A Review of Control Methods for Cavity Flows and Feasibility of Laser Energy Deposition as an Actuator

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ABSTRACT
Studies related to supersonic cavity flow are very important for aeronautics applications. Understanding the physics of cavity flows is crucial for both fluid mechanics and engineering applications. Supersonic cavity flow and control techniques for this type of flow have been studied for many decades. A review of literature on numerical and experimental cavity flow is provided and the flow mechanism inside the cavity is explained using example studies from literature. It is necessary to understand the complex nature of the flow before developing control methods for the cavity flow oscillations. The literature on the development of methods to control the flow oscillations in cavities which are harmful for aircraft is also reviewed. Feasibility of laser energy deposition as an actuator for flow control is investigated demonstrating examples from literature.

1. INTRODUCTION
High speed flows over open cavities, which are used as model configurations for interior carriage of storages that enhance the survivability of the aircraft by providing some advantages (drag reduction, radar signature reduction and an increase in the lift), can be a reason for complex unsteady flow field formations that are practical concerns in aerospace applications [1]. These complex unsteady flow fields can be a source of hazardous interactions such as pressure fluctuations and relatively high sound pressure levels. The intense pressure fluctuations and resonant acoustic fluctuations can damage the structure of the aircraft and can decrease the chance of success in mission.

To avoid the dangerous effects of this type of configuration, researchers have studied flow control over past decades and flow control has become a broad and important topic. Many control techniques have been developed and applied to control the supersonic cavity flow.

In this article, firstly, cavity flow phenomenon is explained demonstrating the numerical and experimental studies in literature. Secondly, the control techniques which are developed to control various types of flows as well as cavity flow are presented with examples from the studies in literature. Additionally, the feasibility of laser energy deposition which was shown to be effective for the control of other types of flows is also examined.

2. CAVITY FLOW
In this section, cavity flow mechanism is presented with some key studies from literature. Firstly, the cavity flow mechanism is explained by giving a common approach to understand the problem. Then, numerical and experimental studies are given to introduce the problem for further control approaches.

2.1. Cavity Flow Mechanism
As cavity flow phenomenon includes complex flow fields, it is described in several studies by classification depending on many parameters such as geometric properties, flow regimes and Mach number to explain this mechanism more clearly. Several classification methods are summarized by Syed [2]. The cavity flow mechanism is described based on geometrical properties of the cavity as cavity with L/D<1 is termed as deep cavity, otherwise it is called shallow cavity (L/D>1). In the

shallow cavities, a stronger flow field is seen when the flow is compared with deep cavity flow. The number of recirculation zones in the cavity, depends on the L/D ratio. In deep cavities, a maximum of two recirculation zones are observed [2]. Tracy et al. [3] studied the effect of cavity width and cavity depth on the flow mechanism. In another study performed by Block [4], two dimensional acoustic field in the cavity was computationally obtained when L/W ratio was smaller than 1, L/W>1 flow patterns were shown to be more complex with three dimensional effects.

With the help of the analysis of the flow pattern and floor pressure distributions, experimentally, three main flow regimes are observed; open, closed and transitional flows. In the study of Dover et al. [5], the cavity flow phenomenon was described as closed, open and transitional flow regimes, as well. Closed cavity flow is seen in cavities with L/D ratio greater than 13 at supersonic speeds. The characteristic property of this flow type is flow impingement phenomenon on the cavity floor. In closed cavity flow, shear layer which is coming with free stream separates at the cavity leading edge and as it does not have enough energy to pass cavity, shear layer impinges on the cavity floor and detaches again at the downstream of the cavity and pass over the rear wall with a stagnation point at the trailing edge [5, 6]. The shear layer creates two flow field regions, termed as free stream flow and cavity inner region flow. At supersonic speeds, with the impingement and separation of the flow; shocks appear and Mach number effects are observed strongly in the flow as explained in the studies of Dover et al. and Garner et al. [5, 6].

Open cavity flow characteristics are observed in deep cavities with an L/D ratio smaller than 10 at supersonic speeds. In open cavity flow, shear layer which is developed with the help of the free stream, separates at the cavity leading edge and reattaches at the cavity trailing edge. Shear layer separates the cavity flow and free stream is separated into two different flow regions. Due to the pressure difference between the cavity leading and trailing edges, recirculation zones are formed. The number of recirculation zones depends on the L/D ratio. At supersonic speeds, in order to adapt the shear layer to the free stream conditions, oblique shocks occur. [2, 5, 6, 7]. In the range of $10 < L/D < 13$, transitional flow takes place. If the L/D ratio is decreased from that of the closed cavity slowly, impingement and exit shocks come together and produce a single shock at supersonic speeds. This flow is termed as transitional closed flow. With the decrease of the L/D ratio further, the flow pattern exhibits open cavity characteristics.

The flow pattern is strongly influenced by Mach number as summarized by Syed and Dover et al. [2, 5]. One of the objectives of the research performed by Tracy et al. [3] is to investigate the flow field type by considering the pressure distribution for cavities over the range of subsonic and transonic speeds. Experiments were performed for four different configurations with different W/D ratios and different Mach numbers. As a result of this study, it was concluded that, cavity flow depends not only on the L/D ratio but also on Mach number and cavity width. Open/transitional flow boundary is seen for L/D = 7 and the flow type change is nearly independent from Mach number and width of the cavity. Transitional/closed boundary ratio increases with increasing Mach number and cavity width as explained in detail by Tracy et al. [3].

2.1.1. Numerical and Experimental Studies on Cavity Flow

Researchers, both experimentally and numerically studied rectangular cavity flow to understand the exact cavity flow mechanism in different conditions for further approach for the control of the flow. Experimental studies are based on wind tunnel and flight tests. Numerical studies are based on Computational Fluid Dynamics (CFD) simulations which started in the twentieth century. With today's technology, numerical studies can validate the experiments or vice versa. The general control approaches in cavity flow are about the suppression of the cavity pressure oscillations and decreasing the sound pressure levels and while doing these, examining the shear layer interactions and vortex formations which are underlying reasons for the requirement of control. Results of both experimental and numerical studies in literature are generally shown in terms of sound pressure levels and static pressure distributions at the cavity walls. In addition to this, velocity, pressure contours and Schlieren images are used to understand the flow characteristics. An important part of the studies are performed for military aircraft at supersonic speeds.

