



A BRIEF REVIEW OF PANEL AEROELASTICITY WITH SHOCK INTERACTION

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Abstract

For high-speed vehicles, shock waves are inevitably encountered when traveling at supersonic speeds, which creates challenges in their design and operation. The consequent severe pressure and thermal loads aggravate the aeroelastic response, threatening structural safety of the vehicle. In turn, the aeroelastic response of flexible structures may significantly influence the dynamics of the shock waves, including shock-boundary layer interaction and shock motion. For the analysis of structural and fluid dynamics, various research methods including theoretical, computational, and experimental have been applied. The present review summarizes recent investigations on panel aeroelasticity with shock interaction, including shock impingement and ramp-induced shock, from the perspective of both fluid-structure interactions (FSIs) and shock-boundary layer interactions (SBLIs). Special focus is on the interaction between the shock waves and structural response, which may motivate the development of control strategies for both aeroelastic response and shock waves, thereby improving structural safety and aerodynamic performance of future high speed flight vehicles.

Keywords: Aeroelasticity, Fluid-structure interaction, Shock waves, Shock boundary layer interaction.

1. Introduction

Due to the lightweight requirement of high-speed vehicles, thin, flexible panels are widely used, which may lead to undesirable aeroelastic response thereby threatening structural safety. Shock waves are commonly encountered at supersonic/hypersonic speed, which may couple with the boundary layer bringing the possibility of flow instability. The shock waves cause severe pressure and thermal loads on the flexible panels, seriously increasing the risk of aeroelastic damage. As a major source of aerodynamic nonlinearities, shock waves result in discontinuities in the flow field, which may have significant impacts on the fluid-structure interaction (FSI).

Shock-induced aeroelastic responses have been observed for several existing high-speed vehicles, which may become an obstacle to the development of future supersonic/hypersonic vehicles. Structural damage on the flight vehicles caused by shock impingement has been reported for the X-15, which suffered melting damage and thermal buckling due to the significant heating across the shock waves [1, 2]. Scramjets, as a promising hypersonic propulsion system also experience fluid-structure interaction between flexible structures and the extreme internal flow conditions caused by internal shock waves [3]. The flowfield may be influenced by the fluctuation of side loads induced by the aeroelastic response, which leads to a decrease in aerodynamic performance. The aeroelastic coupling is also an important topic for rocket engines, where shock waves dominate the flowfield. The unsteadiness and asymmetry of the SBLIs result in severe side-loads, inducing aeroelastic response and consequent structural fatigue [4]. The fluid-structure interactions in the shock-dominated flow create complex flow physics and bring challenges to the design and optimization of supersonic/hypersonic flight vehicles and propulsion systems. Understanding the impact of shock waves

on fluid-structure interaction and the underlying mechanism is crucial for the structural design of high-speed vehicles.

In turn, the aeroelastic response of flexible panels may have an impact on the shock dynamics. The deformation and oscillation of the panel can change the motion of the reflected shock and change the topology of the separated area, which further affects the aerodynamic performance of the vehicles. Several efforts have been made to exploit the aeroelastic behavior of flexible structures to implement shock control. As Dowell[5] notes, the source of the basic physical mechanism that leads to shock oscillations and hence enhanced heating and strong excitation of a flexible structure underneath the shock remains unclear.

As a multidisciplinary phenomenon, panel aeroelasticity in a shock-dominated flow has captured the interest of researchers from a wide range of fields. In recent years, many studies have been conducted on the topic. There have been several review papers on aeroelasticity, but few of them have detailed discussions on the role of shock waves. Dowell[6] and Mei et al.[7] provided excellent reviews for the early research of panel aeroelasticity. McNamara and Friedmann[8] pointed out the challenges brought by shocks to the aeroelastic analysis using computational approaches. When reviewing transonic aeroelasticity, Gao and Zhang [9] discussed the effect of shock motion on the aeroelasticity in the transonic buffet flow. When reviewing shock/boundary layer interaction, Gaitonde and Adler [10] provide an introduction to the research progress of SBLI/FSI problems. The present review will summarize the recent achievements in the panel aeroelasticity with shock interaction, concentrating on the interaction between the structural dynamics and the shock dynamics.

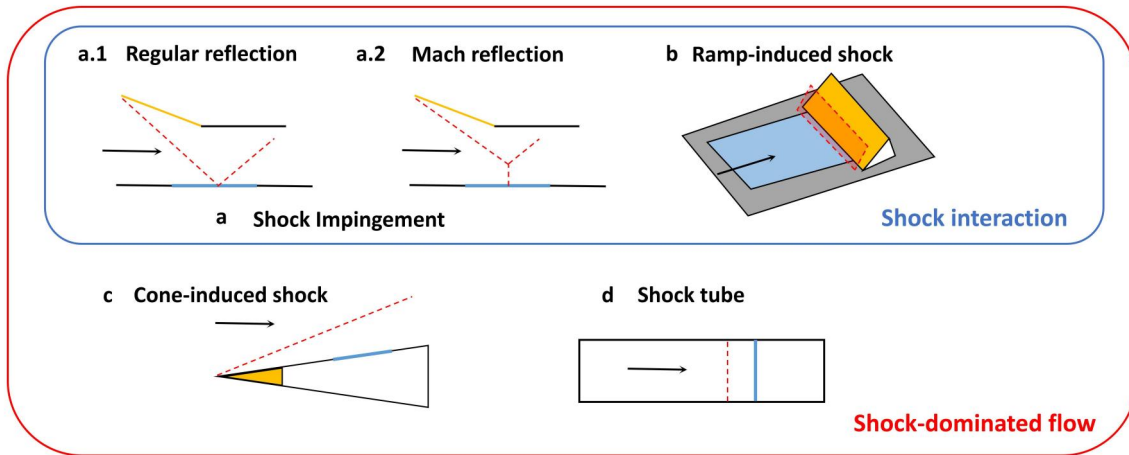


Figure 1 – Panel aeroelasticity in different shock-dominated flow configurations.

A schematic for panel aeroelasticity in different shock-dominated flows is shown in Figure 1. The shock generators are shown in gold, the elastic panels are in blue, and the shock waves are outlined with red dashed lines. The direction of each incoming flow is indicated by an arrow. Usually, there exists a cavity underneath the panel for the shock-interaction configurations. We further divide the configurations based on whether the shock wave directly contacts the panel or not. Since we focus on the interaction between the panel aeroelasticity and the shock dynamics, we only discuss the configuration with shock interaction, namely, shock impingement and compression ramp-induced shock. These two prominent configurations are widely studied to investigate fluid-structure interaction in high-speed flow. Panel aeroelasticity in other shock-dominated flows, where the shock waves do not directly interact with the panel, such as cone-induced shock[11, 12, 13] and shock tube [14, 15, 16], are of importance, but out of the scope of the present paper.

The paper is organized as follow. In section 2, the methodologies of theoretical model, numerical simulation and wind-tunnel experiments applied in the panel aeroelastic problem with shock interaction are described. In section 3, the panel aeroelastic stability and response are discussed under different shock-dominated flow conditions. In section 4, the effects of panel aeroelastic response on the shock dynamics are discussed, based on which several shock control strategies have been proposed. In section 5, the three-dimensional effects in panel responses and shock boundary layer interactions are

illustrated. Conclusions follow in section 6.

2. Methodologies

This section describes the methodologies of theoretical models, numerical simulations, and wind tunnel experiments for the panel aeroelastic problem with shock interaction. The relevant literature is summarized in the form of tables, giving a concise overview of recent advancements.

2.1 Theoretical Model

Although simple theoretical models cannot give detailed information of the flowfield, they provide a rapid and efficient way to predict the long-term aeroelastic response for a wide range of physical parameters and reveal the evolution of the aeroelastic response. Furthermore, efficient stability analysis can be conducted based on the theoretical models, providing insights into the aeroelastic stability. For the aeroelastic theories, the early reviews of Dowell [6] and Mei et al. [7] provided a comprehensive summary and categories. In recent years, progress has been made in improving the accuracy of models when predicting aeroelastic phenomena in various flow conditions, among which the most representative one is shock-dominated flow. A summary of recent theoretical investigation for the panel aeroelasticity with shock interaction is presented in Table 1. To establish the theoretical model of the aeroelastic system in the presence of shock waves, the major obstacle is in evaluating unsteady aerodynamic loads on the panel exerted by the flowfield.

