Design for the Control of a Rotatable Stabiliser

S. J. Childs

Department of Mathematics and Applied Mathematics, University of the Free State,
P.O. Box 339, Bloemfontein, 9300, South Africa.
tel: +27 51 4013386, email: simonjohnchilds@gmail.com

Abstract

This research sets out a design for the control of a rotatable stabiliser which, it is proposed, might augment, or fully replace, the conventional control mechanisms for pitch and yaw in aircraft. The anticipated advantages of such a device are around 25% less drag, for a capability which ranges between equivalent and greater than twofold that of the conventional tail. One, anticipated handicap of such a device is the potential for it to stall, from its tips, inward, if rotated too fast. For succinctness, a mapping between states of the device and the position of a two-axis controller (e.g. a joystick) is formulated. The function of the joystick traditionally assigned to the control of ailerons is replaced by that traditionally associated with the rudder pedals. Its function is otherwise conventional. From this topology it follows that small and continuous adjustments of the controls should cause the stabiliser to rotate in a direction opposite to that of the joystick (when viewed from aft) and the deflection of the hinged control surface is proportional to the radial displacement of the joystick from its centred position. For what would amount to large and contradictory rotations of the device in terms of this protocol (e.g. rotations of 90° or greater), movement can be more efficiently effected by regarding the device’s original orientation to differ by 180° and its original deflection to be the negative of what it actually is. One consequence of this latter mode of control is that a symmetrical aerofoil (e.g. the NACA 0015) is indicated.

Keywords: Rotatable stabiliser; rotatable stabilator; swivelator; tail; horizontal stabiliser; vertical stabiliser; elevator; rudder.

1 Introduction

This research sets out to design a protocol for the control of an aerofoil (or rotor) whose in-flight orientation is actively adjusted by swivelling around an axis parallel, or approximately
parallel, to the aircraft’s longitudinal axis. The purpose of the envisaged device, is to augment, or fully replace, the conventional control mechanisms of pitch and yaw in aircraft.

Conventional aircraft tails consist of an horizontal and vertical stabiliser at right angles to each other, as well as their respective control surfaces, the elevator and rudder. The elevator provides for the control of pitch, while the rudder provides for the control of yaw. Both the pitching and yawing forces combine to give a resultant force, the magnitude of which is given by Pythagoras’ theorem. The magnitude of the resultant is always less than the sum of its pitching and yawing components, a fact which infers that the same force can be achieved with a lesser area of aerofoil. It is for this reason that a more efficient device is sought. A single aerofoil in the correct orientation will always be able to produce the same lift force while incurring a much lower drag. It is for this reason that deploying a rotatable aerofoil, precisely in the direction in which lift is required, is contemplated as an alternative to the conventional tail.

![Figure 1: A conventional tail and a rotatable stabiliser as viewed down the longitudinal axis of an aircraft.](image)

The function of the vertical stabiliser, is to maintain the aircraft’s orientation about the vertical axis and to diminish weathervaning of the tail, something which ultimately manifests itself as dutch roll. Dutch roll is a phenomenon particularly problematic in wide-bodied, multi-engined aircraft with a poorly defined and variable centre of gravity; hence higher and offset moments of inertia. It is for this reason that a pronounced vertical stabiliser is often a feature of such aircraft, particularly those with pronounced sweepback. For smaller, unmanned, single-engined aircraft with a well defined and constant centre of gravity, the vertical stabiliser is of diminished importance. Examples of such aircraft would include drones, U.A.Vs. and missiles. The rudder, itself, ordinarily gives rise to an adverse rolling moment about the longitudinal axis. This is due to its asymmetrical positioning relative to that axis, its superior position in the conventional tail configuration. The adverse rolling moment never manifests itself, however, since it is over-compensated for by yet another rolling moment, one which is yaw-induced: Yawing causes the outside wing to speed up, consequently, to lift. It also causes the inside wing to slow down, to meet the remote, free air flow at a lower incident angle and be slightly shielded by the fuselage, thereby losing lift. The aircraft ultimately rolls in the direction of yaw, which happens to be the same direction as the bank the yaw is intended to combine with in a coordinated turn. (Of course, when the tail weathervanes, the oscillatory yaw gives
rise to an oscillatory version of the yaw-to-roll phenomenon just outlined. This is known as
dutch roll.) Ordinary v-tails, such as the V35 Beechcraft Bonanza, suffer from adverse roll
too. Only inverted v-tails (such as that of the Predator drone) and tails in which the vertical
stabiliser is positioned below the longitudinal axis do not suffer from adverse roll. They give
rise to a moment which reinforces both the yaw-induced roll, as well as the bank the yaw
is intended to combine with in a coordinated turn. Such tails have what might therefore be
termed an advantageous roll as a bi-product. Since the tail mostly exerts a downward force
during flight, an anhedral or inverted v-tail has the same levelling tendency as a dihedral wing,
whereas the ordinary v-tail has a destabilising effect. The envisaged, rotatable stabiliser should
produce no adverse roll once in the correct orientation. This prediction is based on its proposed
symmetrical arrangement about the longitudinal axis. A moment of adverse roll may, however,
 arise during the rotation of the device; unless separate control surfaces (or the angles of attack)
on either side of the axis, are adjusted in the direction of rotation.

