Mitteilung

Fachgruppe: Turbulenz und Transition

Linear Instability Analyses of Supersonic and Hypersonic Flows over Rotating Cones

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Introduction

Rotating objects are present in numerous real-world applications. The state of the boundary layer significantly effects the skin friction drag and thermal load of aeronautical objects in high-speed flow. To understand and predict the laminar-to-turbulent boundary-layer transition on rotating configurations, the prevailing boundary-layer instabilities involved in the transition process need to be known depending on the rotation speed and inflow velocity. Basic research on the influence of rotation on boundary-layer instabilities has focused mainly on simple geometries such as rotating disks and cones. However, even for such simple geometries, the effect of rotation on boundary-layer instabilities is not yet fully understood, especially for compressible inflow. Recently, Song & Dong [1] numerically studied the impact of rotation on the instability characteristics of the 1st-Mode, the crossflow-, and centrifugal instability for the boundary layer on a 7° half-opening angle cone subjected to supersonic axial flow. This work extends the study to more half-opening angles, rotation speeds, and to hypersonic axial inflow velocity. The aim is to investigate whether rotation has a stabilizing or destabilizing effect on the primary instability mechanisms as a function of half-opening angle and inflow velocity using local linear stability theory. Furthermore, the influence of the Coriolis and centrifugal force terms (in combination: rotation terms) appearing in the linearized disturbance equations on the instability characteristics is of particular interest as well as the metric terms, which represent effects of surface curature and conical divergence.

Numerical Approach

The laminar basic flows for the rotating cone geometries with super- and hypersonic axial inflow at zero degree angle of attack are computed with the DLR TAU code on a structured grid. Grid converegence was checked and the final grid consists of 550 points along the centerline, 484 points in the wall normal direction, and 3 points in the circumferential direction. The simulations were performed with a moving wall boundary condition and rotational periodicity. The rotational velocities in the simulation were adjusted to have fixed ratios of boundary-layer edge velocity to the circumferential wall velocity (i.e., $\overline{\Omega}$) at $x = 0.4$ m, where x is the streamwise coordinate along the cone's surface. The freestream conditions for the supersonic case match the values as used by Song & Dong [1] (Ma_∞= 3.214), whereas Ma_∞= 6.1 was set for the hypersonic case. Linear local stability theory is used to analyze the instability properties of the primary instability mechanisms at $x = 0.4$ m, using the DLR in-house instability code NOLOT, which has been extended for rotating reference frames [2]. In this work, n describes the number of wave fronts in circumferential direction (i.e., the wavefront count) and ω is the angular frequency.

Results

Figures 1 & 2 show the unstable domain in the frequency-wavefront-count space of the 1st- and the 2nd-Mode for the 7°-cone with hypersonic axial flow. In Figure 1, the cone is not rotating, while Figure 2 visualizes the influence of rotation on both modes: The symmetrical characters of the 1st- and the 2nd-Mode break, as the 2nd-Mode shifts towards negative wavefront counts (waves travelling against the cone's rotation) and higher frequencies and the 1st-Mode towards positive wavefront counts and lower frequencies. Further, rotation has a general destabilising effect on both the 1st- and the 2nd-Mode, as the maximal growth rates of both modes increase with increasing rotation intensity. Figures 3 & 4 show growth-rate curves as functions of the wavefront count *n* to visualize the effects of the metric and rotational terms, as well as the Coriolis and centrifugal terms. Figure 3 shows the growth rate curves of the 2nd-Mode, while Figure 4 is based on the linear stability results for the 7° cone with supersonic axial flow and therefore shows the growth-rate curves of the 1st-Mode. For both modes, the metric terms have a stabilizing effect, because their exclusion from the stability equations leads to increased growth rates. The opposite holds for the rotation terms, which therefore have a destabilizing effect on the 1st- and the 2nd-Mode. Furthermore, Figure 4 visualizes that the centrifugal terms also have a stabilizing effect on the 1st-Mode, while the Coriolis terms represent a destabilizing mechanism. Note that the instability results for the 1st-Mode are consistent with the literature [1] when both the metric and rotational terms are included in the stability analysis. In Figure 2, the extension to negative frequencies is identified as a crossflow mode. Its destabilization is caused by the onset of a cross-flow velocity component in the base flow.