Table 1 – A summary of recent theoretical models for the panel aeroelasticity with shock interaction.

Researcher	Mach number	Deflection angle/°	Aerodynamic theory	Structural theory
Ellen [17]	3,4,5	15~ 35	steady aerodynamic theory	von Kármán plate
Coleby et al. [18]	/	/	N-wave model	D'Alembert theory
Brouwer et al. [19]	2,3	/	CFD-enriched piston theory	von Kármán plate
Ye et al. [20, 21]	2.5,3,3.5	18~ 35	classical piston theory	von Kármán plate
Fredylin et al. [22]	2.5	30	classical piston theory	Lagrange equation
He et al. [23, 24]	2~ 5	0~ 30	compressible potential theory	von Kármán plate
Stanton et al. [25]	5.8	31	nonlinearized piston theory	Lagrange equation
Zhou et al. [26]	2	5.5	local piston theory	von Kármán plate

Through the analogy to the piston motion in a one-dimensional channel, the piston theory provides a rapid and accurate prediction for the aerodynamic loads in the supersonic flow, widely applied in the aeroelastic models. Despite its simplicity and efficiency, the classical piston theory encounters several deficiencies in its application in the shock-dominated flow. First, the accuracy of the classical piston theory experiences a reduction in complex flow conditions, including viscous effects, shock impingement, and consequent SBLIs. To overcome the shortcoming, Brouwer and McNamara [19] developed a CFD-enriched piston theory for modeling aeroelastic loads in shock-dominated flows, which replaced the freestream flow parameters with the local ones obtained through a steady CFD numerical simulation. The modified piston theory provided a reasonably accurate and efficient prediction of aerodynamic loads in the presence of shock impingement. However, due to the quasi-steady flow assumption, the accuracy of the theory is substantially related to the characteristics of the separation region. Second, the restriction on its applicable Mach number range results in the limitation of aeroelastic models when a low supersonic region is formed $M_2 < \sqrt{2}$ behind the reflected shock [24]. Also, the flutter mechanism is confined to the coupled-mode flutter in the existing literature. However, with a low supersonic region in the flowfield, the flutter mechanism may change to the single-mode flutter due to negative aerodynamic damping. Based on a series expansion inverse powers of the square of the Mach number and frequency, Dowell and Bliss [27] extended the piston theory, which proved to be effective in low supersonic flow. The aeroelastic model using an extended piston theory would provide valuable insight into the flutter mechanism in the presence of shock impingement. The development of the extended piston theory provides a more accurate prediction for the aerodynamic loads. For a detailed description of piston theory and its variants, Meijer and Dala [28] provided a comprehensive review.

Under certain circumstances, such as Mach reflection, the supersonic flow is decelerated due to shock waves, forming subsonic regions in the flowfield. As for evaluating the unsteady aerodynamic pressure in the subsonic flow, the classical potential theory, which is also applicable in the supersonic flow, is widely applied. Especially for the shock-dominated flows, the piecewise treatment of aerodynamic loads further complicates the solution of the potential equation. By replacing the original compressible wave equation for potential flows with the Laplace equation and quoting its solution from thin airfoil theory, an explicit expression for the unsteady aerodynamic pressure in incompressible subsonic flow is obtained, greatly simplifying the calculation. However, for the subsonic region behind shock waves, the flow remains compressible. Thus, He et al. [23] introduced the Prandtl-Glauert compressibility correction into the expression, whose results showed good agreement with that of the full potential theory as shown in Figure 2. The compressibility-corrected theory provides a rapid evaluation of aerodynamic loads at the cost of omission of time-derivative terms in the full potential equations.

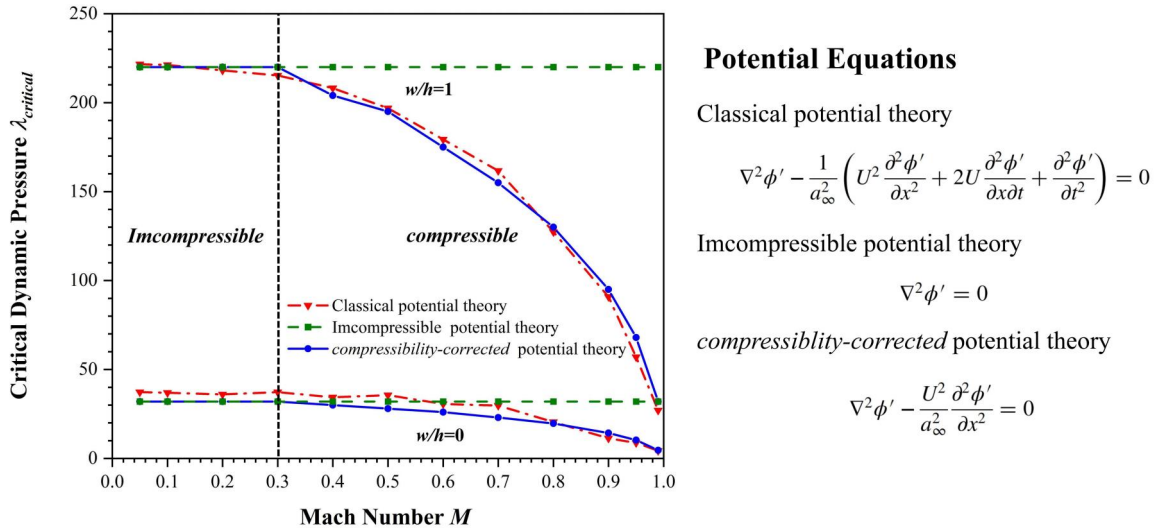


Figure 2 – Shock-reflection transition induced panel aeroelastic hysteresis [23].

Besides the improvement of aerodynamic theories mentioned above, the development of the reduce-order models (ROMs) provides a computationally inexpensive way for the prediction of aeroelastic responses. This topic will be introduced in the discussion of modal decomposition methods. Other than the assistance from the CFD approach, efforts have been made to refine the analytical model, improving its ability to reflect the FSI from real-world physics. He et al. [29] modified the panel aeroelastic model in Mach reflection by introducing the quasi-one-dimensional flow assumption, reflecting the flow properties behind the Mach stem shock. The acceleration and nonuniformity of the quasi-one-dimensional flow exhibited aggravating effects on the aeroelastic instabilities. Stanton et al. [25] considered the movement of the shock impingement location and varying oblique shock angles in response to changes in local curvature in the analytical model, disclosing their strong nonlinear effects for the large deflections of cantilevered panels. The perturbation solution of the analytical model showed good agreement with the aeroelastic response obtained through viscous numerical simulation. However, further exploration is still necessary since the influences of complicated factors of SBLI, such as flow transition and flow instability cannot be fully reflected in the theoretical model.

2.2 Numerical Simulation

The developments in both computational fluid dynamics (CFD) and computational solid mechanics (CSM) make it potentially possible to capture the complicated physics of SBLI and the nonlinear response of the panel. The coupling between the fluid solver and the solid solver is a crucial aspect of the FSI simulation. Generally, the FSI numerical simulation techniques can be classified into two main categories: partitioned algorithms and monolithic algorithms [30]. The partitioned algorithms, where the fluid and structure equations are solved separately and then coupled, are widely considered. Partitioned algorithms can be divided into loosely and strongly coupled approaches according to

the different temporal strategies. Despite the limitation of first-order accuracy, the loosely coupled schemes are suitable for aeroelastic problems, where the added-mass effect is insignificant. Based on the loosely coupled approach, different frameworks have been proposed to investigate the FSI of the flexible panel with shock interaction. A summary of recent numerical simulations for the panel aeroelasticity with shock interaction is presented in Table 2.

