External-Compression Supersonic Inlet Free from Violent Buzz

Hao Chen,† Hui-jun Tan,‡ and Ya-zhou Liu¶

Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, People’s Republic of China

and

Qi-fan Zhang§

Chinese Academy of Sciences, 100190 Beijing, People’s Republic of China

DOI: 10.2514/1.J057811

To greatly improve the supersonic inlet stability at low cost of structural weight and complexity, a novel buzz suppression strategy based on fixed-geometry air bleed is developed. It is designed to have plenty of narrow flush slots that are widely distributed along the compression surface. Using the natural pressure gradient varying with the terminal shock position, it is capable of creating self-adaptive bypass flow removal upstream of the internal duct. A strong stabilizing effect can be thus automatically produced on the subcritical flowfield by eliminating shock-induced separation and discharging excessively captured airflow. Simultaneously, the undesired air leakage at the critical regime can be naturally restricted to prevent a prohibitive performance penalty during normal operation. To verify the effectiveness, an external-compression inlet model is specially designed and carefully tested at freestream Mach numbers of 2.0 and 2.5 with an almost full exit throttle range considered (0–99.1%). Results indicate that the subcritical stable-flow range is remarkably extended from a throttle threshold of 53.7% to that of 86.4% and 73.7%, respectively, after the usage of the proposed bleed method. Moreover, intense flow instability is totally eliminated, even when the duct exit is almost closed. Further analysis reveals that the bleed flow rate at the near-critical state is not beyond 1% of the inlet flow rate for both freestream conditions. It actually causes no obvious loss of the inlet flow rate. Also, the following total pressure drop and drag increase are below 0.4%. Additionally, the observed unique buzz flow implies that the buzz origin is not necessarily limited to the two known sources, as opposed to the long-established understanding.

I. Introduction

SUPersonic inlet buzz [1] is a great threat to air-breathing supersonic vehicles. Usually, it is triggered by an accidental downstream pressure- or thermal-driven flow blockage, which can throw the inlet into the undesirable subcritical mode featuring a terminal shock standing upstream of the inlet entrance [2,3]. Once the buzz occurs, self-excited streamwise normal-shock oscillations are generated along with periodic duct pressure fluctuations, provoking a sharp drop in captured air flow and the consequent engine thrust penalty. What’s worse, the accompanying unsteady aerodynamic and thermal loads may further cause combustion flameout, engine surge, and even catastrophic aircraft crash in some instances. Therefore, the inlet buzz with intense fluid unsteadiness should be avoided or at least remarkably delayed, of which the realization draws great academic interest.

Generally, the ramp flow separation induced by the expelled terminal shock is one of the major factors triggering the supersonic inlet buzz [4–9]. In this sense, a workable solution to the flow instability is to weaken the shock wave–boundary-layer interaction (SWBLI), and great efforts have been made in introducing various boundary-layer control techniques into the inlet design. Among them, the vortex generators (VGs) are widely used in practical conditions [10–12]. Typically, they are shaped into vanes or ramps [13–17] and installed ahead of the interaction region. Streamwise vortices are thus created to transfer the high-momentum fluid of the main flow to the near-wall zones, enhancing the resistance of boundary-layer flows to the shock-induced adverse pressure gradients. For an active usage, the conventional mechanical structure can be replaced with air jets [18]. In addition to the VG devices, a novel flow manipulation method named “dielectric barrier discharge actuator” [19] is also preliminarily validated to have positive effects on stabilizing the inlet flow.

Unfortunately, alleviating the flow separation alone is theoretically far from adequate to eliminate buzz when a severe downstream choking arises. The reason behind this problem is the serious mismatch between the air supply and demand, which can trigger a global collapse of flowfield by a fast chamber pressure build-up [9,20–21]. To deal with this, more powerful strategies have to be adopted to discharge the excessively captured airflow rapidly. One feasible option is to produce sufficient flow spillage before the duct entry by means of variable-geometry approaches, such as movable spoiler [22,23] and translatable spike [2]. However, the structural weight and complexity are substantially increased in this way. Moreover, the aerodynamic performance is sacrificed so greatly that such a measure should not be put into use unless necessary, which demands an active control. Consequently, a detection system monitoring the flow state

Nomenclature

\( \Delta \text{exit} \) = cross-sectional area of duct exit, \( \text{m}^2 \)

\( \Delta \text{Aplug} \) = throat area near plug, \( \text{m}^2 \)

\( F_d \) = inlet drag, N

\( M_0 \) = freestream Mach number

\( m, m' \) = inlet mass flow rate for no-bleed and bleed cases, respectively, kg/s

\( m'_{b} \) = bleed mass flow rate, kg/s

\( p \) = static pressure, Pa

\( p_0 \) = freestream static pressure, Pa

\( p_{\text{a}} \) = root mean square of pressure signal, Pa

\( R^2 \) = goodness of fit

\( t' \) = characteristic moment, ms

\( x \) = abscissa, m

\( x_r \) = leading-edge position of bow shock, m

\( \sigma, \sigma' \) = total pressure recovery coefficient at diffuser exit for no-bleed and bleed cases, respectively

Supersonic inlet buzz [1] is a great threat to air-breathing supersonic vehicles. Usually, it is triggered by an accidental downstream pressure- or thermal-driven flow blockage, which can throw the inlet into the undesirable subcritical mode featuring a terminal shock standing upstream of the inlet entrance [2,3]. Once the buzz occurs, self-excited streamwise normal-shock oscillations are generated along with periodic duct pressure fluctuations, provoking a sharp drop in captured air flow and the consequent engine thrust penalty. What’s worse, the accompanying unsteady aerodynamic and thermal loads may further cause combustion flameout, engine surge, and even catastrophic aircraft crash in some instances. Therefore, the inlet buzz with intense fluid unsteadiness should be avoided or at least remarkably delayed, of which the realization draws great academic interest.

