow control," "aerodynamic instabilities," and "shock-wave interactions." The focus was on sourcing recent research articles, review papers, and conference proceedings published.

Selection Criteria

Articles were selected based on their relevance to the objectives of the review paper. Studies addressing cavity-induced flow instabilities in supersonic flight, active and passive flow control methods, and the integration of these approaches were considered. Articles that provided insights into the fundamental mechanisms, numerical simulations, experimental validations, and practical applications were prioritized.

Data Extraction and Analysis

Selected articles were carefully examined to extract relevant information, including theoretical concepts, methodologies, experimental setups, numerical simulations, and findings. The information gathered from these articles was analysed to identify common trends, challenges, and advancements in the field of supersonic flight control and cavity flow management.

Synthesis of Findings

The collected data was synthesized to construct a cohesive narrative that addresses the review paper's objectives. The synthesis involved categorizing the findings into sections related to cavity-induced effects, active control techniques, passive control strategies, and integrated approaches. Comparative analyses were performed to highlight the strengths, limitations, and practical implications of each technique.

Discussion and Implications

The synthesized findings were discussed in the context of their contributions to the understanding of supersonic flight control and cavity flow management. Implications for future research, technological development, and practical applications were explored, emphasizing the potential impact on aircraft performance, stability, and safety.

Motivation of this review

In order to counter the negative impacts of the cavity that is on the aircraft, control strategies are put in place, these control strategies are split into active control and passive control techniques which uses components which can be turned on or off as required and fixed structural alternations which reduce the weight of the aircraft respectively, and by placing these onto the cavity, it disrupts the cavity flow. This gave rise to the integration of both active and passive control technique together in a hybrid situation, where both the benefits of the control strategies are taken into account.

Limitations

It's important to acknowledge the limitations of this review paper, such as potential biases in the selection of studies and the inherent challenges of summarizing a vast and diverse body of research.
In summary, the methodology employed in this review paper involved a systematic literature review, careful selection of relevant articles, extraction and analysis of data, synthesis of findings, and a comprehensive discussion of implications and limitations. This methodological approach ensures that the paper effectively addresses its objectives, contributes to the understanding of the field, and guides future research directions.

RESULTS AND DISCUSSION

Cavity-Induced Effects during Supersonic Flight

The analysis of the current literature highlights the widespread agreement that cavities have a significant influence on the dynamics of supersonic flight. Figure 1 shows a typical flow stream across a cavity. Open cavities are subject to dynamic aerodynamic forces and instabilities because of the interaction between cavity configuration and high-velocity airflow. When a shear layer forms at the leading edge of a cavity in a supersonic flow, the cavity experiences a feedback flow that is fuelled by the shear layer's contact with the trailing edge. Different resonance frequencies are produced by this interaction [13]. Together, these processes are responsible for increased drag, weakened aircraft stability, and increased noise emissions. The studies emphasized how crucial it is to comprehend the complex shock-wave dynamics within cavities and their overall impact on flight performance. In one instance, given a Length to Depth (L/D) ratio of 2, regardless of the width ratio, the pressure amplitude showed greater magnitude in a 2D cavity operating at frequencies of 8.27 kHz as opposed to a 3D cavity operating at frequencies of 4.24 kHz and 8.30 kHz.

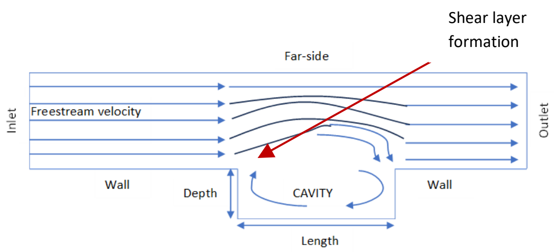

Figure 1: Schematic diagram of a typical flow stream across a cavity

Active and Passive Cavity Flow Control Techniques

The effectiveness of active and passive methods to mitigate the negative impacts of cavity-induced instabilities during supersonic flight has been thoroughly investigated in several studies. Active

Control Methods: Research on active control techniques has shown how jets [14], and actuators [15] can be used to change cavity flow patterns and reduce instabilities. Real-time adjustments, aided by feedback loops and computer algorithms, give the potential for adaptive control in rapidly varying flying situations. For example, plasma actuators can control localized flow, reducing flow separation and increasing aerodynamic effectiveness.