2.1.1.1. Experimental studies

The pioneer of the cavity studies, Rossiter [8–11], performed experimental tests on weapon bay geometries. According to these tests, Rossiter analyzed cavity flow in four main steps. Firstly, vortices form at the cavity leading edge and proceed to cavity rear wall. At the second stage, vortices, which are formed at the leading edge of the cavity hit the trailing edge and produce acoustic waves. In the third step, these acoustic waves are divided into two parts as acoustic field and pressure waves. Finally, pressure waves, which are spread into the cavity, move towards the cavity leading edge and hit the front wall, after which pressure waves induce the formation of vortices. A feedback mechanism is created by acoustic waves and vortices [2, 5, 6].

In 1964, a semi-empirical formula was derived by Rossiter [8–11] for predicting the resonant frequencies of the cavity oscillations [12]. His formulation predicts the oscillation frequencies for subsonic and transonic flows with the formulation given below.

$$f_m = \frac{u_\infty}{L} = \left[\frac{m - \alpha}{M_\infty + \frac{1}{K}} \right] \tag{1}$$

Heller and Bliss [13], modified Rossiter's formulation and their modified formulation can be used in subsonic, transonic and supersonic flows.

$$St = \frac{fU_\infty}{L} = \left[\frac{m - \alpha}{M_\infty \left(1 + \left[(\gamma - 1)/2\right] M_\infty^2\right)^{-1/2} + 1/K} \right] \tag{2}$$

In equations 1 and 2, K and α are experimental constants, m is the mode of oscillation. K changes with Mach number and α is related to cavity geometry. U_∞ is the free stream velocity, M_∞ is the free stream Mach number, St is the Strouhal number. Rossiter modes are determined with modified Rossiter formulation; however there is no analytical formulation to determine oscillating pressure amplitudes [2, 13].

According to Perng [14], incoming boundary layer which flows over a cavity, causes an unstable streamline and unsteady pressure difference between high speed free stream flow and vortex flow structure in the cavity. This unsteady pressure difference induces vortex shedding in the cavity [13]. Unsteadiness of the streamline and the interaction between cavity trailing edge and the streamline is responsible for cavity flow oscillations. At the cavity leading edge, as cavity pressure is lower than the incoming free stream flow, the streamline becomes unstable and deflected down letting mass and momentum inside the cavity. Dissipative process slows down the ingested mass and cavity pressure increases. With the higher pressure values inside the cavity than free stream pressure values, the streamline is deflected out of the cavity and mass is thrown away from the cavity.

Unalmis et al. [15] measured fluctuating pressure values for a Mach number of 5 with cavity length to depth ratios of 3, 4, 5, 6 and 7. According to their results, shock frequencies and impingement of shocks are not affected from the varying depth. According to researchers, shear layer shock is induced by shear layer wall interactions [15].

Bueno et al. [16] investigated Mach 2 cavity flow with different L/D ratios. They measured the pressure at different locations on the cavity floor to determine resonance modes and their local effects.

Stallings [17] conducted an experimental investigation to determine aerodynamic characteristics of a supersonic cavity for varying depths. According to his results, increase of the cavity depth has an important effect on pressure distribution. For shallow cavities flow, separates at the front face and reattaches downstream on the cavity ceiling. Second separation occurs in the cavity ceiling. For deep cavity, shear layer bridges the cavity and impinges on the rear face [17].

Chung [18] and Heller et al. [19] found out in their experimental study that pressure fluctuations were larger in the cavity trailing edge because of the interaction of the shear layer and the wall.

Disimile and Toy [20] investigated the effect of cavity length on flow oscillations using an open subsonic cavity. According to their results, mode switching occurs with increasing cavity length and Strouhal number is a function of cavity length and depth. They suggest that resonant frequencies are dependent on the cavity length not depth.

Zhuang et al. [21] worked at a supersonic wind tunnel that has a Mach number of 2 to investigate the effect of cavity depth. Different L/D and L/W values lead to different wave propagations and different patterns in the cavity. For L/D = 3.1 and 5.1 cavities, large recirculation zones and reverse flow are observed. Microjet control method reduces the overall sound pressure levels up to 13 dB.

The flow in rectangular cavities was investigated experimentally in the study of Haigermoser et al [22]. The ratio of cavity length to incoming momentum layer thickness (L/θ) is related to pressure oscillations in the cavity. If $L/\theta > 80$, oscillations exist in the cavity. With the decrease of L/θ, oscillations also decrease. Therefore, cavity flow is significantly affected from turbulent boundary layer structure. In the case of the thick boundary layer due to the low L/θ ratio, no self-sustained oscillations were observed in their study [22].

2.1.1.2. Numerical studies

Numerous numerical research studies were performed on cavity flow in order to understand the flow physics. The most common approaches to simulate the turbulent flows using Navier-Stokes equations are; Direct Numerical Simulations (DNS), Reynolds Averaged Navier-Stokes equations (RANS), Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) [23]. As in the experimental studies, some key numerical studies are given to examine the parameters used in the control applications.

Shieh and Morris [24] used URANS Spalart-Allmaras turbulence model on their two dimensional (2D) and three dimensional (3D) simulations. 2D and 3D cavity flow characteristics are very different from each other. In 3D, weaker vortical structures are observed in cavity region and flow is less violent in the cavity in 3D simulations. Reasonable agreement is seen between the 3D simulation and experimental data by Plentovich [25].

Shih et al. [26] used k-ε turbulence model at a Mach number of 1.5 in an open cavity. Their important finding is that shear layer instabilities are related to the mass that goes in and out of the cavity. The periodic shedding of vortices from the leading edge and the shear layer deflection is observed. They validated their numerical results with Kaufman et al.'s [27] experimental results.

Ashcroft and Zhang [28] solved compressible Navier-Stokes equations, with k-ω turbulence model. The cavity flow investigated corresponds to the experimental work done by Ahuja and Mendoza [29]. In the simulations, sound pressure levels observed are nearly 5 dB more than experimental values.