Table 2 – A summary of recent numerical simulation for panel aeroelasticity with shock interaction. (NS-Navier Stokes equations, VK plate-von Karman plate equations)

Researcher	Mach number	Deflection angle(°)	Fluid equations	Structure equations	Coupling
Gao et al. [31]	2	8	3D NS	Timoshenko beam	Two-way
Sullivan et al. [32]	6.04	35 (ramp)	2D NS	Momentum conservation	Two-way
Zhou et al. [26]	2	5.5	2D Euler	S4R type shell element	Two-way
Laguarda et al. [33]	2	10.66	3D NS	Cauchy's first motion equation	Two-way
Shahriar&Shoele [34]	2	5.5	2D NS	Others	Two-way
Palakurthy et al. [35]	2	8	3D NS	Mindlin plate/Bernouli beam	Two-way
Meng et al. [3]	1.6	-(train)	2D NS	VK plate	Two-way
Shinde et al. [36, 37]	2	5.62	3D NS	VK plate	Two-way
Shinde et al. [38]	4	35	3D NS	Others	One/Two-way
Hoy & Moreno [39]	3	15~32.5 (rotate)	3D NS	Others	One/Two-way
Li et al. [40]	2	3.1, 5.5	2D NS	Others	Two-way
Miller et al. [41]	3	7~13 (rotate)	2D NS	VK plate	Two-way
Liu et al [42]	1.6	-(train)	2D NS	Others	Two-way
Boyer et al. [43, 44]	2	1.6, 3.1, 5.5	3D Euler/NS	VK plate	Two-way
Pasquariello et al. [45]	3	20	3D NS	Saint Venant-Kirchhoff	Two-way
Visbal [46, 47]	2, 2.5	*1.6, 3.1, 5.5, 8.4	2D NS	VK plate	Two-way
An et al. [48]	2	*1.6, 3.1, 5.5, 8.4	2D Euler	Others	Two-way
Zhang et al. [49]	2	3.1	2D Euler	VK plate	Two-way

* The deflection angles here are calculated from the overall pressure ratio given in the original literature.

To capture the critical features of SBLI, a high-fidelity computational scheme is essential for the fluid domain. Pasquariello et al.[45] first applied large-eddy simulation (LES) to simulate the turbulent SBLI over a flexible panel, whose results exhibited a good consistency with some experimental results. The LES simulation also displays an advantage in capturing the low-frequency unsteadiness of SBLI. Hoy and Bermejo-Moreno [39] proposed a loosely-coupled framework applying wall-modelled large-eddy simulation (WMLES), which significantly reduced computational cost while retaining the capability of describing critical flow features properly. The computationally efficient scheme make it possible to conduct long-time simulation to capture the low-frequency unsteadiness. Recently, Gao et al.[31] developed a loosely-coupled high-order framework aiming at the FSI problems of an elastic panel subjected to SBLI. Compared with the low-order solvers, the high-order framework provides the possibility of highly accurate FSI simulation with less computational cost. An improved adaptive filter was proposed for shock capturing with accuracy and flexibility. A comparison was conducted between one-way and two-way FSI simulation for a panel subjected to the SBLI by Shinde et al. [38]. The results showed that the panel responses were identical at short times, while with the evolution of time, the effect of the SBLI modification emerged, leading to a lagged panel deflection with lower amplitude for the two-way simulation. The attenuated vibration was attributed to the increased level of turbulence caused by the panel flexibility. Despite the difference in the time history of panel response, the two results shared similar frequency characteristics.

The monolithic algorithm, where the fluid and structure equations are solved simultaneously, is another major approach to conducting FSI simulation. The algorithm may exhibit advantages when it comes to robustness and accuracy. Unfortunately, the technique is still under development due to difficulties establishing monolithic codes. In the future, the monolithic techniques may provide an efficient, low-cost approach to conducting FSI simulation.

2.3 Wind-tunnel Experiments

Despite the rapid development of high-precision numerical simulation and efficient theoretical models, experimental verification is quite necessary. The experimental data can be used to assess the accuracy of the computational approach and provide guidelines for the design of aerospace structures. Of course *theoretical* models can guide the design of experiments. The requirement of multiple and simultaneous measurements, which is meanwhile required to minimize the influence on the flowfield and panel response, makes the experimental setup more complex and challenging.

As early as 1971, Maestrello and Linden[50] had conducted an experimental investigation on the response of a panel excited by shock boundary-layer interaction. However, limited by the experimental techniques, only single point measurements of the flowfield and panel displacement were obtained, which is not sufficient to characterize the extreme loading environment and the dynamic response of the panel. The unsteadiness caused by SBLI and the facility vibrations require high-precision structural response measurements in the shock-dominated flow. Due to the advancement of non-intrusive, full-field measurement techniques, it is now possible to obtain a full description of the flowfield and structural response. A summary of recent experiments for panel aeroelasticity with shock interaction is presented in Table 3.

For the panel deflection measurement, digital image correlation (DIC) can provide a complete description of the panel displacement in different shock-dominated flows, such as ramp-induced shock [51], shock impingement [52], and shock tubes [14, 15]. Surface laser scattering (SLS) [53] makes it possible to utilize the raw PIV images to measure the panel deflection without additional devices, greatly reducing the cost of the experiment. For the surface pressure measurement, pressure sensitive paint (PSP) has been widely used. However, the surface temperature gradients induced by SBLI bring difficulties in the application of the paint and calibration of the data, which makes the data obtained of limited value. The unsteady pressure measured is likely to be underestimated due to the finite response of the paint and the resultant spectral attenuation, for which Funderburk and Narayanaswamy [54] presented a systematic analysis and a correction procedure. Full flowfield measurement techniques, such as particle image velocimetry and schlieren visualization, have been applied, following their previous application when investigating the SBLIs impinging on rigid plates [55]. Surface streakline visualization has been used to obtain quantitative information about the separation flowfield, which is a crucial characteristic for SBLIs, when investigating the effect of the flexibility of the panel on the separation bubble.

For the simultaneous implementation of multidimensional, multivariate measurements, additional care should be taken to avoid the measurement techniques impacting each other. For example, since most non-intrusive measurement techniques work based on optical principles, such as PIV and DIC systems, additional measures should be taken to prevent optical interference between the different measurement systems. D'Aguaano et al.[59], who are the first to investigate the shock-induced panel flutter with PIV and DIC simultaneously, employed fluorescent paint, dedicated light sources, and camera lens filters to implement optical isolation, which successfully captures the dynamics of both the flowfield and the structural deformation. A similar approach using a suitable viewing window was applied by Brouwer et al.[52] to deal with the conflict between DIC and FLIR measurements.

Despite the significant progress on the simultaneous capture of panel response and flowfield dynamics, there remain some obstacles to some other measurements, which are essential for the specific purpose. The new paragraph treatment of panel boundary conditions is a key consideration since the ideal boundary conditions cannot be always achieved. The supporting frame and other components connected with the panel are usually made of elastic materials modifying the deflection of the panel. It is necessary to measure the temperature field over the panel considering the temperature increment across the shock waves. Temperature-sensitive paint (TSP) has been applied to measure the surface temperature of the panel. However, the quality of the data obtained is less than satisfactory due to the difficulties in consistently applying the paint and condensation on the viewing window [75]. The application of a forward-looking infrared (FLIR) sensor, as a noncontact, full-field technique, faces a similar challenge. Aerodynamic heating increases the window opacity in the IR spectrum and reduces the amount of IR radiation passing through, which makes it difficult to calibrate the FLIR camera [52].

