

Virtual Wind Tunnel Testing for Mathematics of the Adaptive Rotor / Propeller Blades

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Investor points

In earlier posts it has been shown, theoretically, that for the tiltrotor family of Bell and Boeing (V-22, MV-75 etc.) - with special regard to the low speed operations, vertical takeoff and landing, hover etc. - it is impossible to achieve full control of flight unless their proprotor blades are upgraded to the adaptive technology.

Even those who may agree, will also admit that such a requirement is a most serious one. It would practically involve a prototyping process for the whole proprotor unit. Optimistic expectation is that engines can be kept as they are. (Loads are rather expected to reduce, and in no way to increase.)

When a development task is expensive, usually, for the investors it is good to have some kind of guarantee they will really get what they are about to pay for. Luckily, mathematical support for the adaptive rotors and propellers can provide such a guarantee. More exactly, there exist formulas, which are capable to prove - with sufficient certainty - that the promised improvements are feasible.

What exactly the math can prove?

It is known to be typical for all present day rotors and propellers that their main characteristics – such as thrust and efficiency – remain excellent in a relatively narrow range of axial speed only. Deterioration happens (basically) due to the changing axial speed causing a growing difference between the actual value of the angle of attack (AOA) experienced by the blades, from the optimal value of the same. In short, AOA gets spoiled by the changing axial speed. Also, to make a bad case worse, the wrong AOA values keep appearing along the blades (or, which is the same, along the rotor / propeller radius) in an uneven, nonlinear way.

The proposed mechanical solution claims to maintain a near optimal AOA at all sections of rotor/propeller blades, in a wide range of changing axial speed. This exactly is the point to be proved mathematically.

The approach

We will use the 3D scheme of components of the airspeed. (The very components defined by the Blade Element Theory, BET of propeller design.) A vector diagram built around a section of a rotor/propeller blade, with the latter charted in 3D too. This kind of viewing allows noticing when a blade loses alignment with the airflow, and an AOA Error is created. AOA Errors cause blade stall and losses, and are therefore undesirable.

Our objective is to prove – using vector geometry - the adaptive blades are capable to handle a widely changing axial speed without the creation of AOA Errors. In other words they (blades) are capable to

keep their alignment with the resulting airspeed however greatly the axial (speed-) component may change.

The plan is to have equations describing 3D geometry of both the active section of a blade, and of the speed vectors of the resulting wind around that section. It is expected that the two groups of equations will show strong similarity. (In fact, it is shown they are the same.) If yes, then it means the blade surface and the speed vectors of the airflow (rather a vector field) are in alignment. (Mathematically they are the same surface.)

The wind tunnel

A sequence of vector diagrams built for different phases of an aerodynamic process can be used to create animation, which will emulate testing of an object in a wind tunnel. By using this **virtual wind tunnel** one can do fantastic things! E.g. we can make the axial speed changing cyclically between two extremes of V_{axMAX} and V_{axMIN} , and keep that cycling go on indefinitely, for any chosen duration. Such a regime can help us watch and analyze behavior of the airflow over a single blade of a propeller while the circumstances (axial speed) will keep changing wildly. Animation (e.g. a GIF) also helps making easier to follow the 3D nature of the research.



Fig. 1.

Selecting field of view for the GIF

A fixed pitch propeller blade (section) is picked below, because creation of the AOA Errors is more spectacular here compared to that on a variable pitch propeller. (Similar animations also for variable pitch propellers can be found at the stallfreepropellers.com website.)

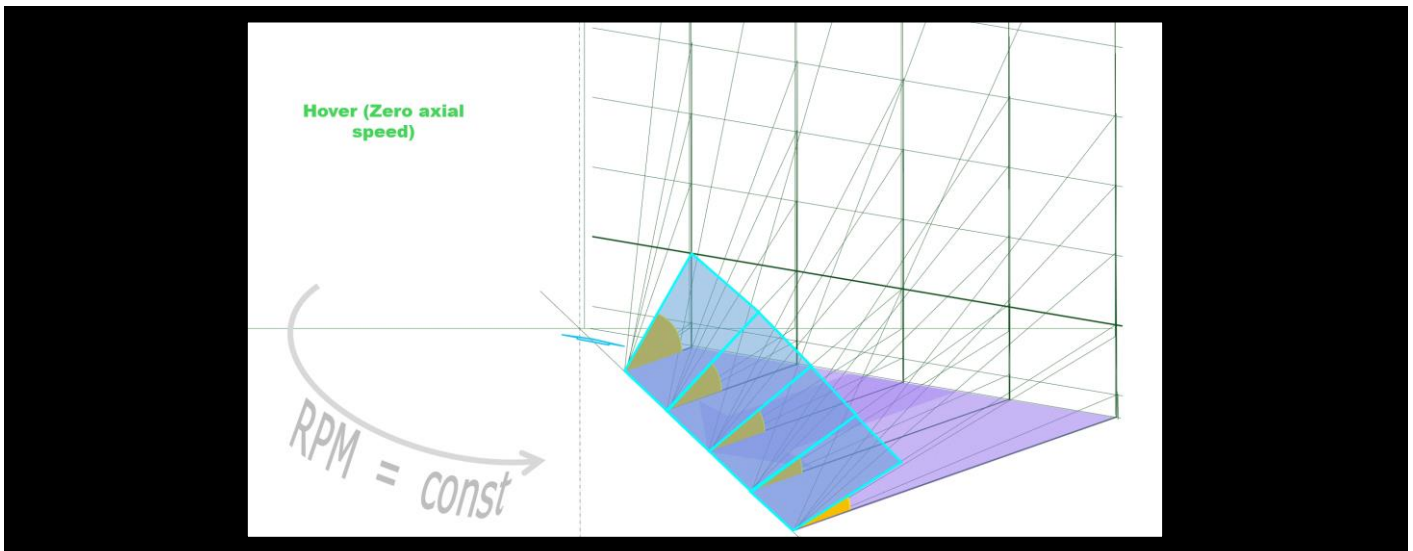


Fig. 2.

