

Off-design performance of 2D adaptive shock control bumps

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Adaptive shock control bumps can exploit the on-design drag-reducing potential of 2D bumps, while mitigating their off-design performance deterioration through geometric modifications. In this study, experiments and simulations have been employed to investigate the wave-drag reducing potential of (actuated and unconstrained) 2D adaptive shock control bumps over a wide range of shock positions. Experiments were carried out in the Imperial College supersonic wind tunnel, modelling the adaptive bump as a flexible surface placed beneath a Mach 1.4 shock wave. 2D RANS CFD simulations of the flow in a parallel channel with a solid bump complement experiments. Wave drag was demonstrated to be proportional to the ratio of inlet to exit stagnation pressure in a blow-down wind tunnel for a given shock position. The shock exhibits a hysteretic behaviour when travelling in the wind tunnel working section, governed by the wave drag reducing potential of the bump. The actuated adaptive bump tested reduces wave drag over a wider operational envelope than solid bumps as experiments revealed the presence of three preferred structural configurations, which lead to a significantly enlarged hysteresis region. Finally, tests on unconstrained bumps were shown to increase wave drag, both on- and off-design, due to the unfavourable bump shapes that result from (only) passive actuation, suggesting that some constraints are required to achieve desirable surface deformations.

I. Introduction

Shock control bumps (SCBs) are a flow control mechanism with potential for application to improve the performance of transonic aerofoils. Normal shock waves inevitably occur on the upper surface of the wings of modern transonic aircraft, and their strength is expected to increase in the next decades due to the aspiration to raise cruise speed, and the application of technologies such as low-sweep wings and natural laminar flow aerofoils. However, shock waves lead to wave drag, and their low frequency unsteadiness is also a potential danger to airframe integrity. As Fig. 1 illustrates, shock control bumps, placed in the vicinity of the shock wave, bifurcate the normal shock into a λ -shape. A two-step pressure rise is obtained, and improved pressure recovery is achieved, with the effect of reducing wave drag [1]. The

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streamwise location of the oblique shock is fixed by the surface curvature at the front of the bump, and this has been reported to have the additional beneficial effect of stabilising the shock [2].

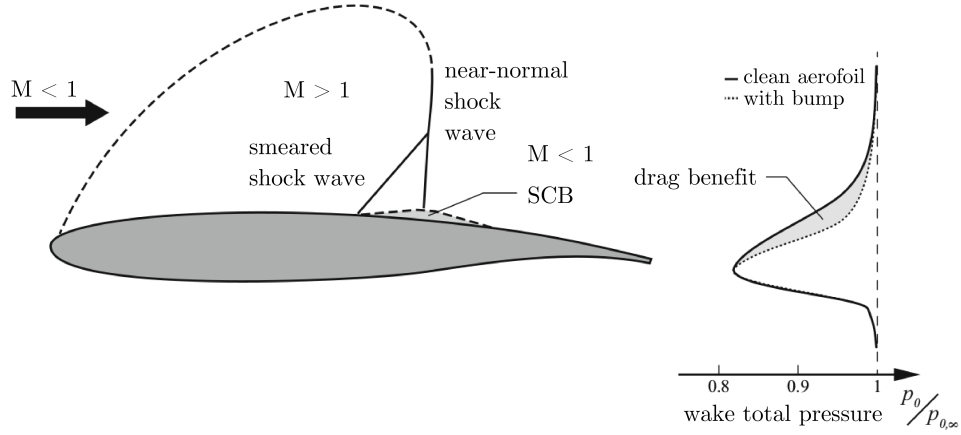


Fig. 1 Shock structure and stagnation pressure recovery for a 2D shock control bump [3].

The potential of shock control bumps on design is clear [3]. However, the high sensitivity of SCB performance to flow conditions (e.g. shock strength and position, upstream boundary layer and post-shock adverse pressure gradient), and the consequent performance deterioration off-design are also well known [3]. In fact, it has been shown that variations in shock position of as little as 10% of the SCB length (approximately 2-4% of the wing chord) cause significant changes to the nature of the flow, and, at certain operating points, a fixed geometry bump would lead to an overall increase in drag [3].

Therefore, adaptive SCBs are an attractive option, as they can exploit the on-design drag saving capabilities of 2D bumps, while minimising any detrimental off-design behaviour by geometric modifications. The initial concept of an adaptive SCB, shown in Fig. 2, was proposed in 1992 by Ashill *et al.* [4], and was followed by studies of the aerodynamic and structural behaviour of 2D and 3D adaptive bumps, with a focus on optimisation of the deformed bump shape [5–8] and actuation method [5, 9]. These studies demonstrated the potential of adaptive shock control bumps as a flow control mechanism, but they did not explore the detailed aero-structural behaviour of the flexible bump. Visbal [10], and Pasquariello *et al.* [11] presented results of simulations of a flexible plate subject to an oblique shock, but little is known about the effect that small perturbations in flow conditions might have on shock stability.

Ogawa and Babinsky [12] pointed out that any successful control mechanism introduces a shock instability problem in wind tunnel testing, such that it is impossible to hold a shock structure in certain locations. They developed a new setup including a shock holding plate for accurate and stable shock positioning [12]. While this allows the detailed study of the shock in an otherwise (unobtainable) unsteady region, the employment of a shock holding plate (which artificially stabilises the shock) in previous studies meant that shock stability could not be assessed.

In this paper we explore the performance envelope of 2D adaptive shock control bumps. We focus on their impact on

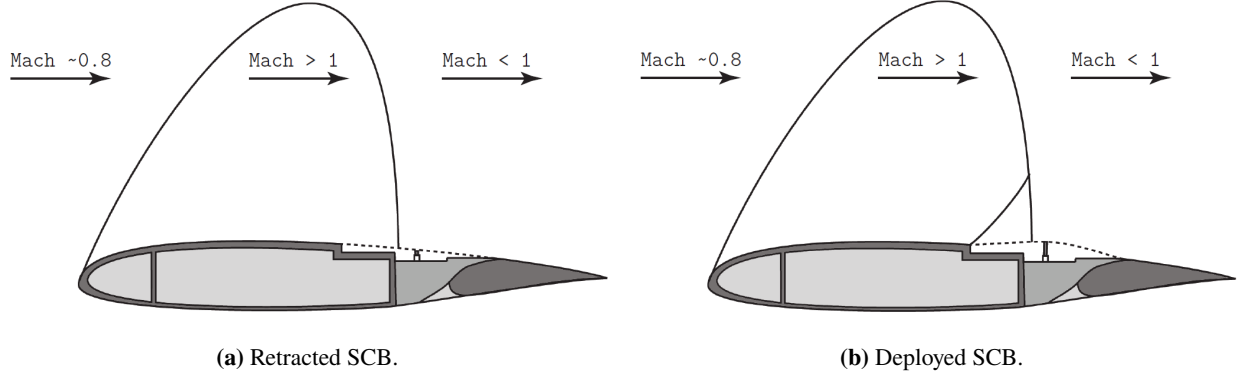


Fig. 2 Initial SCB concept, proposed by Ashill *et al.* [4].

wave drag, and relate their drag-reducing potential to the presence of instability regions in the transient shock behaviour. Experimental results are employed to assess the complex aero-structural behaviour of flexible bumps under the effect of the varying pressure loading imposed by the shock. Detailed investigation is aided by accurate measurement of the bump deformation using point-tracking photogrammetry. CFD simulations of rigid shock control bumps complement experimental results in an effort to decouple aerodynamic and structural effects, and hence highlight the advantages of adaptive over rigid structures.

II. Experimental setup

Experiments were carried out in the Imperial College supersonic wind tunnel (Fig. 3): a blow down facility, with a maximum run time of approximately 1 minute. The working fluid is air and the working section has a square cross section with side 150 mm and length 727 mm. A convergent-divergent nozzle is used to generate uniform Mach 1.4 flow in the test section, which is terminated by a normal shock around the streamwise position of the bump. The strength of this shock is representative of that expected on the suction surface of a next generation transonic wing.

The tunnel is operated using a LabVIEW program, consisting of a proportional-integral-derivative (PID) controller, which controls the pressure in the settling chamber by adjusting the aperture of a pneumatic pressure valve. The desired stagnation pressure is typically obtained with a standard deviation of 0.16% [14]. The inherent low frequency stagnation pressure oscillations (of the order of 1 Hz) are somewhat representative of the unsteady flow conditions encountered by a real transonic wing.

