Contents lists available at ScienceDirect

Theoretical & Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Letter

Passive shock wave/boundary layer control of wing at transonic speeds

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HIGHLIGHTS

- A sequential quadratic programming (SQP) optimization methods coupled with adjoint method was adopted to achieve the optimized shape and position of the bumps.
- Computational fluid dynamics (CFD), force test and oil test with half model all indicate that passive shock wave/boundary layer control (PSBC) with porous, slot, and bump generally reduce the drag by weaker lambda shock at supercritical conditions.
- Bump normally reduce drag at design point with shock wave position being accurately computed.

ARTICLE INFO

Article history:
Received 25 August 2017
Accepted 5 September 2017
Available online xxxx
*This article belongs to the Fluid Mechanics.

Keywords:
Wing
Shock wave/boundary layer interaction
Bump
Drag reduction
Transonic
Optimization design

ABSTRACT

At supercritical conditions a porous strip (or slot strip) placed beneath a shock wave can reduce the drag by a weaker lambda shock system, and increase the buffet boundary, even may increase the lift. Passive shock wave/boundary layer control (PSBC) for drag reduction was conducted by SC(2)-0714 supercritical wing, with emphases on parameter of porous/slot and bump, such as porous distribution, hole diameter, cavity depth, porous direction and so on. A sequential quadratic programming (SQP) optimization method coupled with adjoint method was adopted to achieve the optimized shape and position of the bumps. Computational fluid dynamics (CFD), force test and oil test with half model all indicate that PSBC with porous, slot and bump generally reduce the drag by weaker lambda shock at supercritical conditions. According to wind tunnel test results for angle of attack of 2° at Mach number $M = 0.8$, the porous configuration with 6.21% porosity results in a drag reduction of 0.0002 and lift–drag ratio increase of 0.2, the small bump configuration results in a drag reduction of 0.0007 and lift–drag ratio increase of 0.3. Bump normally reduce drag at design point with shock wave position being accurately computed. If bump diverges from the position of shock wave, drag will not be easily reduced.

Shock wave/boundary layer interaction is classical phenomenon in fluid mechanics field, which is appeared in supersonic front/rear step flow, transonic wing shock wave induced separation and high speed inlet flow [1]. It plays an important role in increase lift and drag reduction of aircraft, improvement inlet performance, and lessening pressure fluctuation. In spite of complexity of shock wave/boundary layer interaction, research on shock wave/boundary layer interaction is always the hot point in high speed aerodynamics field.

Lift increase and drag reduction of aircraft are eternal topics of research, which have been fueled largely by the aircraft design engineer and commercial transport industry. The aircraft drag directly influence its performance and economical efficiency. For USA's C-5 transport, one drag unit (0.0001) increment can result in load weight decrease of 454 kg. One method of drag reduction is to spread the laminar flow region or to delay boundary layer transition. Another method is to reduce drag at turbulence flow conditions, including passive shock wave/boundary layer control such as porous/slot, bump, ribs and vortex generator, active shock wave/boundary layer control such as blow/jet, micro jet, plasma control, magnetohydrodynamic (MHD) control and so on.

In 1971, Dennis Bushnell of NASA Langley research center suggested a passive shock wave/boundary layer control (PSBC) concept [2]. This concept refers placing a thin cavity with a porous top surface at airfoil position where shock wave will appear. The higher pressure downstream of the shock wave forces decelerated boundary layer air into the cavity and up ahead into the

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https://doi.org/10.1016/j.taml.2017.11.006

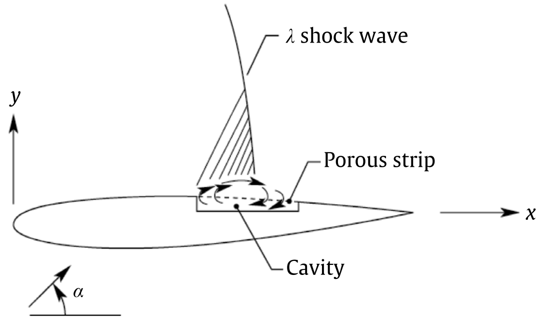


Fig. 1. The principle drag reduction of PSBC.

lower pressure region ahead of the shock wave. This thickens the upstream boundary layer and sends compression waves into supersonic region which weakens the strength of the shock wave. Nagamatsu et al. [3] achieved a drag reduction of 30%–40% on a super-critical airfoil by PSBC concept at Mach number $M = 0.85$–0.87. In 1992, Ashill et al. [4] first suggested two-dimensional bump concept at upper wing surface to reduce drag, including two kinds of method to weaken the strength of the shock wave, such as "strong interaction" of lambda shock system and "weak interaction" of isentropic compression [5]. After this, Eastwood and Jarrett [6] and Qin et al. [7] investigated three-dimensional bump control technique. Because three-dimensional bump geometry is more complex, the multiparameter optimization algorithm should be used. DASA-Airbus's research [8] indicated that if bump is applied in A-340's hybrid laminar wing, 2.11% fuel saving can be achieved at $M = 0.84$ cruise speeds.