Generally, the ramp flow separation induced by the expelled terminal shock is one of the major factors triggering the supersonic inlet buzz [4–9]. In this sense, a workable solution to the flow instability is to weaken the shock wave–boundary-layer interaction (SWBLI), and great efforts have been made in introducing various boundary-layer control techniques into the inlet design. Among them, the vortex generators (VGs) are widely used in practical conditions [10–12]. Typically, they are shaped into vanes or ramps [13–17] and installed ahead of the interaction region. Streamwise vortices are thus created to transfer the high-momentum fluid of the main flow to the near-wall zones, enhancing the resistance of boundary-layer flows to the shock-induced adverse pressure gradients. For an active usage, the conventional mechanical structure can be replaced with air jets [18]. In addition to the VG devices, a novel flow manipulation method named “dielectric barrier discharge actuator” [19] is also preliminarily validated to have positive effects on stabilizing the inlet flow.

Unfortunately, alleviating the flow separation alone is theoretically far from adequate to eliminate buzz when a severe downstream choking arises. The reason behind this problem is the serious mismatch between the air supply and demand, which can trigger a global collapse of flowfield by a fast chamber pressure build-up [9,20–21]. To deal with this, more powerful strategies have to be adopted to discharge the excessively captured airflow rapidly. One feasible option is to produce sufficient flow spillage before the duct entry by means of variable-geometry approaches, such as movable spoiler [22,23] and translatable spike [2]. However, the structural weight and complexity are substantially increased in this way. Moreover, the aerodynamic performance is sacrificed so greatly that such a measure should not be put into use unless necessary, which demands an active control. Consequently, a detection system monitoring the flow state...
in real time as well as a regulation system always ready for action are required. In fact, those devices are pure burdens while the inlet operates normally. Even if an emergency occurs, the success of controlling is often challenged by buzz identification failure or unacceptable time delay from geometry transformation, as far as the state of the art.

Unlike the preceding methods, the air bleeding method can easily weaken the flow separation [12,24] and balance the airflow rate [25,26], showing great potential to prevent inlet buzz. The bleed system is often designed as rows of slots [27–31] or holes [32–34], which are usually mounted in the neighborhood of throat or duct entrance and vented to a place with a lower pressure. Hence the shock-induced separated boundary layer and the excessive air can be automatically dumped overboard or reused by other systems. However, the air flow bleed is usually accompanied by an increase in aerodynamic drag and a loss of the compressed airflow [12], which both lead to an impaired engine thrust. Therefore, the air bleed should be carefully controlled to alleviate this negative effect and regulated according to the operating condition for a wide-range stability. In this regard, the most common treatment is, to the authors’ knowledge, adding a controllable throttling device, like a valve [26,35], into the bleed system. If so, an extra set of detection and regulation system becomes necessary for the sake of active control. Under the circumstances, preventing inlet buzz at low cost of structural weight and complexity is still a serious challenge.

After in-depth studies on the subcritical flow of an external-compression inlet [21,36], this work turns attention to this tough issue of inlet buzz suppression. A general strategy based on passive boundary-layer bleed is developed herein with the intention of postponing the buzz onset as well as eliminating the violent buzz over the full scope of exit blockage. To verify the stabilizing effects, an inlet model is specially designed and carefully investigated at both the design condition and a typical overspeed condition by experimental and numerical methods.

II. Description of Buzz Suppression Method

Figure 1 depicts a simplified external-compression inlet integrated with a fixed-exit bleed system entirely embedded into the ramp body. This bleed system is composed of flush-mounted slots, internal plenums, and exhausting tubes, connecting the upper compression flowfield with the lower ambiance. Those narrow slots are distributed on the ramp surface, covering a broad region where the detached terminal shock may stand. They are quite different from the commonly used bleed configurations (e.g., Refs. [29,31]). The internal plenums serve to collect and mix the airflow coming from the connected bleed slots. The exhausting tubes underneath the plenums play the role of directing the collected air outside and also act as the throats to limit the maximum bleed flow rate.

Once the external compression is established, the driving pressure difference is formed and the bypass flow is naturally created. Although the geometry of the bleed system is fixed, the distributed slots allow the bleed flow rate to be adjusted with the operating condition. For the case of near critical operation that features a terminal shock standing near the entrance, high total pressure recovery and flow rate should be ensured and ideally a zero-bleed airflow rate is required. At that state, the ramp flow above the bleed slots just passes the weak ramp shock and compression waves (Fig. 1a), and the pressure difference established between two ends of the bleed system is rather small. As a result, the actual air leakage is quite limited, although unavoidable. If an undesired deep subcritical operation arises, protecting against flow instability is a matter of utmost urgency. Under the circumstances, the bleed airflow increases rapidly due to the upstream expulsion of the terminal shock and generates strong stabilizing effects on the entire flowfield. The underlying mechanism involves the following three aspects (Fig. 1b).

First, the air bleed forming before the SWBLI can reduce the near-wall low-energy fluid, thereby improving the resistance of the boundary layer to separation in advance. Second, a localized air bleed with an even larger flow rate is also formed within the interaction region to suppress the suddenly thickened boundary layer or the ongoing flow separation, which eliminates the triggering factor of violent inlet buzz. Finally, the remarkably increased bleed airflow behind the terminal shock compensates effectively for the lack of outflow capability at the duct exit. Actually, the more upstream the terminal shock is pushed, the more bleed airflow occurs due to the increase in slots under the high-pressurized region. As a result, a more powerful control is naturally exerted under a more serious downstream blockage.