Ayli et al. [30] used two dimensional compressible time dependent Reynolds Averaged Navier-Stokes equations with k-ω turbulence model to investigate the effect of cavity length to depth ratio. According to their results, a single mode occurs for L/D = 1 cavity while other cavities have multiple modes and within the limits of the open cavity, the increase of the cavity length induces the shear layer deflection which is associated with the vortex production in the cavity.

Aradag et al. [31] used RANS equations to investigate the effects of different numerical flux schemes, effect of computation time for convergence and the effect of flux limiter on the computed flow. According to results, Roe and AUSM schemes have better results than Van Leer Scheme.

Rizetta and Visbal [32] used LES to compute cavity flow with a Mach number of 1.19 and L/D ratio of 5. At the cavity leading edge, large scale vortices are seen and those structures are transferred to trailing edge.

Basu et al. [33] used DES for a cavity with a Mach number of 0.128. DES model successfully captured the flow features which are observed in Driver et al.'s [34] experiment. Barakos et al. [7] performed simulations with DES for Mach and Reynolds numbers of 0.85 and one million respectively. With this model, frequencies of Rossiter modes are predicted correctly. SPL values obtained from simulations are higher than that of experimental SPL measurements.

Bres and Colonius [35] used DNS method to resolve the three dimensional open cavity flow. Hamed et al. [36] used DNS for a Mach number of 0.9 and 1.1. According to their results increase of Mach number increases pressure fluctuations. They predict first mode frequency value with % 6 deviation from Rossiter frequency value.

3. FLOW CONTROL

Over past decades, many problems arose in flow applications. To overcome such problems, several researchers studied on flow control. As a result, various control techniques were developed. These flow techniques can be separated in two main groups; one is passive and other is active flow control techniques.

3.1. Passive Control Techniques

The passive control techniques are mainly applied by making permanent changes on the flow. Changing the geometry of the flow or placing barriers in the flow are methods of passive techniques to modify the flow. These techniques are not expensive and can be applied to flow by using a variety of mechanisms such as; mixers, vortex generators or sloped surfaces in geometry.

There are many passive technique application examples in cavity flows which were reviewed in the study of Colonius [37] such as; placing a vortex generator to separation point, making changes on cavity geometry, setting some rods above the cavity or putting a surface to the separation point which reduces lifting force. Even if such techniques are successful for cavities, they may change the flow physics and can result in unexpected effects. Control systems need to be developed with the exact understanding of the cavity flow mechanism [38, 39]. There are many studies about using passive techniques to control the cavity flow oscillations.

Lai and Luo [38] performed computational fluid dynamics simulations with control by using Large Eddy Simulation (LES) as a numerical approach. By using porous wall, the flow developed in the cavity was forced to be let in and out from the walls. This event occurred depending on the local pressure differences between the porous wall and the cavity region. In addition, the unstable flow approached to a stable state, the intensity of the vortex was reduced and the absorption of noise was observed. When cavity base was replaced with a porous structure, sound pressure levels were reduced. The porous side walls were observed to be the most efficient way of damping noise. The porous structure reduces collisions and damps deflections of the flow. As the pressure oscillations were examined, it was observed that the amplitude of pressure was reduced due to the porous structure [38].

In the study of Unalmis et al. [40], the purpose was to investigate the interaction between shear layer dynamics and cavity acoustics at different Mach numbers, experimentally. The measurements were made for fluctuating surface pressure for a free stream Mach number of 2 and 5. The SPL results at Mach number of 2 were 15 dB less than that of Mach number of 5. Then, the interaction between acoustics and the shear layer was investigated by testing the cavity with and without a plate covering over 80% of the cavity. To achieve the goal of this study, the cover plate was placed to separate the cavity from the shear layer. The L/D ratio is 6 and the W/D ratio is 3. In addition, the boundary layer thickness is 1.93 cm for a Mach number of 5 and for a Mach number of 2 the thickness is 1.3 cm. For the Mach number of 2, the uncovered-cavity resonance frequency results agreed well with Rossiter's formula. However, for the covered cavity model, results were not coherent with Rossiter's formula but with closed-box acoustics. The result of the study of uncovered and covered-cavity for the Mach number of 5 agreed well with each other and also with Rossiter's model and the closed-box model. In conclusion, the interaction between cavity acoustics and the shear layer was less at high Mach numbers.

Perng and Dolling [41] studied cavity flow experimentally at a free stream Mach number of 5. The aim of the study was to change the cavity geometry to understand whether it affects the pressure fluctuations or not. In conclusion, even the strongest oscillation modes were reduced by placing a barrier at the cavity base.

In the study of Sarpotdar et al. [42], a rod in cross flow which is a flow control technique used for suppressing cavity tones was investigated. They worked on the potential of the cylinder on changing the stability characteristics of the shear layer. The cavity with L/D ratio of 2 and with Mach number changing between 0.5 and 0.8 was taken. The location of actuator is obtained as a important parameter on suppression of the cavity tones. The cylinder location in the freestream was optimized for suppressing performance. Results show that, as the freestream Mach number increases, the performance of the cylinder to decrease the cavity tones decreases. Locating the cylinder upstream, decreases the efficiency in suppressing the cavity tones. Similar to this study, Panickar and Raman [43] also used linear stability theory to evaluate the cavity flow control and design flow control systems.

3.2. Active Control Techniques

Active control techniques can change and adapt to different flow conditions [44]. Therefore, these techniques are more advantageous than passive ones. They are also important as they include small control mechanisms which are vital specifications for local control problems. These techniques are mainly applied by providing the system an external energy. Several methods are applied such as mass injection, mechanical excitation, acoustic driving and microjets [12]. The disadvantage of these techniques is that they are more expensive than passive techniques. Many researchers studied active control techniques as a flow control method for cavities.

In the study of Bueno et al. [16], the effects of mass injection method on mean pressure levels and pressure fluctuations of cavity flow at a Mach number of 2 were investigated. The process was accomplished with high frequency pulsed jets located just upstream of the cavity leading edge. The effects of continuous and pulsed injections were also examined for short and long cavities. Throughout the study, as a result of the continuous mass injection, the mean pressure on the cavity floor is reduced approximately 8% in dB except for the cavity with L/D ratio of 5. The results are also shown to be dependent on pulse duration and cavity configuration. For longer cavity configurations, continuous mass injection seemed to be effective. The most probable reason for this was that the discontinuities resulted from mass injection had more time to effect the flow for longer cavities. The overall conclusion was that the continuous mass injection was more effective than pulsed injection on reducing the acoustics modes and sound levels.

