3-D Navier-Stokes Analysis of Blade Root Aerodynamics for a Tiltrotor Aircraft In Cruise

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6 January 2006

Abstract

The blade root area of a tiltrotor aircraft's rotor is constrained by a great many factors, not the least of which is aerodynamic performance in cruise. For this study, Navier-Stokes CFD techniques are used to study the aerodynamic performance in cruise of a rotor design as a function of airfoil thickness along the blade and spinner shape. Reducing airfoil thickness along the entire blade will be shown to have the greatest effect followed by smaller but still significant improvements achieved by reducing the thickness of root airfoils only. Furthermore, altering the shape of the spinner will be illustrated as a tool to tune the aerodynamic performance very near the blade root.

Notation

d	Airfoil section drag
l	Airfoil section lift
Q	Rotor torque
R	Rotor radius
T	Rotor thrust
V_∞	Freestream velocity
Ω	Rotor angular velocity
η_p	Propulsive efficiency, $\frac{T \cdot V_\infty}{Q \cdot \Omega}$

Introduction

The goal of any designer is to strike a balance between competing factors in a concept. Consider the following task confronting the designer of a tiltrotor aircraft:

The high pitch angles near the root of a tiltrotor's proprotor in cruise mean that the root airfoils experience freestream velocities similar to the flight speed of the aircraft. Furthermore, this orientation requires that the airfoils contribute minimally to thrust and primarily to torque and aircraft drag. This is in stark contrast to the same rotor in hover, which sees very low freestream velocities and yet generates measurable thrust at the blade root. Geometry that is a benefit in one environment is a burden in the other. In traditional aircraft (i.e. helicopters and fixed-wing aircraft) this is of little concern; however, these disparate environments clash in the tiltrotor aircraft—an aircraft with a single proprotor that must operate efficiently in either flowfield.

The tiltrotor designer must also consider the fact that the root of the blade must be designed to bear the massive loads generated by a hovering rotor. Occasionally, the shape of the blade's root is constrained by unconventional requirements, such as the need to accommodate folding mechanisms. The designer's task is further encumbered by the presence of the spinner, the shape of which has significant effects on the flow near the root of the blade.

This paper will endeavor to provide guidance to the designer forced to find balance between aerodynamic performance, which urges toward vanishingly thin airfoils, and structural considerations which demand thick root airfoils.

Presented at the AHS Vertical Lift Aircraft Design Conference, San Francisco, California, January 18-20, 2006.

Approach

Proprotor Geometry

The proprotor used for this study was the result of the preliminary design stages of the Heavy Lift Rotorcraft Systems investigation. [1] The proprotor was designed to meet the requirements of a heavy lift rotorcraft capable of 350 kt. cruise at 32,000 ft. The specifics of the design operating in cruise are as follows:

Number of blades: 4
Radius: 42 ft.
Tip speed: 550 ft./sec.
Required thrust (per rotor): 2520 lb.
Solidity: 0.09
Chord (constant): 2.97 ft.
Inboard twist rate (<50% R): -48°·r/R
Outboard twist rate (>50% R): -30°·r/R
Total twist: 39 deg.

The preliminary design did not have custom tailored airfoils. Therefore, the baseline blade was fashioned from the XN series of airfoils distributed in roughly the same fashion as on the V-22 itself, namely:

r/R	Airfoil	Thickness
0.06	XN28	28%
0.50	XN18	18%
0.75	XN12	12%
1.00	XN09	9%

The blade cross section between specified airfoils derives from linear interpolation between defined airfoils.

For simplicity, rotor collective was trimmed to yield the same thrust for all cases considered in this study. Furthermore, no attempt was made to model blade elasticity or motion other than rotation.

The baseline centerbody was taken to be a NACA 0024 airfoil revolved about its chord line. This centerbody was necessary to simulate the presence of a spinner and to preserve the steadiness of the flowfield. The centerbody was 1/2 radius long with the rotor plane located at the point of maximum thickness. The blades were joined to the centerbody cleanly without any attempt to model bearings or pitch control hardware.