Overall, the basic strategy is to suppress inlet buzz by producing the self-adaptive flow removal depending on the terminal-shock position. An inlet equipped with this bleed system is expected to operate freely without facing intense flow unsteadiness over the entire flight envelope. One key issue is whether sufficient stability can be attained without a prohibitive penalty of the normal-state performance caused by the inevitable air leakage, which is also the major consideration when the effectiveness of the measure is discussed hereinafter. By the way, one should note that the ramp bleed is not always detrimental to an inlet operating at near-critical and super-critical states, though the importance of reducing bleed airflow is emphasized here. An appropriate amount of boundary-layer removal is beneficial for the reduction of total pressure loss and flow distortion as well.

III. Experimental Setup and Numerical Approach
A. Test Model

The test model is exactly identical to that used in [21,36] except for the addition of a bleed system in the forebody, as shown in Fig. 2. It is a rectangular external-compression supersonic inlet designed for a shock-on-lip Mach number of 2.0, including a blunt-tipped cowl, a partially isentropic ramp, a generic diffuser, and two unswept sidewalls with optical windows. Compared with the original model, a total of fourteen 90-deg flush slots with a length of 0.5 mm, a width of 50 mm (1.25 times the duct width), and a depth ranging from 2.4 to 4.3 mm are recessed into the ramp part at an interval of 3.5 mm. The slotted zone originates from the position 16.4 mm downstream of the ramp tip and takes up 60% or so of the entire ramp surface. There are three isolated plenums with a volume of about 0.05 m³, which are connected with the first five slots, the succeeding five, and the
remaining four, respectively. Each plenum is further vented overboard via four spanwise uniformly distributed tubes, which are all 4 mm in diameter and 85° in inclination relative to the freestream. Different opening combinations may lead to different bleed airflow rates. However, this is not the focus of the present study. Currently, two middle tubes of the second plenum and four tubes of the third plenum are kept fully open, whereas the others are well sealed. In other words, the first plenum of the bleed system is not put in service. The exhaust areas of the second plenum and the third plenum are 25.1 and 50.2 mm², respectively.

A throttle plug is installed at the duct end. The plug can slide along the duct centerline by means of a remote-controlled electric motor. The switching signal of the motor, which contains two values, is recorded during each test to obtain the time-varying plug state. The lower value indicates that the plug is moving upstream, whereas the other denotes that the plug is standing by. As per usual, the throttling ratio (TR) is used to describe the blocking degree at the duct exit. Its definition is given below:

\[
TR = \left(1 - \frac{A_{\text{th,plug}}}{A_{\text{exit}}} \right) \times 100\% \tag{1}
\]

where \(A_{\text{th,plug}}\) is the throat area near the plug and \(A_{\text{exit}}\) is cross-sectional area of the duct exit. In each test, the TR value starts from 0\% (corresponding to the fully opened exit) and ends at 99.1\% (corresponding to an almost closed exit) after 27 times of plug advance.

B. Wind Tunnel and Data-Acquisition Systems

All tests are carried out in the supersonic wind tunnel of the Nanjing University of Aeronautics and Astronautics, which operates in an air-breathing mode and has an effective operating duration over 20 s per run. The facility consists mainly of, from upstream to downstream, an interchangeable rectangular Laval nozzle with a 200 mm square exit, a fully closed test chamber, a 400 m³ vacuum tank, and the associated vacuum pumps. For an easy flow observation, optical glass windows sized 200 mm × 205 mm are recessed into the sidewalls of the test chamber. The detailed freestream conditions of the current tests are given in Table 1. Besides, it is worthy of note that theoretically the backpressure of the plenums in use can be as low as 0.38 \(p_0\) and 0.31 \(p_0\) for the Mach 2.0 test and the Mach 2.5 test, respectively, due to the flow expansion induced by the lower ramp surface, which allows the ramp bleeding to operate under a choked condition.

Thirty-one dynamic pressure transducers with a measuring range of 300 kPa (CYG-503; Double Bridge Inc.) are used to sense the transient flow patterns during the throttling process, as shown in Fig. 2a. They are flush-mounted along the midlines of the internal ramp and cowl surfaces, numbered consecutively with prefix “C” or “R” by location. Each transducer has a natural response frequency of 50 kHz. Obviously, the internal cavity in a transducer and the connecting conduit lead to a compromise of frequency characteristic. An estimation based on [37] indicates that the actual cutoff frequency is no less than 2085 Hz, which is adequate for the current research. Two National Instruments cards (DAQ PCI-6255) are adopted to acquire the pressure signals at a sampling rate of 20 kHz. To assess the uncertainties of dynamic and average pressure measurements, an evaluation is performed in advance, as in a similar way to [21]. It is shown that the maximum error of the instantaneous pressure is 0.3 kPa and that of the time-averaged pressure is the higher one between 0.23 kPa and 1% of the measured value. Additionally, it is worth to mention that the transducer R14, red-colored in Fig. 2a, was found out of work at the beginning of the Mach 2.0 test and so was one more transducer (R09) in the Mach 2.5 test. The corresponding data are not included in the discussion hereinafter.

The real-time flow images are captured by a high-speed Schlieren system using a horizontal knife edge. It incorporates a MEMRECAM HX-3 digital camera from NAC Inc. and a 400 mm f/5.6 lens from Nikon Inc. The sampling rate is set as 4000 frames per second. The achieved frame resolutions are 1728 × 472 and 1664 × 496 for Mach 2.0 and Mach 2.5 tests, respectively. The camera is triggered by an external signal, which is also recorded to synchronize the visualization process with the pressure acquisition process.