Fig. 4a shows a side view of the 2D adaptive bump. It is modelled as a 1 mm-thick flexible plate, made of aluminium alloy Al-7075-T6, and fixed to the wind tunnel floor such that the free portion is a square with length $L =$ width $W = 150$ mm. The bump thickness is reduced slightly to 0.8 mm close to the leading edge ($0 < x/L < 0.08$) to increase compliance in this region and allow increased deformations during runs. The ends are glued to solid blocks and the two sides are unconstrained. The shape of the bump is altered between different experiments by two linear actuators, placed

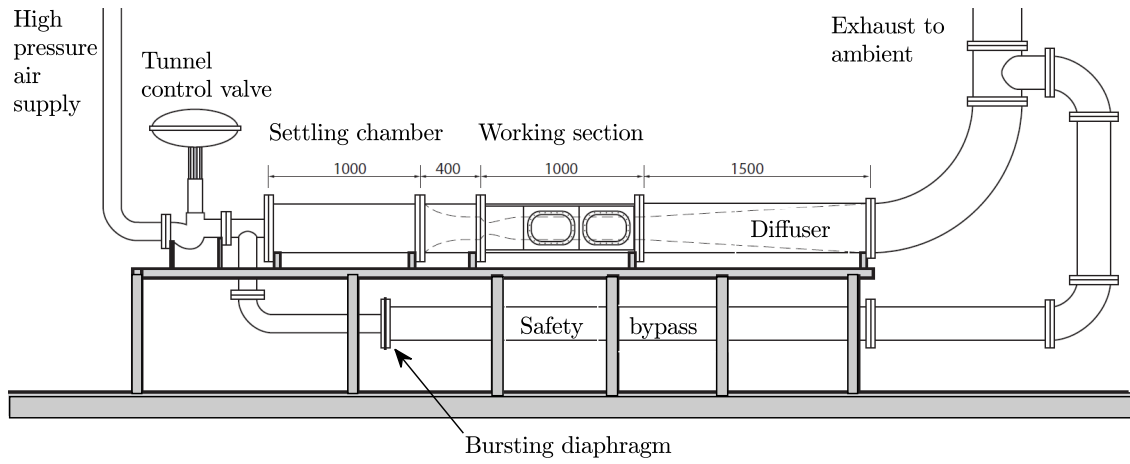
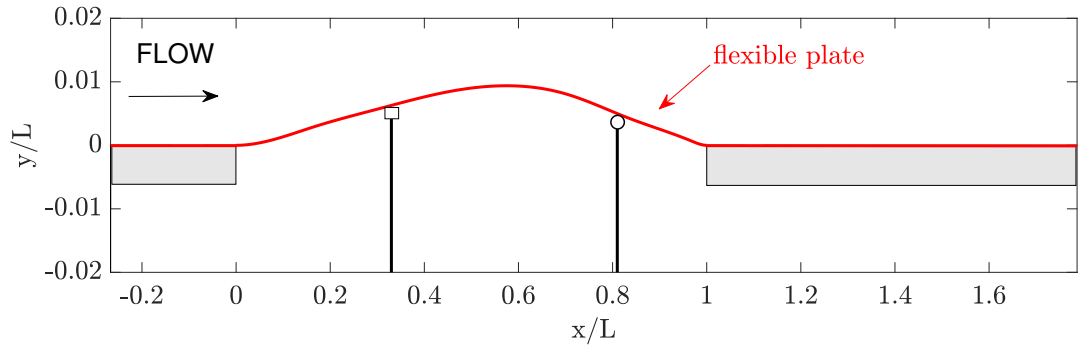
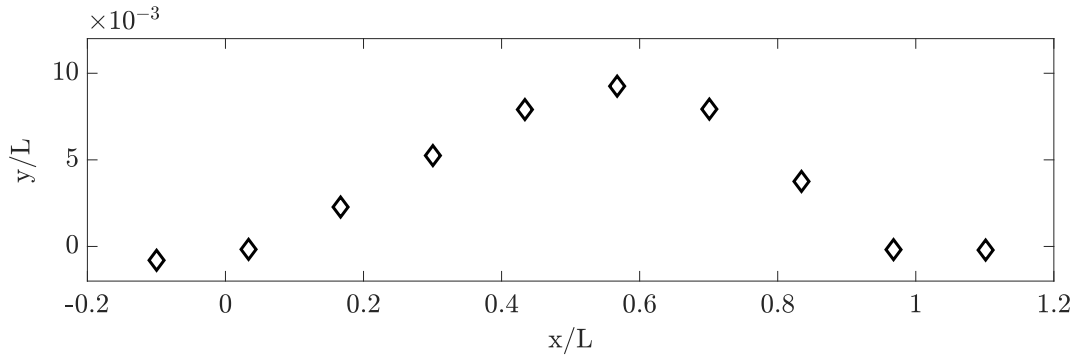


Fig. 3 Schematic of the Imperial College supersonic wind tunnel [13].



(a) Sketch of the flexible plate glued to solid blocks.



(b) Measured bump profile at $z/L = 0.033$, taken from photogrammetry (wind off).

Fig. 4 Side view of the adaptive bump. The vertical scale has been enlarged for clarity.

at $x_1/L = 0.33$ and $x_2/L = 0.81$, and glued to spanwise strips to apply a uniform displacement across the width of the plate. The first actuation point is fully fixed, while the second is free to rotate. When the actuators are deployed, the bump assumes a loaded beam geometry, with no curvature at the two fixed ends. The location and type of the constraints were chosen based on the results of FEA simulations. The experiments presented in this paper focus on the steady state behaviour of the bump, i.e. the actuators are deployed for the whole length of the run. The transients associated with the deployment and retraction of the bump are therefore not considered.

Fig. 4b shows the measured bump profile at a spanwise location of $z/L = 0.033$, obtained from photogrammetry at wind off conditions. The actuation heights are $y_1 = 0.60\%L$ (at $x_1/L = 0.33$) and $y_2 = 0.50\%L$ (at $y_2/L = 0.81$). The bump crest is initially located at $x_C/L = 0.56$ with height $y_C = 0.91\%L$. With respect to the displacement thickness of the incoming boundary layer, this corresponds to $y_C/\delta^* = 1.49$. To assess the impact of the passive actuation associated with the varying pressure loading, some experiments have been performed without the linear actuators (unconstrained flexible plate). A solid flat plate is also tested to simulate the flow over a clean aerofoil.

Static pressure tapings, connected to 32 pressure transducers sampling at 100 Hz, are located along the nozzle and the working section. A Z-type schlieren arrangement is utilised with a horizontal knife edge configuration. 2048×1400 pixel resolution images are recorded at a frame rate of 100 Hz and with an exposure time of $30 \mu s$. Point-tracking photogrammetry is employed to obtain accurate model deformation data during the experiments. As described in [15] and [16], four Phantom high-speed cameras are placed around the working section, and 80 coded targets, made of white vinyl, are attached to the flexible plate to facilitate the generation of the 3D model using the commercial photogrammetry software photoModeler by EOS Motion [17]. For this setup, the RMS error was calculated to be $30 \mu m$ [16], which can be considered negligible for the experiments presented in this paper.

III. CFD simulations

In order to achieve a better understanding of how adaptive shock control bumps affect drag reduction, and decouple the aerodynamic and structural phenomena taking place, experiments are complemented by 2D CFD simulations of the flow over a rigid shock control bump.

As shown in Fig. 5, the computational domain chosen is a 2D parallel duct with dimensions 600×150 mm, with the bump, of total length $L = 150$ mm, placed between $x = 0$ mm and $x = 150$ mm. The bump has a loaded beam geometry, with $y_1 = 1.1\%L$ at $x_1/L = 0.25$ and $y_2 = 1.6\%L$ at $x_2/L = 0.5$. This bump shape was chosen based on previous experiments on adaptive bumps carried out at Imperial College [14]. The computational results presented in the next Sections provide a methodology to estimate wave drag from experiments, and do not depend on the exact bump shape. Therefore, this method can be applied to the experimental results presented in this paper, despite the slightly different bump shape tested.

A Cartesian structured mesh is used, with mesh refinement added to the near wall region to better capture the

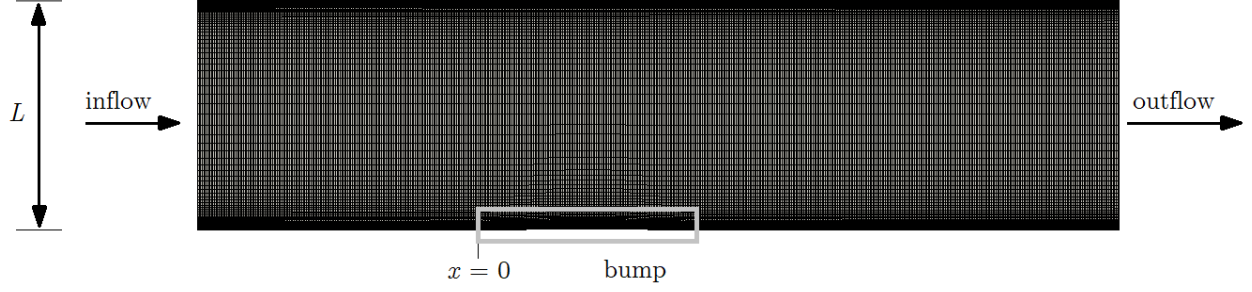


Fig. 5 Computational domain for the CFD simulations (a coarser mesh is shown for clarity).

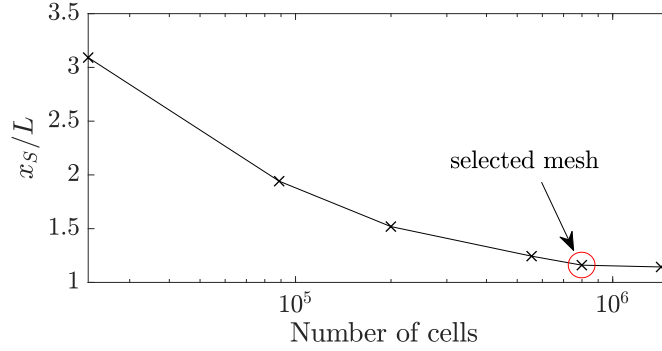


Fig. 6 Mesh convergence study for the 2D parallel duct. The shock position (x_s) is normalized by bump length ($L = 150$ mm).

boundary layer. Fig. 6 presents the results of a mesh convergence study for the clean 2D parallel duct (without a bump) using shock position, defined as the point where $M = 1$, as the metric. The chosen mesh, labelled on Fig. 6, has $900 \times 900 = 8.1 \times 10^5$ cells, which ensures $y^+ \approx 1$ at the wall. All the results presented in this paper are obtained from temporally (steady state is reached by time-marching CFD computations) and spatially converged simulations.

