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Passive hypersonic boundary layer transition control using an ultrasonically absorptive coating with random microstructure - Part 2: Computational Analysis

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Abstract

The damping of acoustic second mode instabilities by passive porous surfaces is investigated numerically and compared with experiments for different hypersonic boundary-layer flows. The used geometry is a blunt 7° half-angle cone model with exchangeable nose tip. The cone surface consists partly of an ultrasonically absorptive material, which has a natural, random porosity. For the analyses of the second modes the DLR stability code NOLOT, NOnLocal Transition analysis code, is used. Two different numerical approaches for the boundary condition of the porous surfaces are compared: one for regular pores in combination with the hydraulic diameter and a new implemented condition for porous surfaces with natural porosity, which based on material measurements shown in part 1 of this paper by Wagner et al.\textsuperscript{27}. The numerical results are compared with wind tunnel measurements on porous surfaces, which were performed in the DLR High Enthalpy Shock Tunnel Göttingen (HEG).

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1. Introduction

Hypersonic laminar flow control to achieve delayed laminar-turbulent transition is of high importance for hypersonic vehicles since early transition results in an increase in the heat transfer by factors between 3 and 8, resulting in a cost and weight increase of thermal protection systems\textsuperscript{18,19}. A lot of different strategies are used to delay or prevent the transition process. Classical flow control strategy began with natural laminar flow (NLF), which has been applied since the 1930s and implies delaying transition by modifying the body shape. In contrast, active laminar flow control (LFC), which started around the same time, uses suction or wall cooling/heating to influence the boundary-layer instability modes\textsuperscript{9}. In the present work the manipulation of the transition is performed in a passive way, which usually

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provides a lower cost compared to active systems. Also the hypersonic environmental conditions make the use of active LFC more difficult than in other flight regimes.

In this paper the manipulation of the transition is performed by the use of porous surfaces to influence the growth of the second mode. The second mode, or so called Mack mode\textsuperscript{13}, is the dominant mode for essentially 2D boundary layers at high local Mach number ($M_{\infty} > 4$) and/or cool walls.

In an early work, Fedorov et al.\textsuperscript{3} have shown theoretically by using linear stability theory a strong stabilization effect of the second mode by a passive porous surface, which partially dissipates disturbance energy inside the pores. Using an analytical model of flow within blind, thin pores, typically with about 10-20 pores per wavelength of the Mack modes and a porosity about 25\%, the growth rate reduction is predicted to be a factor of two\textsuperscript{3}. Experiments of Rasheed et al.\textsuperscript{16} on a 5\(^\circ\) half-angle sharp cone ($M_{\infty} \sim 5$-6) equipped with equally spaced, blind, cylindrically micro-pores, confirmed the theoretical predictions. Continuation activities, theoretical as well as experimental ones, around the working group of Fedorov have demonstrated robustness of this laminar flow control concept (see e.g.\textsuperscript{4,5,14}). Direct numerical simulations confirmed the results of the linear stability theory for smooth and porous surfaces equally well (see e.g.\textsuperscript{2,4,17}).

In this paper the stability code NOLOT of the Germany Aerospace Center (DLR) is used to predict the second modes for a hypersonic boundary-layer flow. Previous numerical investigations have shown a good agreement between NOLOT results and direct numerical simulations, DNS. For example in Wartemann et al.\textsuperscript{32}, second-mode stability analysis were performed for a boundary layer flow at Mach 6 over different porous walls. The two different approaches were compared successfully: DNS, by a fourth-order finite difference code, which is used to provide complete solutions, including the flow inside pores, was compared with the linear stability code NOLOT. The trends of the predicted functions for both methods were identical: small differences for the predicted growth rate were less than 2\%. Also different hydraulic diameters, which are used for the comparison of different pore shapes, were investigated in\textsuperscript{32}. Previous comparisons of second modes between linear stability calculations of NOLOT and measurements in the HEG using a cone geometry with smooth surface and with similar nose radii and free stream conditions as in this paper have shown a good agreement\textsuperscript{12,23}. A comparison of the growth rates of the second mode between NOLOT calculations and measurements in the HEG confirmed the LST approach for this cone geometry in the HEG\textsuperscript{33}.