Furthermore, with the inclusion of both the metric and rotational terms, the centrifugal instability (cf. [1]) is destabilized.

Each of these modes is analyzed in terms of the influence of rotation and the dependence on the metric, rotational, Coriolis, and centrifugal terms. In addition, the effects of the half-opening angle and the two different inflow velocities on the instability characteristics are studied.

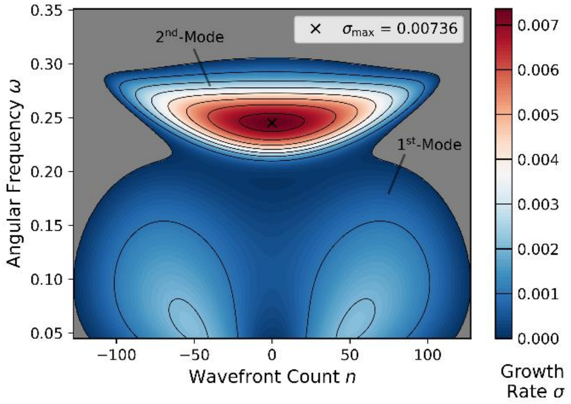

Figure 1: Isosurfaces and contour-lines of the 1st- and the 2nd-Mode in the frequency-wavefront-count domain for the non-rotating 7°-cone with hypersonic axial flow ($\overline{\Omega} = 0$).

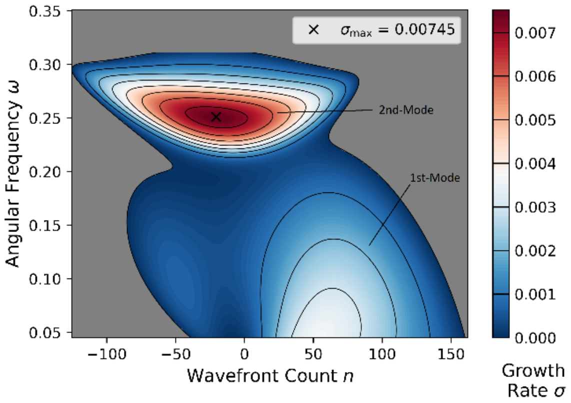

Figure 2: Isosurfaces and contour-lines of the 1st- and the 2nd-Mode in the frequency-wavefront-count domain for the rotating 7°-cone with hypersonic axial flow ($\overline{\Omega} = 0.3$).

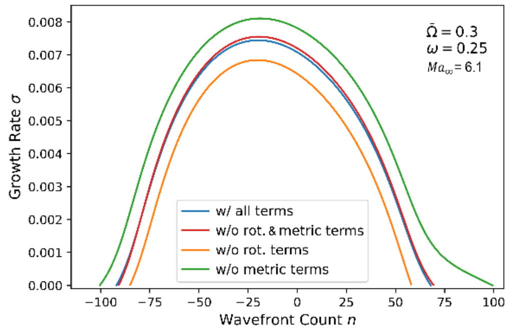

Figure 3: Growth-rate curves as a function of the wavefront count *n* for the 2nd-Mode.

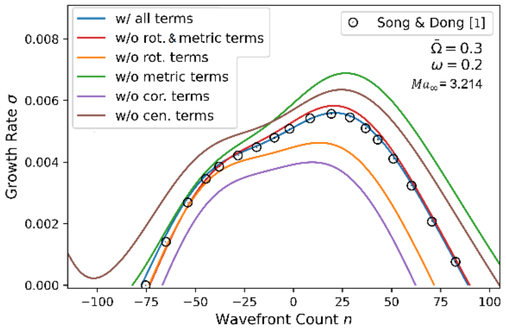

Figure 4: Growth-rate curves as a function of the wavefront count *n* for the 1st-Mode.

[1] Song, R. and Dong, M. (2023). Linear instability of a supersonic boundary layer over a rotating cone. Journal of Fluid Mechanics, 955:A31.

[2] Dechamps, X. and Hein, S. (2018). Extension of the pse code NOLOT for transition analysis in rotating reference frames. In Dillmann, A., Heller, G., Krämer, E., Wagner, C., Bansmer, S., Radespiel, R., and Semaan, R., editors, New Results in Numerical and Experimental Fluid Mechanics XI, pages 179–188, Cham. Springer International Publishing