C. Numerical Approach

The Reynolds-averaged Navier–Stokes solver integrated in the commercial software, ANSYS Fluent, is used to improve the understanding of the stable flow characteristics and to evaluate the inlet near-critical performance. In solving the flow equations, a point Gauss-Seidel scheme is used to perform the time marching and the Roe’s scheme is employed for the inviscid flux calculations at the control surfaces. The one-equation Spalart-Allmaras model, which has been already validated in quite a few examples of inlet flow with boundary-layer bleed (e.g., Refs. [33,38]), is adopted to describe the turbulence on all scales. The corresponding governing equations are discretized by a second-order upwind scheme. Given the symmetry of geometry and boundary conditions, only half of the real fluid domain is

---

**Table 1** Freestream conditions of the wind-tunnel tests

| Property               | Value       |
|------------------------|-------------|
| Nominal Mach number    | 2.0, 2.5    |
| Actual Mach number     | 1.92 ± 0.01, 2.41 ± 0.01 |
| Total temperature, K   | 294.7 ± 0.1, 294.7 ± 0.1 |
| Total pressure, kPa     | 101.0 ± 0.3, 101.7 ± 0.3 |
considered in simulations (Fig. 3). To fill up the computational domain, hexahedral cells are constructed and the mesh near the regions where steep parameter gradients may exist are specially refined. Meanwhile, the y+ values of most near-wall cells are controlled around 30 to meet the requirement of the turbulence model.

To validate the numerical approach, a grid convergence study is conducted first, and three grids with increasing spatial resolution are tested at a typical operating condition, as shown in Fig. 4. The clear consistency between the results from the fine grid and the dense grid indicates that the flow simulation is not sensitive to the cell number if the cells are no less than $1.1 \times 10^7$. In this case, the fine grid is eventually used for the purpose of saving computational resource. Further, the fine-grid-based numerical approach is examined in accuracy by comparing the experimental pressure curves and flow patterns with the calculated ones for both freestream states (Figs. 5 and 6). Evidently, good agreement is reached. It is thus inferred that the said method is basically qualified for the current investigation.

IV. Flow Development with Bleed in Throttling Process

The inlet flow behaviors with ramp bleed at both the design condition and a typical overspeed condition are acquired in the almost entire throttle range (0–99.1%). General comparisons with the past studied no-bleed cases in which an exactly same course of plug transfer is involved are performed in Fig. 7 by the surface pressure histories from the survey point C17. For clear contrast, the time ruler of the no-bleed signal is recalibrated to have a same origin as the corresponding bleed data in each subplot. It can be seen that, at either operating Mach number, there exists an almost identical supercritical period compared with the previous test. But in the subcritical period,

---

**Fig. 3** Computational domain and boundary conditions.

**Fig. 4** Calculated surface-pressure distributions based on different grids ($M_0 = 2.0$, TR = 0%; coarse grid, $5.2 \times 10^6$ cells; fine grid, $1.1 \times 10^7$ cells; dense grid, $2.1 \times 10^7$ cells).

**Fig. 5** Surface-pressure distributions from experiments and simulations at TR = 0%.

**Fig. 6** Flow patterns from experiments and simulations at TR = 0% (I, ramp shock; II, barrier shocks and isentropic waves; III, cowl shock; IV, sidewall shocks; V, expansion waves; VI, flow separation; VII, separation shock; VIII, reattachment shock; IX, secondary shock or recompression shock).
A. Design Mode (\(M_0 = 2.0\))

As illustrated in Figs. 6a and 8, a progressive transition from the flow-through state to the near-critical state, which is fairly similar to that of no-bleed case studied by [21], is observed in the early throttling process. At the very beginning, a combination of oblique shock, curved shock, and isentropic waves is generated above the ramp surface to compress the freestream, and a nearly fully supersonic flow containing a progressively attenuated shock system is formed inside the duct (Fig. 6a). What is special is that a series of noncrossing weak barrier shocks is additionally produced from the slot edges and participates in the external compression process. As the TR is increased to 41.0%, a bifurcated near-normal shock emerges in the diffuser, leaving the downstream region full of subsonic air (Fig. 8a). When the value of TR reaches 45.5%, the terminal shock shifts upstream further to the vicinity of the duct entry plane and merges with the cowl shock as shown in Figs. 8b and 9, exhibiting the near-critical state of the inlet. It is worthy of note that the external supersonic compression fieldflow is hardly affected during the throttling process by far, so is the bleed flow rate.

The subcritical operation of the inlet commences since the TR is raised beyond 45.5%, as what occurred previously. However, under the influence of an ever-growing bleed flow, an increasingly different flow pattern is created during the remaining throttling process. It can be seen in Fig. 10 that the observation of subcritical flow begins with a steady terminal shock standing slightly upstream of the duct entrance. An image measurement shows that the shock distance away from the cowl lip is close to that of the corresponding no-bleed case (Fig. 11). Under the circumstances, a similar interaction arises with the leading ramp shock, and the resultant increase in subsonic spillage over the cowl is expected to be at a same level. But due to the ramp bleed, rows of weak shear layers are extra generated. Moreover, no ramp separation shows up herein in spite of the direct shock impingement. Consequently, the terminal shock enjoys a bare shape instead of a bifurcated one. The following rise of TR to 53.7% causes a nearly same upstream move of the terminal-shock compared with the old result, as shown in Fig. 11. After that, continued advances are steadily made by the terminal shock till the TR exceeds 86.4% in current case, which poses a striking contrast to the scene without bleed where the sudden onset and continuous enhancement of inlet buzz is exhibited. Interestingly, for the reason not fully understood, the present shock movement follows exactly a linear trend against TR, as illustrated in Fig. 11. It is also impressive that there is a short TR range, that is, from 79.1 to 86.4%, for the terminal-shock foot to be unmoved (Fig. 10).