In this paper the used geometry is a blunt 7\(^\circ\) half-angle cone model with exchangeable nose. One third of the cone surface was equipped with C/C (carbon/carbon), a fibre reinforced ceramic material with a natural, random porosity. For the analyses of the second modes two different numerical approaches in NOLOT for the boundary condition of the porous surfaces are compared: one for regular pores in combination with the hydraulic diameter and the second for porous surfaces with natural porosity. The numerical results are compared with the measured damping of the Mack modes and the effect on the transition by the ultrasonically absorptive ceramic material is analyzed.

2. Numerical methods

The NOLOT code, NOnLocal Transition analysis code\textsuperscript{8}, was developed in cooperation between DLR and the Swedish Defence Research Agency (FOI) and can be used for local as well as non-local analyses. The equations are derived from the conservation equations of mass, momentum and energy, which govern the flow of a viscous, compressible, ideal gas. All flow and material quantities are decomposed into a steady laminar base flow $\bar{q}$ and an unsteady disturbance flow $\hat{q}$

\begin{equation}
q(x, y, z, t) = \bar{q}(x, y) + \hat{q}(x, y, z, t).
\end{equation}

The laminar base-flow $\bar{q}$ is calculated by the DLR FLOWer code\textsuperscript{11}. The FLOWer code solves the compressible Navier-Stokes equations for a perfect gas flow on block-structured grids, using second order finite volume techniques and cell-centered or cell vertex variables. The disturbance $\hat{q}$ of equation 1 is represented as a harmonic wave

\begin{equation}
\hat{q}(x, y, z, t) = \hat{q}(x, y, z) \exp[i(\alpha x + \beta y - \omega t)]
\end{equation}
with the complex-valued amplitude function \( \hat{q} \). In the following, the hat over a variable denotes an amplitude function. In this paper the local approach is used, which is a subset of the nonlocal stability equations. Since NOLOT is a spatial code, the wavenumbers \( \alpha \) and \( \beta \) are complex quantities and the frequency \( \omega \) is a real value. The growth rate \(-\alpha_i\) stands for the quantity of primary interest. The boundary conditions in NOLOT for a smooth wall (at \( y = 0 \)) are:

\[
\hat{u}_w, \ \hat{v}_w, \ \hat{w}_w, \ \hat{T}_w = 0.
\]  

(3)

The NOLOT code is validated by several test cases against published results, including DNS (direct numerical simulation), PSE (parabolized stability equations), multiple scales methods and LST (linear stability theory). A good summary of the validation is given by Hein et al.\(^8\). For the treatment of porous surfaces additional boundary conditions are implemented: for regular pores and porous surfaces with natural porosity.

2.1. Boundary condition for regular pores

In this subsection the boundary condition for regular pores are described. This boundary condition is taken from Koslov et al.\(^10\) and Maslov et al.\(^14\), a complete derivation can be found in these references. The conditions are given by

\[
\hat{u}_w, \ \hat{w}_w, \ \hat{T}_w = 0, \ \hat{v}_w = A \hat{p}_w,
\]  

(4)

where a subscript \( w \) denotes a value at the wall. The admittance \( A \) is calculated by

\[
A = \frac{n}{Z_0} \tanh(md).
\]  

(5)

The pores of the boundary condition are equally spaced, blind, cylindrical pores with a depth \( d \), a radius \( r \), both normalized with the displacement thickness, and a porosity \( n \). The characteristic impedance \( Z_0 \) and the propagation constant \( m \) are

\[
Z_0 = -\frac{\sqrt{\rho}}{Ma \sqrt{T_w}}, \quad m = \frac{i \omega Ma \sqrt{\hat{\rho} \hat{C}}}{\sqrt{T_w}},
\]  

(6)

where the dimensionless complex dynamic density \( \hat{\rho} \) and dynamic compressibility \( \hat{C} \) are expressed as

\[
\hat{\rho} = \frac{1}{1 - F_1(\Lambda)}, \quad \hat{C} = 1 + (\gamma - 1)F_2(\hat{\Lambda}).
\]  

(7)

The function \( F \) and the macroscopic parameter \( \Lambda \) depend on the pore shape:

\[
F(\Lambda) = \frac{2J_1(\Lambda)}{\Lambda J_0(\Lambda)},
\]  

(8)

where \( J_0 \) and \( J_1 \) are Bessel functions of the argument \( \Lambda \) and \( \hat{\Lambda} \):

\[
\Lambda = r \sqrt{\frac{i \omega \rho_0}{\mu}}, \quad \hat{\Lambda} = \Lambda \sqrt{Pr}.
\]  

(9)

\( \omega \) represents the dimensionless angular frequency. All dimensionless flow quantities are normalized by the values at the boundary-layer edge.