Rizzetta and Visbal [32] also examined supersonic cavity flow. The free stream Mach number is 1.19 and L/D ratio is 5. The cavity flow was analyzed with and without high frequency mass injection. The acoustic modes were damped as a result of the mass injection on the shear layer.

In the study of Hamed et al. [45], 3D transonic open cavity flow was numerically analyzed. Mass was injected to the cavity from leading edge to control the flow. A hybrid two-equation turbulence model is used with Detached Eddy Simulations (DES) to simulate the flow and acoustic fields. The study was performed with the following conditions; L/D is 5 and W/D is 0.5, Reynolds number is 0.6×10^6 and Mach number is 1.19. Different amounts of mass injection were used. Results of the sound pressure levels were compared with the experimental results of Ross et al. [46]. According to the simulation results, 500 and 1000 Hz were observed to be the dominant modes as in the experimental study. The computed sound pressure levels were 5 dB less than the experimental ones. The root mean square of the pressure values were reduced by 7.5% for an injection ratio of 0.6 and 10% for an injection ratio of 0.9. In addition, in peak amplitude values, an 8 dB reduction was predicted for an injection ratio of 0.6 and a 12 dB reduction was predicted for an injection ratio of 0.9.

In the study of Raman et al. [47], miniature fluidic devices were used to suppress the cavity resonance. The cavity has L/D ratio of 6. For measurements, spark schlieren system was used to visualize the flow. Pressure sensitive paint (PSP) was used to map the steady pressure values onto the cavity region. The fluidic devices had no moving parts and could provide oscillatory flow at frequencies up to 3 KHz. The flow-induced resonance produced by a jet flowing over cavity. When it was located at the upstream end of the cavity floor, the cavity tones were suppressed approximately 10 dB by the miniature fluidic devices. Similar mass flow rates of oscillatory flow near the downstream end of the cavity floor showed no effect on the cavity resonance. To investigate the effects of different conditions, mass flow addition was performed at the same levels as those for fluidic excitation. This experiment resulted with a small reduction in cavity tones as 1 dB. Also, acoustic excitation at the same frequency as performed by fluidic device and at meaningful amplitudes showed no effect on cavity tones.

Schmit et al. [48], compared the high and low frequency actuators in flow control. They researched the effectiveness of zero-low and high-frequency flow control methods applied to cavity.

Microjet is also an advantageous method for flow control especially for the cavity flow. Small dimensions, capability of producing high momentum flux with very small mass flux and their efficiency in controlling the cavity flow can be listed as advantages of microjets [49]. Zhuang et al. [49] studied supersonic microjet control devices. Flow in the cavity with the following conditions; Mach number of 2 and L/D ratio of 5.19 was controlled by microjets which were located at the beginning of the cavity. With the activation of microjets, a 20 dB reduction in cavity tones and a 9 dB reduction in overall sound pressure levels were observed. The instability in the cavity was also reduced by flow control.

Zhuang et al. [21], studied cavity flow control for four different L/D ratios which are 1, 2, 3 and 5. The effects of L/D ratio and microjets were investigated. The resonance of the flow was induced with the activation of the microjets. The overall sound pressure levels and cavity tones were also reduced. The required mass flux of the microjets changed with the L/D ratios. Also, with small mass fluxes, a reduction of 5 to 11dB in the sound pressure levels and a reduction of 13 to 28 dB on the cavity tones were obtained.

Even they are not directly about the cavity flow control, the studies performed by Alvi et al. [50] about the design of supersonic jets with the specifications of short take off and vertical landing and Choi et al. [51] about the two active control strategies to control harmful flow tones, can be examined due to their results including reduction in the sound pressure levels which is one the aims of flow control for cavity flow.

In practice, efficiency of mechanical apparatus which are used in the active techniques is an important topic and there are disadvantages of them related to control. The installation difficulties, the problems with reliability of systems and hesitations about the efficiency in the icing conditions are such problems that make researchers intend to study different control techniques [52].

There are flow control techniques which include energy deposition to the flow. The energy deposition is provided by energy sources such as; plasma arcs, microwaves and laser. The advantages of these techniques are as follows; they can be controlled electronically, they can adapt to different conditions rapidly and the rapid response which is the basics of real-time control can be obtained [53].

In literature, many studies have been performed to show the effect of the energy deposition on several flows. Knight [54] researched on energy deposition as a control method for aerodynamic flows. In the first part of his study, physical effects of the energy deposition to the ideal gas were investigated. The second part was divided into three main captions; aerodynamic flow control, modifications in the shock structure and magnetohydrodynamics (MHD) control. For 1D flow, while $M > 1$, the changes on physical variables are given Table 1.

The modeling of energy deposition for 1D and 2D flow for different conditions was studied in many studies. Knight [54] defined energy deposition ratio as in the following equation;

$$\varepsilon = \frac{M_\infty^2 q_0 L}{\rho_\infty u_\infty^3} \tag{3}$$

For 2D energy sources, Belokon et al. [55] defined;

$$q = Q_0 \exp\left[-\frac{x^2 + z^2}{r_0^2}\right] \quad \text{for} \quad x^2 + z^2 \geq 0 \tag{4}$$

For 3D energy sources, Krasnobaev and Syunyaev [56] defined;

$$q = \frac{U_\infty^3 r_0}{(x^2 + y^2 + z^2)} \quad \text{for} \quad x^2 + y^2 + z^2 \geq 0 \tag{5}$$

Terent'eva [57] expanded the 3D linearized supersonic solution. Terent'eva modified the solution for infinite dimensional cylindrical energy source and defined the energy deposition parameter as;

$$q = \begin{cases} Q_0 & 0 \leq z \leq 1 \qquad x^2 + y^2 \leq r_0^2 \\ 0 & \qquad\qquad \text{other situations} \end{cases} \tag{6}$$

The aerodynamic flow control includes; control of drag, lift and interactions of moment. Researchers studied control of drag, quite often. Georgievskii and Levin [58] investigated the continuous energy deposition to the body with conditions of supersonic flow and zero angle of attack. In another study, Levin and Terent'eva [59] worked on the continuous energy deposition to a cone with conditions of supersonic flow and zero angle of attack. Yuriev et al. [60] investigated the effects of continuous energy deposition near a NACA 0012 airfoil at the range of $0.8 \leq M_\infty \leq 0.9$. As a result of the Euler simulations used in this study, drag was reduced by 25%. In aerodynamics, research is still going on for different geometries and flow types.