Because of the remarkable extension of steady subcritical scope, a special flow change can be additionally found, that is, the gradual appearance of local reverse flow below the forepart of cowl plate. Evidence can be derived from the visible variations near the cowl lip. As it can be seen in Fig. 10a, there is a small dark fan at the beginning of subcritical state, which results from the rapid flow expansion along the lower surface of the cowl lip. With the TR rising, this dark expansion fan shrinks consistently (Fig. 10) and finally replaced with a bright one that denotes an outgoing expansion behavior surrounding the cowl lip when TR gets to 79.1%. In the meantime, the shear layer, which stems from the ramp shock–terminal shock interaction, bends upward progressively to such an extent that the tail of the shear layer is nearly turned backward. Both those facts suggest that the airflow within a small region near the cowl lip is already reversed by far. This tendency gets reinforced further afterward. At TR = 86.4%, even almost half of the captured air shows a sign of flowing backward shortly after entering the duct. The pushing effect of the reversed flow may explain why only the upper part of the terminal shock shifts upstream as TR varies from 79.1 to 86.4%. Taken altogether, the emergence of the cowl-side backflow contributes effectively to the duct flow balance under a seriously choked condition by reducing the intake flow. But at the same time, it is apt to interfere directly with the state of the terminal shock, imposing a potential threat on the inlet stability.

Further increase of TR to 90.0% initiates the unsteadiness of inlet flow and since then, small-amplitude flow oscillations appear. For a clear presentation of the unsteady flow features, Fig. 12 shows the Schlieren images of a typical oscillation cycle at TR = 95.5% as an
example. It can be found that, unlike the separation-dominated global oscillations observed on the past no-bleed inlet at a similar exit-throttle opening \([21]\), a type of terminal shock instability with a traveling distance less than 4 mm arises here. And no obvious separation emerges on the ramp throughout the cycle because of the airflow suction, though there is a boundary-layer thickening near the shock foot. Another marked difference that accompanies the usage of bleed is the appearance of consistently strong cowl-side reversed flow. For an instant of shock motion, the backflow even has a supersonic speed, which can be inferred from the short shock circled in Fig. 12. Because of its high strength, an inevitable head-on collision with the upcoming airflow leads to the visualization of a curved interface. Also, the pressure fluctuation peaks at the forepart of the cowl accordingly, as displayed by Fig. 13.

Besides the flow pattern, the frequency property of current buzz is found different from the no-bleed situation. As it can be observed in Fig. 14, where typical slices of the pressure-time history at \(TR = 95.5\%\) are plotted, there is no constant period of the present oscillation. A joint time-frequency analysis of the signal C17 based on the continuous wavelet transformation, which is convenient to show the frequency transition over time (e.g., Refs. [6,39]), further reveals that there are actually several frequencies of similarly high energy concentration at a moment and they vary irregularly with time (Fig. 15a). Obviously, a distinct picture is presented compared with the no-bleed buzz case of which the frequency is explicit (Fig. 15b). It is speculated that this difference is closely related to the advent of supersonic backflow. Regarding this point, a much clearer illustration can be accessed from the follow-up Mach 2.5 test.

B. Overspeed Mode \((M_0 = 2.5)\)

As the inlet runs at \(M_0 = 2.5\), all of the ramp waves reduce markedly in inclination angle and therefore interfere with the cowl
Fig. 14 Typical surface pressure-time histories during oscillations at $M_0 = 2.0$ (TR = 95.5%).

shock below the cowl plate. When the TR increases from 0% to 45.5% step by step, the inlet flow evolves steadily from a supercritical regime to a near-critical regime. As similar to what was described in [36], it is observed in this process that a terminal shock emerges and slides upstream progressively till it coalesces with the cowl shock at the duct entrance, as shown in Figs. 6, 16, and 17. Also, there is a same transition of the ramp shock–cowl shock interactional configuration, specifically, from a regular-reflection structure to a $\lambda$-shaped shock via a complex Mach-reflection structure. In principle, the contributing factor for the shock-pattern changes is the backpressure-induced growth in the angle of the curved cowl shock, which has been specially discussed in Ref. [36].

With the complete expulsion of the terminal shock, the subcritical operation begins at $TR = 50.1\%$. Recalling the Mach 2.5 test without bleed, a steady detached shock was found in the throttling-ratio range from 50.1 to 68.2%, including the broad separation-related little-buzz phase ($53.7\% < TR \leq 68.2\%$), and upstream shock moves following a parabolic trend were observed as TR increases within that scope. For the present case, roughly consistent shock variations can be measured at corresponding throttling ratios, as illustrated in Figs. 18 and 19. Further, this tendency of shock development gets extended to the TR of 73.7% with the ramp-side boundary layer remaining unseparated and the inlet flow staying stable. Continuous terminal-shock excursions suggest that there are significant increases in subsonic spillage during this throttling process. What’s more, a close observation reveals that a local backflow is gradually produced over the cowl lip to help sustain the flow balance at high TRs (Figs. 19e and 19f), as what happens in the aforementioned design condition. Inlet buzz is activated when the TR rises to 75.5%. Since then, a type of flow dynamics, which is characterized by a lightly traveling bow shock and a synchronously varying stream of cowl-side backflow, is exhibited, as shown in Fig. 20. Superficially, it resembles the “medium buzz” flow described in the no-bleed overspeed case [36], except that no ramp separation is actually incurred here. Moreover, a close similarity to the bleed-influenced flow unsteadiness at design mode can be also discovered. But there is a detail worth attention that two different phases can be found in the current instability. The first one ranges from 75.5 to 86.4%. In this phase, the reverse flow at top appears subsonic all the time. And there is an overall tendency for the backflow to intensify as TR rises. Meanwhile, shock motion with an ever-increasing amplitude is observed. In the extreme case (i.e., $TR = 86.4\%$), the streamwise extent of oscillation reaches about 10 mm. The second phase starts at $TR = 90.0\%$. In this phase, the airflow captured by the bottom flow channel is too excessive for the approximately closed inlet to be discharged downstream instantly. As a result, a supersonic reverse flow is forced to appear transiently, as displayed in Fig. 20c. More specially, the unsteady cowl-side backflow stays at a supersonic state all the time when the TR passes 95.5% (Fig. 20d). Possibly because of the resultant significant alleviation of the virtual flow choking, the shock-oscillation scope of the second phase drops back to the level (about 3 mm) shown at the onset of first-phase buzz and keeps basically unchanged all along.