Table 3 – A summary of recent experiments for panel aeroelasticity with shock interaction. (LP-laser profilometer, SLS-Surface laser scattering, DIC-digital image correlation, DS-distance sensor, PG-photogrammetry, PSP-pressure sensitive paint, PS-pressure sensor, PIV-particle image velocimetry)

Researcher	Mach number	Shock Deflection angle(°)	Measurement		
			Panel Deflection	Pressure	Flowfield
Talluru et al.[56]	5.8	0~10°(rotate)	LP	PSP/PS	Schlieren
Varigonda et al.[57, 53]	2.5	8	SLS	PSP	PIV
Eitner et al.[51, 58]	2	20 (ramp)	DIC	PSP	-
D'Aguanno et al. [59]	2	11	DIC	-	PIV
Vasconcelos et al. [60]	5.8	2, 3, 8, 10 (rotate)	LP	PSP	Schlieren
Daub et al.[61, 62]	5.33	20	DS/DIC	PS	Schlieren
Eitner et al.[63]	5	28	DIC	PSP	Oil-flow
Peltier et al.[64]	4	6.5	DIC	PS	Schlieren/Oil-flow/PIV
Gramola et al.[65, 66]	1.4, 2	10	PG	PS	Schlieren
Tripathi et al.[67, 68, 69]	2	10	DS	PSP/PS	Shadowgraph/Oil-flow/PIV
Brouwer et al. [52]	2	4, 8, 12	DIC	PSP	Schlieren
Currao et al.[70, 71, 72]	5.8	0~10 (rotate)	Schlieren	PSP	Schlieren
Neet& Austin[73]	4	25~35°(rotate)	DS	PSP	Schlieren
Whalen et al.[74]	6	10, 20, 30-35 (ramp)	PG	PS	Schlieren
Spottswood et al.[75]	2	8	DIC	PSP	Shadowgraph
Tan et al.[76]	2	10	Schlieren	PS	Schlieren/Oil-flow
Pham et al.[77]	2.5	16, 20 ,24(ramp)	-	PS	Schlieren/Oil-flow
Daub et al.[78, 79]	3, 4	0~20°(rotate)	DS	PS	Schlieren
Willems et al.[80]	2.5~4.5	20	DS	PS	Schlieren/Oil-flow

3. Panel Aeroelasticity

Due to the complexity of the flowfield for SBLI, the panel aeroelastic responses exhibit distinct characteristics for inviscid shock impingement and shock/boundary layer interaction cases. Thus, the discussion on the panel aeroelasticity with shock impingement is conducted separately for the inviscid and viscous conditions.

3.1 Inviscid shock impingement

For the shock impingement forming a regular reflection, the panel flutter instability is adversely impacted; while for the shock impingement forming an irregular reflection, the panel exhibits multiple instabilities, including divergence, flutter, and post-divergence flutter. Due to the static pressure differential across the panel, the flutter instability is suppressed with the static deformation of the panel with a weak shock impingement. Only when the shock strength increases sufficiently do the adverse effects of shock impingement on the panel flutter emerge.

Panel response to shock impingement also may create a change shock parameters, including shock strength and shock impingement location. However, when considering cavity pressure, the weak shock impingement stabilizes the panel response due to the stiffening effects of static deformation. The effect of shock impingement location is complex. [69]

In supersonic panel flutter, the cavity pressure underneath the panel has been proven to be an important characteristic, which creates a static pressure differential across the panel and thus a static deformation of the panel, merely suppressing the panel flutter. For the shock-induced panel flutter, the effect of cavity pressure is amplified due to the increased static pressure jump across the shock. Usually, the panel has a positive deformation near the leading edge due to the lower static pressure ahead of the shock compared with the cavity pressure. On the contrary, the deformation near its trailing edge is negative due to the static pressure above the panel behind the shock. The deformation shape is recognized as similar to the second bending mode and has been reported by several investigators [47]. However, this is not always the case. A typical first bending mode shape has also been observed by Willems et al [80], where the panel exhibits a negative mean deformation. The difference in the panel mean deformation may be associated with the different settings of the

cavity pressure. The influence of static pressure differential is difficult to eliminate by adjusting cavity pressure. The static deformation caused by static pressure differential stiffens the panel, which delays the onset of flutter, accounting for the elimination of flutter with weak shock impingement [47].

The initial conditions also play a crucial role in the aeroelastic responses. For the panel with shock impingement, Visbal [46, 47] found that the difference in the initial conditions resulted in distinct panel responses. As shown in Figure 4, for the case of $p_3/p_1 = 1.4$, there exist two different solutions with the same freestream dynamic pressure λ . The panel has a static deformation without flutter when employing the steady deformed panel at lower dynamic pressure as the initial condition, but exhibited limit cycle oscillations when considering the flat panel as the initial condition. The hysteretic behavior was attributed to the occurrence of subcritical bifurcation instead of supercritical bifurcations. Recently, Zhang et al. [49] took a further look at the hysteresis phenomenon, disclosing its sensitivity to the changes in cavity pressure. The hysteresis loops exhibit different sizes and shapes depending on the cavity pressure. The detailed discussion revealed the strong association between the evolution of hysteresis behaviors and the cusp catastrophe.

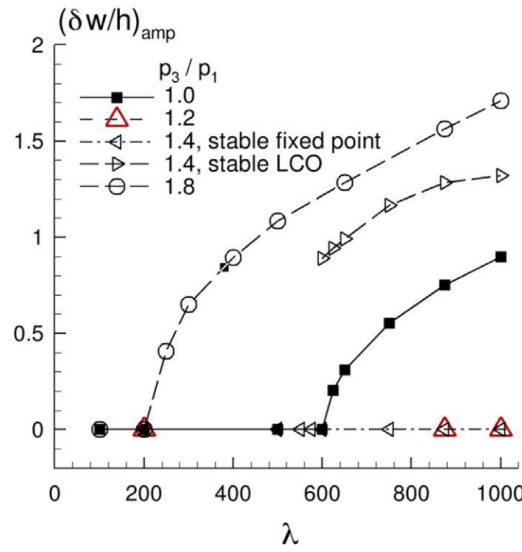


Figure 3 – Initial conditions induced panel aeroelastic hysteresis. [47]

From another perspective, the initial condition of a steady deflected panel at the lower dynamic pressure can be treated as a preconditioned curved panel, providing a potential explanation for its non-flutter response at large dynamic pressure. For the chordwise curved panel in supersonic flow, the curvature was found to destabilize the panel, aggravating the flutter instability [81], contrary to the results obtained by Visbal. However, An et al. [48] investigated the aeroelastic behaviors of a curved panel with oblique shock impingement, disclosing the nonmonotonic impact of curvature on flutter onset in shock-dominated flow. Different from the situation in supersonic flow, an appropriate curvature can significantly delay the onset of flutter. The stabilizing effect of curvature in shock-dominated flow supports the explanation for the hysteretic response. Furthermore, pre-flutter deformation under static aerodynamic loads, giving additional stiffness to the panel [82], might also account for the non-flutter response. Notably, the curved geometry exhibiting the first bending mode was considered in the early research and An et al.'s research. However, the panel displays the deformation shape of the second bending mode due to shock impingement, which might significantly alter the aeroelastic responses. The sensitivity of hysteresis responses to the cavity pressure might also stem from the resulting static deformation shape. Further investigation is necessary to better understand the aeroelastic responses of curved plates with different shapes in shock-dominated flow, and the underlying mechanism of the hysteresis phenomenon induced by initial conditions.

3.2 Shock/boundary layer interaction

In shock-dominated flow, the incoming boundary layer interacts with the shock waves, resulting severe unsteady loads.

The presence of a SBLI significantly alters the panel flutter response. Despite the significant decrease in critical dynamic pressure, the panel response was restabilized at sufficiently high dynamic pressures. The restabilization may come from the joint effect of geometric structural stiffening and large changes in mean flow due to large mean deflections at high shock strength and dynamic pressures. The flutter amplitude shows a nonmonotonic, complicated variation with increasing dynamic pressure, especially for the strong shock impingement case. This is due to the energy transfer to higher modes, activated by the boundary layer instabilities amplified by higher shock strength.

