WINGTIP VORTICES FROM AN EXERGY BASED PERSPECTIVE

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ABSTRACT

INTRODUCTION

Exergy is the measure of thermodynamically "available" energy as determined through the second law of thermodynamics.

Exergy is investigated in a wingtip vortex in the near wake over a range of angles of attack.

The experiments were conducted in a circular water tunnel at the ILR Aachen in Germany.

Velocity data was taken three chord lengths downstream in the Trefftz plane of an aspect ratio (AR) 5 Clark-Y wing with a square edged wingtip using Particle Image Velocimetry (PIV).

WHAT IS KNOWN?

The exergy-based approach is more comprehensive than energy-based methods. It provides precise results for component as well as system analysis.

The crossover point between wake-like and jet-like wingtip vortex axial core flows corresponds to maximum lift over drag ratio angle of attack (maximum aerodynamic efficiency).

WHAT WAS FOUND?

Even though only 2-d Trefftz plane data was used to obtain the exergy, the crossover point for the *out-of-plane* change from wake-like to jet-like wingtip vortex core axial flow (indicating the peak lift to drag ratio) was identified by the *in-plane* exergy distribution.

The increase in exergy at maximum lift-to-drag ratio from 4° to 7° angle of attack determined this transition in the profile.

This crossover point is not identifiable in the more traditional in-plane derived quantities such as vorticity or circulation distribution.

Exergy holds promise as a metric for the improvement of aircraft performance through the reduction in lift induced drag or the displacement of the maximum L/D operating condition.

- Graftieaux, L., Michard, M., and Grosjean, N., "Combining PIV, POD and Vortex Identification algorithms for the study of Unsteady Turbulent Swirling Flows," Measurement Science and Technology, Vol. 12, 2001, pp. 1422-1429.

PROBLEM STATEMENT

- To perform exergy-based analysis on the wingtip vortex velocity-field data as a function of angle of attack.
- To answer, through the exergy-based approach, why there is a change in the vortex profile (transition from wake-like to jet-like) at max L/D

ANALYSIS

For the Clark-Y Airfoil - The viscous dissipation rate in the Trefftz is represented by,

$$\Phi = \mu\left[2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2\right]$$

The entropy generation rate per unit volume is given by:

$$\dot{S}_{gen} = \frac{\Phi}{T}$$

The lost work potential is calculated through the exergy destruction rate

$$\dot{X}_{dest} = T\,\dot{S}_{gen}$$

EXPERIMENTATION

- Circulating water-tunnel with 100 *mm* x 540 *mm* x 540 *mm* test section.
- Duct contraction ratio = 1/1.8
- Freestream velocity range U_∞ =0 - 4 m/s
- Reynolds number = 200,000
- Freestream velocity range for tests U_∞ =2.2-2.5 m/s