Simulations are performed using the *rhoCentralFoam* solver within OpenFOAM, which solves the conservative form of density-based Reynolds Average Navier-Stokes equations through the finite volume method with Kurganov flux scheme coupled with the van Leer flux limiter method [18]. The system is closed using the one-equation Spalart-Allmaras turbulence model [19]. The boundary conditions set in the simulations are the inlet and outlet static pressure, and the inlet velocity profile. A seventh order power law is used for the turbulent boundary layer, and this gives a shape factor of 1.25 before the shock, which matches that in the wind tunnel [13]. The two solid walls are set to a no-slip condition.

IV. Results

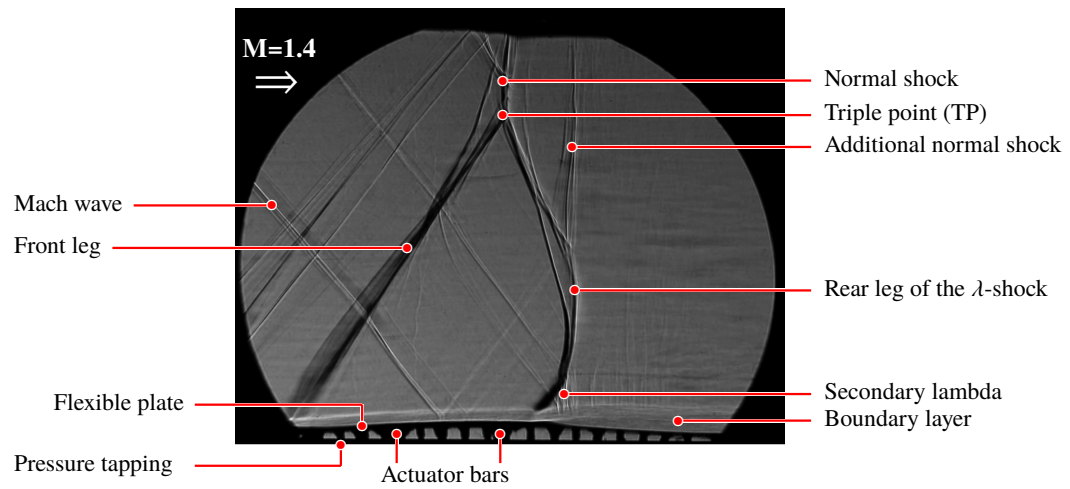
All dimensions in this paper have been normalised by bump length ($L = 150$ mm), x , y and z are the streamwise, vertical and spanwise coordinates respectively, streamwise distances are measured from the front of the flexible plate (where $x = 0$), and $z = 0$ corresponds to the tunnel centerline.

A. Flow features

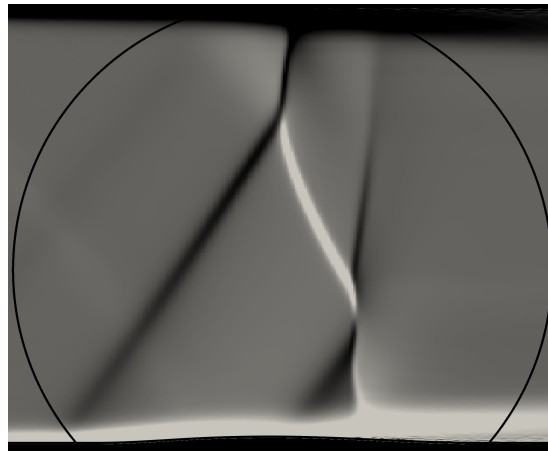
A typical schlieren image of the actuated flexible plate is shown in Fig. 7a. Labels indicate the location of the main flow structures and features of the bump. In particular, the typical λ -shock structure can be observed: the surface curvature at the front of the bump generates an oblique shock (front leg), which intersects the normal shock and the rear leg at the triple point. Another bifurcation (secondary lambda) can be seen close to the surface, where the rear leg interacts with the boundary layer. An additional weak normal shock extends between the rear leg and the top of the tunnel, to maintain flow uniformity in the working section. Fig. 7b shows the corresponding numerical schlieren image for a solid bump with the same shock position and plate shape as the adaptive bump in Fig. 7a. The black circle in Fig. 7b marks the field of view from schlieren photography. The main shock structures, labelled on Fig. 7a, can also be identified in Fig. 7b. The simplified nature of the simulations, which model a 2D section rather than the complex 3D wind tunnel structure, mean that some differences between Fig. 7a and 7b are inevitable. However, keeping these differences in mind, results from simulations are used here to complement those from experiments, exploring and quantifying additional features of shock control bump behaviour and performance.

Fig. 8 shows Mach number profiles on the adaptive bump (for $x/L > 0$) for several shock positions along the bump. Fig. 8a presents experimental results, plotted every 20 ms, and Fig. 8b the Mach number distribution obtained from six converged CFD simulations. It should be noted that the behaviour in Fig. 8a for $-0.92 < x/L < -0.14$ can be attributed to a lack of resolution: if some pressure tappings were placed in this region, smoother profiles (similar to those in Fig. 8b) would be observed. In both plots, M was calculated from pressure ratios (P/P_0) on the floor (either from pressure tappings on the flexible bump or from computational results at $y/L = 3 \times 10^{-5}$ for the solid bump), assuming that $P_0 = P_{0,\text{in}}$, i.e. neglecting stagnation pressure losses due to the shocks, which leads to an inaccuracy of the order of 1% in M estimation [14]. On design, when the rear leg impinges on the flexible surface close to the bump crest (e.g. one of the red intermediate profiles), a two step pressure rise (or Mach number drop) can be observed. This λ -shock structure is known to be beneficial for wave drag reduction, as oblique shocks compress the flow more efficiently than normal shocks [3]. However, the well-known performance deterioration of shock control bumps off design can also be seen in Fig. 8. For upstream shock positions (e.g. yellow profile), a normal shock occurs just upstream of the bump, and the subsonic post-shock flow accelerates on the first half of the bump and decelerates on the second half, with the possibility to develop an additional (weaker) shock. For downstream shock positions (e.g. brown profile), severe supersonic reacceleration takes place, leading to a strong (and lossy) rear leg. Despite a lack of numerical profiles for shock positions around the bump crest, the comparison between Fig. 8a and 8b indicates consistency between the computational and experimental results presented, giving further confidence to the validity of CFD simulations.

The additional normal shock that can be observed in Fig. 7 appears when supersonic flow reacceleration leads to a rear leg of the lambda of $M \approx 1.3$ or stronger. This threshold was calculated assuming that there are no discontinuities in static pressure between the regions above and below the triple point, and is consistent with what observed from the

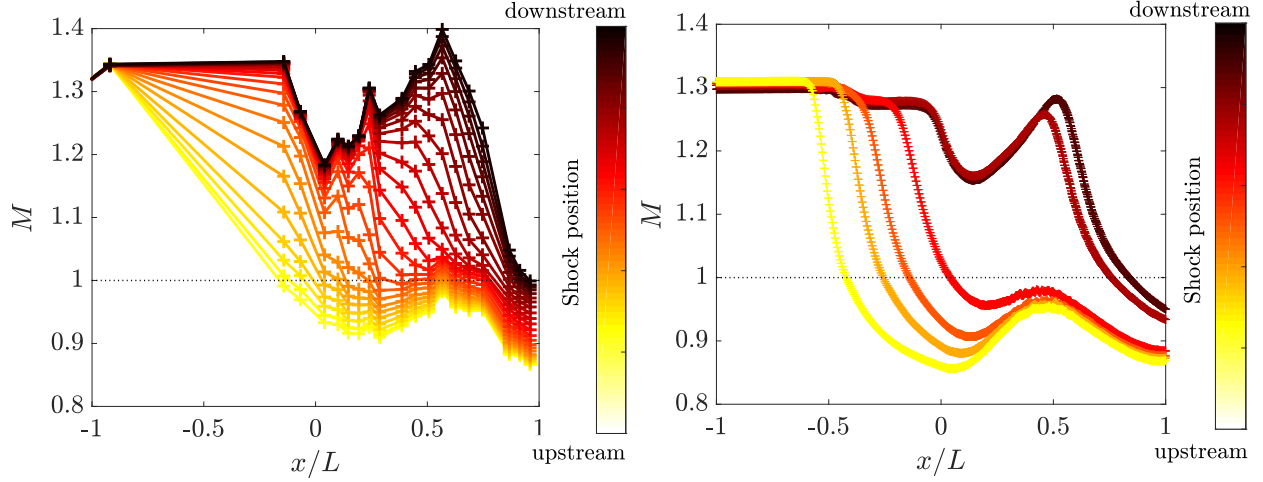


(a) Annotated experimental schlieren for an adaptive bump [14].



(b) Numerical schlieren for a solid bump (the black circle marks the field of view from schlieren photography).

Fig. 7 Comparison between experimental and numerical schlieren images.