The regular limit cycle oscillations may change to aperiodic, high-frequency oscillations. Additionally, the flutter response takes much longer to become statistically stationary. Considering the aperiodically oscillating modal amplitudes, the complicated flutter responses may come from the energy shifting among the active modes over time [44]. The panel response changing from low-frequency high-amplitude oscillations to high-frequency fluctuations exhibits a potential chaotic pattern [47]. Possibly chaotic oscillations were observed, which was attributed to the SBLI unsteadiness considering that the panel oscillations cease to exist for the inviscid shock impingement [38]. A similar chaotic motion of the panel was also observed by Palakurthy et al. [35], which exhibits one dominant frequency superposed with the higher frequencies coming from the flow instabilities of the flowfield. The flow instabilities might be the source of the chaotic motions, for which a further exploration is necessary. The application of a Micro-Vortex Generator, which serves as a boundary layer control approach, reduced the chaotic flutter into limit cycle oscillations (LCOs). The influence of traditional flow control strategies on the shock-induced flutter is of interest, based on which novel aeroelastic control strategies might be developed. Due to the aperiodic response, the spectral characteristics of the panel response significantly changed, which contained multiple concurrent frequencies [44].

With a weak shock impingement, the panel displayed a higher-order response significantly different from the standard panel flutter response in supersonic flow. With the increase of incident shock strength, the spatial distribution of the panel response exhibited high wave number variations, for which a lower dynamic pressure resulted in a relatively high-order model response, where the boundary layer instabilities became a prominent factor. This was attributed to the increased geometric stiffening of the panel at higher dynamic pressures, decreasing susceptibility to the pressure fluctuations associated with transitional flow.

The enriched physics of the panel aeroelastic response highlighted the complexity of considering shock/boundary layer interaction.

3.3 Unsteady Shocks

For supersonic/hypersonic vehicles, changes in operating conditions usually cause unsteady shock waves. The motion of the shock generator is likely to be induced by vehicle maneuvers, control surface modulation, or aeroelastic response [70], which results in oscillating shock or moving shock above the fuselage or other components. The movement of the shock decreases the concentration of pressure and thermal loading by dispersing them, and thus increases the surface area that is subjected to time-varying pressure and thermal loading [56]. Also, shock oscillation caused by the motion of the shock generator usually occurs at lower frequencies ($O(100)\text{Hz}$) than unsteadiness induced by SBLIs [70], which introduces an additional frequency content into the flowfield.

As early as 1967, Crocker [83] noted the problem and investigated the panel response to the oscillating and moving shock waves through a theoretical model. It was found that the shock oscillations with subharmonic frequencies of the panel natural frequency ($\omega/2, \omega/3, \omega/4, \dots$) excited the panel modes, disclosing the tight coupling between the shock oscillating frequency and panel natural frequency. Miller et al. [41] observed a large amplitude panel oscillation induced by an oscillating shock, which was however suppressed due to thermal buckling. Daub et al. [78] conducted an experimental investigation on the FSI of an elastic panel impinged by a fast-moving oblique shock, applying a rotatable wedge driven by a servomotor, which rotated about 20 degrees in 10ms. It was found that the fast movement of the shock results in panel oscillations on the order of 1mm, which are significantly larger than that induced by fixed shock impingement on the order of 0.01mm. A similar rotatable shock generator is applied by Neet and Austin [73] to induce oscillating shock impingement, which provides a direct way to force frequencies of interest into the flow, making it possible to investigate experimentally the coupling between flow frequency and structural frequency on the same order. Replicating

the wind tunnel experiment by Duab et al.[78], the pitching shock generator was numerically simulated by Pasquariello et al. [45] to induce time-varying pressure load on the panel and subsequent flow separation, resembling typical overexpanded nozzle flow conditions. Hoy and Moreno[84] also performed high-fidelity numerical simulation on the panel impinged by a fast-moving shock, revealing the three-dimensional effects in the panel response. The shock motion significantly aggravates and complicates the aeroelastic response of the panel, where the relationship between the flow frequency and structural frequency plays a vital role. The wind tunnel start-up provides another interesting scenario, where a normal shock traverses the flexible panel. A unique panel response during the wind tunnel start was observed by Spottswood et al. [75], where the large-scale oscillation at short times evolved into small-scale vibration, which appeared to be the single well of a bi-stable system. Fredyin et al. [85] modeled the panel aeroelastic system during the wind tunnel start, through which a good agreement with the experimental data was obtained with an appropriate temperature scaling.

As a primary source of aerodynamic nonlinearity, shock motions have significant impacts on the nonlinear aeroelastic responses [86]. Under the combined effects of structural and aerodynamic nonlinearities, the panel aeroelastic response may exhibit distinctive nonlinear characteristics. Ye et al. [87] conducted a preliminary investigation on the nonlinear behaviors of a panel response with oscillating shock impingement forming regular reflection. With shock oscillation, the panel exhibited complicated nonlinear responses, including single/multi-periodic LCOs, quasi-periodic motions, and chaotic motions. Also, the coupling of shock oscillating frequency with the natural frequencies of the panel is also of concern. With the shock oscillating frequency close to the natural frequency of the panel, the panel response is more likely to exhibit complicated nonlinear characteristics. Recently, He et al. further extended their research to the Mach reflection case and systemically studied the nonlinear panel response induced by an oscillating shock. The shock oscillation enriched the nonlinear responses of the panel, which are found to be sensitive to the shock oscillating properties. Depending on the relationship between the shock oscillating frequency and the natural frequency of the panel, the panel exhibits different chaotic characteristics. With the shock oscillating frequency close to the natural frequency, the panel response tends to exhibit limited or narrow-band chaos. The panel with oscillating shock impingement provides a suitable configuration to investigate the combined effects of aerodynamic and structural nonlinearity.

In addition the shock motion mentioned above, self-induced shock oscillation occurs and brings additional unsteadiness to the flowfield (the basic physical mechanism for the self-induced shock oscillation is still in question and worthy of further study). Usually, self-induced shock oscillations occurs at transonic flow conditions, which is also called transonic buffet. Gao and Zhang [9] provided an excellent review and provide a detailed discussion on the impact of shock oscillation. The self-induced shock oscillation in the hypersonic regime and its effect on the aeroelasticity is worthy of further investigation, for which a dynamical bifurcation global instability analysis might provide new insight. The changes in flow conditions can not only result in an unsteady shock, but also induce shock-reflection transition. Considering the significant difference between the two shock reflections, the shock-reflection transition can lead to significant changes to the panel aeroelastic response. Due to the existence of two different criteria for the shock-reflection transition process, there exists a dual-solution domain where either type of shock reflection is theoretically possible with the same parameter conditions. The existence of the dual-solution domain leads to a hysteresis phenomenon in the shock-reflection transition process, which has been found to induce another hysteresis. Similarly, the shock-reflection hysteresis can induce a novel aeroelastic hysteresis. He et al. [24] discussed the aeroelastic hysteresis phenomenon and its characteristics. As shown in Figure 4, two types of hysteresis are theoretically possible: deflection-angle-variation-induced hysteresis and flow-Mach-number-variation-induced hysteresis, whose hysteresis loops are reversed. The two hysteresis processes correspond to different aircraft maneuvers. There exists a similar hysteresis phenomenon in the temperature distribution on the panel, which is likely to induce another aerothermoelastic hysteresis. Furthermore, it should be noted that the results in Ref.[24] were obtained based on the two steady shock-reflection configurations, ignoring the shock-reflection transition process. However, the shock-reflection transition is a complicated process with significant unsteadiness [88], which might significantly alter the panel aeroelastic response.