CFD Methodology

The flow solver used was OVERFLOW-D. [2] OVERFLOW-D is a software package that solves the Reynolds-averaged Navier-Stokes (RANS) equations on body fitted curvilinear grids overset by a series of Cartesian background grids. As configured in this study, OVERFLOW-D uses 4th order accurate central differencing with artificial dissipation for spatial terms. Double fringing (in which two boundary points are interpolated from overlapping grids) is employed to ensure continuity of gradient as well as solution information across grid boundaries. The steady nature of this problem permits the use of an LU-SGS algorithm with local timestep scaling to accelerate convergence of temporal terms.

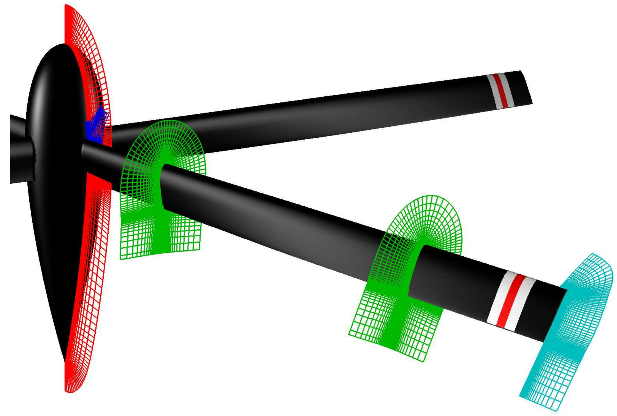

Figure 1: Overset Grid System

Based on preliminary proprotor design, a system of overset grids was produced (Figure 1). Only one of the blades and 1/4 of the centerbody was gridded for inclusion in the RANS model although much more is shown in Figure 1 for clarity. In the model, the three absent blades are modeled with periodic boundary conditions. The centerbody is modeled by a single axi-symmetric O-grid shown in red. The blade is represented by three overlapping grids: a collar grid (blue) that mates the blade to the centerbody, a blade grid (green) that models the majority of the blade, and a tip cap (cyan) which is necessary to accurately model the flow at the tip of the blade. These four grids are embedded in a series of ever-larger Cartesian box grids that fill in the remainder of the domain. In total, the grid system contained approximately 8 million points.

Because this study required numerous changes to the grids, much of the grid generation was automated. Scripts were developed to automatically generate the three blade component grids at arbitrary collective angles to facilitate the trimming of the propeller for thrust. Apart from this collective adjustment, the grids are rigid and do not move or deform. Also, software was created that allows the thickness of all or part of the blade to be changed quickly by simple scaling.

This study required many solutions to be computed. A solution was judged to be converged when the rotor's thrust and torque had stabilized. This generally required 2000 to 3000 flow solver iterations (roughly 3 hours on 16 IBM P4 CPUs). Each converged solution was analyzed for thrust, and then collective trim was adjusted as necessary before starting the next solution. Generally 3–4 of these trim iterations were required in order to arrive at a single trimmed, converged solution.

Performance Improvement Procedure

For this investigation, three approaches were used to improve the aerodynamic performance of the baseline rotor. The first, and most obvious, was simply reducing the thickness of the blade. Since the XN series of airfoils was never intended to operate under the high speed conditions specified for this rotor, aerodynamic performance along the entire blade was poor. For this reason, initial forays into blade thinning sought to improve propulsive efficiency by thinning the whole blade from root to tip. The goal of this effort was to improve the performance of the tip airfoils enough that poor performance outboard did not mask the performance of the inboard airfoils. Further improvement of outboard airfoil performance is left as an exercise in true airfoil design.

Upon determining a blade thickness that yields moderate performance outboard, the next phase of blade thickness analysis began. This phase was targeted at improving the performance of the root airfoil sections independently of outboard performance. Since the root of the blade was defined by two airfoils—the XN28 at 6% R and the XN18 at 50% R—adjusting the thickness of only the 6% R airfoil will have the effect of thinning the blade inboard of 50% R without affecting the outboard portion of the blade. This technique was used to study perturbations to the blade root thickness.