Besides, there exist another two flow changes going with the buzz conversion. First, a conspicuous pressure-fluctuation jump arises in the region near the cowl lip, as can be learned from Fig. 21, where dimensionless RMS curves from two phases are compared. Second, the buzz frequency becomes vague and erratic. As shown in Figs. 22a and 22b, the dominant frequency of a throttling condition
within the first phase is explicit and compatible with the acoustic estimation based on Ref. [40] (200–220 Hz). By comparison, more frequencies of high energy come out once the second phase starts. They are distributed irregularly over a broad band and not fixed even for a given TR (see Figs. 22c and 22d).

Apparently, this sequence of small variations renders the current buzz flow closer to the foregoing instability at design mode. On the one hand, a fundamental similarity is indicated between two buzz cases. On the other hand, clear evidence can be therefore derived from that buzz transition to support the speculation made at the end of last section; that is, it is the supersonic reverse flow that is responsible for the frequency uniqueness. In a deeper aspect, one reasonable explanation is that the supersonic backflow interrupts the downstream disturbance convection, thereby interfering with the buzz frequency.
There is also a chance that the sudden massive air discharge breaks the steady acoustic reflection from the downstream flowfield by intermittently impeding the establishment of sonic choking.

V. Overall Assessment and Further Discussion

An overall assessment of the present strategy is conducted in this section. First to be considered is the suppressing effect on inlet buzz. As noted previously, for both the design mode and the overspeed mode, the inlet flow operating without bleed was already destabilized when the TR just rises beyond 53.7%. And shortly after that, severe separation-dominated flow oscillations appeared, displaying the rapid collapsing and reestablishing of the entire flowfield. By comparison, the throttling interval of subcritical stability is expanded to 86.4% and 73.7% for the current cases, respectively. More important, even if the inlet oversteps the stable-flow limit, global instability is never triggered and the intensity of the resultant buzz is always restricted to a low level, as addressed above. To further reveal the instability degradation after the equipment of the bleed system, comparisons of oscillating strength are drawn under all of the subcritical conditions, as shown in Fig. 23.
Obviously, considerable reductions occur in the bleed cases, especially under the seriously throttled environments. Thus, a conclusion can be easily made that the proposed measure is highly effective in buzz suppression. Focus is then shifted onto the bleed impact at critical mode. Table 2 collects the changes of main indices describing inlet performance based on CFD data. As can be seen, the actual flow rate of the air leakages accounts for not beyond 1% of that of the air finally flowing into the inlet (i.e., inlet flow rate) despite the ventilation and it is found too small to cause an observable loss of the inlet flow rate. In the meantime, it is clear that the performance is almost not sacrificed from the standpoints of total pressure recovery and inlet drag. Interestingly, even a small saving in drag is achieved when the inlet operates at $M_0 = 2.5$, perhaps because of the bleed-induced weakening of the pressure difference across the ramp. As far as the current results are concerned, the side effects consequent on the bleed system are far from worrying. Altogether, this bleed technique seems to be a promising scheme against the longstanding supersonic inlet buzz problem.

Besides, the interesting results present herein encourage an extended discussion with regard to buzz origin. As well known, a supersonic inlet buzz scenario always involves the instability of either a shear layer situated near the cowl or the shock-induced separation from the compression surface [5]. In the present context, it turns out that there is no chance for the ramp separation to be relevant to the unsteadiness, seeing that the SWBLI is well suppressed all the time. A doubt that the shear layer acts as the trigger may arise then, if it is noticed that the buzz takes place shortly after the swallowing of the shear layer originating from the leading ramp shock–terminal shock interference at the design mode. However, it can be soon cleared up by a further review of the overspeed bleed case, in which extremely similar buzz behaviors are developed with all shear layers staying distant from the cowl plate. Under the circumstances, a bold but plausible hypothesis is made that the potential origins of buzz are not necessarily limited to those two known sources. Observation further implies that there is a great possibility for the cowl-side reverse flow, whose state is very sensitive and easily perturbs the entire flowfield by influencing the upstream detached shock, to play the triggering role in the present study. By the way, the fact that the large-amplitude flow instability disappears together with the ramp-side flow separation seems to support the classical viewpoint; that is, the separation is a necessity for violent buzz.

### VI. Conclusions

To delay supersonic inlet buzz considerably and eliminate violent buzz at low costs of structural weight and complexity, a novel buzz suppression approach based on fixed-geometry air bleed is brought forward in the current investigation. Unlike the commonly used bleed configurations, narrow flush slots are widely arranged along the compression surface herein. In this way, self-adaptive bypass flow can be created upstream of the internal duct using the natural pressure gradient that varies with the terminal shock location. With that effect, the subcritical stability of the inlet is expected to be greatly improved by an automatic combined prevention of boundary-layer separation and mass flow rate mismatch. Simultaneously, the undesired air leakage at the critical state can be naturally restricted to a pretty low level so that a prohibitive performance penalty can be averted during normal operation.