Virtual wind tunnel test of a propeller blade for changing axial speed (the GIF)

Original for download:

https://stallfreepropellers.com/wp-content/uploads/2025/10/Fixed-Pitch-Prop-Speed-Vectors_01_02_corr.gif

Legend of the GIF:

- Blue arrow represents the axial component of the speed of the aircraft (it is opposite(!) to the direction of the speed of the airflow $\mathbf{V}_{\text{aircraft}} = -\mathbf{V}_{\text{airflow}}$) ;
- Violet is the resulting speed of the airflow (a vector field);
- Bright yellow segments indicate presence of an AOA Error.

Note

Optimal AOA is a very small value of around 4 degrees. Resolution of the chart is too low for a sensible representation of it. Instead an $\text{AOA}_{\text{optimal}} = 0$ degrees approximation is used. Therefore the expression "in alignment" in the text practically means the sections/airfoils are working at $\text{AOA}_{\text{optimal}}$.

Most important part of the GIF is the shape in violet, in the center. Multiple arrows representing the resulting speed of the airflow at different points of the airfoil, blend together to form it. A point to notice is that although the shape is made of straight lines, it has a curved surface. It is twisting.

The charts, on the basis of which the above GIF has been created, are sufficient to write the 3D equations describing vector geometry of the resulting airflow. It is practical to pick the angle between the vectors of the resulting speed and the plane of rotation of the propeller as the means to describe the geometric surface of that violet shape. The outcome is an uncomplicated ARCTG function made dependent also on the value of the propeller radius.

The details required for the proper derivation can be found in the eBook. Also, clippings from this eBook are included here as Fig. 3. to show geometry for the mathematical model of the adaptive blade. An effort was made to achieve similarity between the two models (resulting speed and adaptive blade surface, respectively) in order to help their comparison.

3D model of blade geometry

Identification of reference parts:

- Plane of feathered state (plane X-Y, shaded yellow) ;
- Propeller's plane of rotation (plane Y-Z) and axis of rotation (axis X);
- The masts („A-B-C-D”) with their axis of rotation;

Important detail:

The propeller's axis of rotation is different from that of the masts!

- The **TTM** -s, or more exactly their **medians** (TTM1-i-n);
- The sails (elements of skin).

Blade angle, β

$$\beta = \arctg \frac{C1}{r - r_{HUB}}$$

When looking for conformity it is good news the angles of both the blades and the resulting wind are governed by the **same type** of function along the radius :

$$y \sim \arctg \frac{1}{x}$$

Angle of resulting wind, γ

$$\gamma = \arctg \frac{C2}{r}$$

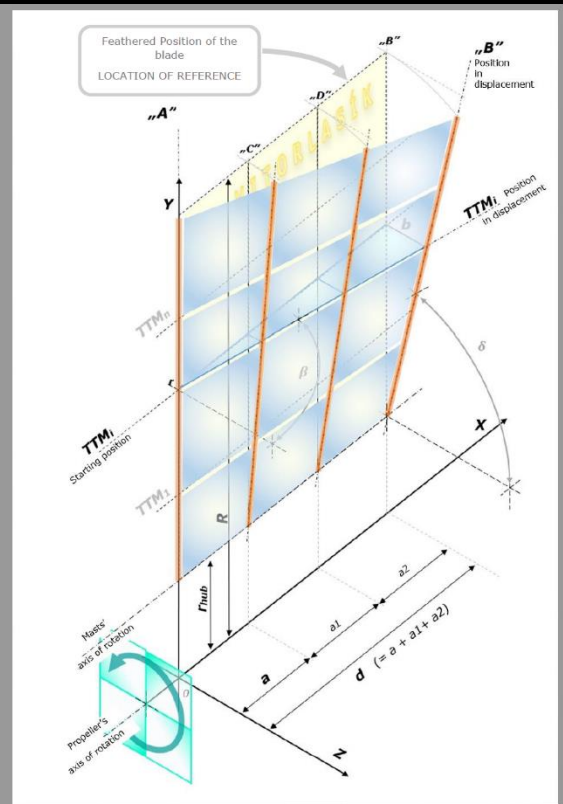


Fig. 3.

Blade geometry model built for the comparison process with the similar 3D model of the resulting airspeed (the violet shape on Fig. 2.)

Original for download:

https://stallfreepropellers.com/wp-content/uploads/2025/10/Clipping_02.png

Proved: adaptive blades keep AOA optimal for any axial speed

We used the blade geometry model shown in Fig.3. to obtain equations, which would describe position of the skeletal rods (the TTMs) of the adaptive blades, through their angle relative to a reference plane.

It was achieved that both the resulting speed vectors, and the skeletal rods of the adaptive blade had their positions

- described by the same angle (approximately);
- with the distribution of the values of those angles along the propeller radius, **governed by the same function.**

The above achievement proves that

- it will be always possible for the pilot to find a position (pitch) for the rotor/propeller blades that will **fully align** them with the direction of the resulting wind, along the whole radius of the rotor/propeller disk, **for any axial speed.**

27 October 2025