Effects of the energy deposition on shock profile were investigated in several studies. These studies can be grouped according to the region where energy is deposited, the effects of energy on shock waves and experimental methods to provide energy deposition. The study of Golyatin et al. [61] can be given as an example for this type of studies.

Table 1. 1D energy deposition (M > 1) [54]

Specification	Behavior	Specification	Behavior
M	↓	P	↑
u	↓	T	↑
ρu^2	↓	ρ	↑

MHD control forms an additional force unlike other energy deposition methods. This provides an advantage compared to the energy deposition methods. MHD control has been investigated since the 1950s. Pogie and Gaitonde [62] presented a study about the effects of this method on drag.

Miles [53] worked on the control of flow using energy deposition with different energy sources. The purpose of the study is to control the flow around aircrafts to increase the performance of them. Three different concepts are used. The first one is energy deposition with microwave under the control of laser and electron beam. The second is energy deposition with electron beam and the last one is an acoustic energy deposition in proportion with megahertz level frequencies. The aim of energy deposition with microwave to the front section of the aircraft is to reduce the drag and increase the maneuvering capability. The purpose of energy deposition with electron beam is to create transmission in high speed air effectively for MHD power addition and power removal applications.

Knight et al. [63] created a gas dynamics model for microwave energy deposition in air using 23 species and 238 reactions. The model is applied to a cylinder for supersonic flow with a Mach number of 2. The interaction between the plasma formed because of the microwave and blunt object shock formed because of the cylinder is investigated. Figure 1 shows the flow configuration.

As a result of the interaction between the plasma formed due to the microwave and blunt object shock formed because of the cylinder, an instant toroidal vortex and a reduction in the stagnation pressure value at the central axis of the cylinder are observed [63].

Use of plasma actuators is another control method with energy deposition. Samimy et al. [64] used plasma actuators to control jet at a Mach number of 0.9 and a Reynolds number of 7.6×10^5 at the exit of a nozzle. Eight actuators were located inside and at the exit of the nozzle. They studied for different plane modes for a wide range of Strouhal numbers. Results are obtained when the jet axis is at 30 and 90 degrees. For a Strouhal number between 0.2–0.5, a 2–4 dB reduction in sound levels is obtained. For a higher Strouhal number range, a 0.6–1 dB reduction is observed. The highest reduction is obtained when the Strouhal number is between 1.5–2 and the jet axis is at 30 degrees, and when the jet axis is at 90 degrees and the Strouhal number is between 3-3.5. In another study of Samimy et al. [65], the use of plasma actuators in high speed jets was also examined.

Flow control systems with energy deposition are used efficiently both to explore the flow structure and to control the flow. The researchers are still going on research on this subject due to the insufficiency of the results obtained up to now. One of the active flow control techniques is laser energy deposition which also has advantages against passive ones. It can be adapted to different flow conditions and it can be applied by using movable devices. Also including small devices, it can be used for local control problem as in study of Adelgren [66]. It can provide a real time control approach which means faster control process. Installations and maintenance problems are less than other active control technique such as mass injection, microjets. This is a new and promising flow control technique and the next section is devoted to this subject.

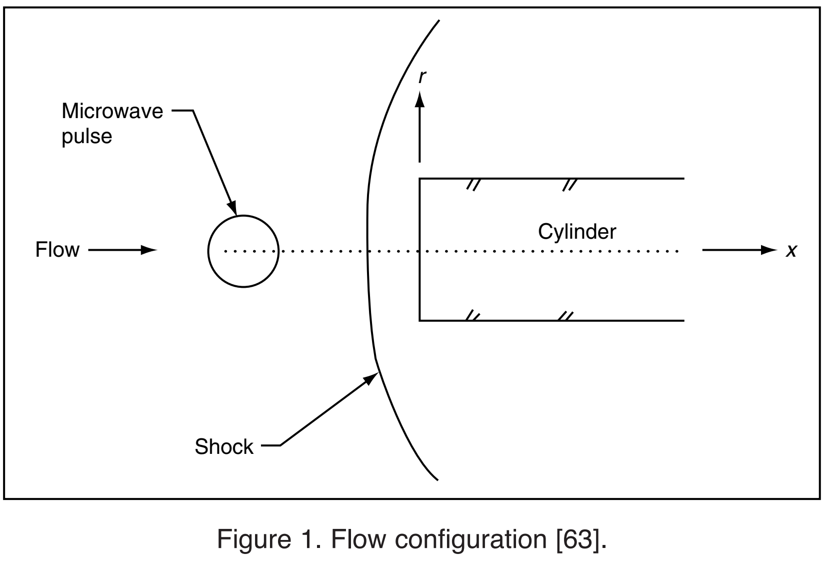

Figure 1. Flow configuration [63].

3.3. Flow Control with Laser Energy Deposition

Since the discovery of the laser induced spark in 1963, laser beam has been used as an energy deposition method [67]. With an improvement in the understanding of flow mechanisms, several research studies have been performed on laser energy deposition.

Ghosh and Manesh [68] investigated the impact of laser energy deposition on stagnant air. For the simulations, Navier-Stokes equations are solved. Three different models are created. In Model-1, chemical reactions are ignored and flow properties are assumed as constant. In Model-2, it is assumed that the properties change only with the temperature. In Model-3, it is assumed that properties change both with temperature and pressure. In Model-1, a small development due to weak pressure gradients is obtained. Unlike Model-1, flow field developed faster in Model-2 and two different expansion areas exist. The results of Model-3 are between Model-1 and Model-2. The effects of laser energy deposition and Reynolds number are examined. Elevations, which are in front of the shock, are changed depending on the deposited amount of laser energy. In contrast, formation of the shock waves and reverse flow are the same for different amounts of energy. At very low Reynolds numbers, plasma core has no important role [68].

In the study of Glumac and Elliott [69], the effects of ambient pressure, which changes between 0.1–1 atm, on temperature profile, electron intensity and the absorbed laser energy ratio in plasma region which occur in laser induced air are investigated.