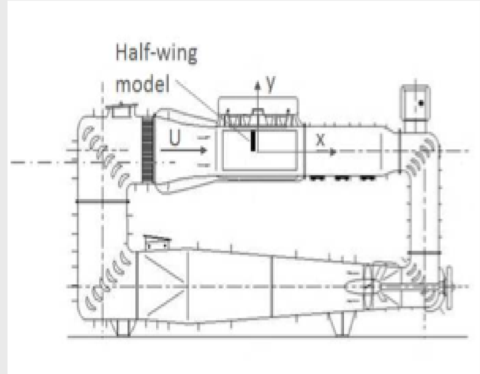

Figure 1. Circulating water-tunnel in Aachen, Germany

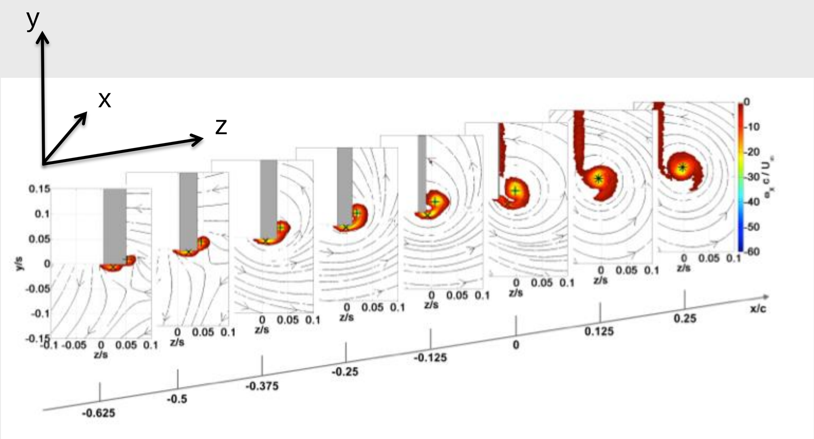

Figure 2. Representative PIV results and coordinate axis definition for the experiments

RESULTS

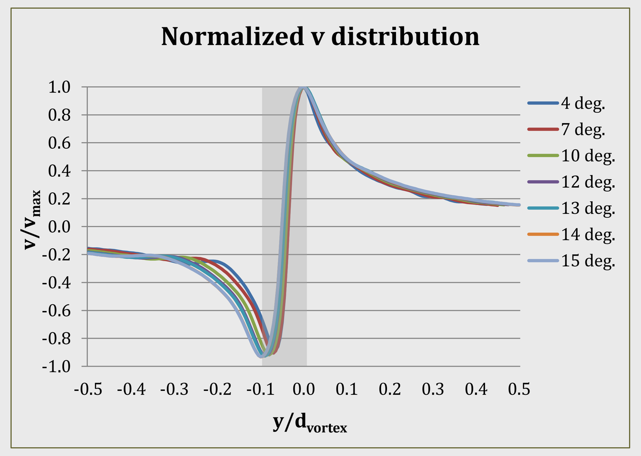

Figure 3. Normalized v distribution showing that the distribution is similar across different angles of attack (α). The shaded region indicates the approximate boundary of the vortex inner core.

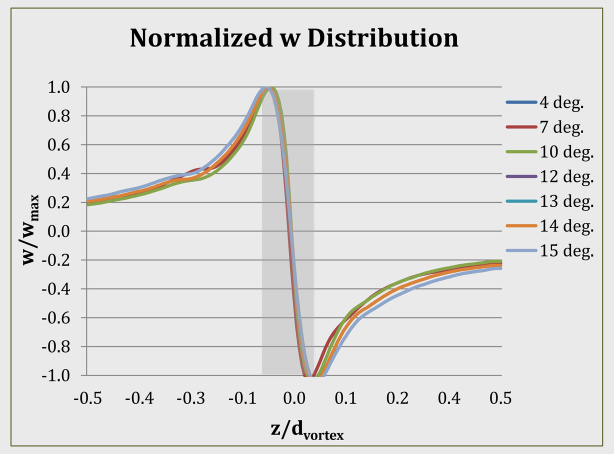

Figure 4. Normalized w distribution showing that the distribution is similar across different angles of attack (α). The shaded region indicates the approximate boundary of the vortex inner core.

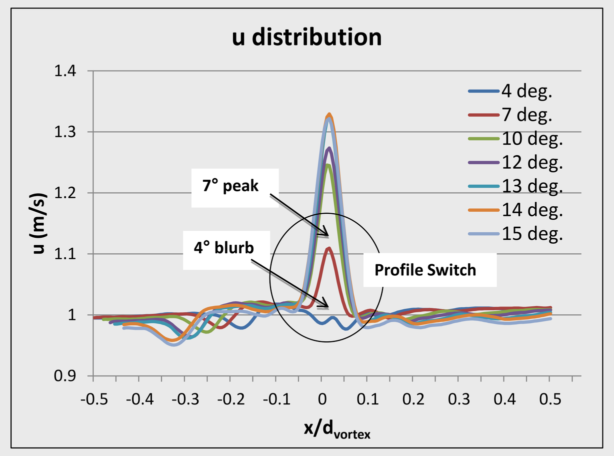

Figure 5. *u* distribution (normalized by the freestream) shows a distinct difference in the distribution. There is a switch from wake like to jet like profile from 4° to 7° α.