The primary function of the horizontal stabiliser and its control surface, the elevator, is to
counter the gravitational moment about the centre of pressure associated with the wing. A
centre of gravity forward of the centre of pressure is an arrangement essential to the funda-
mental stall characteristics any aircraft must possess. Since the elevator is used to adjust the
pitch of the aircraft and, therefore, the angle of attack of its wings, a secondary function of
the elevator is to determine the speed of the aircraft as well as the lift force, consequently the
rate of climb, or descent. When the airspeed drops below that required for the wing to produce
sufficient lift, the usual pilot-response is for the elevator to be adjusted so as to cause the an-
gle of attack of the wings to exceed the stalling angle. Under such circumstances, the wing is
no longer a streamlined body and, since Bernoulli’s equation only applies along a streamline,
the wings stall. In summary, the horizontal stabiliser may be considered more important than
the vertical stabiliser, barring certain aerobatic applications and spin recovery. One variation
on the horizontal stabiliser theme of the conventional tail is worthy of mention and that is the
stabilator. The stabilator is an horizontal stabiliser in which the entire stabiliser becomes the
control surface. The entire horizontal stabiliser assumes the function of the elevator.

What is ultimately envisaged in this research is an aerofoil whose in-flight orientation is ac-
tively adjusted by swivelling\(^1\) relative to the aircraft, around an axis parallel, or approximately
 parallel, to the longitudinal axis (an axis designed to be approximately parallel to the relative
air flow), thereby affording the aerofoil the capability of exerting a lift force in any direction
about the said axis. The direction of this lift force can, furthermore, be affected continuously,
for all changes. It is anticipated that such a device may be used either aft or forward of the
wing and centre of gravity. That is, in either a tail or canard-wing position. The purpose of
the envisaged device, is to augment, or fully replace, the conventional control mechanisms of
pitch and yaw in aircraft, although more ambitious applications are not excluded. For example,
the possibility of implementations in which the device might also augment, or fully replace,
the function of the ailerons can not be ignored, should the device have separate, hinged control
surfaces, on either side of the axis about which it rotates (or a split device in the instance of a
stabilator-like implementation). The device may, or may not, include a split, variable pitch, a
mechanism for warping, or similar for rapid rotation at low airspeeds.

\(^1\)Note the capability implied by the use of the operative word “swivelling” as opposed to “tilting”.
In helicopters the tail consists of a rotor and pitch control is more complicated. While the concept of directed lift is presently developed in the context of an aerofoil, an analogous description for a rotor is easily deduced. If one were to coin a term for a whole family of such devices e.g. ‘swivelator’ it would refer to an aerofoil (or rotor) whose in-flight orientation is actively adjusted by swivelling, relative to the aircraft, around an axis parallel, or approximately parallel, to the longitudinal axis, thereby affording the device the capability of exerting a lift force in any direction about the axis. The magnitude of the lift force is designed to be adjustable by way of a hinged control surface, changing the angle of attack (a lá a stabilator), or additionally, in the case of a rotor blade, spinning faster or changing the pitch of the rotor blades.

2 The Advantage Over a Conventional Tail

In the case of a conventional aircraft tail, the envelope of maximum force is rectangular about the aircraft’s longitudinal axis (Fig. 2). In the case of a rotatable stabiliser the envelope of maximum force is circular (Fig. 2), implying that it is able to exert a maximum lift force in any direction. This is in contrast to the conventional tail, which is limited to produce its maximum in only four, unique directions.

