Investigation on the depth effects of the micro-grooves on the suppression of the second modes in the hypersonic boundary layer

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Abstract. The transition of the hypersonic boundary layer and the corresponding control have been extensively interested since the strong engineer background. In the present work, a hypersonic boundary layer over a flat plate of Mach 6 is computed using the high-order finite-difference scheme. The influences of the two-dimensional micro-grooves on the evolution of the second-mode instability wave are investigated. The comparison is carried out between different depths of the micro-groove. The results indicate that the actual control effect does not significantly vary with the depths under the condition with large grooves. The DNS prediction show different results with the theoretical model for the acoustic reflection coefficient. It is suggested that new model should be derived to guide the design and optimize of the parameters of the micro-groove.

1. Introduction

There exist strong motivations to effectively control the laminar boundary layer flows from becoming turbulent ones in the aerospace engineering. Such laminar flow control methods can be classified into active control, passive control and hybrid control [1]. Under the hypersonic flow condition, the passive control is considered as the most promising method due to the extreme aerodynamic and aerothermal environment. During recent years, the flow-control method based on the porous surface has attracted plenty of interests. The porous surface is reported to be able to absorb the second-mode instability waves in the hypersonic boundary layer, and delay the transition location dominated by the second-mode instability. This passive control method shows good potentials for delaying the transition of the laminar boundary layer.

Since the acoustic feature of the second-mode instability waves, Fedorov et al. [2] derived the theoretical model of the acoustic characteristics for the deep and thin pores. The model to describe the influence of a single pore on the flow and acoustic field was given \( (\nu' = Ap) \). Bres et al. [3] built the reflection coefficient model according to the acoustic propagating theory in the long and thin tube. The acoustic-absorbing characteristics based on the different meta-surface were assessed in [4]. Zhao et al. [5] have re-built the theoretical model of the regular porous surface, through taking the acoustic interaction/interference between the micro-structure of the porous surface into consideration. The prediction accuracy for the acoustic characteristic of the porous surface was increased.

Although the fast optimization and design of the key parameters of the micro-pores/grooves seems practicable employing the theoretical model, some certain contraints still exist. First, the acoustic absorbing theory presume that the incident waves are plane nomochromatic ultrasonic acoustic waves,
and their wave-length is much larger than the size of single pore or groove [3, 5]. For a typical hypersonic boundary layer, the wave-length on the wall-normal direction of the second-mode has the order of 1mm, thus the above assumption is only satisfied when the size of single pore or groove is under the order of 0.1mm, otherwise the model could be inaccurate.

From the view point of practical manufacturing, the smaller the pores/grooves are, the larger difficulty the implementation will encounter. Based on our former studies [6], the control effects of the width 0.4mm grooves are assessed. The size is the same order of the incident acoustic waves, which makes effectiveness of the theoretical model unknown.

In this paper, we preliminarily compared the prediction of the theoretical model and the DNS computation through altering the depth of the micro-grooves, aiming at examine the actual control effect of the interested size.

2. Computational details
The simulation is performed based on the two-dimensional Navier-Stokes equations. The numerical methods is chosen as the high-order finite difference scheme. The inviscid term is discretized by the fourth-order weighted essentially non-oscillatory and non-free-parameter (WENN) scheme, while the viscous term is discretized by the fourth-order central scheme. The third-order Runge-Kutta scheme is employed as the time discretization. The freestream Mach number is 6.0, and the Reynolds number based on 1mm is 10000. The temperatures of the freestream and the isothermal-wall are set as 216.65K and 300K respectively.

| porosity | depth (mm) | aspect ratio |
|----------|------------|--------------|
| $\phi=0.5$ | $H=0.943$ | $s/H=0.424$ |
| | $H=1.392$ | $s/H=0.287$ |
| | $H=1.815$ | $s/H=0.220$ |
| | $H=2.000$ | $s/H=0.200$ |
| | $H=6.000$ | $s/H=0.067$ |

Figure 1. Schematic of the two-dimensional micro-grooves configuration.

Figure 2. Schematic of the two-dimensional micro-grooves configuration.
Figure 3. Variations of the acoustic reflection coefficient with the normalized frequency

The most-unstable second mode instability wave with $f=400$kHz is added at the inlet of the computational domain. As shown in Fig. 1, the width of the micro-groove is set as $s=0.4$mm. The porosity is defined as $\phi=s/L=0.5$. The computational grids are shown in Fig. 2. According to the theoretical model in [5], the variation of the acoustic reflection coefficient $R$ with the normalized frequency $f_H/f_w$ can be obtained, where $f$ is the frequency of the second-mode instability wave, $H$ is the depth of the micro-groove and $c_w$ is the acoustic speed on the wall. As explained in [3], the smaller the reflection coefficient is, the more absorption for the second-mode instability waves the porous surface can achieve.

In order to make comparison, we choose five different values of depth $H$ (see Table 1) to perform the computations. The normalized frequencies corresponding to the former four depths are marked by the red dotted lines in Fig. 3. The largest depth ($H=6$mm) is employed to approximated the infinitesimal aspect ratio (or $H\to\infty$).

3. Results and discussions

After an adequate computational time for the evolution of the second-mode instability waves, the instantaneous fields are obtained. The contours of the fluctuation of wall-normal velocity $v'$ are given in Fig. 4. The significant influence on the instability waves from the micro-grooves can be observed. In the grooves, the transversely propagating acoustic waves can be clearly seen.
As reported in our former work [6], the total drag can be reduced by the increase of the porosity. Here, the drags from the frictions (Cdf) and the pressure differences (Cdp) are also examined for each case. The results are shown in Fig. 5. It can be seen that either component of the drag is almost fixed with the variation of the depth, which indicates that the influence on the drag came from the flow near the surface.

For quantitively examining the influences on the instability waves, we compute the wall-normal integral of the disturbance amplitude, denoting by $\bar{U}$. In Fig. 6, the streamwise variations of $\bar{U}$ in different cases are shown. The black solid line is the evolution of the second-mode instability wave on a flat plate without micro-grooves (or smooth wall), the linear growing is clearly seen. It is also observed that either of the micro-grooves with different depths can effectively suppress the amplification of the second-mode instability wave. However, the variation of the control effect with the depths is not that obvious, except for that the smallest depth ($H=0.943\,\text{mm}$) show the weakest control effect compared to other cases. This is not agree with the theoretical model shown in Fig. 3, in which the predicted control effect of $H=2.0\,\text{mm}$ should be worse than the three smaller depths.

A sample point is positioned just at the downstream of the porous surface and 0.1mm away from the wall. The time-evolutions of the pressure fluctuation on this sample point in each case are compared in Fig. 7. It is shown that all the results are kept as a single-frequency mode, indicating that there is no additional instability mode introduced by the porous surface.
4. Conclusions
In this paper, the control effects on the second-mode instability wave of the micro-grooves with different depths are compared based on the numerical simulations performed by the high-order finite difference scheme. Under the configuration of the micro-grooves ($s=0.4\text{mm}$ and $\phi=0.5$) interested here, the numerical results indicate that larger size of the micro-grooves would not lead to significant variation of the control effect with the varying depths. It is also indicated that there exist discrepancies between DNS result and the theoretical model of acoustic reflection coefficient. This is caused by the failure of the assumption that the wave-length of the incident wave is much larger than the size of single pore or groove. A more accurate theoretical model might be derived with taking the influences of the shear layers into consideration, which will be studied in the future.

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