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Control methods

Due to its intricate geometry and the hostile nature of the incoming flow, controlling a cavity flow can be a very difficult operation. in order to avoid the drag, instability, and buffeting caused by vortices, eddy formation, recirculation zones, pressure fluxes, and flow separation in supersonic cavity flow. Cavity flow can harm structures by wearing them out and causing vibrations as a result. Control strategies are put in place to lessen the negative effects, boost effectiveness, and enhance efficiency of the flow characteristics brought on by the cavity. The active control and the passive control techniques, which are described in more detail below, are the two primary categories of the control methods that are being used throughout.

Active control method

Active control methods are used to suppress the pressure fluctuations inside the cavity. This type of control method requires the use of energy such as mechanical or electrical to adjust an actuator or other kinds of active controls to control the flow. This type of control is applicable for a wide variety of flow conditions as they are efficient [8].

Plasma actuators [9], microjet injection [16], laser energy deposition [17], pulsed and steady mass injections [18] are among the few active controllers that are used to fluctuate the pressure during cavity flow. Several studies have been conducted both experimentally using the wind tunnel as well as using numerical solutions using computational fluid dynamics.

Experimental techniques such as shadowgraph flow visualization, particle image velocimetry (PIV), and schlieren flow visualization were conducted to mitigate the dynamic loads associated with the cavity for a supersonic cavity flow at Mach 2, a series of supersonic microjets containing nitrogen were positioned near the cavity's leading edge. The microjet controls produced promising results on reducing the resonance, also resulting in a cavity tone reduction of 20 dB and a sound pressure level reduction above 9dB in the study conducted by Zhuang et al., [18].

The resonance can also be controlled and suppressed using localized arc filament plasma actuators (LAFPA) during supersonic flow cavity. A 14 dB peak reduction is observed in the 2D excitation scenario whereas at the 3D excitation, a peak tone reduction of 11 dB can be observed. One drawback is that electromagnetic interference plays a role which obstructs the ability to draw clear conclusions regarding the LAFPAs resonance enhancement [9]. Other control methods such as the micro actuators that eject microjets near the leading edge of the cavity can be modified using piezo stack to control the flow fluctuations. In one of the studies conducted, three different scenarios were tested, which are pulsed resonance enhanced microjets, active pulsed resonance enhanced microjet (SmartREM) and the steady control modes. It was observed that using pulsed and active pulsed actuators, dominant peak overall sound pressure levels and broadband levels were reduced significantly to 7 dB, 4 dB, and 4 dB, respectively. However, the SmartREM and REM modes did not show a significant difference in the actuator's performance when compared. When the actuators were controlled at steady modes, tremendous results were obtained as the overall sound pressure levels were reduced to 10dB and the peak amplitudes were reduced to 25 dB [16].

In a study conducted by Yilmaz et al., [17] 100 mJ of laser energy is deposited on the leading edge above an open rectangular cavity flow and a 7 dB sound pressure level reduction was obtained, which was measured at the back of the cavity wall. Laser energy is more efficient if the laser is exposed for a longer duration in terms of suppressing the pressure agitation. Example of the locations of an active controller such as the microjets placed on a cavity is shown in Figure 2.