Consider the capability of a conventional tail, in which the vertical and horizontal stabiliser are comprised of three identical members, for simplicity and as depicted in Fig. 2. If the area of each member is $S$, then the maximum resultant is obtained by combining the maximum force
exerted by both the horizontal and vertical stabilisers simultaneously, that is

\[
\sqrt{\left(\frac{1}{2} \rho C_L v^2 S\right)^2 + \left(\frac{1}{2} \rho C_L v^2 2S\right)^2} = \frac{1}{2} \rho C_L v^2 S \sqrt{1 + 2^2} = \frac{1}{2} \rho C_L v^2 2.236 S, \quad (1)
\]

in which \(\rho\), \(C_L\) and \(v\) are the usual, density of the air, coefficient of lift and velocity of the incident air, respectively.

The above result, Eq. (1), is immediately recognizable as the lift formula for an aerofoil of area \(2.236 \times S\). In this way it becomes clear that only \(2.236 \times S\) of correctly-orientated aerofoil is required to produce the same maximum lift as a \(3 \times S\) area of conventional tail. A far smaller area of aerofoil than the combined area of the horizontal and vertical stabiliser is required to produce the same force. A reduction in drag of approximately 25% is therefore one consequence of resorting to a rotatable stabiliser. The maximum capability is, furthermore, unrestricted in the case of the rotatable stabiliser, whereas the conventional tail is only able to attain this maximum in four, unique directions. The only four directions for which the conventional tail under consideration fairs this well are

\[
\pm \left[ \arctan (2) + n \pi \right] = \pm \left( 63^\circ \times \frac{\pi}{180^\circ} + n \pi \right) \quad n = 0, 1, \cdots
\]

radians. For a purely yaw-related requirement, the rotatable device is, furthermore, able to exert more than twice the force of the conventional tail, by Eq. (1). A rotatable stabiliser therefore has the advantage of being able to exert the maximum lift force in any direction, which can amount to more than twice the capability, for a much reduced drag. Of course, the individual members of a conventional tail do not operate independently from an aerodynamic point of view, they operate rather as a single system, the respective flows over each surface interacting with each other. The device in question might therefore also be expected to facilitate a lower interference drag, there being two less intersecting surfaces involved.

Such an analysis is, of course, a gross over simplification and the significance of tail drag, itself, needs to be put into perspective. Drag ordinarily depends on the flight regime, the percentage of laminar flow, etc. and induced drag can also become a factor, depending on the speed of the aircraft. The relatively low aspect ratio of the device, preferred for rotation, is a disadvantage from an induced drag point of view. When it comes to parasitic drag, however, a close in engine installation, gear doors and a plethora of other factors are by far the greatest budget of drag on the airframe, the largest contributors to the overall drag. Interference drag, cooling drag and propeller effects in the absence of laminar flow are just a few of the other issues which bring the significance of tail drag into perspective.

Possible disadvantages of a rotatable device are that there is a limit on response time, as will be shown, and a rotating link might exceed the mass of the conventional system of cables and pulleys. In a manned aircraft the response of the normal tail configuration is instantaneous, at least in so far as the human input is. In a remotely controlled aircraft one relies on servos etc. anyway.
3 Desired Topology and its Implied Control Protocol

Since a rotatable stabiliser involves two degrees of freedom, namely its orientation and the deflection of a hinged control surface (or change in angle of attack, for an all-moving device), any two-axis input device will suffice as a controller. A two-axis joystick is probably the most intuitively obvious device in terms of which to explore the concept of controlling a rotatable stabiliser, even though yaw and pitch are conventionally controlled separately by rudder pedals and the forward or aft position of a joystick in most aircraft. (There is no loss of generality in making this joystick–only simplification; pedal inputs can just as easily be substituted for the lateral movements of a joystick.) What follows is a description, which is just one example of how a continuous, one-to-one, conformal mapping between the position of controls and the rotatable stabiliser, itself, might be expected to be established in order for the device to function.