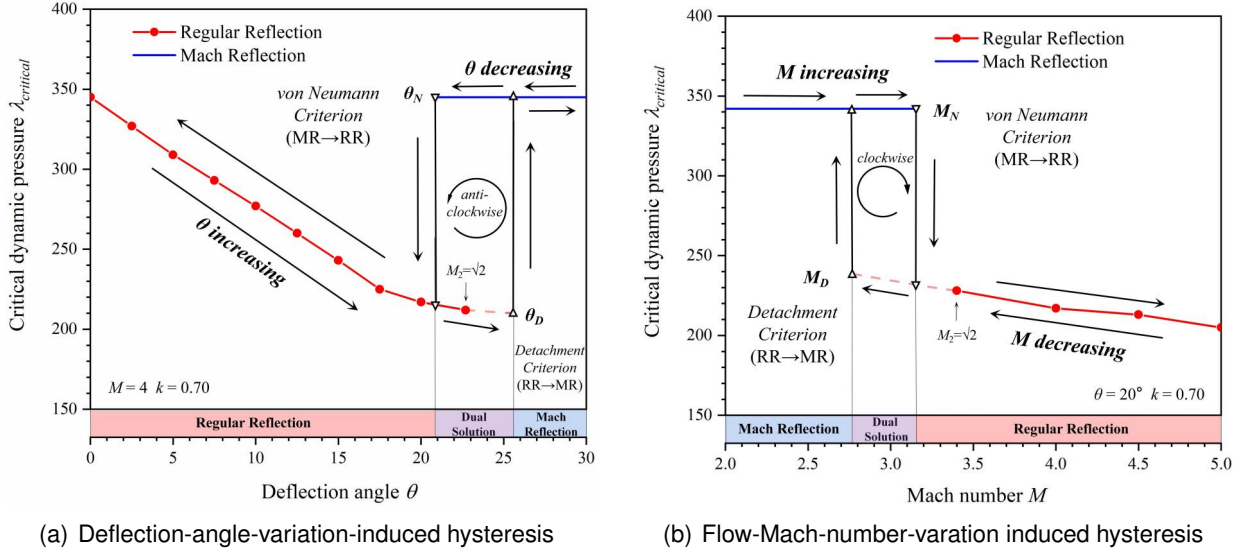


Figure 4 – Shock-reflection transition induced panel aeroelastic hysteresis [24].

4. Shock Dynamics

The violent dynamic response and static deformation of the panel may significantly influence the shock dynamics above the panel. Under certain circumstances, the modification in the shock characteristics may be beneficial to the aerodynamic performance, based on which different shock control strategies have been suggested.

4.1 Shock-boundary Layer Interactions

Usually, SBLI investigations are conducted on rigid panels to serve as a reference case. Several comparisons are conducted between the shock-boundary layer interactions above the rigid panel and flexible panel to investigate the effect of panel aeroelastic response on the specific flow structure of SBLIs.

A prominent feature of the SBLI above flexible panel is the compression and expansion waves induced by the aeroelastic deformation of the panel, whose intensity and location varies with the panel response. The compression/expansion waves induced by panel deflection further complicate the flowfield. Usually, a negative temporally-average deformation is observed for the panel, forming two expansion fans near the leading/trailing edge, between which a compression wave is induced. The complicated wave structures account for the fluctuation in the pressure distribution. The acceleration effects of the upstream expansion fan have been confirmed through several investigations. However, differences emerge in its effect on the separation region. A downstream movement of the separation-starting position was observed by Pasquariello et al.[45], while a slight upstream movement was observed by Gao et al.[31] and Meng et al.[3].

Due to the vibration of the panel, the fluctuations in the separated area are more intense, which could drive the panel at resonance causing severe structural damage. For now, both the increase and the decrease in the separated bubble length have been reported in the presence of flexible panels, which are determined by the deflection of the panel, the shock impingement location, shock strength, cavity pressure, etc. The variations in the separation bubble length caused by the flexibility of the panel reported in the literature, usually obtained through skin-friction coefficient and wall pressure distribution, are summarized in Table 4. Boyer et al. [44] revealed the sensitivity of the separation region to the freestream dynamic pressure when considering strong shock impingement. The separation region exhibited a strong correlation with the panel response: increasing flutter/LCO amplitude and decreasing mean deflection resulted in a decrease in separation region length and vice versa. For the situation where the panel deflection amplitude is much smaller than the panel thickness and incoming boundary layer thickness investigated by Varigonda et al. [53], the fluid-structure interaction is too weak to create any significant modifications to the separation region, further demonstrating that the variation in separation region is highly related with the magnitude of panel response.

Table 4 – Variations in time-averaged separation bubble length reported in experimental and numerical investigations.

Researcher	ΔL_{sep}	x_i/l	Method
D'Aguanno et al.[59]	+8%	0.55	Exp
Daub et al.[78]	+	Moving	Exp
Pasquariello et al.[45]	-15 %	0.36	Num
Varigonda et al. [53]	0%	0.80	Num
Tripathi et al. [68]	-	0.50	Exp
	-13% ~ +15.2%	0.75	Exp
Visbal [47]	-31%	0.50	Num
Pham et al. [77]	-25%	Ramp	Exp
Hoy et al. [39]	+60%	Moving	Num
Gao et al.[31]	+49%	0.50	Num
Shinde et al.[38]	-	0.50	Num
Pham et al. [77]	-25%	Ramp	Exp
Boyer et al. [44]	-/+	0.50	Num

Visbal [47] observed a reduction in both streamwise extent and maximum height of the separation zone, attributed to the forcing of the flow due to the self-excited panel fluctuations. The inference was reinforced by a close match of the pressure distribution between the flexible and rigid panel case when panel oscillation changed to larger static deformation at high freestream dynamic pressure. Reduction in separation can be achieved through forced panel oscillations with low reduced frequency, indicating a potential flow control strategy. Tripathi et al. [68] found that the cavity pressure had a significant impact on the size of the separation bubble, whose reduction led to a reduction of the separation bubble length. Daub et al.[78] found the separation bubble length decreases with the decrease of the incident shock angle and the shock strength. A change in the shape of the separation region, indicated by the change in the distribution of skin-friction profiles, was also observed [31]. Besides the variation in the time-averaged properties of the separation region, the location and length of the separation region also exhibit significant variation. The variation of the separation bubble at the top and bottom walls exhibits different tendencies [3].

Considering the contradictory findings, the underlying mechanism and decisive parameters for the influence of the aeroelastic response on the separated bubble remain uncertain. Furthermore, the temporal evolution of the separation region is uncertain.

For vehicles operating at high Mach numbers, transitional SBLIs are commonly encountered, resulting in enhanced unsteadiness. Due to the flexibility of the panel, the boundary layer transition was advanced to $Re \sim 40,000$ from $Re \sim 70,000$ for the rigid panel case [37]. A further investigation of the effects of the structural parameters disclosed the distinct impacts of the mass ratio on both structural response and transitional SBLI. The flow transition was induced by flow instabilities, which are highly coupled with the higher-mode panel deflection. Based on the time-averaged skin friction coefficient, Boyer et al.[44] also observed the effect of a flexible panel on the turbulent transition. A comparison between the two studied cases demonstrated that a more severe flutter oscillation at the higher dynamic pressure further aggravated the turbulence, fostering the transition.

The multi-source low-frequency unsteadiness is another aspect of interest for SBLIs, which come from separation region, Kelvin-Helmholtz shedding, etc. [89]. Due to the panel dynamic response, an additional low-frequency unsteadiness is introduced into the flowfield, coupling with the separation-induced unsteadiness, which was indicated by enriched frequency content in the wall pressure PSD. However, it is uncertain whether the panel vibration has an impact on the low-frequency unsteadiness originally possessed by SBLI. Though a high-pass filter, Gao et al. [31] filtered away the frequency content induced by panel response in the PSD. A further comparison with the PSD of SBLI on a rigid panel demonstrated that the FSI effects had no obvious impact on the separation-induced flow unsteadiness. The modal characteristics of the SBLI are also altered by the panel response. The DMD analysis conducted by Shinde et al. [38] revealed that the flexibility of the panel reduced the participation of the first mode but strengthened other sub-prominent modes. A similar situation was

observed by Varigonda et al. [53] in their experimental study. Moderate unsteadiness was observed at the root of the incident shock.

