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Hao Chen; Qi-Fan Zhang ✉; Wei-Hang Luo; ... et. al

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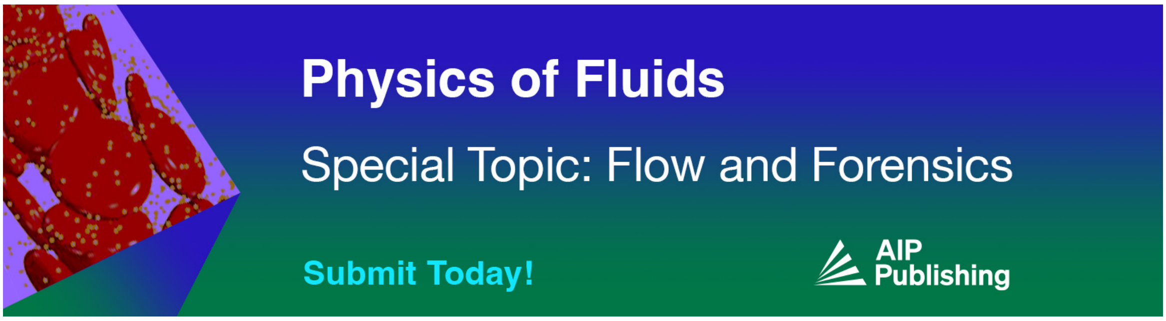

Switching between symmetric and asymmetric separation-induced shock reflections in an oscillatory duct flow

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Hao Chen,[1] Qi-Fan Zhang,[1,a)] Wei-Hang Luo,[2] and Lian-Jie Yue[1,a)]

AFFILIATIONS

[1]State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

[2]Wide Range Flight Engineering Science and Application Center, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

[a)]Authors to whom correspondence should be addressed: zhangqifan@imech.ac.cn and yuelj@imech.ac.cn

ABSTRACT

Separation-induced shock reflections in straight ducts are generally considered asymmetric for Mach numbers beyond 2.2, but our experiment shows that this is not always the case. A symmetric shock pattern, a proven outcome of following the free-interaction theory (FIT), is observed to appear in an oscillatory duct flow at a Mach number of 2.47. Interestingly, its existence is restricted to the period when the shocks move forward. Once a full retreat starts, it changes suddenly into an utterly asymmetric style that conforms to the past observation. This behavior indicates that the FIT fundamentally plays a limited role in supersonic duct flows.

Backpressure or mechanical throttling exerted on a supersonic duct flow can provoke a complex phenomenon known as a shock train.[1–3] It is prevalent among aerospace units such as scramjet isolators,[4–8] nozzles,[9,10] and supersonic cascades,[11,12] playing a crucial role in decreasing the incoming flow speed and cutting off the undesired downstream disturbances.[13–15] Its core element is the reflection that occurs between two leading shocks induced by flow separations, which largely shapes one's physical attributes; among them is whether the appearance is symmetric or not. In engineering, it is one of the critical issues concerning aircraft design and manipulation due to the potential grave threats from lopsided force[10] and an excessive thermal concentration that follows an asymmetric shock structure. Meanwhile, the complex flow mechanism behind it also makes itself a long-standing intriguing mystery in fundamental research.[16]

Long-term observation reveals that the asymmetry (or symmetry) of a separation-induced shock reflection in a straight duct mainly depends on the incoming Mach number. If the Mach number is lower than 2.2,[17] the shock structure is usually shaped into a Mach-reflection style, being symmetric at least in part.[18–20] Otherwise, it is mostly a regular reflection and tends to be utterly asymmetric even though the duct configuration and boundary condition are fully symmetric.[18,21,22] Interestingly, the latter case actually presents a picture that conflicts with not only intuition but also the well-established theory—the free-interaction theory[23] (FIT), according to which the angles of two leading shocks should be basically equal regardless of Mach numbers due to the consistency in the plateau pressures inside the separations for a given incoming condition. In this case, it is natural to suspect that the FIT might fail to work somehow within the framework of supersonic duct flows once the Mach number exceeds the threshold, which challenges the present understanding of separated flows and inevitably requires systematic evidence. Therefore, unless this hypothesis is adequately confirmed, doubt would remain regarding whether the shock reflection is bound to be asymmetric for a high Mach number as observed previously.