(a) From experiments with the actuated adaptive bump (profiles plotted every 20 ms). (b) From simulations (6 steady converged solutions).

Fig. 8 Mach number profiles.

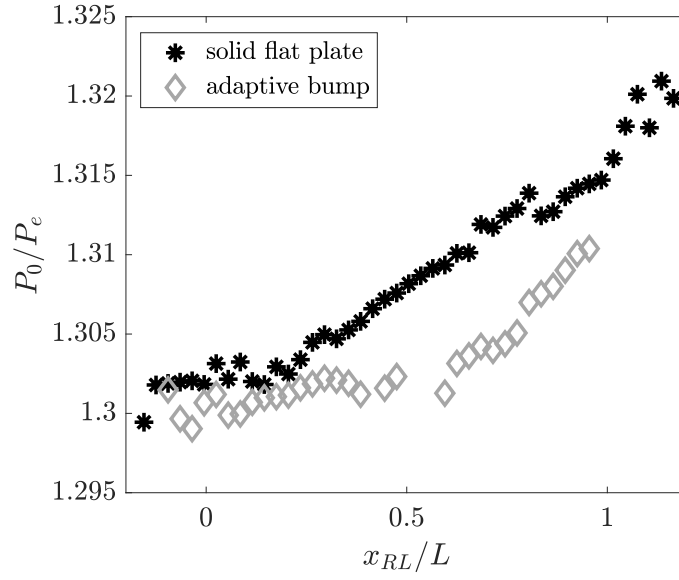
schlieren videos. The interaction of this shock with the upper surface of the wind tunnel inevitably leads to increased viscous losses in the boundary layer. However, the shock is expected to be very weak in all the cases presented in this paper because Fig. 8 shows that the strength of the rear leg never exceeds $M = 1.4$, so the additional pressure rise required is small. The detrimental effect on the boundary layer can therefore be considered negligible for the purpose of this study.

In addition, during experiments some interaction between the side wall boundary layer and the λ -shock structure is inevitable. However, consistency between the results presented in this paper for experiments and simulations (which assume infinite span) suggests that this interaction does not affect the main trends.

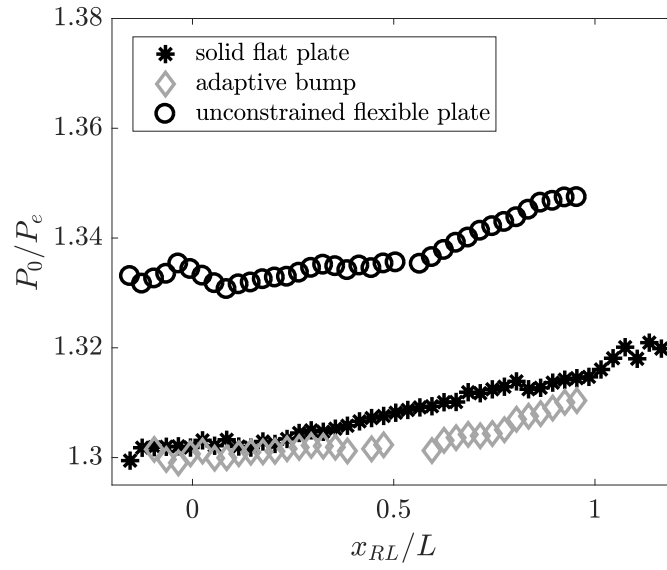
B. Wave drag

1. Average shock position

To determine the range of shock positions over which the bumps have a beneficial effect, the average flow structure above the bumps is studied and compared with a baseline (uncontrolled) case of a $M = 1.4$ normal shock above a solid flat plate. The uncontrolled normal shock was found to exhibit considerable unsteadiness due to small oscillations in the wind tunnel stagnation pressure. To characterise the behaviour of the flow above the bump, the evolution of the key features of the lambda shape has been tracked during a run. Specifically: the streamwise location of the triple point and the intersection between the rear leg of the λ -shock and the flexible surface. As described in [14], the triple point position (x_{TP}) is detected from schlieren images, while the location of the rear leg of the lambda shock (x_{RL}) is defined to be the point at which $M = 1$, according to the pressure readings on the bump. Throughout this paper, the shock



(a) Solid flat plate and actuated bumps.



(b) Solid flat plate, actuated bumps and unconstrained flexible plate.

Fig. 9 Plots of stagnation pressure ratio as a function of normalised shock position (bin size of $\Delta (x_{RL}/L) = 0.03$). All measurements are from experiments.

position is indicated by either triple point or rear leg position, based on which part of the λ -shock is of interest. However, it should be noted that the shock structure evolves above the bump such that an increase in x_{TP}/L corresponds to an increase in x_{RL}/L .

Fig. 9 shows plots of stagnation pressure ratio (where P_e is the tunnel exit pressure) against normalized shock position for the adaptive bump and the baseline case of the solid flat plate, obtained from experiments. Statistical binning of the instantaneous data is employed to calculate representative mean values. Fig. 9a compares the actuated bump with the solid flat plate only, while Fig. 9b includes the unconstrained flexible plate profile as well. The chosen bin size is $\Delta(x_{RL}/L) = 0.03$, and an average value is not calculated for bins with less than five elements.

Given that the wind tunnel exhausts to atmosphere (which fixes the stagnation pressure loss in the working section for a given inlet P_0) and that viscous losses in the supersonic boundary layer are greater than in the subsonic boundary layer, in previous studies [14] P_0/P_e has been regarded as an indication of the wave drag associated with the λ -shock structure: thus, for a given shock position, a lower P_0/P_e corresponds to lower wave drag. In Sec. IV.B.2 and IV.B.3, CFD will be employed to back up this assumption, and hence obtain a reliable way to compare the wave drag associated with several shock structures during wind tunnel experiments.

2. Stagnation pressure profiles

Stagnation pressure profiles downstream of the bump are useful to understand the impact of shock structure on wave drag. A Pitot rake was designed and tested, but unfortunately the additional blockage introduced prevented the wind tunnel from starting; simulations are therefore employed for this purpose. Fig 10a shows the variation of pressure recovery coefficients ($P_{0,out}/P_{0,in}$) at a fixed distance ($1.43L$) downstream of the impingement point of the rear leg on the floor for three representative shock structures, and the baseline case of the solid flat plate. The corresponding numerical schlieren pictures are presented in Fig. 10b-10e. Fig. 10a indicates that, when the shock is just upstream of the bump ($x_{TP}/L = 0$), the overall losses are similar to the baseline case, hence this bump does not have a strong influence on the post-shock flow. However, the other two λ -shock structures show a significantly different P_0 profile. For $x_{TP}/L = 0.38$, the presence of a clear lambda means that the flow is compressed more efficiently by an oblique shock (front leg) and a weak normal shock (rear leg) below the triple point ($y/L < 0.6$), with a pressure recovery coefficient close to 1 outside the boundary layer. However, above the triple point, the $P_{0,out}/P_{0,in}$ profile follows the baseline, as a single normal shock can still be seen in Fig. 10c. Finally, for $x_{TP}/L = 0.53$, the rear leg impinges on the bump past the crest, and expansion waves lead to supersonic reacceleration, increasing its strength, and leading to an additional bifurcation (secondary lambda), with associated stagnation pressure drop. However, the more downstream location of the triple point leads to a taller lambda, which can therefore affect a larger proportion of the flow, reducing the size of the strong normal shock above the triple point. Fig. 10a also shows that the solid flat plate exhibits the lowest stagnation pressure loss in the boundary layers, particularly the bottom one due to the detrimental effect that the bump inevitably