Finally, the effect of the spinner was studied as a tool to tune the performance of the rotor's root airfoils. The spinner alters the flow near the blade root primarily by redirecting incident flow toward the blade. This has the effect of accelerating the flow in an amount proportional to the spinner radius. An ideal spinner would be infinitely thin, but this is not physically realizable—the spinner must have sufficient volume to contain the hardware necessary to retain and control the flying rotor blade. This study seeks to minimize the spinner's effect on the blade root by reducing its radius only in the immediate vicinity of the rotor plane. This produces an effect reminiscent of the "Area Rule" applied to the fuselages of supersonic aircraft. The result is a reduction in the spinner's effect on the blade while maximizing the volume available inside.

Results

Blade Thinning

Two options were explored when changing the thickness of the blade: thinning the whole blade by a constant proportion and thinning the inboard and outboard sections of the blade independently. Blades which have been thinned along the entire span will be referred to by the thickness of the tip airfoil. For example, the "7% tip" blade is created by scaling the thickness of all the baseline blade's airfoils by a factor of 0.78, resulting in a 7% thick tip airfoil and a 22% thick root airfoil. Blades which have been scaled by different amounts inboard and outboard will be referred to with both a tip and root thickness. For example, the "6% tip, 20% root" blade is generated by scaling the airfoils inboard of 50% R by a factor of 0.71 and the airfoils outboard of 50% R by 0.67.

Figure 2 illustrates the results for all of the blade thickness configurations considered in this study. The red line represents the results obtained when the entire blade is thinned by a constant amount. The baseline blade, constructed from unmodified XN airfoils, is in the lower right-hand corner. The baseline blade performs poorly, with an efficiency of just 0.66. This is not indicative of deficiency in the XN airfoils but rather is a consequence of the different design conditions specified for the V-22 rotor and the rotor of this study. For this series of blade thicknesses, efficiency was improved substantially, reaching a maximum of nearly 0.78 by thinning the blade to a tip thickness of just 6%.

Note that there is a knee in the red curve at 8% tip thickness. The 9% tip blade suffers badly from wave drag as a consequence of strong shockwaves at the root and tip. The peak Mach number for this blade is 1.38 at the tip and 1.20 at the root. At 8% tip thickness, the shock waves at the tip of the rotor have weakened substantially. The peak Mach number for this blade is just 1.18 at the tip. This large reduction in shock strength near the blade tip is responsible for most of the improvement in propulsive efficiency between the 9% tip blade and the 8% tip blade. As the blade is thinned below 8% tip thickness, the shockwaves continue to weaken, but as a fraction of total drag, these weak shockwaves are less significant than the strong shockwaves of the 9% tip