The verification of the in NOLOT implemented boundary conditions of regular pores against the Southampton LST code and direct numerical simulations is given in Wartemann et al.\(^{28,29,32}\). First comparisons with experiments using a sharp cone, which has a smooth surface on one side and is covered with cylindrical, equally spaced, blind micropores on the other side are analysed in \(^{30,31}\). In combination with the hydraulic diameter this boundary condition for regular, cylindrically pores can be also used for porous surface with natural porosity. Usually the hydraulic diameter is used to compare different for shapes, like cylindrically pores with rectangular pores; thus an additional boundary condition for porous surfaces with natural porosity is implemented in NOLOT (see next section).
Table 1. Operating conditions of the present study in HEG

<table>
<thead>
<tr>
<th>operating condition</th>
<th>XIV</th>
<th>XVII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re_u \times 10^6/\text{m}$</td>
<td>1.4</td>
<td>2.4</td>
</tr>
<tr>
<td>$H_0 \times \text{MJ/K}$</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>$T_0 \times \text{K}$</td>
<td>2650</td>
<td>2730</td>
</tr>
</tbody>
</table>

2.2. Boundary condition for porous surfaces with natural porosity

For the treatment of the natural porosity of the porous surface, which are described in more detail in section 3, a new boundary condition is implemented in NOLOT. Instead of using the median hydraulic diameter and porosity for the numerical calculations, a more precise approach for this kind of material with random structure is to use: the measured wave resistance and propagation. The measurement technique and the measurements of these values are show by Wagner et al. \textsuperscript{27}.  

3. Wind tunnel and wind tunnel model

The experiments were performed in the DLR High Enthalpy Shock Tunnel Göttingen (HEG). The tunnel is a free driven shock tunnel, which allows to investigate flow past hypersonic flight configurations from low altitude Mach 6 up to Mach 10 at approximately 33 km altitude \textsuperscript{7}. The investigated test series in this paper has a free stream Mach number of 7.5 at a stagnation enthalpy of $H_0 = 3.2 \text{MJ/kg}$ and a temperature ratio of $T_{wall}/T_0 \approx 0.1$ using different unit Reynolds numbers: $Re_u = 1.4 \times 10^6/\text{m}$ and $Re_u = 2.4 \times 10^6/\text{m}$ (see also table 1). For the numerical calculations, the wall temperature is set to environmental temperature: $T_{wall} = 290 \text{K}$, due to the short measurement times of < 5 ms. Further, a Prandtl number of 0.72, a ratio of specific heats of 1.4 and the Sutherland’s law for the viscosity is used for the LST calculations.

Figures 1 and 2 show the HEG cone model. The model is a 7° half-angle blunted cone with an overall length of 1,100 mm and an exchangeable nose with nose tip radii of 2.5 mm and 5 mm. The tested model is equipped with 49 thermocouples, 8 pressure transducers of type KULITE XCL-100-100A and 12 piezoelectric PCB132A32 fast response pressure transducers. The model is supported by a sting system in HEG at nominal 0° angle of attack.