3.1 Desired Topology

Convention dictates that the joystick retains the traditional pitch-altering function of the aircraft. This necessitates that the orientation of the stabiliser and the deflection of its control surface correspond to those of an horizontal stabiliser and elevator, respectively, for positions of the joystick along the line $x = 0$. The preferred orientation of the rotatable stabiliser is therefore parallel to the lateral axis of the aircraft for positions of the stick in the longitudinal plane (pitch up or pitch down). What is traditionally the banking function of the joystick is, however, replaced by the yaw-altering function traditionally assigned to the rudder pedals (or mode one on most traditional radio control apparatus). The orientation of the stabiliser and the deflection of its control surface correspond to those of a vertical stabiliser and rudder, respectively, for positions of the joystick along the line $y = 0$. The preferred orientation is parallel to the vertical axis of the aircraft for positions of the stick in the lateral, or $y = 0$ plane (yaw left or right replaces what was traditionally bank left or right).

Figure 3 relates the orientation of a rotatable stabiliser and the deflection of its hinged control surface to positions of the joystick. Starting from the top, clockwise in Fig. 3: Stick forward, nose pitches down; right pedal or stick, nose yaws right; stick back, nose pitches up; left pedal or stick, nose yaws left. For an all-moving device, the specified deflection relates to the trailing edge of the stabilator, instead of a hinged control surface. In the instance of a rotor, the depicted deflection specifies the direction of thrust, instead.

Although the orientations are the same for the canard implementation as they are for the tail version, deflection is obviously in an opposite sense to that depicted in Fig. 3. Aileron inputs may be superimposed in implementations where the rotatable stabiliser is used to augment, or fully replace, the function of the ailerons by having separate control surfaces on either side of the axis about which it rotates.
3.2 The Control Protocol which Stems from this Topology

A logical outgrowth of the above topology is to require that the rotatable stabiliser rotate in a direction opposite to that of the joystick and the deflection of its hinged control surface to be proportional to the radial displacement of the joystick from its centred position. For movements of the controls through the origin (or close to it), it may be preferable to reverse the sense of deflection, rather than have the device rotate excessively. Unproductive and petulent rotation due to small, repeated corrections and over-corrections can, in this way, be avoided. Unproductive and petulent rotation can readily be defined as adjustments of the joystick which require rotation greater than 90° (movements of the joystick through the centre, into a new quadrant). The proposed remedy is to apply the aforementioned protocol as if the actual orientation of the device differs by 180° and its deflection is the negative of what it is. For this mode of movement alone, deflection of the hinged control surface is not always to the same side, advocating the use of symmetrical aerofoils. This is no cause for concern, however, as
symmetrical aerofoils, such as the NACA 0015, have an almost identical performance to that of the NACA 2412 (Jacobs et al., 1933), the latter being the preferred choice in most of the Cessnas.

The proposed deployment of the rotatable stabiliser could be summarised as follows:

1. The orientation of the stabiliser and the deflection of its control surface correspond to those of an horizontal stabiliser and elevator, respectively, for positions of the joystick on the line $x = 0$. The orientation of the stabiliser and the deflection of its control surface correspond to those of a vertical stabiliser and rudder, respectively, for positions of the joystick on the line $y = 0$.

2. The rotatable stabiliser rotates in a direction opposite to that of the joystick, when the former is viewed from aft.

3. The deflection of the hinged control surface (or the angle of attack of the aerofoil in the case of a stabilator-like implementation) is proportional to the radial displacement of the stick from the centred position.

4. For adjustments of the joystick which militate a rotation greater than 90° in terms of the aforementioned protocol, it is more efficient to apply that same protocol as if the actual orientation of the device differs by 180° and its deflection is the negative of what it is.

In the conventional tail, two linearly independent inputs are mapped to two linearly independent outputs, which combine to give a resultant. In the rotatable-stabiliser concept the two linearly independent inputs are mapped directly to a resultant. Notice that the transformation between states is continuous, conflicting control inputs being the exception. Clearly, there would be a fundamental loss of continuity in the aforementioned diagrams, were a tilting, as opposed to a fully rotating device to be used.

4 Rapid Rotation at Low Speeds and its Implications for the Angle of Attack

Once the stabiliser is being rotated, the angle of attack is no longer that between the chord and the remote, free air flow. Under such circumstances the incident air acquires an additional component of velocity, opposite to the direction of rotation. Rapid rotation of the device is therefore expected to complicate matters in a slow moving aircraft. Likewise, rotation of the device when deployed close to its maximum deflection (the stalling angle) can be predicted to be problematic. The outer tip of the stabiliser will begin to stall during rotation, should rotation cause the maximum angle of attack to be exceeded. Either the stabiliser must be rotated at a slower speed or a differential pitch must be added.