The results of the study [69] can be listed as;

- When the amount of the given laser energy is constant, the amount of absorbed energy changes with pressure. The absorption of laser energy is reduced more than the increase in pressure.
- As pressure decreases, radius of the spark and the maximum absorption intensity decrease; but the temperature profile is almost constant.
- As pressure values decrease, the disruption density in the laser spark is faster than that in atmospheric pressure.

Schüelin et al. [70] studied laser energy deposition as a flow control technique. The impact of laser energy deposition on the shock wave transformation is investigated numerically and experimentally. Distance between energy outlet and energy applied region, different amounts of energy and delay time between each energy pulse are examined. The density gradients as a result of single pulsed energy deposition are given in Figure 2.

Changes in the distance affected combination of blast wave and hot region. As the amount of energy is increased, the interactions between the structures in the flow increase. At different energy values, observed pressure changes in the flow are given in Figure 3.

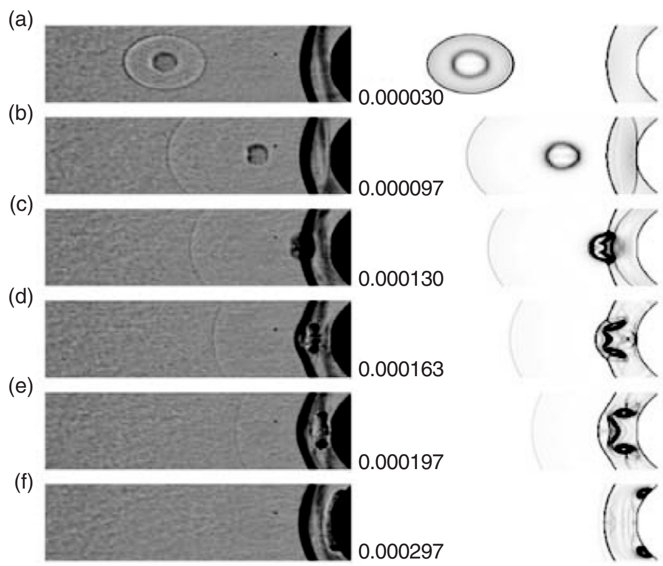

Figure 2. Shadowgraph images of flow obtained from experiments (left) and calculated density gradients (right) for single pulsed energy deposition of 333 mJ [70].

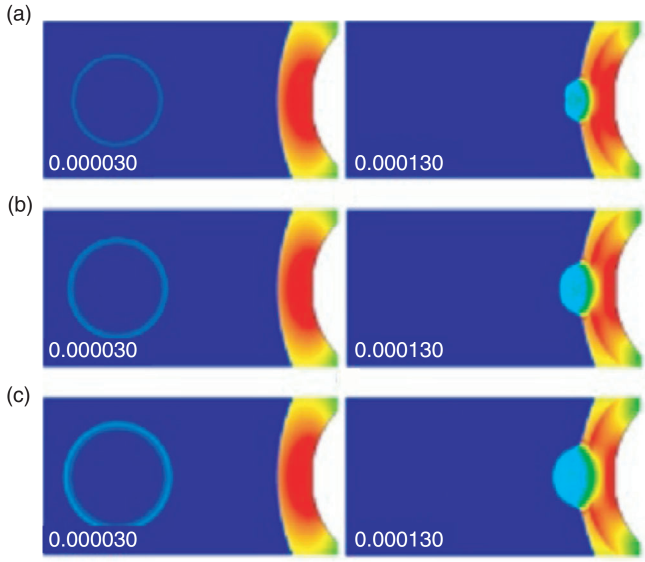

Figure 3. (a) 151 mJ, (b) 333 mJ, and (c) 666 mJ [70].

As seen from Figure 3, with an increase in the amount of energy, the interactions obviously increase. However, the delay time between laser energy pulses did not affect the interactions very much.

Zaidi et al. [71] examined the impacts of energy deposition on shock waves in supersonic flow by using a small wind tunnel. The interaction between laser and flow model at a Mach number of 2.4 is simulated. Specifications of the laser pulses are 350 mJ of energy per pulse and 10 ns pulse width. Dynamic interaction is observed with Schlieren and shadowgraph methods and images are obtained by taking 500,000 snapshots in one second. The interaction between a shock wave and energy pulse which is related to a hot region and an oblique shock with energy pulse is examined computationally. By using the results of the interaction between the hot region and the model shock obtained from a small scale wind turbine, a numerical model is validated for which the energy deposition for practical applications can be optimized.

The study by Adelgren et al. [72] is on the examination of two standard supersonic flows with laser energy deposition: a sonic transverse injected wall jet and shock waves in a dual domain interactive space in a supersonic turbulent boundary layer. The purpose is to obtain useful changes on the flow properties with laser energy deposition for both cases. Transverse injected wall jets are used in many applications for supersonic boundary layers. The use of transverse injected wall jets is important for aerospace applications, especially for thrust vector control and fuel injection for supersonic combustion. This study is carried out under the conditions summarized in Table 2.

In the experiment, shock interaction separated with a laser applied region resulted in the movement of shock waves. This movement is similar to the result of laser pulse that appears on a sphere in a supersonic flow and blunt object shock interaction [73]. It is observed that shock separated from the interaction between the laser applied region and the complex shock interaction structure moves upward and the separation area gets larger. This contributes to the reduction of Mach number at the region of laser application.

The control of transitions from regular reflection to Mach reflection for intersecting shocks is also important. In the study of Adelgren et al. [72], the effect of laser pulse on the transition from regular to Mach reflection is observed. Test conditions are given in Table 3 and the parameters used are shown in Table 4.

Table 2. Test conditions in study of Adelgren et al. [72]

Property	**Tunnel**	**Jet**
M_∞	3.45	1.0
$p_{t\infty}$(MPa)	1.06	1.03
$T_{t\infty}$(K)	293	293

Table 3. Test conditions [72]

Property	**Tunnel**
M_∞	3.45
$p_{t\infty}$(MPa)	1.06 MPa
$T_{t\infty}$(K)	293

Table 4. Model parameters for colliding shocks [72].