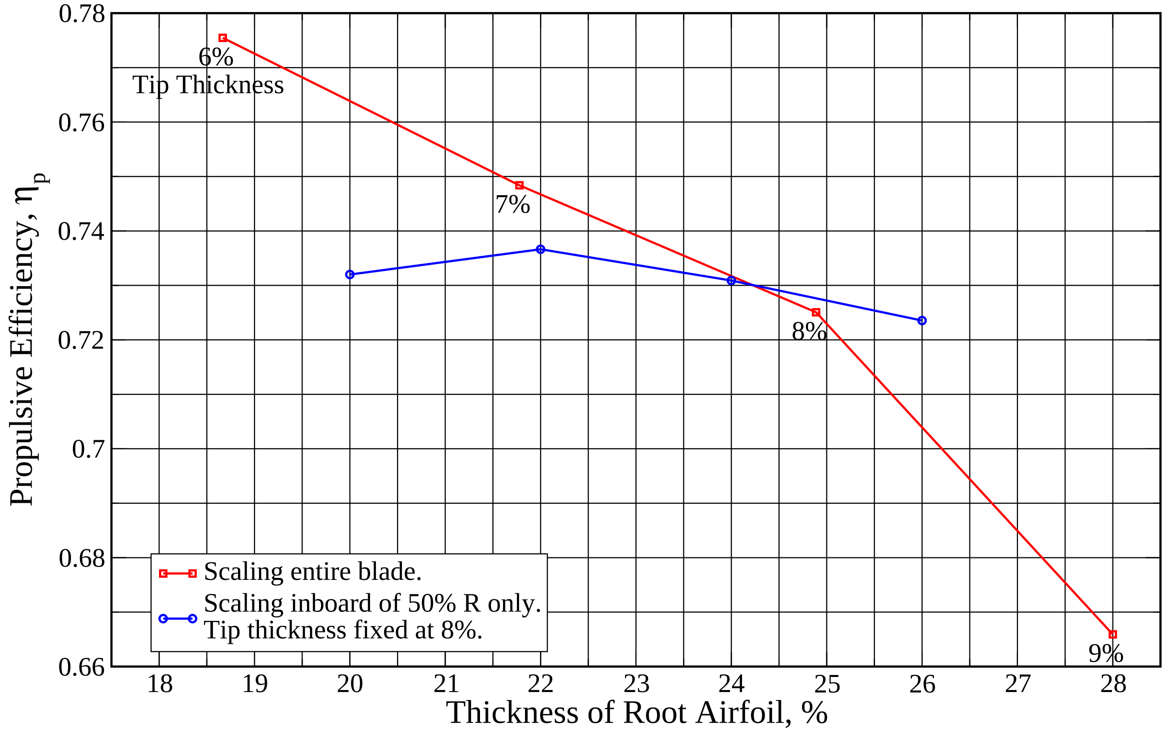

Figure 2: Propulsive Efficiency at Various Thickness Distributions

blade. Consequently, the improvements in propulsive efficiency realized for blades below 8% tip thickness arise from modest reductions to all forms of drag and are much smaller in magnitude than the improvement witnessed in thinning from 9% tip thickness to 8% tip thickness.

Thinning airfoils in this manner is a poor substitute for rigorous airfoil design. The interplay between airfoil lift and drag is too complex to be optimized by simply scaling thickness. Airfoil thickness is used in this study only as a tool to coarsely improve rotor performance by minimizing wave drag. Since the 8% tip blade forms only weak shock waves, it meets this goal and further improvement should be left to more rigorous airfoil design. However, root airfoils do not play an important role in providing thrust but rather degrade propulsive efficiency by contributing to aircraft drag and rotor torque. Therefore, any measure that reduces root airfoil drag—regardless of its deleterious effects on lift—will act to improve efficiency.

For these reasons, the 8% tip blade is used as a starting point for exploring the effects of thinning the root sections of the blade independently of the outboard sections. This series of calculations is represented by the blue line in Figure 2. From this curve, it is clear that there is substantially less benefit to thinning the inboard half of the blade than there is in thinning the whole blade. Figure 3 will yield some enlightenment. This figure illustrates sectional performance along the blade span for selected blade thicknesses. From this figure, it is clear that the benefits obtained from thinning the whole blade (black, red, and blue curves) are large and occur all along the blade span. Conversely, when only the inboard portion of the 8% blade is thinned (green and purple lines), the benefits are smaller and confined to the root portion of the blade. The magnitude of the improvement is not surprising since much of the wave drag was already eliminated in thinning the whole blade from 9% at the tip to 8% at the tip.

The 8% tip, 20% root blade illustrates a case in which simple thinning without regard for other airfoil design parameters failed to produce an improvement in performance. Thinning the blade root beneath 22% root thickness results in degraded overall performance. Efficient airfoils of this thickness may be attainable but require more thorough design efforts.

Figure 4 gives a more qualitative view of blade performance. In this figure, regions of supersonic flow are shown in red. For the baseline blade, there is clearly substantial shock activity along the entire upper surface and along the inboard half of the lower surface. This is in contrast with the 8% tip, 22%