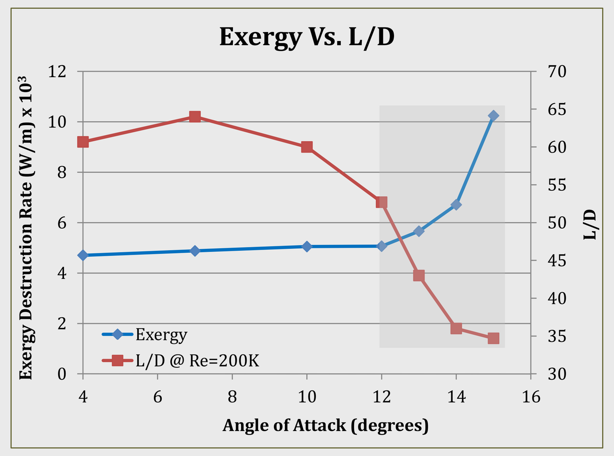

Figure 6. Combined Integrated exergy and L/D plot showing steady increase in exergy and L/D from 4° to 7° before a crossover point at 7° α. The shaded area shows the region of significant change in the profiles

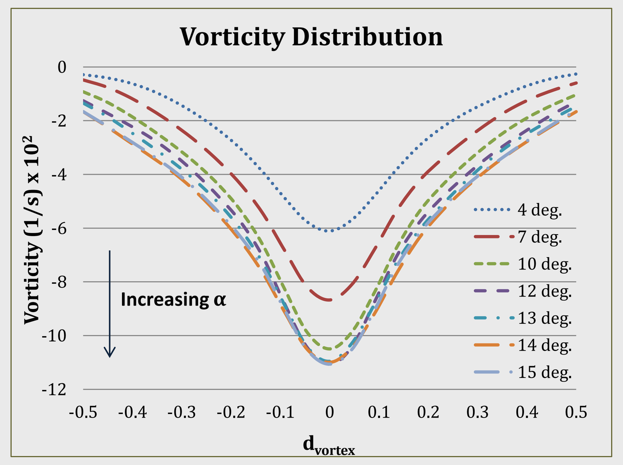

Figure 7. Vorticity normalized by its maximum value changes shape as the α increases. There is a big difference from 4 ° to 7 ° and no difference between 12 ° and 13 ° as well as between 14 ° and 15 ° α.

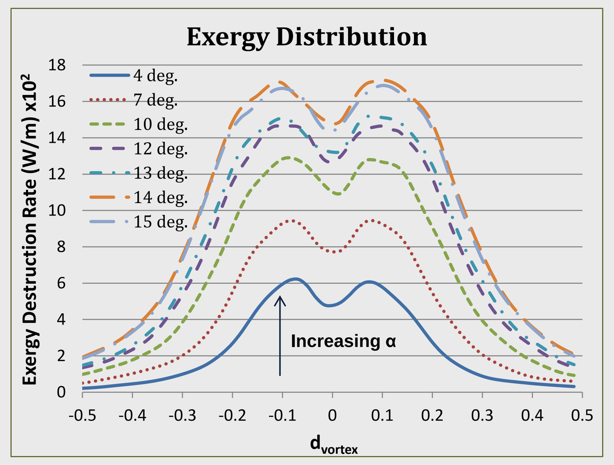

Figure 8. Exergy Distribution, similar to vorticity, changes shape as the α increases. There is a big difference from 4 ° to 7 ° and no difference between 12 ° and 13 ° as well as between 14 ° and 15 ° α.