No	**θ(degree)**	**α**	**x**	**w (mm)**	**b (mm)**
1	21	36	0.16	25.4	55.8
2	22	37.2	0.47	25.4	55.8

where:

θ: Edge angle
α: Shock angle
x : $\left(\frac{\alpha - \alpha_N}{\alpha_D - \alpha_N}\right)$
w: Shock generator length,
b: depth

Nd: YAG laser (wavelength = 532 nm) is applied with an energy of 317 mJ. Firstly, symmetric laser pulse is applied. A vortex formation is observed due to the interaction between the laser applied region and intersecting shocks. Asymmetric laser pulse is also applied. It is observed that, because of the interaction between the hot section formed as a result of laser and the Mach stem, the Mach stem moved towards the region with higher temperature. This result is similar to the interaction given at the study of Adelgren et al. [73]. When asymmetric laser is applied in this case, there is a 20% instant fall at Mach stem height and the height reaches its previous value.

In the study of Yan et al. [74], the effect of the laser energy deposition on quiescent air and intersecting shocks is investigated experimentally and numerically. In the first part of the study, the purpose is to understand the effects of single-pulsed laser on quiescent air. The aim of the second part is to apply asymmetric pulsed laser to intersecting shocks at a Mach number of 3.45 to realize the capacity of laser energy deposition on reduction of Mach stem height. The second part is studied experimentally. The supersonic wind tunnel at Rutgers University Gas Dynamics and Laser Diagnostics Laboratory is used. The effect in quiescent air has a formation of an age drop. After a suitable amount of time, this formation turns to a spherical form. This formation triggered the idea of occurrence of spherically symmetric temperature profile which depends on laser energy deposition with constant volume.

The gas is accepted as an ideal gas and Gaussian temperature profile is assumed as in Eq. 7 [74].

$$\Delta T = \Delta T_0 \times e^{\frac{-r^2}{r_0^2}} \tag{7}$$

ΔT_0 can be calculated by using an overall energy. The overall energy is defined as in Eq. 8 [74];

$$E = \int_0^{2\pi}\int_0^{\pi}\int_0^{\infty} r^2 sin\theta \rho_\infty c_v \Delta T dr d\theta d\varnothing \tag{8}$$

c_v is specific heat at constant volume. By substituting Eq. 7 into Eq. 8 and integrating Eq. 9 [74] is obtained;

$$\Delta T_0 = \frac{E}{\pi^{\frac{3}{2}} r_0^3 \rho_\infty c_v} \tag{9}$$

The results agree well with the experimental results of Adelgren et al. [73]. As a result, the Gaussian temperature profile is found to be appropriate to model single laser energy pulse.

Lazar et al. [12] studied energy deposition to control cavity flow experimentally. Q-Switched Nd:YAG laser is applied at the cavity leading edge. The Mach number is 1.4 and L/D ratio is 5.29. Laser beams are sent to the cavity from the leading edge as in the study of Aradag et al. [75] and changes in the shear layer are examined experimentally. The aim of the study is to understand the capacity of energy deposition to form huge scale structures in the shear layer to improve air-fuel mixture in scramjet motors. With Schlieren imaging and two-component measurements, a desired huge scaled structure is obtained in the shear layer with laser energy deposition.

Aradag et al. [75] studied laser energy deposition to control cavity flow oscillations, numerically. The effects of laser energy deposition are investigated by examining supersonic cavity flow having a Mach number of 1.5 and an open cavity configuration with L/D ratio of 5.07, with and without laser energy deposition. The laser energy deposition model which is defined in Yan et al. [74] is used. The first energy given is 1 mJ and dimensionless energy value is 4. The first laser is applied to the cavity after 12 Rossiter periods, corresponding to 10,000 time steps. At the beginning of each Rossiter period, same amount of laser energy is applied to the same location inside the cavity. The distribution of sound pressure levels on cavity floor with and without laser is given in Figure 4.

The distribution of sound pressure levels on upstream face of the cavity with and without laser is given in Figure 5.

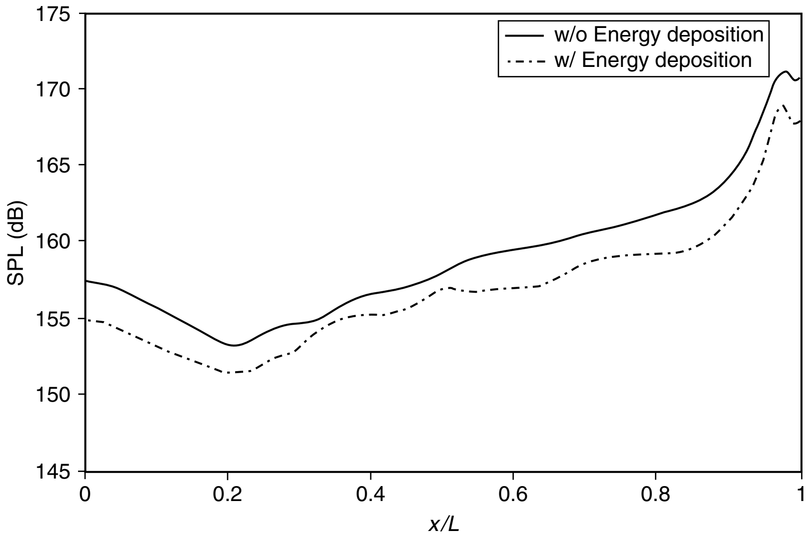

Figure 4. Pressure distribution on cavity floor before and after energy deposition [75].

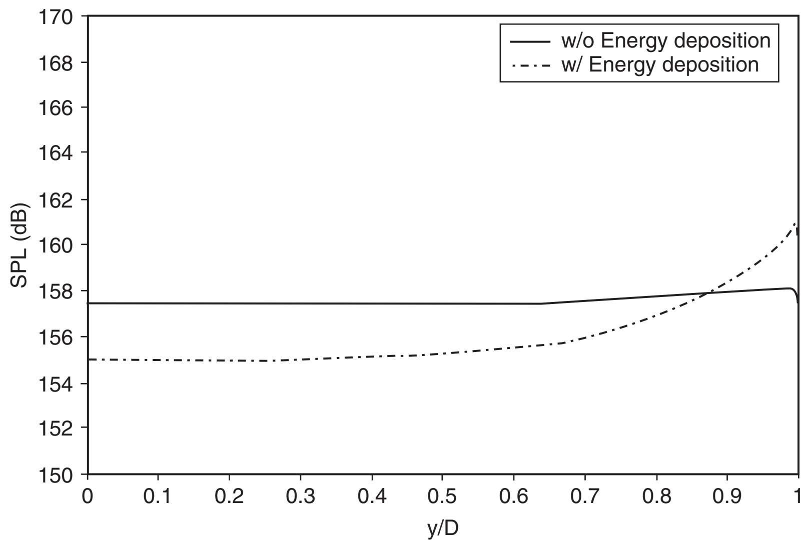

Figure 5. Pressure distribution on upstream face of the cavity before and after energy deposition [75].