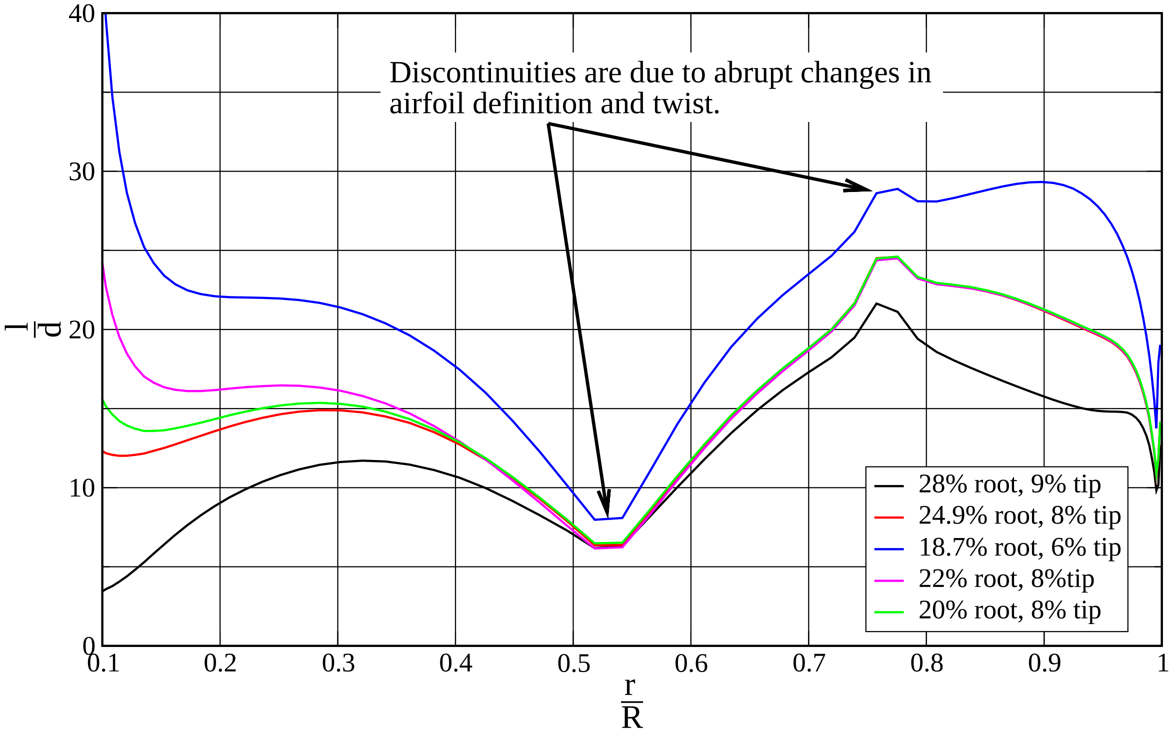

Figure 3: Spanwise Blade Performance

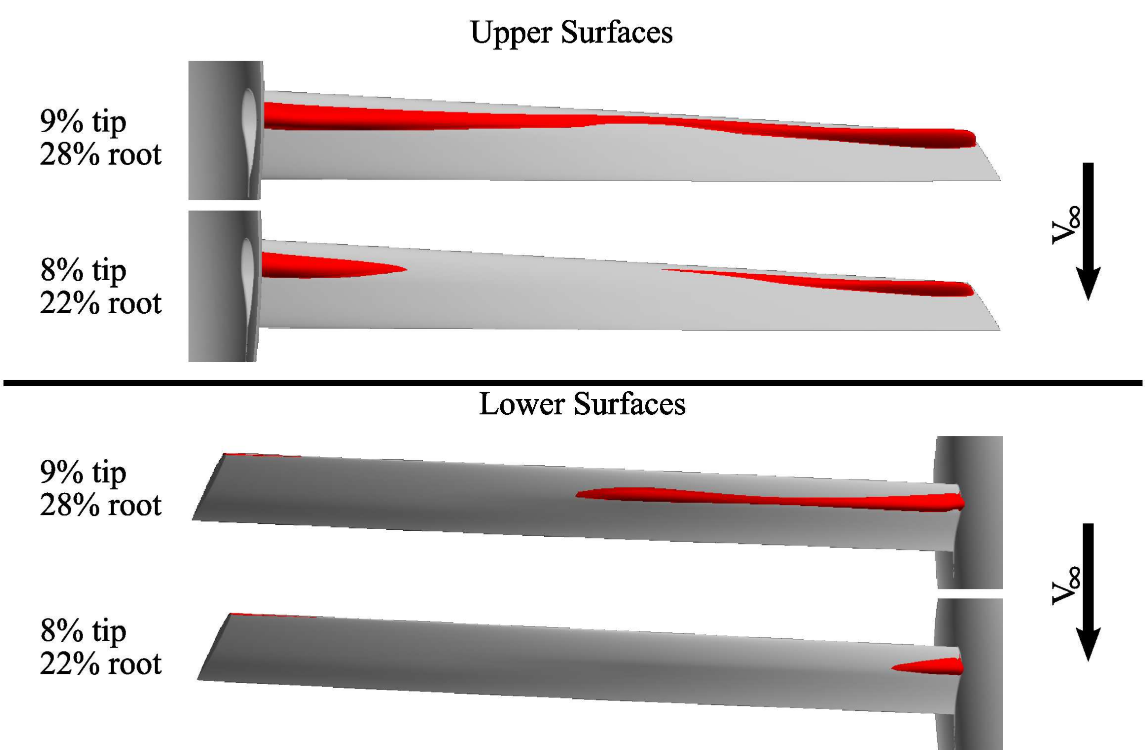

Figure 4: Regions of Supersonic Flow on Blade

root blade in which the shocks are much smaller and weakened considerably.

Reshaping the centerbody

It is clear from Figure 4 that even thinning the root airfoil to 22% still leaves a substantial region of supersonic flow present at the root of the blade. Careful airfoil design would likely alleviate this problem but is beyond the scope of this text. However, there is more that can be done to slow the flow near the root of the blade. Rather than continue thinning the root of the blade until the flow remains completely subsonic, consider Figure 5. From this figure, it is clear that there is a strong correlation between the location of peak Mach number on the centerbody and the region of supersonic flow on the blade. Recall that the rotor plane was placed at the point of maximum thickness of the centerbody. If the thickness of the centerbody were reduced in the immediate vicinity of the rotor plane, it would reduce the centerbody's contribution to flow velocity at the root of the blade while maximizing the volume available within the spinner.

The baseline centerbody profile was modified using a simple exponential function:

$$y = a \cdot \mathrm{e}^{-\frac{(b-x)^2}{c}} \tag{1}$$

This function creates a smooth and easily controlled "bump" that can be applied to the centerbody as shown in Figure 6. The parameter b locates the exponential function along the centerbody's longitudinal axis, the parameter c controls the width of the exponential function's effect, and a controls the peak value of the exponential function. A value of 0.04 for b and 0.016 for c were selected to locate and size the exponential commensurate with the blade root.

Selection of the a parameter is slightly more difficult. The 8% tip, 22% root blade experienced a peak Mach number of 1.12 at the blade root. Assuming that superposition applies, a Mach number reduction of 0.12 along the centerbody will slow the flow until it is just sonic at the blade surface. Shown in red on Figure 7 is the Mach number along the centerbody surface. A 0.12 reduction in Mach number at the rotor plane would yield a Mach number of 0.62. Also from Figure 7, notice that a Mach number of 0.62 occurs at an x value 0.2 upstream of the rotor disk. From Figure 6, it is clear that the baseline centerbody is 18% thick at this point. A value of 0.03 for the a parameter was therefore selected to reduce the thickness of the centerbody to 18% in the rotor plane.