With pressure fluctuations as an indicator of unsteadiness, Visbal [47] observed significant pressure fluctuations extending over a large portion of the panel, propagated away from the plate along the reflected compression/expansion system. Such propagation might be unfavorable for internal flow applications considering potential unsteady aerodynamic loading on the opposing solid surface. A stronger low-frequency movement of the separation shock was observed for the flexible panel by Daub et al. [78], which demonstrated that its aeroelastic response had an influence on the topology of the SBLIs. A study was conducted by Hoy and Bermejo-Moreno [84] with high-fidelity numerical simulation, which provided more details for the SBLI above the panel. The compression/expansion waves induced by panel deflection further complicate the flowfield. Usually, a negative temporally-average deformation is observed for the panel, forming two expansion fans near the leading/trailing edge, between which a compression wave is induced. The complicated wave structures account for the fluctuation in the pressure distribution. The acceleration effects of the upstream expansion fan have been confirmed through several investigations. However, differences emerge in its effect on the separation region. A downstream movement of the separation-starting position was observed by Pasquariello et al. [45], while a slight upstream movement was observed by Gao et al. [31] and Meng et al. [3].

4.2 Shock Motion

In addition to an oscillating shock produced by rotating shock generator, shock oscillation can also be caused by the aeroelastic behavior of the panel.

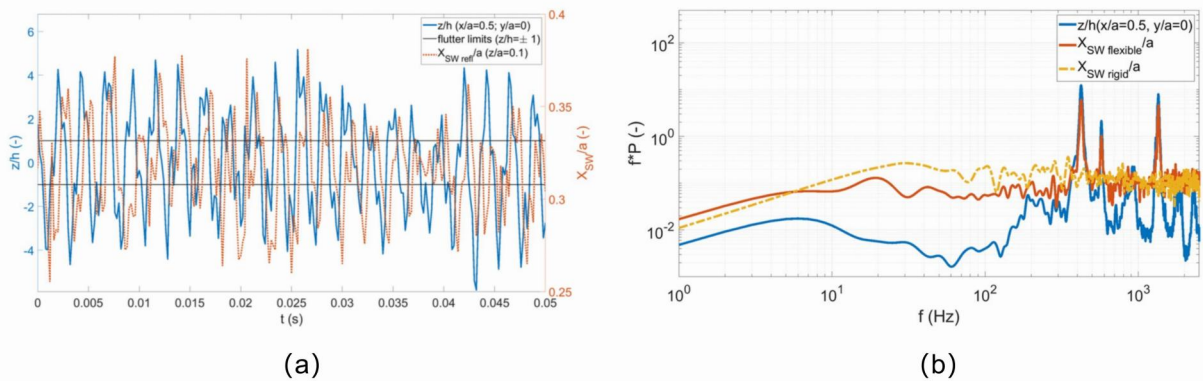


Figure 5 – (a) Temporal behavior and (b) spectral characteristics of the displacement at the midpoint of the panel and of the reflected shock motion. [59]

There can exist a strong coupling between the panel aeroelastic response and the shock motion. The motions of the reflected/separated shock, which are driven by the separation bubble pulsations, receive a lot of attention. As shown in Figure 5a, despite a lag, a good agreement between the displacement of the panel and the reflected shock location was observed, whose variations in amplitude are consistent [59]. When the panel deflection is negative, the reflected shock moves upstream and vice versa. The spectral analysis in the form of power spectral density (PSD) showed that the two signals share similar spectral content, which further confirmed the correlation between the fluctuation of the flow and the structure. The cross-correlation analysis conducted further verified the correlation between the two signals. The strong coupling was also observed by Peltier et al. [64] conducting a cross-correlation between the reflected shock position and POD temporal coefficients, which revealed the strong correlation of shock motion with the first two POD modes. A similar large-scale motion of separated shock was also observed by Pasquariello et al. [45], which was however attributed to the shock generator oscillation. The motions of shock structures might come from a superposition of shock generator oscillation and panel aeroelastic response. Thus, a spectral analysis is necessary to determine the source of shock motion for the SBLIs over a flexible panel.

The aeroelastic responses of the panel were also observed to cause upstream movement and tran-

sient fluctuation of the shock train structure, indicating that the panel flexibility compromised the resistance of the shock structure to the backpressure [3]. Such shock motions are undesirable, which might lead to the loss of aerodynamic performance and even unstart problems.

Also, panel aeroelastic behaviors can have an impact on the shock oscillation in transonic flow. Liang et al. [90] numerically investigate the shock oscillation caused by a downstream pressure fluctuation on a rigid/flexible wall in the transonic flow. The flexibility of the wall reduced the shock oscillation slightly and pushed the shock root downstream. Flexible panels might provide a potential way to regulate the self-induced shock oscillation in transonic flow.

4.3 Shock Control

To avoid undesirable separation and unsteadiness caused by SBLIs, which might lead to higher total pressure losses and consequently lower aerodynamic performance, shock control is essential for the supersonic/hypersonic vehicle. Flexible panels, as the commonly used components for aircraft, potentially provide a simple and convenient way for flow control through their aeroelastic effects. Several investigations have been conducted on the application of flexible panels in the regulation of flow transition [91]. Unfortunately, limited control effects have been achieved. Recently, the potential of flexible panels implementing shock control has been exploited. When investigating the interaction between SBLIs and a flexible panel, Visbal [47] suggested that an aeroelastically tailored flexible panel can serve as a means of passive flow control for its capability of reducing separation region through its self-excited oscillation (the exact influence of flexibility on the separation region is still in question as discussed in the previous section). Considering the impact of the panel deformation and vibration on the shock dynamics, different shock control strategies have been proposed and developed based on the fluid-structure interaction.

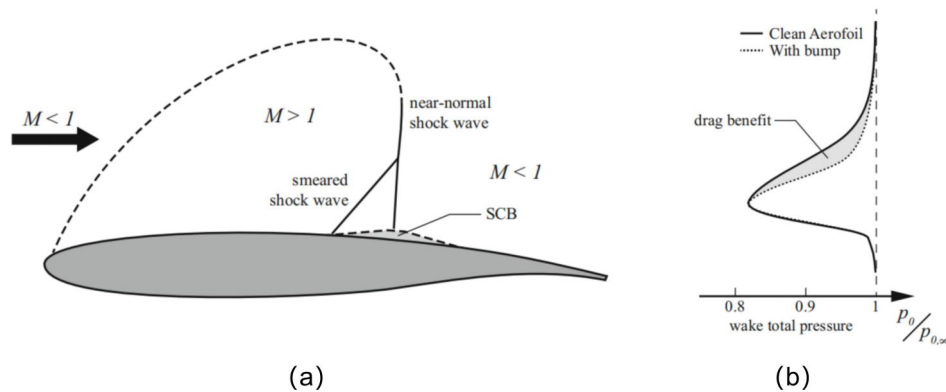


Figure 6 – Control principle of operation of a SCB on a transonic wing:(a) shock structure; (b) reduced total pressure loss in the wake [92].

Shock control bumps (SCBs) [92] consist of a physical bump placed on an aerodynamic surface impinged by a shock wave, whose control capability has been demonstrated for hypersonic inlets [93, 94] and especially for transonic wings. Usually, SCBs are designed to deal with the near-normal shock occurring on the upper surface of the transonic wings. As shown in Figure 6, when impinged by the shock, SCBs bifurcate the near-normal shock into a λ -shape shock foot bringing a lower total pressure loss and consequently lower drag. Its application has been also extended to the control of oblique shock/boundary layer interaction [95, 96]. Despite the effectiveness of the bump for shock control, its performance at off-design shock strength and impingement locations is less than satisfactory and might even worsen aerodynamic performance.

In recent years, Gramola et al.[65] verified the feasibility of using a flexible panel without extra actuation to form a shock control bump by adjusting the cavity pressure underneath the panel to control its aeroelastic deformation. This also exhibits the potential for improving the off-design behavior of SCBs. Preliminary results showed that a higher cavity pressure, whose adjustment can be achieved by both active control through a vacuum tank and passive control through breather holes on the panel, brought more reduction in the total pressure loss. Gomez-Vega et al.[97] further investigate

the application of the concept to the oblique shock control and its sensitivity to the shock impingement location. The reduction in separation length of up to 40% and in total pressure losses of up to 10% can be achieved depending on the shock impingement location. Besides SCBs, SBLIs control through a morphing surface [96, 98, 99], for which experimental investigation is still lacking, may be realized through flexible materials.