In this Letter, we report a special wind tunnel experiment conducted on the supersonic direct-connect test facility located at the Institute of Mechanics, Beijing. It is shown that it is possible for the separation-induced shock reflection with an incoming Mach number of 2.47 to assume a relatively stable and symmetric shape. Furthermore, that symmetric structure can coexist with a distinctly asymmetric one in some way. Those findings are expected to expand the understanding of the role of the FIT in deciding the separated flows, as detailed below.

Figure 1 illustrates the main body of the experimental setup. It includes three parts, namely, a Laval nozzle, a test article, and a plug.

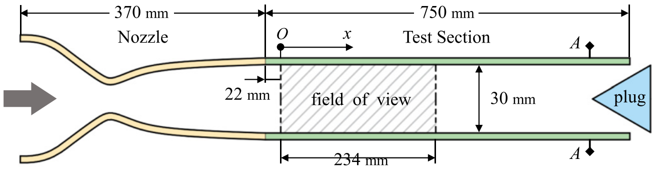

FIG. 1. Schematic diagram of the experimental setup. The origin of the x-axis is placed 22 mm downstream of the nozzle exit. Point A is where the backpressure is monitored, located at $x = 703$ mm.

The nozzle is used to speed up the upstream flow to the target Mach number, i.e., 2.47, and its profile is specially designed to prevent undesired shocks. The test article is a rectangular constant-area duct, being 750 mm long, 30 mm high, and 100 mm wide. To visualize the flowfield in the area of interest, a pair of optical glasses, which is 234 mm in length, is recessed into two sidewalls and placed 22 mm away from the nozzle. The plug installed at the duct exit serves as a throttling device. It can slide accurately along the centerline with the aid of a servo motor to produce different backpressures. In the current test, the plug stayed far downstream at the beginning; after the full establishment of the duct flow, it moved gradually to the designated location and then stood still till the end. The final blocked proportion of the exit area is 51.6%, and the consequent backpressure measures 5.9 times the incoming static pressure. Additionally, a schlieren system using a vertical knife is arranged to record the flow images in real time. It contains a Basler acA1920–155um camera, which operated at a frame rate of 100 fps and a shutter speed of 34 μs throughout the test. The frame resolution is 900 × 200 pixels.

Under the test condition described in Table I, the duct flow is no longer stable, and shocks start to move back and forth repeatedly along the duct. As exemplified in Figs. 2–4, a typical oscillatory cycle falls roughly into four phases, i.e., the shock advance, secondary oscillations, shock transformation, and shock retreat. At the very beginning ($t = 0$ s), all shocks stay downstream, beyond the scope of view. The only structure visible at that moment is two boundary layers adhering to the top and bottom walls. But shortly afterward, two oblique shocks, which are the leading part of a shock train and stem from the boundary-layer separations (as can be spotted later), come into sight ($t = 0.03$ s). Interestingly, they appear bilaterally symmetric in position and angle, standing in stark contrast to the past reports. In a subsequent short period ($t = 0.03$–0.16 s), the shocks shift upstream smoothly, and meanwhile, the surprising symmetry continues. After reaching the most upstream location of this phase, they stop to head downstream. However, they do not retreat back directly; instead, a type of small-amplitude secondary instability takes place and lasts for hundreds of milliseconds ($t = 0.16$–0.31 s). It is important to note that this change in flow behavior still does not break the shock symmetry.

TABLE I. Test condition.

Property	Value
Mach number	2.47
Total pressure, Pa	6.49×10^5
Static pressure, Pa	3.98×10^4
Total temperature, K	282.0
Static temperature, K	127.0
Unit Reynolds number, m^{-1}	6.95×10^7
Boundary-layer thickness,[a] mm	3.5
Turbulence intensity	0.19%
Throttling ratio at the exit	51.6%
Ratio of backpressure to incoming static pressure	5.9
Effective runtime, s	4.0

[a] The boundary-layer thickness is measured at $x = 0$ mm.