Figures 5 and 7 show the effect of the modified centerbody geometry on Mach number near the rotor disk. The modified centerbody profile was successful in reducing the peak Mach number in the rotor plane by 0.07. Fortunately, this turned out to be enough improvement as the reduced flow velocity combined with the new trim condition virtually eliminated supersonic flow at the blade root. The peak Mach number with the modified centerbody is just 1.01, and propulsive efficiency for the whole rotor increased from 0.74 to 0.75.

Conclusions

Blade root design is important for tiltrotor aircraft because of the difficult balance between minimizing aerodynamic penalties in cruise, maximizing hover performance, and maintaining structural rigidity. This paper offers a computational technique for modeling the flow around a high-speed proprotor and has applied this technique to the analysis of blade features with the potential to provide aerodynamic benefit.

The baseline blade design suffered badly from wave drag incurred by airfoils operating far off-design. The first, and most effective, technique for improving performance involved reducing airfoil thickness along the entire blade. This had the effect of weakening strong shocks that plagued the baseline blade. The largest improvement came from thinning the entire blade 11% which results in a blade that is 8% thick at the tip, 25% thick at the root, and improves propulsive efficiency by 9%. Significant benefits have been shown by further thinning of the blade, but this is ill advised as the outboard airfoils are sensitive to degraded performance arising from this low fidelity approach to airfoil design.

Because the inboard airfoils do not make any beneficial aerodynamic contributions in cruise, they can tolerate additional thinning. Thinning the inboard airfoils to 22% thickness at the root yielded an additional 2% improvement in propulsive efficiency. Further thinning resulted in degraded airfoil performance.