For verification of the real stabilizing effect, a ramp bleed system of the proposed configuration is specially designed on the basis of a repeatedly studied rectangular external-compression inlet with a shock-on-lip Mach number of 2.0. By careful wind-tunnel tests, the modified flow behaviors at both the design mode and a typical overspeed condition are obtained with an almost full throttling range considered. A detailed comparison with the corresponding no-bleed cases indicates that the subcritical stable-flow margin is remarkably extended at each operating Mach number after the equipment of such a system, specifically, from a maximum throttling ratio threshold of 53.7% to that of 86.4% and 73.7%, respectively. Within the stable range, it is observed that the expelled terminal shock always stands steadily on the compression surface without causing an obvious separation at a given throttle and moves upstream consistently with the TR rising, following a linear or a parabolic trend. In the meantime, it is found that a stream of reverse flow takes shape gradually under the cowl plate, which in fact contributes effectively to the duct flow balance under a seriously throttled condition by reducing the intake flow. As the exit blockage exceeds the foregoing stability limit, inlet buzz occurs. But at the critical freestream condition, only a mild flow oscillation regime featuring a slightly traveling shock and a varying cowl-side backflow appears, even when the duct exit is almost closed. This poses a striking contrast to the corresponding case without bleed in which global unsteadiness is exhibited soon after the destabilization of inlet flow. Besides, a quantitative analysis shows that the bleed flow rate at the near-critical state is not beyond 1% of the inlet flow rate for both conditions. It actually causes no obvious loss of the inlet flow rate. Also, the following total pressure drop and drag increase are below 0.4%. It is thus proved that the proposed strategy is capable of suppressing buzz effectively at subcritical mode and at the same time producing few side-effect during normal operation.

Additionally, there is an interesting finding that the currently observed unique mild buzz is not related to the Ferri instability or the Dailey instability. In this case, a bold hypothesis that conflicts with the long-established buzz understanding is made that the origins of buzz are not necessarily limited to the two known sources. But the fact that the large-amplitude instability disappears together with the shock-induced flow separation seems to support the classic viewpoint; that is, the separation is a necessity for violent buzz.

### Acknowledgments

This work was funded by the National Natural Science Foundation of China (Grant No. 11532007) and the Jiangsu Province “333” Project (Grant No. BRA2018031).

### References

[1] Oswatitsch, K., “Pressure Recovery for Missiles with Reaction Propulsion at High Supersonic Speeds,” NACA TM-1140, 1947.

[2] Seddon, J., and Goldsmith, E. L., Intake Aerodynamics, 2nd ed., AIAA Education Series, AIAA, Washington, D.C., 1999, Chaps. 5, 12. doi:10.2514/4.473616

[3] Oates, G. C., Aircraft Propulsion Systems Technology and Design, AIAA Education Series, AIAA, Washington, D.C., 1989, Chap. 4. doi:10.2514/4.861499

[4] Dailey, C. L., Supersonic Diffuser Instability, Ph.D. Dissertation, California Inst. of Technology, Pasadena, CA, 1954.

[5] Fisher, S. A., Neale, M. C., and Brooks, A. J., “On the Sub-Critical Stability of Variable Ramp Intakes at Mach Numbers Around 2,” National Gas Turbine Establishment Rept. ARC-RM-3711, Fleet, England, U.K., Feb. 1972.

[6] Trapier, S., Duveau, P., and Deck, S., “Experimental Study of Supersonic Inlet Buzz,” AIAA Journal, Vol. 44, No. 10, 2006, pp. 2354–2365. doi:10.2514/1.20451

[7] Lee, H. J., Lee, B. J., Kim, S. D., and Jeung, I., “Flow Characteristics of Small-Sized Supersonic Inlets,” Journal of Propulsion and Power, Vol. 27, No. 2, 2011, pp. 306–318. doi:10.2514/1.46101

[8] Chima, R. V., “Analysis of Buzz in a Supersonic Inlet,” NASA TM-2012-217612, 2012.
[9] Soltani, M. R., and Sepahi-Youssi, J., “Buzz Cycle Description in an Asymmetric Mixed-Compression Air Intake,” *AIAA Journal*, Vol. 54, No. 3, 2016, pp. 1040–1053. doi:10.2514/1.J052214

[10] Chang, J., Li, N., Xu, K., Bao, W., and Yu, D., “Recent Research Progress on Unstart Mechanism, Detection and Control of Hypersonic Inlet,” *Progress in Aerospace Sciences*, Vol. 89, Feb. 2017, pp. 1–22. doi:10.1016/j.paerosci.2016.12.001

[11] Im, S., and Do, H., “Unstart Phenomena Induced by Flow Choking in Scramjet Inlet-Isolators,” *Progress in Aerospace Sciences*, Vol. 97, Feb. 2018, pp. 1–21. doi:10.1016/j.paerosci.2017.12.001

[12] Babinsky, H., and Harvey, J. K., “Some Aspects of Supersonic Inlet Stability,” *Progress in Aerospace Sciences*, Vol. 74, April 2015, pp. 209–280. doi:10.1016/j.paerosci.2014.12.006

[13] Panaras, A. G., and Lu, F. K., “Micro-Vortex Generators for Shock Wave/Boundary Layer Interactions,” *Progress in Aerospace Sciences*, Vol. 74, April 2015, pp. 16–47. doi:10.1016/j.paerosci.2014.12.006

[14] Varma, D., Saurav, S., and Ghosh, S., “Flow Control in a Mach 4.0 Inlet by Slotted Wedge-Shaped Vortex Generators,” *Journal of Propulsion & Power*, Vol. 33, No. 6, 2015, pp. 1–11. doi:10.1109/TPS.2015.2457277

[15] Oorebeek, J., Nolan, W., and Babinsky, H., “Comparison of Bleed and Vortex Generator Effects on Supersonic Boundary-Layers,” 50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, AIAA Paper 2012-0045, Jan. 2012. doi:10.2514/1.510624

[16] Varma, D., Saurav, S., and Ghosh, S., “Flow Control in a Mach 4.0 Inlet by Slotted Wedge-Shaped Vortex Generators,” *Journal of Propulsion & Power*, Vol. 33, No. 6, 2015, pp. 1–11. doi:10.1109/TPS.2015.2457277

[17] Baydar, E., Lu, F. K., and Slater, J. W., “Vortex Generators in a Two-Dimensional External-Compression Supersonic Inlet,” *Journal of Propulsion and Power*, Vol. 34, No. 2, 2018, pp. 521–538. doi:10.2514/1.B36414

[18] Valdivia, A., Yuceil, K. B., Wagner, J. L., Clemens, N. T., and Dolling, D. S., “Control of Supersonic Inlet-Isolator Unstart Using Active and Passive Vortex Generators,” *AIAA Journal*, Vol. 52, No. 6, 2014, pp. 1207–1218. doi:10.2514/1.J052214

[19] Im, S., Do, H., and Cappelli, M. A., “Plasma Control of a Turbulent Boundary Layer in an Unstarting Supersonic Flow,” 49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, AIAA Paper 2011-1143, Jan. 2011.