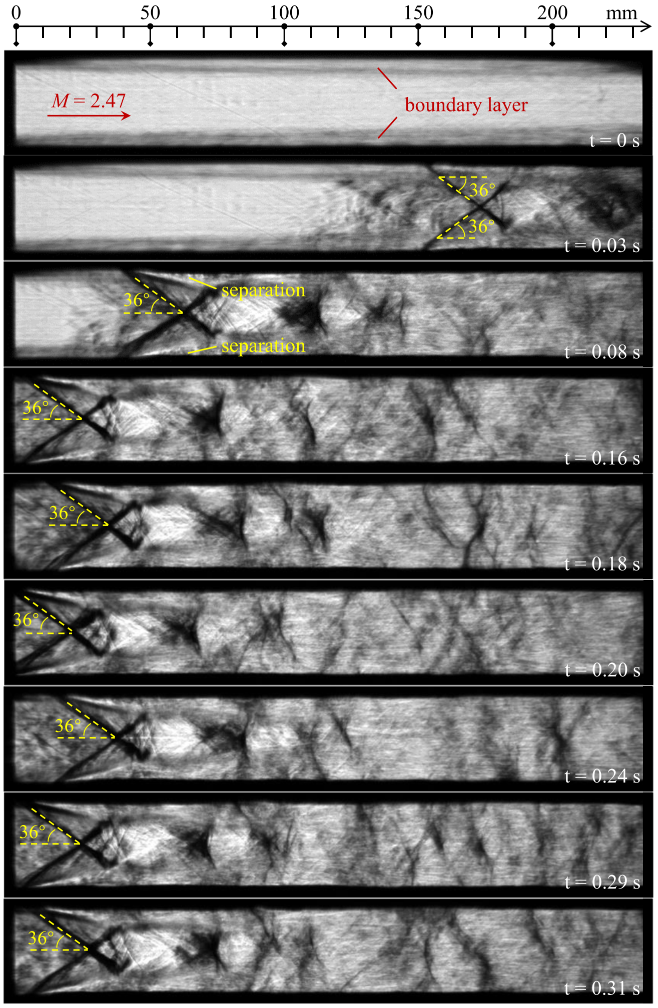

FIG. 2. Flow evolution during phases of shock advance ($t = 0$–0.16 s) and secondary oscillations ($t = 0.16$–0.31 s). The ruler on the top is used to show the physical distance the shocks move during oscillations. The variable t denotes the characteristic time in an oscillatory cycle, and its zero point is when the shocks start to advance from downstream. The angle of the lower shock remains to be 36° between 0.08 and 0.31 s, and annotations are intentionally excluded to prevent unnecessary coverings on images.

Suddenly, a transformation occurs. As can be seen in Fig. 3, the shocks travel forward a little bit at first after the secondary oscillations ($t = 0.32$ s), and when they get back, the situation is different ($t = 0.33$ s). While the angles look the same as before, the positions

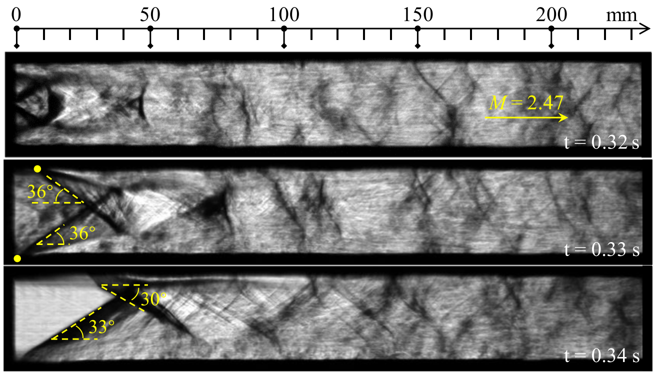

FIG. 3. Sudden transformation in the shock pattern after the secondary oscillations ($t = 0.32$–0.34 s). Yellow dots denoting the shock feet are used to reflect the positional mismatch between two shocks.

begin deviating from each other: the lower shock stands a little ahead of the upper. This difference even becomes much greater soon ($t = 0.34$ s), and with that also come significant variations in the shock angle. Although it is difficult to quantify the inclinations precisely due to the newly emerging curvature at the shock roots, measurement of their main parts indicates that the angles reduce overall, and the upper one suffers more. These changes together reshape the shock pattern to a highly asymmetric extent, rendering it much closer to the previous conclusion. Since then, the shocks retreat progressively to the place they start from, and in the meantime, nothing special arises, as displayed in Fig. 4. But considering the symmetric appearance at the outset, it can be concluded that there is a reversed shock switchover before the next cycle, despite the lack of direct observation. By the way, a detail of note is that the asymmetric shock structure does not always tilt upwards during the test, and an upside-down case happens in some cycles.