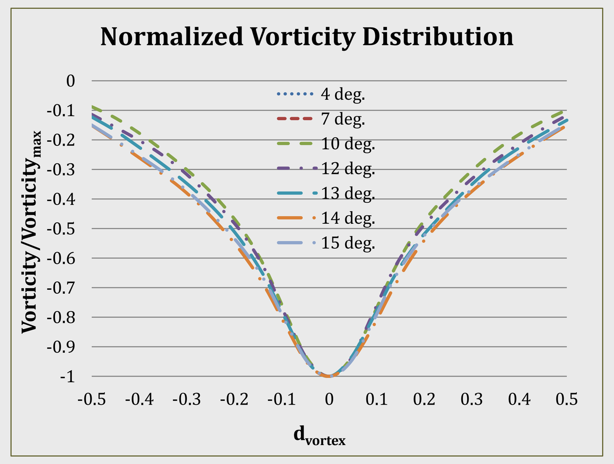

Figure 9. Vorticity normalized by its maximum value shows no significant change in overall shape regardless of α.

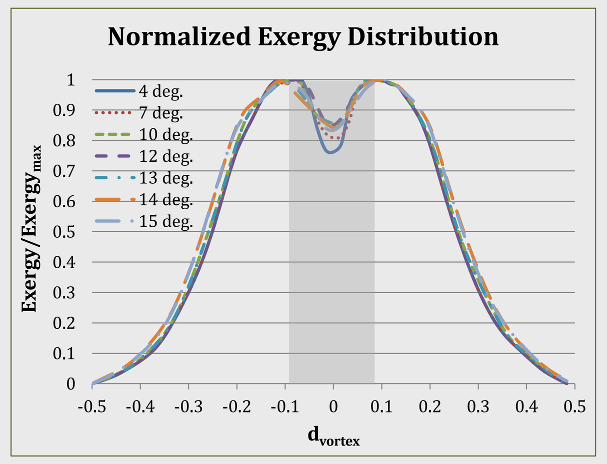

Figure 10. Normalized Exergy distribution for all angles of attack shows a significant change in shape at the critical crossover from 4 ° to 7 ° α.

RESULTS

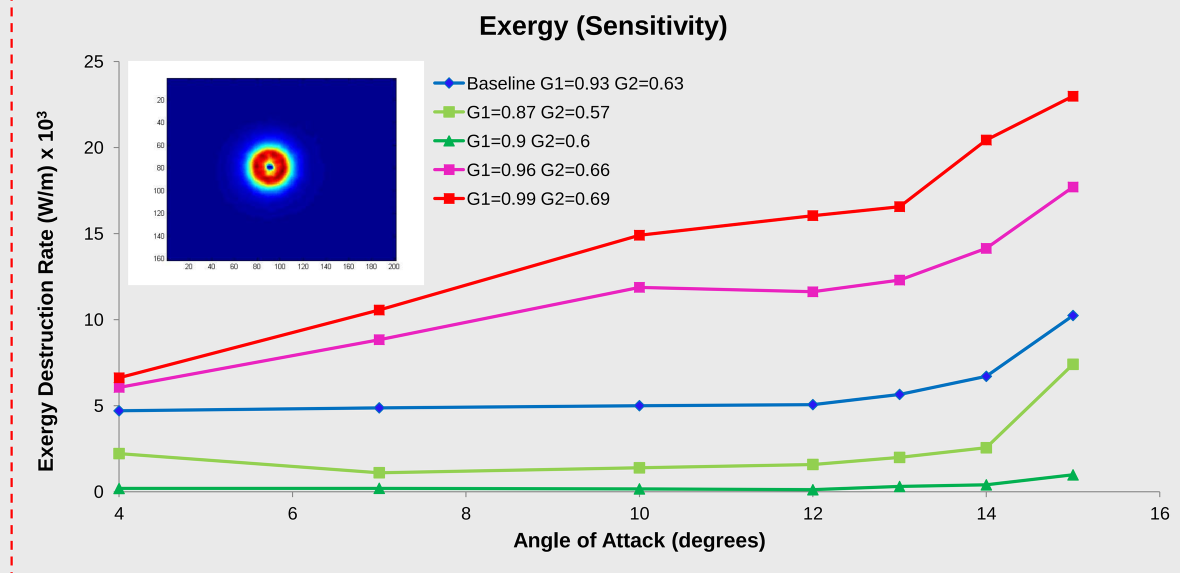

Figure 11. Sensitivity analysis for the exergy distribution derived from a vortex identification technique (Graftieux et al.).The graph shows sensitivity up to 30% in both directions. Regardless of the choice of Gamma1 and Gamma2, the trends remain same with obvious changes in the absolute magnitude.

