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ORIGINAL PAPER

Boundary-layer transition measurements on Mach-scaled helicopter rotor blades in climb

Armin Weiss[1] · Anthony D. Gardner[1] · Christian Klein[1] · Markus Raffel[1]

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Abstract In this work, laminar-turbulent boundary-layer transition is investigated on the suction side of Mach-scaled helicopter rotor blades in climb. The phenomenon is assessed by means of temperature-sensitive paint (TSP). Results are compared to a data sample acquired by infrared (IR) thermography and accompanied by integral thrust- and local surface pressure measurements at two radial blade sections. Spatially, high-resolved data allow for precise detection of boundary-layer transition along the outer 60% of the blade span. Results obtained via TSP and IR show remarkable agreement with minor deviations due to different surface qualities of the respective blades tested. TSP data are obtained at various collective pitch angles and three different rotating speeds corresponding to chord Reynolds and Mach numbers based on blade tip speed of $Re_{\text{tip}} = 4.8 - 9.3 \times 10^5$ and $M_{\text{tip}} = 0.29 - 0.57$, respectively. The transition position is detected with an accuracy of better than 1% chord and the findings show overall coherence as blade loading and tip chord Reynolds number are varied. Experimental findings are shown to be consistent with two-dimensional simulations using the e^N-envelope method for transition prediction. Based on quantitative agreement between measured and calculated surface pressures, a comparison of the corresponding transition results suggests a critical amplification factor of $N_{\text{cr.}} = 5.5$ best suited for transition prediction in the rotating test facility of the DLR Göttingen.

✉ Armin Weiss
armin.weiss@dlr.de

[1] Institute for Aerodynamics and Flow Technology, German Aerospace Center (DLR), Bunsenstr. 10, 37073 Göttingen, Germany

Keywords Boundary-layer transition · Helicopter rotor blades · Temperature-sensitive paint · Infrared thermography · e^N-Method

1 Introduction

Laminar-turbulent boundary-layer transition has significant impact on the aerodynamics of helicopter main rotors. Increased amounts of laminar flow reduce the power required by the rotor and enhance its efficiency [1]. Therefore, knowledge of the boundary-layer transition position is an important parameter in the design phase of modern rotor blades and needs to be considered for accurate numerical predictions [2]. Because the extent of laminar flow is in principle larger at smaller Reynolds numbers [3], the phenomenon needs to be understood especially when performing tests at model scale ($Re < 10^6$) to eventually overcome issues when scaling to full scale [4].

Boundary-layer transition was previously assessed on model helicopter blades in hover and forward flight by hot wires [5] and hot films [6]. The techniques demand high effort on instrumentation and obtain information at much lower spatial resolution compared to image-based methods. For instance, acenaphthene coatings were used to visualize the effect of boundary-layer transition on hovering rotors at full scale [7, 8] and model scale [5, 9]. The change in skin friction resulting from transition to turbulence was successfully measured using oil film interferometry on hovering tilt rotors [10] and fast rotating propellers [11]. Promising results were also obtained by high-speed infrared (IR) imaging of model and full-scale helicopter blades in hover [12–15] as well as employing temperature-sensitive paint (TSP) on a fast rotating propeller [16] and a