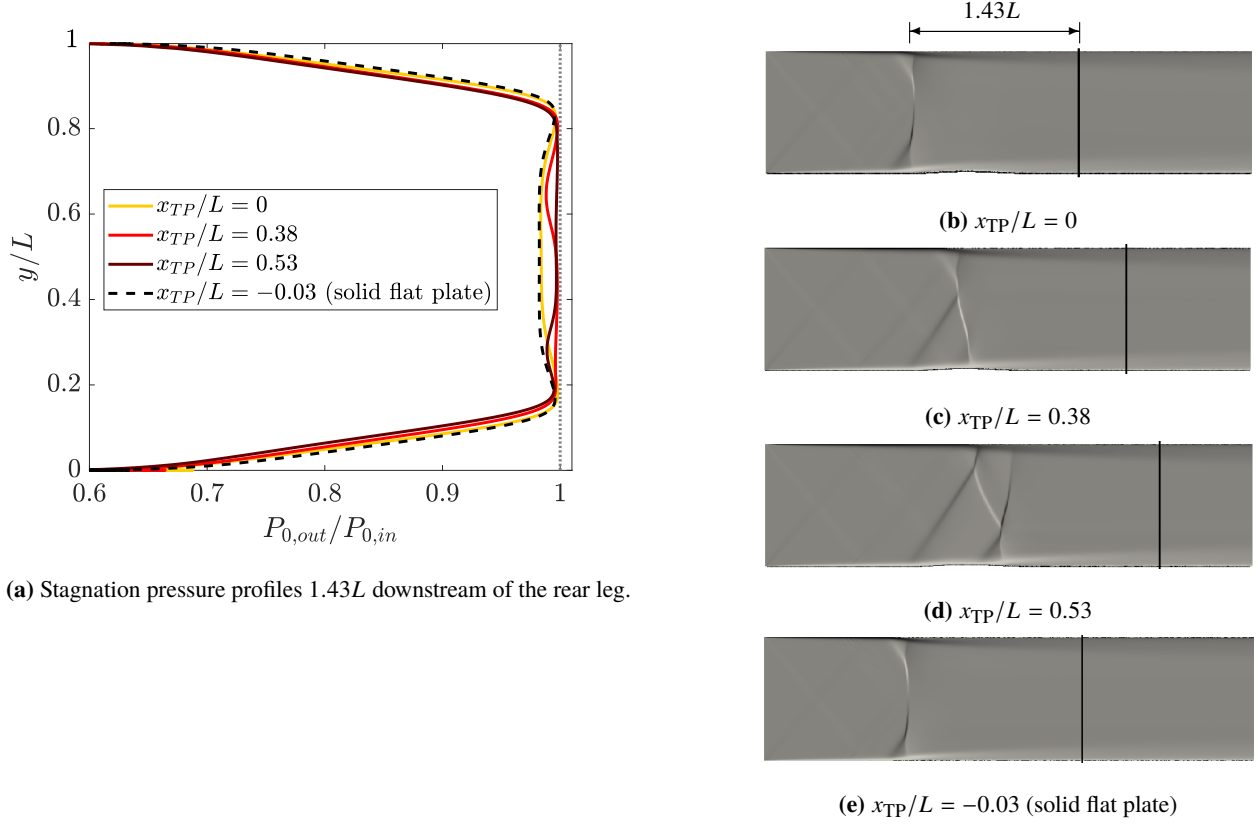


Fig. 10 Exit stagnation pressure profiles for the solid bump (from simulations) for different shock positions and the baseline case of the empty tunnel. The corresponding numerical schlieren images are shown on the right, where the vertical black line indicates the sampling plane.

has on the post-shock boundary layer.

3. Loss coefficient

A mass-flow-weighted total pressure loss coefficient (ϕ) is employed in order to quantify the difference between the cases presented in Fig. 10a. It is defined as

$$\phi = 1 - \frac{1}{\dot{m}} \int_0^1 \frac{P_{0,out}}{P_{0,in}} \rho U \, d(y/L), \quad (1)$$

with

$$\dot{m} = \int_0^1 \rho U \, d(y/L), \quad (2)$$

where ρ and U are the local flow density and velocity respectively. A lower loss coefficient indicates more stagnation pressure recovery, hence reduced losses. Loss coefficients calculated 1.43L downstream of the rear leg for different

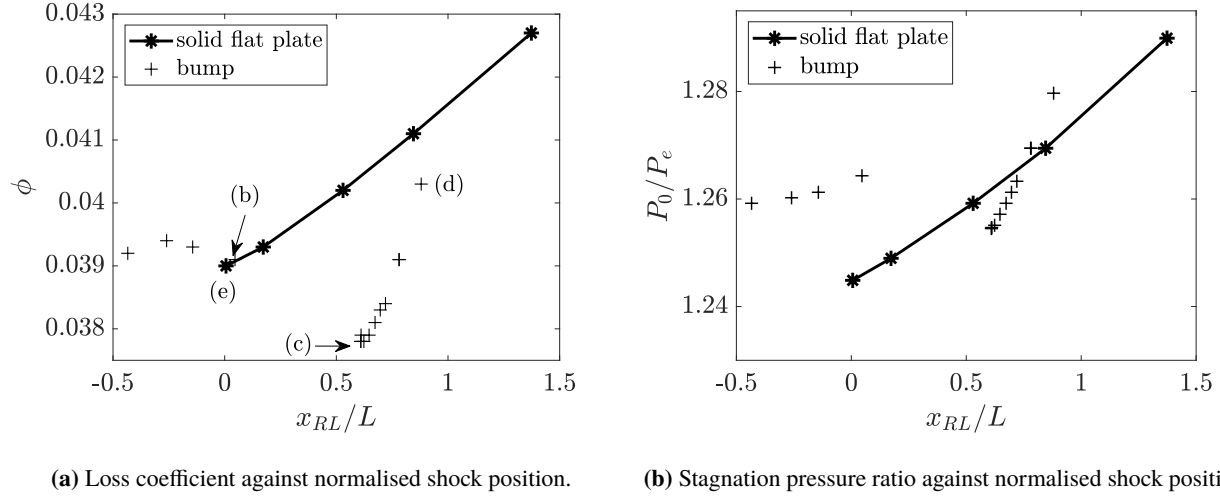


Fig. 11 Simulation results for the bump and the solid flat plate.

shock positions along the bump and the solid flat plate are shown in Fig. 11a, where the letters indicate the corresponding numerical schlieren images (Fig. 10b-10e). As expected, the loss coefficient for the bump is the lowest for rear leg positions around the bump crest ($x_{RL}/L \approx 0.6$), while it increases as the shock moves towards the two edges of the bump. In particular, Fig. 11a indicates that the bump leads to a wave drag reduction, compared with the baseline case of a solid flat plate, for all the shock positions tested, except for $x_{RL}/L < 0$.

Fig. 11b shows a plot of P_0/P_e against x_{RL}/L from simulations, analogous to Fig. 9 from experiments. It should be noted that the computational results in Fig. 11b have a lower stagnation pressure ratio compared with the experimental profiles in Fig. 9. As mentioned in Sec. IV.A, these differences are attributed to the simplified nature of the simulations, which model a 2D wind tunnel section and use a turbulence model. Inevitably, this leads to small inaccuracies in the modelling of the compressible boundary layer (especially its interaction with the shock) and of losses. Fig. 11b shows similar trends to Fig. 11a, although the solid flat plate profile is slightly shifted upwards compared with the bump results. In Section IV.B.1, it was suggested that P_0/P_e was an indication of wave drag, and that the region of the plot below the solid flat plate profile indicated a wave drag saving. The agreement between the two plots in Fig. 11 supports this method for assessing wave drag reduction from experiments. In addition, the upward shift of the solid flat plate profile in the loss coefficient plot suggests that the comparison of the pressure ratio profiles obtained from experiments in a blow down wind tunnel (Fig. 9) actually gives a conservative estimate of the wave drag reduction.

Considering the results in Fig. 9a, it can be concluded that the actuated bump reduces wave drag compared to the baseline case, with a peak reduction around $x_{RL}/L = 0.6$, corresponding to the on-design case in Fig. 8, which decreases towards either side of the bump due to the increased drag associated with subsonic and supersonic flow reacceleration, as discussed in Sec. IV.A. This is consistent with the trends observed in simulations, but a comparison between Fig. 9a

and 11b indicates that the wave drag reducing potential of adaptive bumps extends over a wider range of shock positions than of solid bumps, and this will be discussed in Sec. IV.C.3.

Conversely, the unconstrained flexible plate (Fig. 9b) was found to significantly increase wave drag compared to the baseline case across the range of shock positions tested. This is caused by the unfavourable deformed shape that the unconstrained bump assumes during a wind tunnel experiment, when subject to the pressure loading associated with the shock structure, and will be discussed in more detail in Sec. IV.C.2.

C. Transient shock behaviour

The transient shock behaviour during wind tunnel experiments with adaptive shock control bumps is explored from two perspectives: aerodynamics and structural considerations. These two areas are tackled individually at first, and then an explanation of their interdependence is presented.

1. Aerodynamic hysteresis

To isolate the aerodynamic effects taking place, Fig. 12 presents P_0/P_e profiles obtained for a solid flat plate and a rigid shock control bump from CFD simulations. Simulations revealed that the converged shock structure was influenced by the initial conditions, in particular in which direction the shock had to travel for the simulation to converge. In fact, a hysteresis loop can be identified in Fig. 12, such that, for the same shock position, wave drag is higher for a downstream-travelling shock (red profile) than for an upstream-travelling shock (blue profile). It should be noted that all the points in Fig. 12 correspond to (temporally and spatially) fully converged solutions, and the terms “upstream-” and “downstream-travelling” purely refer to the position of the converged shock structure compared with the initial condition. Two instability regions are present, and they are marked as dashed lines in Fig. 12. It was not possible to obtain a stable solution to the left of the instability region for an upstream-travelling shock, and this is attributed to the size of the computational domain (which only extends to $x/L = -1.2$). However, far enough upstream of the bump, the two branches are expected to converge.

From Fig. 12, the well known off-design performance penalty typical of solid shock control bumps can be observed: the bump reduces wave drag for a range of shock positions ($x_{RL}/L \approx 0.3 - 0.8$), outside of which the uncontrolled shock (black line) is more favourable. The drag increase off-design is experienced for shock positions both upstream and downstream of the bump ($x_{RL}/L < 0$ and $x_{RL}/L > 1$), as its presence inevitably has an adverse impact on the boundary layer.