Based on the aeroelastic effect of the flexible panel, Liu et al.[42] proposed a new concept shock train control strategy, which can be applied to the isolators. By replacing the rigid wall with the flexible panel, the compression and expansion waves induced by the vibration and deformation of the panel interact with the shock train, which effectively delays the thickening of the boundary layer and consequently the formation of the shock train. Similarly, comparing the shock train transition under the action of flexible panels and rigid panels on the cowl side of an inlet, Qin et al.[100] found the aeroelastic behavior of flexible panels successfully suppressed the flow oscillation, prevented the shock train from transitioning, and stabilized the flowfield. However, contrary effects were observed in the research by Meng et al.[3], where the flexibility of the panel resulted in a higher energy loss, worsening the aerodynamic performance. The flexible wall has also proved effective in restricting the undesirable shock oscillation due to the downstream pressure perturbation and limiting its adverse impact on a two-dimensional supersonic intake [101]. The application of flexible panels is promising flow control strategy for supersonic/hypersonic inlets.

The flexible panel provides a desirable structure to develop adaptive shock bump and controlled surface morphing strategies as passive/active shock control techniques. The shock control strategies based on the aeroelastic performance of the flexible panel provide another novel perspective on the utilization of FSI to implement flow control, which is applicable to the development of future supersonic/hypersonic vehicles. Despite its effectiveness and simplicity, the vibration and deformation of the panel may cause fatigue damage to structural components. It is necessary to optimize the control strategies by balancing the shock control effectiveness and structural safety.

5. Three-dimensional Effects

5.1 Panel Aeroelasticity

As shown by Dowell [102], the behavior of the three-dimensional flow over a plate is qualitatively similar to that of the two-dimensional plate for length-to-width ratios up to two in supersonic flow. However, in shock-dominated flow, the nonuniformity of the complicated flowfield above the panel might significantly enhance three-dimensional flow effects, resulting in distinct aeroelastic behaviors for the two-dimensional and three-dimensional panels.

Boyer et al.[43, 44] extended the numerical investigation by Visbal et al.[47, 46] into the three-dimensional panels. For the inviscid case, despite a smaller amplitude and delayed onset of flutter, the panel response along the centerline for the three-dimensional configuration corresponded qualitatively with the two-dimensional simulation. However, three-dimensional effects have a significant influence on the panel response away from the centerline. Compared with the case of the entire supersonic flow, the introduction of the impinging shock excited an additional higher-order spanwise mode, indicating the amplification effect of shock impingement on spanwise aeroelastic variations. For the viscous case, the spanwise characteristics become even more prominent, where the panel response for the three-dimensional configuration differed greatly from the two-dimensional results even along the centerline. The location of maximum flutter amplitude was also shifted away from the centerline. The panel response exhibited high wavenumber variation, which had similar spatial distribution in the streamwise and spanwise directions. To evaluate the three-dimensional effects, Hoy and Bermejo-Moreno [39] compared the full and reduced spanwise panel width, revealing that the reduced spanwise panel displayed enforced spanwise periodicity. Despite the effort to maintain a nominally two-dimensional configuration, the aeroelastic response still displayed three-dimensional characteristics due to the edge effects [80].

Another crucial factor is the aggravated aerodynamic heating across shock waves, forming a nonuniform temperature distribution on the panel, which might significantly alter the aeroelastic behavior of the panel. In the early research by Xue and Mei [103, 104], it was found that the nonuniformity of temperature distribution had a limited effect on the aeroelastic behavior of a two-dimensional panel

but significantly altered the panel aeroelastic behaviors of a three-dimensional panel. Thus, three-dimensional effects in temperature distribution are of concern in shock-dominated flow, especially for Mach shock reflection, where the quasi-one-dimensional flow behind the Mach stem shock will further exacerbate the nonuniformity of temperature distribution. Furthermore, similar to the aeroelastic hysteresis, a hysteresis loop will be formed in the temperature distribution due to the shock reflection transition, which might further increase the difference in aeroelastic performance between the two different shock reflection cases. Thus, it is necessary to further investigate the three-dimensional effects of aggravated, nonuniform temperature distribution on the panel aeroelastic behaviors in shock-dominated flow.

5.2 Shock-boundary Layer Interactions

Similarly, the flexibility of the panel results in a shock-boundary layer interaction with significant three-dimensional characteristics, compared to a rigid panel case displaying a nominally two-dimensional configuration [69].

When investigating the SBLI over a two-dimensional panel, a secondary bubble was observed beneath the main separation bubble when considering a strong shock impingement by Boyer et al. [44]. This became a dominant feature resulting in a much larger separation region than the cases with weaker shock impingement. However, for the three-dimensional case, the secondary, counter-rotating bubble only existed principally near the sides of the panel. Furthermore, the modification in the separation region due to the flexibility of the panel resulted in a difference between the flow features inside and outside the panel, inducing a mean crossflow, whose spanwise variation depended to some degree on the particular spanwise boundary conditions chosen. However, when simulating a fast-moving SBLI over a flexible panel [39], despite noticeable three-dimensional effects in the panel deflection, they are nearly negligible in the flow quantities, resulting in a statistically two-dimensional configuration.

The modal decomposition approach provides a potential way to further investigate the three-dimensional effects of SBLIs over flexible panels. The POD and DMD modes emphasized the spanwise flow inhomogeneity and exhibited extended spanwise coherence for the SBLI over the flexible panel [38]. The stream-wise and span-wise evolution of the structural response can be identified with the DMD modes. When it comes to three-dimensional effects, the transitional SBLIs are of great concern, where the nominally two-dimensional and steady SBLI becomes three-dimensional and unsteady after the transition. Through POD analysis, Shinde et al. [36] found that the presence of flexible promotes flow transition, thus decreasing its critical Reynolds number.

The flow instability in the SBLIs is highly related to the Görtler vortices, which are essentially three-dimensional structures. The Görtler vortices are induced by large separation bubbles. A reduction in the spanwise wavelength of the flow instability in the presence of a flexible panel was observed by Shinde et al. [36]. Despite the cylindrical bending assumption considered in panel flutter, the spanwise effects are evident for the panel with low aspect ratio in the presence of SBLI.

6. Concluding Remarks Regarding Future Work

The paper presents a literature review of the recent achievements in panel aeroelasticity with shock interaction, focusing on the interaction between shock waves and structural response. Despite valuable insights obtained from existing research, several key challenges and obstacles still exist for the development and optimization of supersonic/hypersonic vehicles.

- 1) For the hypersonic vehicle, with the change of the operating condition, the shock reflection type might transit between regular reflection and Mach reflection. Considering the distinct aeroelastic performance of the panel in the regular reflection and Mach reflection, a closer look at the panel aeroelasticity in the Mach reflection and dual solution reflection is necessary.
- 2) For now, contradictory results have been observed for the impacts of flexible panels on the shock/boundary layer interaction, for which the underlying mechanism and decisive parameters are still unclear. Studying the evolution of SBLI with aeroelastic behaviors is essential for the application of flexible panels as shock control strategies.
- 3) Aerodynamic heating, aggravated by shock waves, plays a crucial role in the aeroelastic performance of the panel in supersonic/hypersonic flow. The nonuniformity of the thermal field in shock-

dominated flow might significantly threaten the structural safety of the vehicles. However, the lack of adequate measurement and numerical techniques greatly hinders the relevant investigation. Efforts should be made to develop aerothermalelastic models in shock-dominated flow capturing the complicated physics.

4) Panel aeroelastic systems in shock-dominated flow display rich hysteresis phenomena, induced by initial conditions, shock-reflection transition, cavity pressure, etc. Such hysteresis phenomena are of great importance in engineering applications, which result in multiple aeroelastic responses with the same parameter condition. Further study of these hysteresis responses may provide potential strategies to obtain favorable aeroelastic performance in even extreme operating conditions.

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