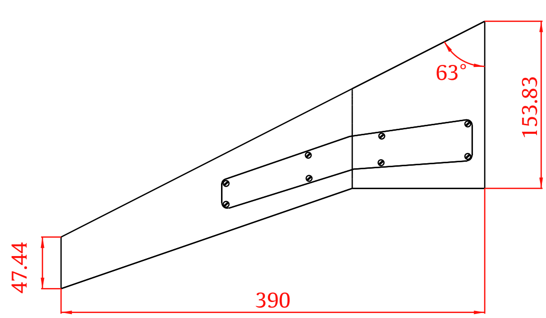
At present, research on three-dimensional wing PSBC technique is seldom be reported, especially relevant wind tunnel test results are more difficult to be noted. At another hand, there is no additional mass add in PSBC technique, which can be convenient to engineering application. In this paper, computational fluid dynamics (CFD), force test and oil test with half model in wind tunnel are conducted to investigate the PSBC with porous, slot and bump, in order to consolidate three-dimensional wing PSBC research.

At supercritical conditions a porous strip (or slot strip) placed beneath a shock wave can reduce the drag by a weaker lambda shock system, and increase the buffet boundary, even may increase the lift. Figure 1 shows the principle of the passive shock wave/boundary layer control for drag reduction. Reynald et al. [9] verified by schlieren that the principle of PSBC drag reduction is almost the same as bump control, which is to weaken shock wave by lambda shock system upon the porous strip.

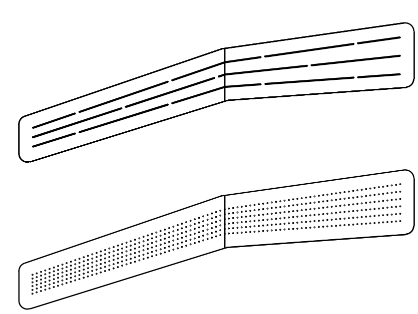
An SC(2)-0714 supercritical wing is investigated, with leading edge sweeping angle of 27°, half span of 390 mm, root chord of 153.83 mm, tip chord of 47.44 mm, and aspect ratio of 9.048. The test Mach numbers range from 0.7 to 0.85, angles of attack range from −4° to 8° with sideslip angle of 0°. Eight wing configurations will be tested by exchanging inserts, which include one baseline insert, 4 porous inserts and 3 slot inserts. Four porous inserts have porosity of 3.17%, 6.21%, 6.45%, and 10.27%, three slot inserts have porosity of 6.4%, 10.07%, and 14.5%, respectively. The insert extends from 5% to 60% of wing's span-wise position, with local length of 15% of chord. The boundary layer diverting plate with diameter of 360 mm and thickness of 18 mm, the half model and balance are installed on the half model rotating window of wind tunnel side wall (see Fig. 2).

The porous/slot control effort is presented in Fig. 3, at $M = 0.7$ and $M = 0.8$. The porous2 insert with 5 rows of holes with diameter of 0.7 mm, has local porosity of 6.21%, and the slot1 insert with 3 rows of gaps with width of 0.32 mm, has local porosity of 6.4%. The test results indicate that at $M = 0.7$, the porous2 and slot1 configurations both result in lift and drag decrease, and lift–drag ratio decrease when angle of attack less than 4°. At $M = 0.8$, the two configurations both result in lift increase and drag decrease when angle of attack less than 2°. At $M = 0.8, \alpha = 2°$ condition, the porous2 configuration results in a drag reduction of 0.002 (about 4%) and lift–drag ratio increase of 0.2 (about 2%) and the slot1 configuration results in a drag reduction of 0.0013 and lift–drag ratio increase of 0.3. The impact of perforation/slot on the surface pressure distributions at $M = 0.8, \alpha = 2°$ condition are illustrated in Fig. 4, based upon the CFD result. The same effort that multiple weaker shock waves upon the porous2 and slot1 configurations replace one shock wave from the baseline configuration can be seen at two span-wise locations. The porous2 configuration makes lift upstream of shock wave decrease but lift downstream of shock wave increase. The slot1 configuration makes lift between the first and the second gap increase and makes lift between the second and the third gap increase. The whole effort is both to make lift of wing a little decrease. Far from the perforation/slot region, no effect on the surface pressure distributions can be seen from Fig. 4.

Effect of bump geometry on drag reduction had been thoroughly investigated by Sommerer, who drew a conclusion that bump geometry does not play more roles in drag reduction than relevant position between bump and shock wave, and bump geometry. High-order linear polynomial is selected to define three-dimensional bump geometry, which is more simple to produce a smooth surface needed. Three-dimensional bump geometric parameterization is presented in Fig. 5. Six parameters can represent bump geometry, including bump crest, relative crest, bump length, bump height, bump span and wing span. The derivative of origin, crest and terminal are all set to be zero, in order to realize the leading and trailing edges of the bump smoothly transition to the wing surface. The bump height and length will be nondimensionalized by span-wise position.



(a) The sketch of the wing model.



(b) The sketch of the inserts (upper: slot1; low: porous2;).

Fig. 2. The sketch of the experimental model (unit: mm).