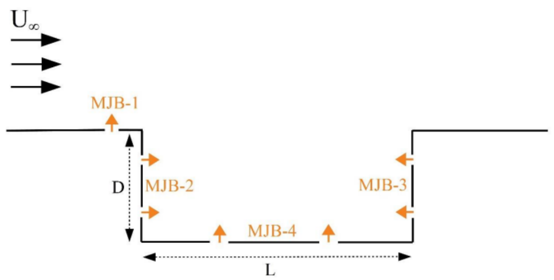

Figure 2: Example of a microjet active controller (adapted from Gelisli et al., [19])

Passive control method

Passive control on the other hand does not use any energy, they rely on geometric modification, small protrusions or placement of ridges which disrupts the flow or the feedback loop that would form in the cavity due to the properties of the cavity flow. Some of the passive control methods that have been implemented over the past years are placement of spoilers at the cavity [20], altering ramp angles [21], cover plates [19], and other kinds of structural modifications that are attached on to the cavity such as mesh, fences, trailing edge wedge and so on, which are employed to disrupt the supersonic flow that strike the cavity.

Placing sub-cavities inside a cavity at different points such as the front or aft or both, modifies the shear layer that is formed at the leading edge of a cavity during a supersonic flow. Placing the sub-cavities at different nodes also plays a crucial role in determining whether the flow is fluid dynamic or fluid resonant inside the cavity [22]. A controlled cavity flow with an upstream injection flow in the leading edge of the cavity has a higher impact on the flow in terms of cavity tones, and feedback loops. It could also be observed that the controlled cavity has an impact in terms of reduced Overall Sound Pressure Levels for different Mach numbers. Due to the employment of the upstream injection, the feedback loop inside the cavity is disturbed which reduces the acoustic waves lower than the broadband noise [23].

A study conducted by Saddington et al., [10] compared the results for 13 different passive control devices for a transonic flow and determined that the square tooth spoiler, flattop spoiler and leading edge wedge were among the most effective passive control technique in suppressing the pressure fluctuation more than the trailing edge modification technique, the passive controls displayed an overall sound pressure level reduction of 8.8 dB, 8.5 dB and 7.5 dB respectively. Various passive control methods such as the aft wall slop, cover plate and the locations of the wall sensors are shown in Figure 3.

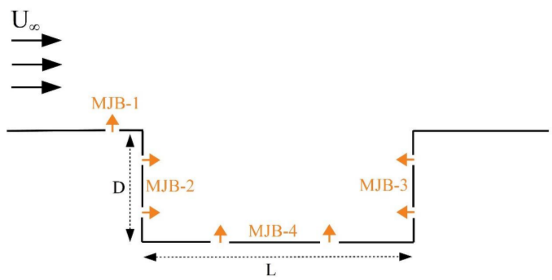

Figure 3: Example of various passive controllers (adapted from Gelisli, et al., [19]).

Integration of Active and Passive Control Approaches

The integration of active and passive control mechanisms emerged as a promising avenue for achieving comprehensive cavity flow management during supersonic flight.

Synergistic Benefits

Studies exploring the combination of active and passive strategies indicated potential synergistic effects. The adaptability of active methods, coupled with the inherent stability provided by passive alterations, promised enhanced stability, reduced drag, and improved overall flight performance. The integration approach sought to capitalize on the strengths of both techniques while minimizing their individual limitations.

Challenges and Optimization

While the integration approach holds promise, challenges related to control logic, actuator placement, and flow interaction complexities were noted. Optimization methods were proposed to determine the optimal combination of active and passive control parameters for specific cavity geometries and operational conditions.

In summary, the results of this review highlighted the adverse impact of cavities on supersonic flight dynamics, the effectiveness of active and passive control strategies in managing cavity-induced instabilities, and the potential synergies offered by their integration. The findings underscored the need for a holistic approach to cavity flow management, combining the advantages of both active and passive methods to achieve optimal stability, efficiency, and control in supersonic flight. By introducing the hybrid method it can reduce the weight of the aircraft through the use of passive control technique and balance it out with the active control technique giving it the advantage of both the control technique for example the use of trailing edge inclined angle as a passive control integrated with the microjet actuator as the active control provides a more advanced control technique which brings in the benefit of both the controllers as well as balancing out the weight of control techniques negating the instabilities caused by the cavity rather than using only one control technique.