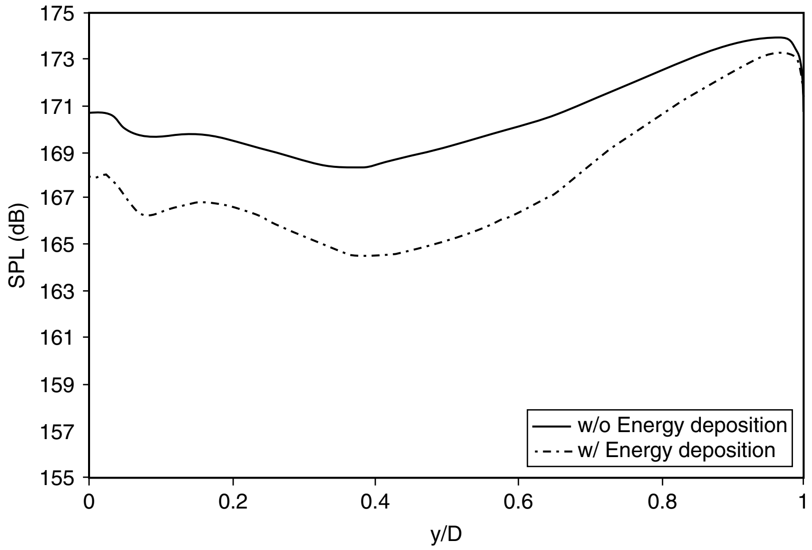

Figure 6. Pressure distribution on downstream face of the cavity before and after energy deposition [75].

Sound pressure level distribution on downstream face of the cavity with and without laser is given in Figure 6.

After laser energy deposition, the pressure values at cavity leading edge, cavity trailing edge and cavity floor decreased. Relatively to the reduction in the pressure values, as it seen in Figure 4, 5 and 6 the sound pressure values also decreased. Figure 5 shows that, there is only one location at which SPL values are not decreased. Due to being at the location that around the y/D ratio is 1 where laser pulse is given, increase in pressure values at this location is meaningful. The general conclusion of this study is, laser energy deposition may provide suppression on pressure fluctuations [75].

Yilmaz et al. [76] performed preliminary study of laser energy deposition to the supersonic cavity flow configuration that is studied by Ayli et al [30], with; an L/D ratio of 5.07 and a Mach number of 1.5. The Reynolds-averaged compressible time dependent Navier Stokes equations in two dimensions are solved. The k-w model is used as a turbulence model. The application of the laser energy deposition is modeled by using the Gaussian temperature profile assuming the density within the spot is initially uniform [74]. Laser energy is deposited to the cavity from the upstream of the cavity leading edge. After 12 Rossiter periods, flow becomes periodic and then laser energy is deposited to the flow at the beginning of each Rossiter periods along the six periods. The sound pressure level distribution on the downstream face of cavity is given in Figure 7.

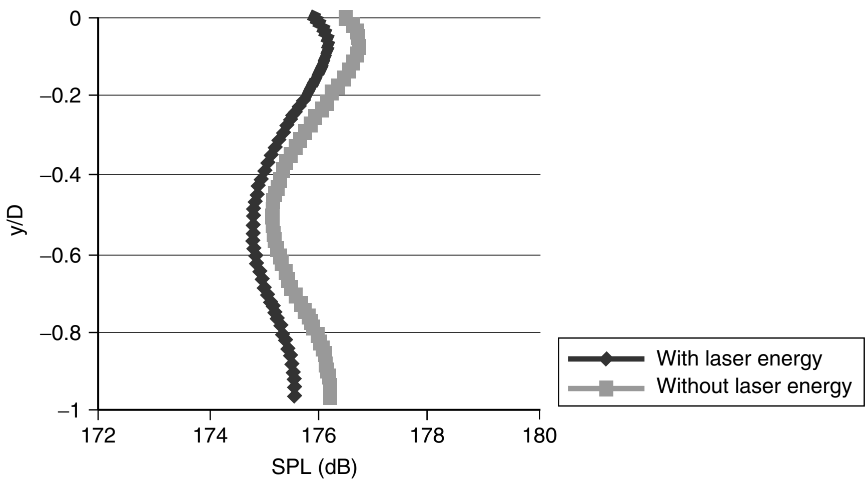

Figure 7. Sound pressure levels along the back wall of the cavity [76].

Literature shows that laser energy deposition is a new and promising technique for several types of flow configurations and might be feasible for supersonic cavity flow.

4. CONCLUSION

A study is performed to review the literature on supersonic cavity flow and its control. The complex unsteady flowfields produced by high speed flow over cavity are presented using the literature on cavity oscillation mechanism. Due to hazardous behavior of the supersonic cavity flow, many control techniques are studied. These techniques are divided two main groups; passive and active flow control techniques. The main distinction of the passive and active control techniques is use of an external energy in active control techniques unlike passive ones. Results of these techniques are almost successful but they may have some dangerous effects. Therefore, new and more reliable flow control techniques need to be investigated. The potential of laser energy deposition as a flow control actuator is presented with studies of Ghosh et al. [68], Schülein et al. [70], Adelgren et al. [72, 73], and Yan et al. [74]. This useful technique can also be applied to control the supersonic cavity flows. The results of the study of Aradag et al. [75] and Yilmaz et al [76] support the statement the laser energy deposition on supersonic cavity flow is effective to reduce sound pressure levels in cavity.

This study is intended to provide a comprehensive review of the literature and to assess the feasibility of laser energy deposition as an actuation method for cavities.

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