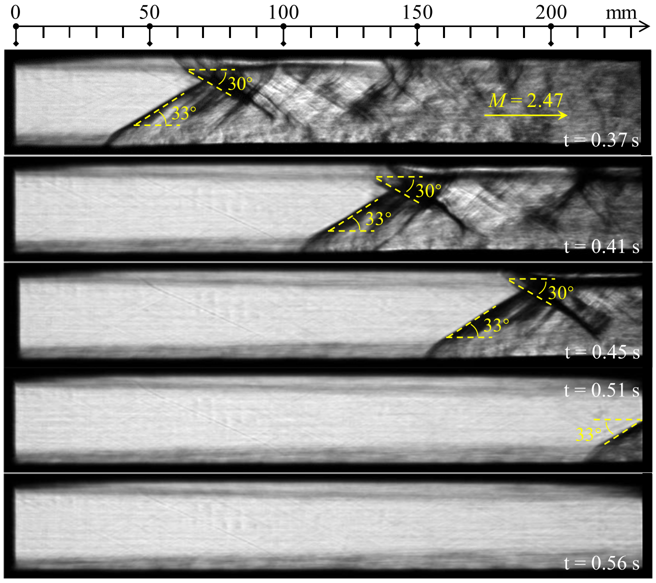

FIG. 4. Retreating process after the shock transformation ($t = 0.37$–0.56 s).

TABLE II. Theoretical shock angles.

Formula	Plateau pressure ratio	Shock angle (°)
Zhukoski[24]	2.24	35.6
Schmucker[25]	2.33	36.3
Tao[26]	2.27	35.8

TABLE III. Measured shock angles.

Phase	Upper shock (°)	Lower shock (°)
Shock advance	36	36
Secondary oscillations	36	36
Shock retreat	33 (Main stem)	30 (Main stem)

The above results show that two different shock patterns coexist under the same operating condition: one of them is symmetric, whereas the other is just the opposite. Given that the shocks originate from the flow separations, an analysis can be performed on the shock angle according to the FIT. Prior to that, the speed of the shock motion needs assessment because of its direct relation to the relative Mach number. A rough estimation based on the foregoing snapshots reveals that the shock speed is less than 5 m/s throughout a cycle, a negligible value relative to the incoming air speed (557.8 m/s), which suggests that the unsteady effect is quite weak. That is to say, the shock behaviors can be basically treated as quasi-steady. With this precondition, theoretical predictions are made based on three classic equations, all indicating that the shock angle should be 36° or so, as shown in Table II. Its comparison with the measurements listed in Table III shows that the symmetric pattern fundamentally is a result of following the FIT, while the other seems a distinct case. It proves that the FIT still takes effect in the ducted separated flows at a Mach number beyond 2.2. Nevertheless, the existence of the asymmetric shock pattern and the shock switching implies that there should at least be one more mechanism that controls the flow state simultaneously. Furthermore, considering the steady or quasi-steady symmetric observations are exceedingly rare at a Mach-number level like that or higher so far, it is speculated that the FIT might be often at a disadvantage in the competition for the decisive role in shaping high-speed duct flows. As for what the additional mechanism exactly is, it is unclear yet, but a recent investigation[27] shows that the minimum entropy production theory has the potential to be the answer. It has successfully predicted the asymmetric behavior between two rigidly positioned oblique shocks and is expected to play a bigger part in the future.

In summary, a stable symmetric separation-induced shock reflection is experimentally observed at an incoming Mach number, where an asymmetric one is generally expected and found capable of switching to an utterly asymmetric one when the direction of shock motion is reversed, which suggests an intricate role of the FIT in the ducted separated flows.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hao Chen: Conceptualization (lead); Formal analysis (lead); Funding acquisition (equal); Writing – original draft (lead); Writing – review and editing (supporting). **Qifan Zhang:** Funding acquisition (equal); Writing – review and editing (lead). **Weihang Luo:** Methodology (lead); Visualization (lead). **Lianjie Yue:** Funding acquisition (equal); Supervision (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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