Fig. 13a shows a schematic diagram illustrating the relationship between shock position and stagnation pressure ratio for a rigid shock control bump such as that seen in Fig. 12. The profile for the solid flat plate is plotted as a dotted line, while the solid black line shows the expected shock stability curve for a drag-reducing shock control bump [12]. The red and blue lines show the paths that a shock is expected to follow as it moves along the bump, in response to an increase or

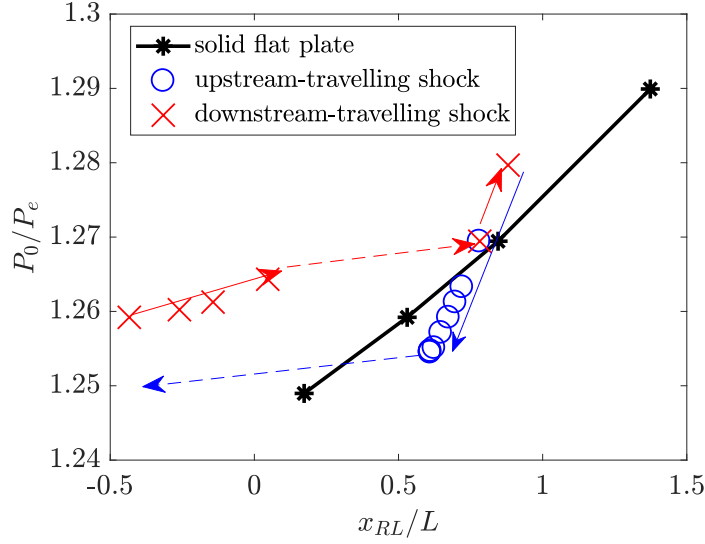
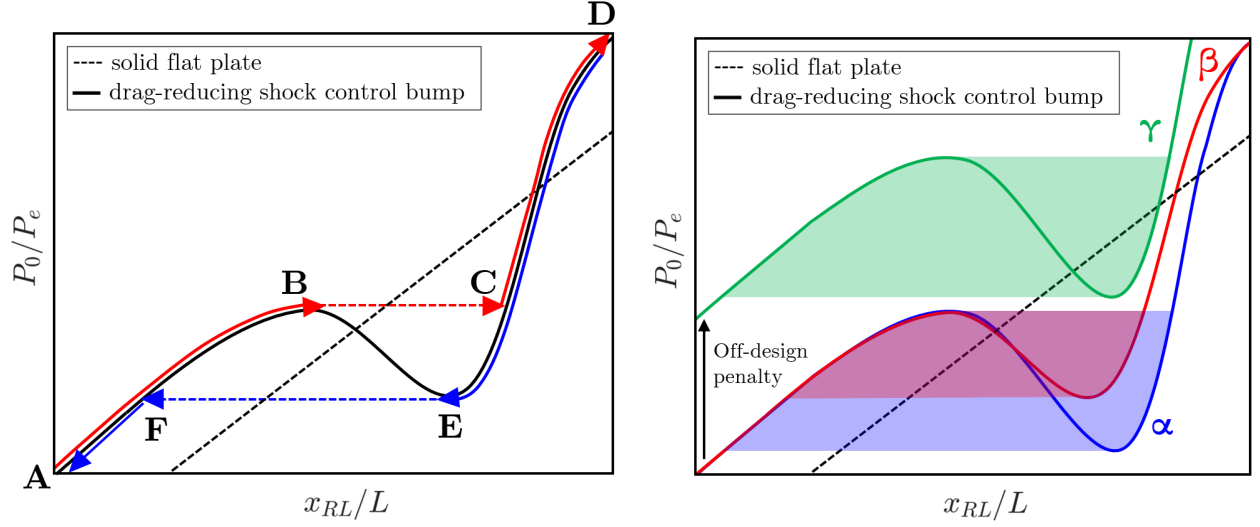


Fig. 12 Plot showing the relationship between stagnation pressure ratio (P_0/P_e) and shock position (x_{RL}/L) for the solid flat plate (baseline) and a rigid shock control bump from simulations. The bump results are divided based on the direction of motion of the shock, revealing a hysteretic behaviour.

reduction of P_0/P_e respectively. Supposing that a shock structure is initially located at point **A**, an increase in tunnel stagnation pressure would make it travel downstream on the bump, until it reaches point **B**, whereafter any further increase in P_0 will make the shock jump to **C**, and then follow the black line until **D**. Conversely, as P_0 is reduced, the shock would travel from **D** to **E**, after which any further decrease will make it jump to **F** and travel back to **A**. The shock will be unstable between **B-C** and **E-F**, and a hysteresis region is present between points **B**, **C**, **E** and **F**, as shown.

Fig. 13b shows hypothetical shock stability curves for the solid flat plate and three arbitrary shock control bumps to illustrate the relationship between the size of the hysteresis region, the location of the shock stability curve, and wave drag. The size of the hysteresis region indicates the wave drag reduction achieved when the shock is on the bump. In particular, the bigger the hysteresis region, the deeper the trough in the shock stability curve and the greater the drag reduction, as shown by the comparison of curves α and β in Fig. 13b (α corresponding to a greater drag reduction). Building upon the results presented in Sec. IV.B, the vertical shift of the shock stability curve of the bump with respect to the baseline indicates the drag penalty introduced off-design: the higher P_0/P_e , the greater the drag increase off-design. For example, curves α and γ in Fig. 13b have the same shape, but γ is shifted upwards, meaning that the off-design performance deterioration due to the bump penalises the improvement on-design. In fact, a drag reduction with respect to the solid flat plate can be observed over a more limited range of shock positions along the bump for γ than for α . Therefore, a successful shock control bump should be associated with a shock stability curve with low values of P_0/P_e off-design, and a large hysteresis region when the shock is above the bump, for example case α in Figure 13b.



(a) Explanation of the origin of the hysteresis loop.

(b) Comparison of shock stability curves for three different bumps.

Fig. 13 Schematic plots illustrating the hysteresis mechanism for the correlation between shock position (x_{RL}/L) and stagnation pressure ratio (P_0/P_e) with the solid flat plate (baseline) and a rigid shock control bump.

While the trends presented in Fig. 13 agree with the CFD results in Fig. 12, they are not seen in the experimental results in Fig. 9. This is because the experimental data were not conditionally sampled to take into account the direction of motion of the shock, and hence Fig. 9 presents average profiles. It is highly promising that they show an “average” decrease in P_0/P_e , but do not tell the whole story. In fact, this section has shown that the shape of the shock stability curve can provide a more complete understanding of the drag reduction associated with the bumps. Hence, this concept will be revisited in Sec. IV.C.3, where the experimental results will be conditionally sampled.

2. Passive structural deformation

Photogrammetry results have been used to quantify the passive bump deformation caused by the changing pressure loading as the λ -shock structure moves along the bump. Profiles of the spanwise-averaged vertical displacement of the flexible plate ($\bar{y}$) as a function of shock position were calculated at ten discrete streamwise positions, where the coded targets were applied. From the lines of best fit through these points, average bump profiles over a range of shock positions were reconstructed.

Fig. 14a shows the variation of bump shape with shock location in the range $-0.1 < x_{TP}/L < 0.8$ with a bin size $\Delta(x_{TP}/L) = 0.01$. For upstream shock locations ($x_{TP}/L \approx 0$) the bump assumes a loaded beam geometry, with zero curvature at either end, as expected. For more downstream shock positions ($0 < x_{TP}/L < 0.4$), the upstream half of the bump was found to deform upwards into the flow with no change in crest height, such that the maximum slope at the front of the bump increases by 15% for $x_{TP}/L = 0.4$. As the shock moves further downstream, the bump becomes taller,

with a maximum increase in crest height of 14% for $x_{TP}/L = 0.8$. This has the effect of reducing the leading edge curvature back to its value at $x_{TP}/L = 0$.

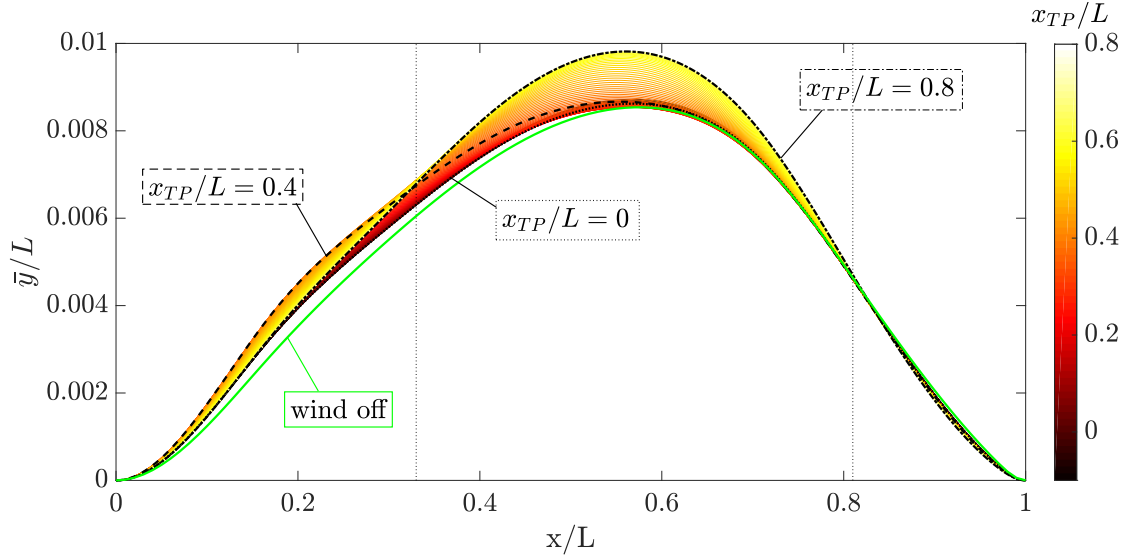
The locations of the two actuation points (at $x/L = 0.33$ and 0.81) are marked with dotted black lines on Fig. 14a, and the green profile corresponds to the wind off bump shape. Although the actuators were kept in the same position for the whole duration of the run, Fig. 14a shows some evidence that the upstream one did move slightly during the course of a test, with a maximum vertical displacement of $\Delta(y/L) = 8 \times 10^{-4}$.