The instrumentation is chosen such that the transition location on the cone is detectable by evaluating the surface heat-flux distribution obtained from the thermocouple readings. The flush-mounted KULITE pressure transducers are used to quantitatively measure the surface pressure so that the angle of attack and the yaw angle can be controlled. Twelve PCB132A32 fast response pressure transducers are grouped in pairs and flush mounted along the model at $x = 650 \text{mm}$, $x = 785 \text{mm}$, $x = 950 \text{mm}$. These pressure transducers feature a resonance frequency of 1 MHz or higher and are used to measure pressure fluctuations in the boundary-layer above the cone surface.
One third of the surface is equipped with C/C (carbon/carbon), a fibre reinforced ceramic material with a natural, random porosity, which was manufactured by the DLR Institute of Structures and Design in Stuttgart. The ceramic insert has a minimum thickness of 5 mm. Using quicksilver-porosimetry, the hydraulic diameter and the porosity, which are needed for the calculations, can be measured/calculated. A description of the quicksilver-porosimetry technique, the detailed analyzed pore side range and the model itself can be found in Wagner et al.\textsuperscript{25,26}. The measured porosity is about 15\% and the median hydraulic pore diameter is about 13 $\mu$m. These values are used for the described boundary-layer condition for regular, cylindrical pores in combination with the measured median hydraulic pore diameter for the first NOLOT calculations (see section 4). The measured absorption coefficient (see paper\textsuperscript{27}) is used for the second numerical boundary condition for porous surfaces with natural porosity.

4. Comparison: measurements with NOLOT (using the boundary condition for regular pores)

As first test case for the comparison a cone with a nose tip of 5 mm at a free stream Reynolds number of $Re_u = 1.4 \times 10^6$/m is chosen.

Figure 3 shows the calculated growth rate of the Mack mode. The black lines mark the results of the smooth cone side and the red lines the results of the porous cone side. The growth rates are completely damped by the porous surface, thus the $N$-factor are zero and, consequently, the $e^N$-values are one. As a result, NOLOT predicts a laminar
boundary-layer flow for the cone with porous surface, which is in agreement with the experiment. The thermocouple measurements show, that on the smooth cone side transition occurs at the downstream end of the cone, whereas on the porous side the boundary-layer flow is laminar. For a detailed comparison of the measured/calculated results, figure 4 shows the Mack mode comparison. The Mack mode measured at the first sensor position is still too weak and in the range of the background noise level, thus the last two sensors are used for comparison. The NOLOT calculations for the smooth cone, marked as line, are compared with the wind tunnel measurements (symbols) for the solid cone, marked with black color, and the porous cone marked with red color. The pressure data can not be compared directly with the numerically calculated $e^N$-values. It is nevertheless possible to compare the damping of the Mack mode. NOLOT predicts for the sensor position $x = 765$ mm a complete damping, which is in agreement with the measurements (figure 4a). The Mack mode is completely damped or in the range of the background noise level. The last sensor position $x = 950$ mm of the smooth side is in the transition region. Thus an examination is necessary, if a comparison with the laminar, linear numerical results is still possible. Comparing the growth of the second mode from the second sensor ($x = 765$ mm) to the last sensor ($x = 950$ mm) on the smooth side, shows that the measured growth is higher:

$$\frac{e^N_{PCB3}}{e^N_{PCB2}} = 2.5 \quad \text{and} \quad \frac{ASD_{PCB3}}{ASD_{PCB2}} = 4.3,$$

using the corresponding values at the maxima. This indicates, that the measured second mode of the third sensor position ($x = 950$ mm) is increased by non-linear effects. Hence it is neither possible to compare the measured second mode of the third sensor with laminar LST predictions nor an analysis of the measured damping at that sensor position. However the measured Mack mode on the porous side is still visible in the experiments (see figure 4b), which indicates that the calculated damping is higher than the measured one. Thus a worst case analysis is performed, using the sensor position $x = 765$ mm. The assumption for the worst case analysis is, that the damped, measured second mode is in the range of the upper limit of the background noise level. For the calculation of the percentage, measured damping of the Mack mode the ASD values at the maxima minus the background noise level are used:

$$100 \% \cdot \frac{ASD_{porous, max} - ASD_{noise}}{ASD_{smooth, max} - ASD_{noise}} \approx 30 \%.$$  

(10)

Consequently, the measurements show a 70 \% damping of the Mack mode using the porous surface instead of the smooth one. NOLOT predicts a 100 \% damping. This results in a maximal possible difference of 30 \% between measurements and calculations for this worst case analysis.

The reason for the shown differences in the damping are the used boundary conditions with cylindrically pores in combination with the measured hydraulic diameter of the porous material with natural porosity. Instead of using the median hydraulic diameter and porosity for the numerical calculations, a more precise approach for this kind of
material with random structure is to use the measured wave resistance and propagation. The results of these two different boundary conditions will be compared in detail with experimental results in this paper.

References