The influence of the spinner on blade root aerodynamics has been illustrated by using the shape of the centerbody to tune inboard aerodynamic performance. An elementary function was used to adjust the centerbody profile in the immediate vicinity of the rotor plane. This had the benefit of eliminating inboard wave drag with a minimum impact on available volume within the spinner.

Blade design is a complex process. These tech-

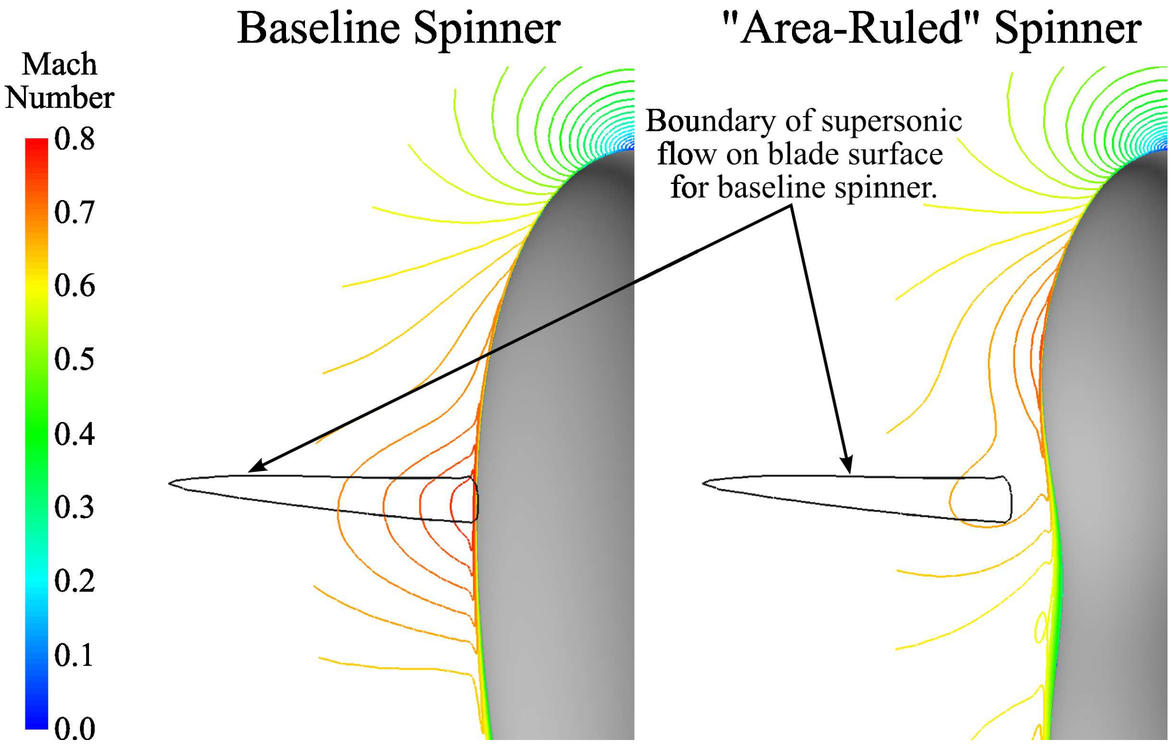

Figure 5: Mach Number Contours on Spinner Surface Between Blades

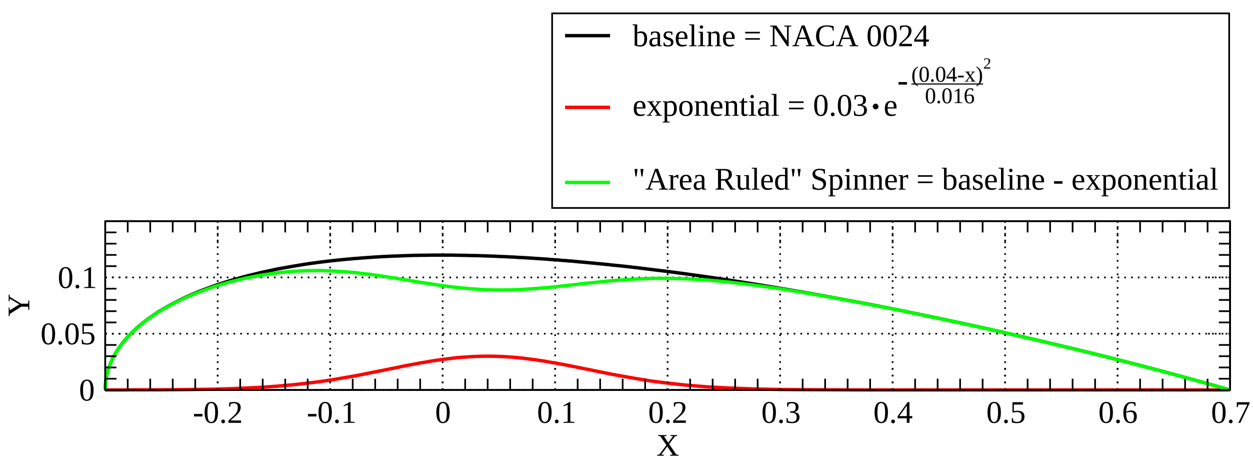

