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Passive hypersonic boundary layer transition control using an ultrasonically absorptive coating with random microstructure: Computational analysis based on the ultrasonic absorption properties of carbon-carbon

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Abstract

Previous investigations in the High Enthalpy Shock Tunnel Göttingen of the German Aerospace Center (DLR) show that carbon fiber reinforced carbon ceramic (C/C) surfaces can be utilized to damp hypersonic boundary layer instabilities resulting in a delay of boundary layer transition onset. Linear stability analyses were performed using the DLR stability code NOLOT, NOnLocal Transition analysis code. To adapt the boundary condition to account for the characteristics of porous C/C material, the ultrasonic absorption properties of C/C were investigated experimentally and theoretically. Therefore, a test rig was set up to directly measure the reflection coefficient in the frequency and pressure range corresponding to the test conditions in HEG. In this frame, the reflection of ultrasonic waves from flat plate test samples with different porous layer thicknesses was investigated and compared to an ideally reflecting surface.

The obtained results were used to improved the boundary condition used for stability analysis above porous surfaces. The numerical results, using the original as well as the improved boundary condition, were compared with wind tunnel tests. These experiments were performed at Mach 7.5 and different unit Reynolds numbers. A 7° half-angle cone model with a nose radius of 2.5 mm and a total length of 1077 mm was used. One-third of the metallic model surface in circumferential direction was replaced by C/C ceramics. The comparison between numeric and experiments includes the investigations of the second modes, the damping of the these modes and the resulting transition shift.

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Keywords: ultrasonically absorptive coating; transition control; passive hypersonic boundary layer transition control; second mode damping; carbon fiber reinforced carbon ceramic (C/C); porous surface; random microstructure; cone experiments; stability analysis

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1. Introduction

The increase of the laminar portion of a boundary layer is of critical importance to the design and optimization of future hypersonic transport vehicles. This motivates the development of concepts to control hypersonic boundary layer transition. In the present paper an ultrasonically absorptive porous coating with random microstructure was used to passively control boundary layer transition.

The second mode instability, commonly referred to as Mack mode [1], is the dominant mode for essentially 2D boundary layers at high local Mach number ($Ma_e > 4$) and/or cold walls. A strong stabilization effect of the second mode instability above porous surface models with regular, cylindrical pores was shown theoretically and experimentally by Fedorov et al. [2] and Rasheed et al. [3]. Analogous results were presented by Fedorov et al. [4], Maslov et al. [5,6] and Lukashevich et al. [7] who investigated randomly structured felt metal. First studies with randomly structured carbon-carbon ceramic (C/C) were conducted by Wagner et al. [8] in the High Enthalpy Shock Tunnel Göttingen (HEG). In all cases a stabilization effect on the second mode instability was observed, resulting in a significant delay of transition onset. C/C is a promising starting material for the development of thermal protection system (TPS) with ultrasonic absorption properties. However, to understand the effect of C/C on the second mode instability the absorption properties have to be known in the relevant frequency range. Investigations of Wagner et al. [9,8], Wartemann et al. [10] and Laurence et al. [11] revealed that for the HEG conditions used, the second mode instabilities occurred in the frequency range of approximately 200 kHz to 400 kHz. To directly cover this frequency range, a new test rig was set up following the concept proposed by Tsyryulnikov et al. [12] and Fedorov et al. [13] allowing measurements at varying ambient pressures. The determined ultrasonic absorption properties data were used to improved the porous wall boundary conditions of the DLR stability code NOLOT, which is described in section 3. The originally implemented boundary condition was based on an approach for regular, equally spaced cylindrical holes (see for example Maslov et al. [14]). The advanced boundary condition is based on semi-empirical relations [5], which includes the experimentally obtained acoustic characteristics of the C/C material. In section 4 the results obtained using the two boundary conditions are compared against experimental results. These experiments were performed in the HEG using a blunt 7° half-angle cone model with a nose radius of 2.5 mm holding a C/C insert covering one third of the model surface in circumferential direction. All tests were carried out at Mach 7.5, different unit Reynolds numbers and a wall to total temperature ratio of 0.1. The investigations of section 4 comprise the comparison of the calculated/measured second mode amplitudes, their damping caused by the C/C surface and the expected shift of the transition.

2. Experimental Approach

The present section describes basic properties of C/C, the wind tunnel setup and the approach followed to determine the absorption characteristic of carbon-carbon.

2.1. C/C Manufacturing and Basic Material Properties

The investigated porous carbon-carbon ceramic is an intermediate product obtained during the manufacturing process of C/C-SiC, Heidenreich [15,16] and was manufactured in-house by DLR. The manufacturing process of C/C comprises the forming of a green body of carbon reinforced plastic using commercially available 0|90° carbon fabrics impregnated with phenolic resin. In the course of the pyrolysis process the phenolic matrix is converted to amorphous carbon which results in a C/C body with random microstructure. As depicted in figure 1 the material exhibits an orthotropic layout which has to be considered if used as porous coating. Figure 1a provides a schematic view of the material with surface 3 being parallel to the 0|90° carbon fabric stacking. A microscopic view of the C/C surface corresponding to surface 1 or 2 is provided in figure 1b. It shows the random micro crack system which is relevant for the ultrasonic wave absorption process and therefore has to be oriented towards the flow field for use as an absorber. The symbol ∞ indicates the free stream direction relative to the C/C material when applied in wind tunnel tests.

The open porosity and the raw densities of carbon-carbon ceramic were determined by means of a gravimetric analysis. An open porosity of 14.98 ± 0.24 % and a density of 1.3304 ± 0.0031 g/cm^3 were obtained, Wagner et al. [9]. Furthermore, the mean length specific flow resistivity of C/C was measured to be 13 MPa $\cdot$ s/m^2, Wagner et al. [17].