A black and white version of the bump profiles is shown in Fig. 14b. The concentration of curves at the top and bottom of the region spanned by the profiles, indicates that, although the shock position increases gradually, the bump shape appears to adopt a small number of preferred configurations. The close up view of the region between $0.1 < x/L < 0.2$ (for $0 < x_{TP}/L < 0.4$ to avoid overlapping curves and hence improve clarity) shows that an additional similar instability is observed in the upstream part of the bump. This suggests that, in fact, three preferred structural configurations may exist, and these are plotted as three thick black lines in Fig. 14a.

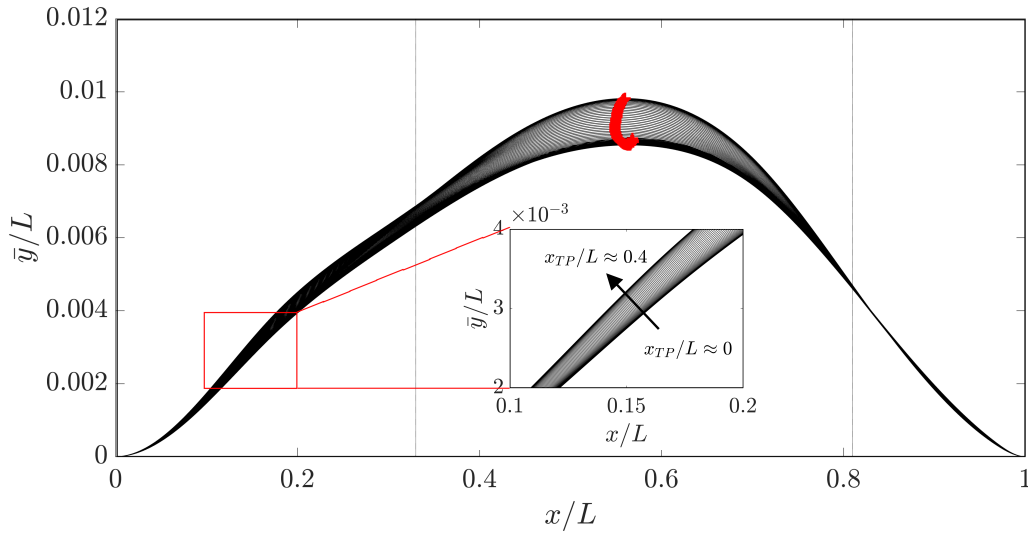
Fig. 15 shows the corresponding spanwise-average bump profiles for the unconstrained flexible plate for $0 < x_{TP}/L < 0.7$ (although the colourmap in Fig. 15a is for $-0.1 < x_{TP}/L < 0.8$ for consistency). A comparison between Fig. 14 and 15 shows that the unconstrained bump (Fig. 15) exhibits larger deformations than the actuated bump (Fig. 14) during the course of a run. In fact, despite being shorter for the most upstream shock positions, the unconstrained bump reaches a crest height of $\bar{y}_c/L = 0.0114$ for the most downstream shocks (14% higher than the actuated bump). Hence, the unconstrained bump possesses a greater leading edge curvature, and a corresponding greater angle of the oblique shock (front leg) for most triple point positions. From Fig. 15b it can also be seen that the absence of actuation points has removed any clustering of the lines, suggesting that the unconstrained bump does not have any clear preferred structural configurations.

The red crosses in Fig. 14b and 15b mark the crest location for each bump shape and they show that, while it oscillates around $x_c/L = 0.56$ for the actuated bump, it was found to vary between $0.37 < x_c/L < 0.47$ for the unconstrained bump. In particular, Fig. 15b shows that, after keeping a relatively constant location up to $x_{TP}/L \approx 0.2$, the crest first moves upstream as the bump height increases due to the low pressure experienced on the upstream region, and only starts moving back downstream for $x_{TP}/L > 0.35$, as the extent of the supersonic region along the bump increases downstream.

It is known that the detrimental off-design effects of shock control bumps are more severe the taller the bumps and the more upstream the location of the crest [3]. Hence, the fact that the unconstrained bump experienced the greatest wave drag in Fig. 9b is consistent with the bump shapes shown in Fig. 14 and 15.

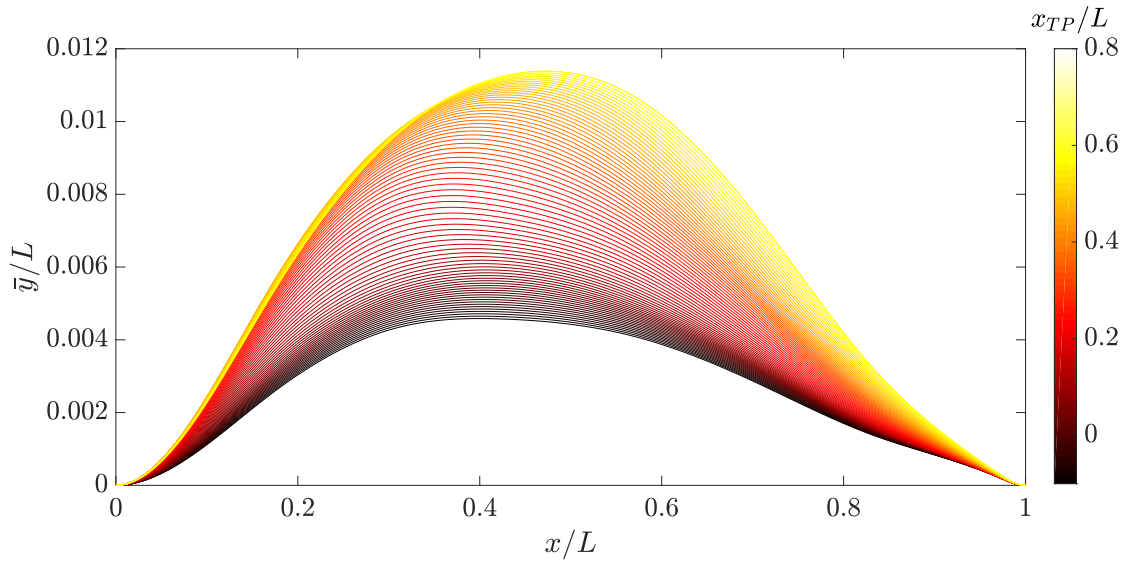


(a) Colour plot, showing the three equilibrium bump shapes for $x_{TP}/L = 0, 0.4, 0.8$ and the wind off bump shape.

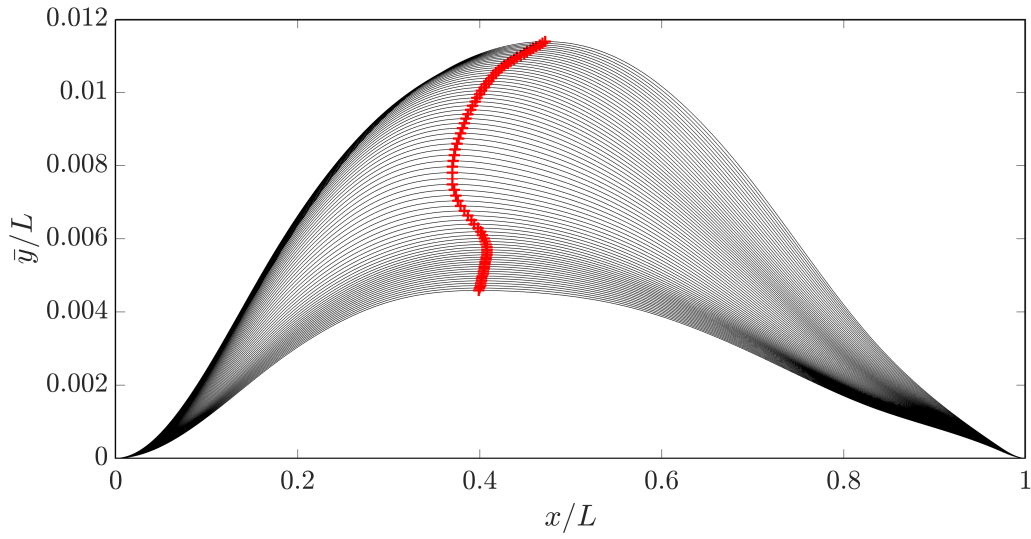


(b) Black and white plot, suggesting the existence of three equilibrium positions. A close-up view of the region between $0.1 < x/L < 0.2$, for $0 < x_{TP}/L < 0.4$, highlights the nature of the multiple preferred structural configurations in this region. The red crosses mark the crest location for each bump shape.

Fig. 14 Plots showing the spanwise-average bump shape as a function of normalised shock position (x_{TP}/L) for the actuated bump. The vertical dotted lines indicate the location of the two actuation points.



(a) Colour plot.



(b) Black and white plot, suggesting a gradual change between the different shapes. The red crosses mark the crest location for each bump shape.

Fig. 15 Plots showing the spanwise-average bump shape as a function of normalised shock position (x_{TP}/L) for the unconstrained flexible plate.