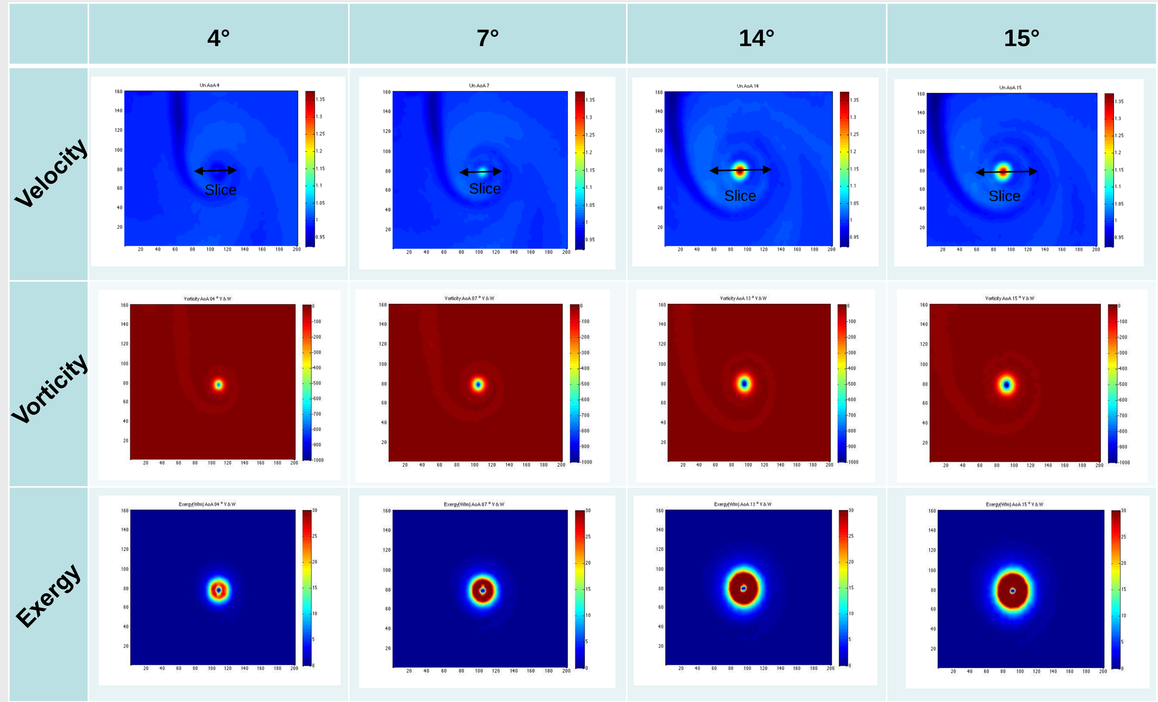

Figure 12. Visual representation of velocity, vorticity and exergy contour of the wake-like profile (at 4° and 7°) as well as the jet-like profile (at 14° and 15°) α. Comparing the velocity contours, there is little definition in the core at 4° compared to other α which have a defined core i.e an indication of a jet-like profile. Across the vorticity contours, a clear increase in absolute vorticity gradient can be observed through the core of the vortex. Between 4° and 7°, there is a substantial change in the absolute inner core exergy contour showing the out-of-plane change in axial core behavior from wake-like to jet-like.

CONCLUSIONS

- The exergy-based analysis is complementary to the traditional approach because it provides detailed information as to how the behavior can be driven towards optimum performance.
- The exergy-based technique identified the change in the out of plane profile (at the crossover point between wake-like and jet-like profile).
- The maximum lift-to-drag ratio does not correspond to the minimum entropy generation.
- As a future investigation, a reduction in the experimental increment in angle of attack in the vicinity of the cross-over/Max L/D point could yield greater insight into the mechanisms responsible for such phenomena.