Figure 6: Deriving the Modified Spinner Profile

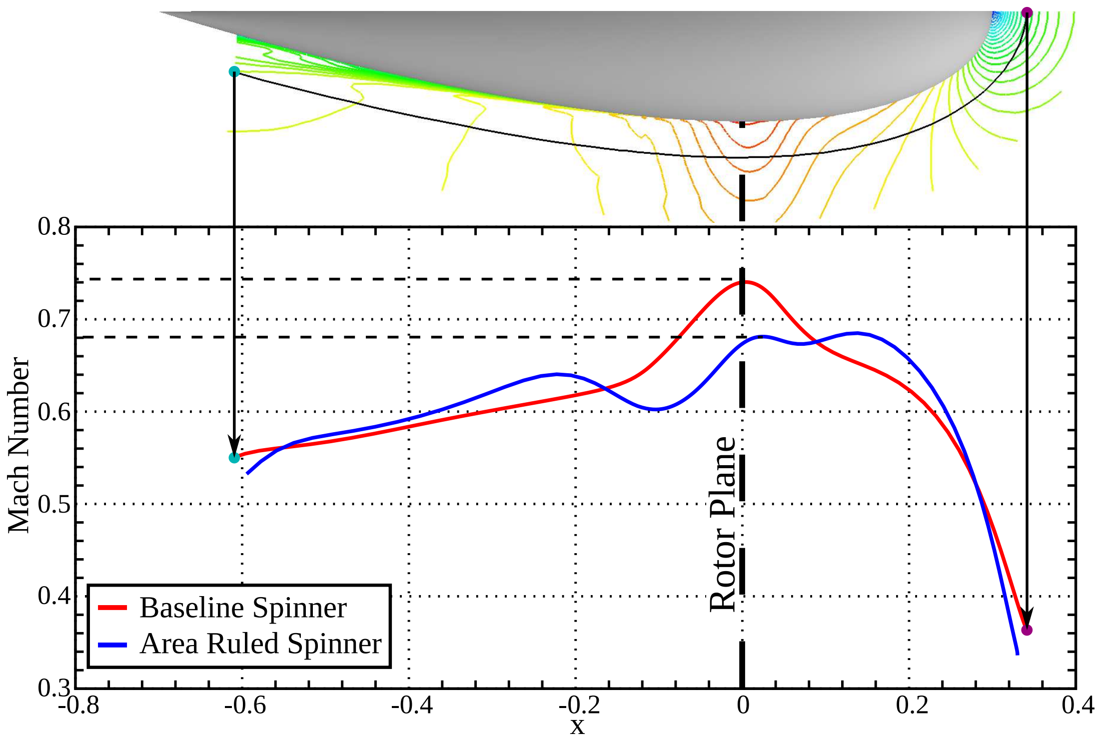

Figure 7: Mach Number Comparison Along Spinner Between Blades

niques are offered as a foundation to—and not a substitute for—more rigorous design procedures. In particular, thorough airfoil design may be able to achieve similar performance gains at higher airfoil thicknesses. Higher thickness will prove beneficial in areas neglected by this study, namely hover performance and structural integrity.

References

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