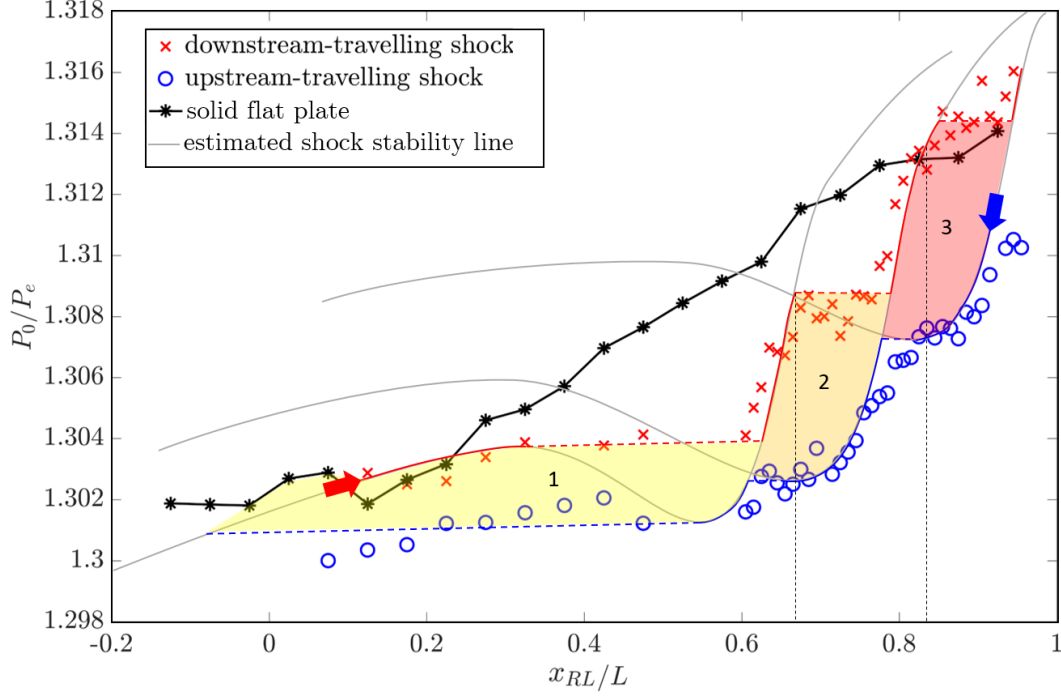


Fig. 16 Plot of stagnation pressure ratio (P_0/P_e) as a function of normalised shock position (x_{RL}/L) for the adaptive bump and the baseline case of a solid flat plate (from experiments). Bin size: $\Delta x_{RL}/L = 0.05$, except for the bump profiles for $x_{RL}/L > 0.6$, where $\Delta x_{RL}/L = 0.01$ to capture hysteresis. Instantaneous results were conditionally sampled to differentiate between downstream (red) and upstream (blue) travelling shocks. The gray lines represent the expected shock stability lines for three solid bumps with slightly different shapes.

3. Aerostructural coupling

Fig. 16 shows plots of P_0/P_e against shock position for the solid flat plate and the adaptive bump from experiments. Unlike in Fig. 9, the bump results have been conditionally sampled based on the direction of motion of the shock to divide them into two subsets. Results were only considered for time intervals when the shock structure was seen to move significantly in one direction (from synchronised schlieren videos), and the data within the time intervals was conditionally sampled to remove the points associated with high frequency shock oscillations in the opposite direction. Data from several wind tunnel runs were considered to yield a total of 2600 and 2011 points for downstream- (red crosses in Fig. 16) and upstream- (blue circles in Fig. 16) travelling shocks respectively. Statistical binning was employed, with a bin size of $\Delta (x_{RL}/L) = 0.05$, except for the region between $0.6 < x_{RL}/L < 1$ on the bump, where there was a sufficient concentration of data to allow a smaller bin size of $\Delta (x_{RL}/L) = 0.01$ to be used. From Fig. 16 it should be noted that, without conditional sampling, the crosses and circles collapse to give the gray diamonds shown in Fig 9b, as expected.

In Sec. IV.C.1 it was shown that one solid bump is associated with a shock stability curve (Fig. 13a), and in Sec. IV.C.2 that the adaptive bump switches between three preferred structural configurations as the λ -shock structure

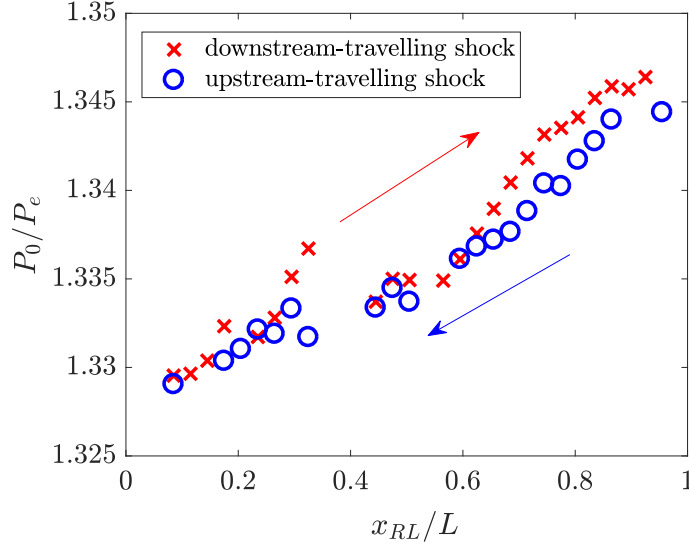


Fig. 17 Plot of stagnation pressure ratio (P_0/P_e) as a function of normalised shock position (x_{RL}/L) for the unconstrained bump. Bin size: $\Delta(x_{RL}/L) = 0.05$. Instantaneous results were conditionally sampled to differentiate between downstream (red) and upstream (blue) travelling shocks.

moves along the flexible surface due to small variations in tunnel stagnation pressure. Hence, it is reasonable to expect three slightly different shock stability curves corresponding to the three preferred shapes. This concept is explored in Fig. 16, where we have fitted three gray lines. Their exact shape was obtained by inspection, considering the distribution of the average experimental data, but each of them is consistent with the characteristic shape predicted in the literature [12].

The red and blue lines in Fig. 16 indicate the path of the shock as stagnation pressure is increased or decreased, following the same rationale explained in Section IV.C.1. The dashed portions correspond to the instability regions, and three hysteresis loops (marked as **1**, **2** and **3**) can now be identified. The points of transition between the three stability curves, shown with dotted vertical lines in Fig. 16, are observed to occur around $x_{RL}/L = 0.65$ (note the blue instability region for $x_{RL}/L = 0.6 - 0.65$) and 0.85 . This corresponds to $x_{TP}/L \approx 0.3$ and 0.5 , which is consistent with the transitions between bump shapes observed in Fig. 14a.

The presence of three overlapping stability curves leads to a significantly enlarged hysteresis region in comparison to a single fixed bump shape. This suggests that actuated adaptive bumps may reduce wave drag for a wider operational envelope than solid bumps (Sec. IV.C.1). In fact, Fig. 16 shows that the area enclosed between the baseline and the average adaptive bump profile is greater than the area between the baseline and each of the three individual gray stability curves.

Fig. 17 shows a plot of stagnation pressure ratio as a function of rear leg position for the unconstrained flexible

plate, equivalent to Fig. 16 for the actuated bump. The solid flat plate profile was not included to avoid a loss of detail (a significantly increased range of pressure ratios would be needed, as shown in Fig. 9b). Fig. 17 shows that the results are not strongly dependent on the direction of motion of the shock, with only a small hysteresis region present for $0.6 < x_{RL}/L < 0.9$. As mentioned in Section IV.C.1, this indicates that, not only is the performance of the unconstrained flexible plate poor off-design, no significant improvement is experienced even when the λ -shock structure is on the bump.

Fig. 16 and 17 show that the actuated and unconstrained bumps exhibit a very different behaviour when subject to the variable pressure loading of a Mach 1.4 λ -shock structure. Therefore, adaptability is a powerful tool to extend the operational envelope of shock control bumps, but constraints have to be applied to achieve the desired surface deformations over a wide range of shock positions.

V. Conclusion

The wave drag reducing potential of 2D adaptive shock control bumps has been studied for a wide range of shock positions through experiments and simulations.

Stagnation pressure profiles downstream of the bump showed that wave drag is proportional to the ratio between inlet and outlet stagnation pressure in a blow-down wind tunnel for a given shock position, thus obtaining a reliable way of estimating wave drag from experiments, confirming previous speculations [14]. In particular, this method gives a conservative estimate, suggesting that the drag saving associated with the adaptive bumps could be greater than presented in this paper. A hysteretic behaviour was observed in the relationship between shock position and tunnel stagnation pressure ratio. The analysis of the hysteresis loop can provide detailed information about the wave drag reducing potential of the bump.

Photogrammetry revealed the presence of three preferred structural configurations during experiments on the actuated adaptive bump, due to the effect of passive actuation. The three bump shapes are associated with three overlapping hysteresis loops, leading to a significantly enlarged hysteresis region, such that actuated adaptive bumps can reduce wave drag over a wider operational envelope compared with solid bumps of a similar initial shape. Conversely, the unconstrained flexible plate was found to deform into a wide range of bump shapes (with similar overall height but a more upstream crest), with no preferred structural configurations, leading to an increase in wave drag both on- and off-design. This suggests that adaptive bumps have the potential to reduce the wave drag associated with a normal shock, but constraints must be employed to achieve the desired surface deformations over a wide operational envelope.

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