[20] Herges, T. G., Dutton, J. C., and Elliott, G. S., “High-Speed Schlieren Analysis of Buzz in a Relaxed-Compression Supersonic Inlet,” 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA Paper 2012-4146, Aug. 2012.

[21] Chen, H., Tan, H. J., Zhang, Q. F., and Zhang, Y., “Bust Flows in an External-Compression Inlet with Partially Isentropic Compression,” *AIAA Journal*, Vol. 55, No. 12, 2017, pp. 4286–4295. doi:10.2514/1.J056066

[22] Obery, L. J., Cubbison, R. W., and Mercer, T. G., “Stabilization Techniques for Ramp-Type Side Inlets at Supersonic Speeds,” NASA RM E55L16a, 1955.

[23] Connors, J. F., “Some Aspects of Supersonic Inlet Stability,” NASA RM E55L16a, 1956.

[24] Delery, J. M., “Shock Wave/Turbulent Boundary Layer Interaction and Its Control,” *Progress in Aerospace Sciences*, Vol. 22, No. 4, 1985, pp. 209–280. doi:10.1016/0376-0421(85)90001-6

[25] Paynter, G. C., Mayer, D. W., and Tjonneland, E., “Flow Stability Issues in Supersonic Inlet Flow Analyses,” 31st *AIAA* *Journal of Propulsion and Power*, Vol. 27, No. 6, 2011, pp. 1186–1195. doi:10.2514/1.B34223

[26] Herrmann, D., and Gulan, A., “Experimental Studies of Boundary-Layer Bleed Impact on Ramjet Inlet Performance,” *Journal of Propulsion and Power*, Vol. 27, No. 6, 2011, pp. 1186–1195. doi:10.2514/1.B34223

[27] Herriman, D., and Gulan, A., “Experimental Studies of Inlet Characteristics of an Airbreathing Missile with Boundary-Layer Bleed,” *Journal of Propulsion and Power*, Vol. 31, No. 1, 2014, pp. 1–10. doi:10.2514/1.B35339

[28] Soltani, M. R., Youssi, J. S., and Farahani, M., “Effects of Boundary-Layer Bleed Parameters on Supersonic Inlet Performance,” *Journal of Propulsion and Power*, Vol. 31, No. 3, 2015, pp. 826–836. doi:10.2514/1.B35461

[29] Soltami, M. R., Dalai, A., Youssi, J. S., and Farahani, M., “Effects of Bleed Position on the Stability of a Supersonic Inlet,” *Journal of Propulsion and Power*, Vol. 32, No. 5, 2016, pp. 1153–1166. doi:10.2514/1.B36162

[30] Sanders, B. W., and Cubbison, R. W., “Effect of Bleed-System Back Pressure and Porous Area on the Performance of an Axisymmetric Mixed Compression Inlet at Mach 2.5,” NASA TM X-1710, Dec. 1968.

[31] Slater, J. W., “Improvements in Modeling 90-Degree Bleed Holes for Supersonic Inlets,” *Journal of Propulsion and Power*, Vol. 28, No. 4, 2012, pp. 773–781. doi:10.2514/1.B34333

[32] Syberj, J., and Koncsek, J. L., “Experimental Evaluation of an Analytically Derived Bleed System for a Supersonic Inlet,” *Journal of Aircraft*, Vol. 13, No. 10, 1976, pp. 792–797. doi:10.2514/3.58712

[33] Mitchell, G. A., and Sanders, B. W., “Poppet Valve Control of Throat Stability Bypass to Increase Stable Airflow Range of a Mach 2.5 Inlet with 60 Percent Internal Contraction,” NASA TM X-1709, Oct. 1975.

[34] Chen, H., Tan, H.-J., Zhang, Q.-F., and Zhang, Y., “Throttling Process and Buzz Mechanism of a Supersonic Inlet at Overspeed Mode,” *AIAA Journal*, Vol. 56, No. 5, 2018, pp. 1953–1964. doi:10.2514/1.J056674

[35] Lv, C. D., *Thermal Parameter Measurement and Processing*, 2nd ed., Tsinghua Univ. Press, Beijing, 2009, pp. 160–161.

[36] Slater, J. W., and Saunders, J. D., “Modeling of Fixed-Exit Poorly Bleed Systems for Supersonic Inlets,” *Journal of Propulsion and Power*, Vol. 26, No. 2, 2010, pp. 193–202. doi:10.2514/1.37390

[37] Tan, H.-J., Sun, S., and Huang, H. X., “Characteristics of an Airbreathing Missile with Boundary-Layer Bleed,” AIAA Paper 1993-290, Jan. 1993.

[38] Tan, H. J., Sun, S., and Huang, H. X., “Modeling of Fixed-Exit Poorly Bleed Systems for Supersonic Inlets,” *Journal of Propulsion and Power*, Vol. 26, No. 2, 2010, pp. 193–202. doi:10.2514/1.37390

[39] Newsome, R. W., “Numerical Simulation of Near-Critical and Unsteady, Subcritical Inlet Flow,” *AIAA Journal*, Vol. 22, No. 10, 1984, pp. 1375–1379. doi:10.2514/3.48577

C. Lee
Associate Editor