In a series of studies shown in Table 1, various control techniques were explored to mitigate noise in supersonic flow cavities: microjet controls achieved significant reductions in resonance and cavity tones, while introducing sub-cavities at different locations altered shear layer formation; a 60^{o} Total Wedge Inclination (TWI) angle led to favourable results with reduced sound pressure levels and uniform pressure distribution; upstream injection in controlled cavities disrupted feedback loops, reducing cavity tones and overall sound pressure levels; and LAFPAs effectively controlled resonance in supersonic flow cavities, yielding notable peak reductions in both 2D and 3D excitation scenarios. Additionally, pulsed and active pulsed actuators reduced sound pressure levels and peak amplitudes significantly in steady modes, with no substantial difference between SmartREM and REM modes.

Table 1: Summary of literature findings on the variation of cavity L/D, Mach no. and control approaches

Ref.	Cavity L/D	Mach no.	Control Approaches	Findings
Zhuang et al., [18]	5.16	2.00	Active	The implementation of microjet controls, while effective in reducing resonance, also achieved a substantial reduction of 20 dB in cavity tones and above 9 dB in sound pressure levels in the study.
Panigrahi et al., [22]	2	1.71	Passive	Introducing sub-cavities at various locations within a cavity, such as the front or aft, or both, alters the formation of the shear layer at the leading edge of the cavity.
Gelisli et al., [19]	5.07	1.50	Active and Passive	A 60° Total Wedge Inclination (TWI) angle yielded the most favourable results, as it led to reduced sound pressure levels, reduced pressure variations, and a uniform pressure distribution within the cavity, with fluctuations observed only at the trailing edge.
Wang et al., [23]	6	1.80	Passive	Injecting upstream into the leading edge of a controlled cavity disrupts feedback loops, reducing cavity tones and acoustic waves, resulting in reduced overall sound pressure levels (OASPL) for Mach speeds of 1.8 and 2.0.
Webb and Samimy, [9]	4	2.24	Active	LAFPAs can effectively control and reduce resonance during supersonic flow cavity, with a 14 dB peak reduction at the 4th Rossiter mode in the 2D excitation scenario and an 11 dB peak tone reduction in the 3D excitation scenario.
Kreth and Alvi, [16]	5.43	1.50	Active	The use of pulsed and active pulsed actuators significantly reduced dominant peak overall sound pressure levels and broadband levels by 7 dB, 4 dB, and 4 dB, respectively, with no significant difference observed between the SmartREM and REM modes, while in steady modes, overall sound pressure levels decreased by 10 dB and peak amplitudes by 25 dB.

Conclusion

In conclusion, this review paper has explored the area of supersonic flight control, focusing on the profound impact of cavities on flight dynamics and the diverse strategies employed to mitigate their effects. The investigation embarked upon three principal objectives: the comprehension of cavity-induced phenomena during supersonic flight, the evaluation of active and passive cavity flow control techniques, and the exploration of an integrated approach that leverages the strengths of both methods.

The analysis of cavity-induced effects revealed the complexity of the interactions between cavities and the surrounding airflow. The resulting shock-wave patterns and disturbances can lead to a range of detrimental consequences, from aerodynamic inefficiencies to compromised controllability and increased noise emissions. This understanding underscores the critical importance of effectively managing these cavity-induced instabilities.

The review of active and passive cavity flow control techniques underscored the versatility of these strategies in addressing cavity-related challenges. Active control mechanisms, driven by real-time adjustments, provide immediate adaptability to changing flight conditions, while passive techniques introduce geometric modifications and surface treatments that inherently alter flow behaviour. Both methods offer unique advantages, and their effectiveness is contingent on factors such as the specific application and desired outcomes.

Of significant importance is the integration of active and passive control methods, which emerged as a promising avenue for comprehensive supersonic flight management. The synergistic combination of real-time adaptability and inherent flow alteration holds the potential to maximize the benefits while mitigating the limitations of each approach. This integrated strategy presents an exciting frontier for future research and development, aiming to create a holistic solution that optimally addresses cavity-induced challenges.

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