What kind of stalling angles are contemplated? Symmetrical aerofoils with a high stalling angle, such as the NACA 0015, are a common choice for stabilators. In theory this aerofoil
stalls just above 22° while simultaneously delivering a lift coefficient just greater than 1.5 and a lift-to-drag ratio slightly above 95 (Jacobs et al., 1933). In the real world induced drag and atmospheric conditions, e.g. wind shear and gusting, can dramatically reduce this angle and the margin of safety. The functional range of angles of attack for aerofoils, in general, is usually cited as -4–16° by more practical references concerned with less ideal conditions (e.g. Thom, 1993).

The deviation in the angle of attack, $\Delta\alpha$, brought about by rotation is readily calculated according to the formula

$$\Delta\alpha = \arctan\left(\frac{\text{tangential velocity}}{\text{airspeed}}\right) = \arctan\left(\frac{\text{revolutions per second} \times 2\pi \times \text{radius in m}}{\text{airspeed in km h}^{-1} \times \frac{10}{36}}\right),$$

in which the radius referred to is the distance along the aerofoil from the point of rotation. From this formula one immediately observes that short spans are conducive of small deviations in the angle of attack, as are the kind of high airspeeds one normally associates with missiles and their like. The area, hence lift, lost in shortening the span can, to a certain extent, be recouped by means of a longer chord.

The implications of rotation are probably best contemplated by way of a few hypothetical examples. If, for example, a device of span 2 m rotates at a rate of $\frac{\pi}{2}$ s$^{-1}$ (15 rpm), the tangential velocity of the tips is 5.65 km h$^{-1}$. For an aircraft flying at a speed of 50 mi h$^{-1}$ this incurs a ± 4° departure from the angle of attack at the tips of the device. Since the lift force may be approximated as linearly dependent on angle of attack, one may average and assume a respective 2° increase and decrease in angle of attack on either side of the rotational axis. The total lift force on the device is preserved during its rotation and the only negative consequence is the adverse rolling moment, mentioned in the introduction. The problem comes in rotating the device when it is already deployed at or close to its maximum deflection. Since the functional range of an aerofoil is usually -4–16° (Thom, 1993), the trouble-free range for the rotatable stabiliser would be expected to be 0–12° at the aforementioned speeds of rotation\(^1\). Of course, were the angle of attack to be increased and decreased by $\Delta\alpha$ on either side of the longitudinal axis, respectively, the complete -4–16° range is recovered and the adverse rolling moment avoided. The problem with this feat is that the precise airspeed needs to be known in order to calculate the exact adjustment in angle of attack. By differentially adjusting the angle of attack on either side, by an amount predicted using an airspeed somewhere between the stall speed and the maximum speed, one might substantially recover the aerofoil’s range.

If a device of the above description and circumstances were, however, to be rotated at a rate of $2\pi$ s$^{-1}$, it would incur a ± 16° departure from the angle of attack at its tips, clearly unacceptable. Of course, at a speed of 600 km h$^{-1}$ this becomes a mere ± 2° and the full range in angle of attack for the aerofoil is almost completely recovered. Similarly, for a radio controlled aircraft with a rotatable stabiliser of 40 cm and a 16 km h$^{-1}$ stall speed, one would expect

---

\(^1\)The experimental work of Jacobs et al. 1933, demonstrates an upper limit usually closer to 22°, however, there are many reasons to revise this value downward in the real world.
rotation at a rate of $\pi/2 \, s^{-1}$ to induce a departure from the angle of attack at the tips which would never exceed $\pm 4^\circ$.

In contrast, consider a device of width $2 \, m$, which rotates at a rate of $\pi \, s^{-1}$, thereby incurring a $\pm 8^\circ$ departure from the angle of attack at its tips and severely constraining the dynamic range of operation for the aerofoil to between $4^\circ$ and $8^\circ$ angle of attack. If the device is split into two, say, all-moving aerofoils on either side of the rotational axis, the possibility for correction arises. If one imparts a $4^\circ$ ‘up’ correction to the upward moving side and a $4^\circ$ ‘down’ correction to the downward moving side, the departure from the angle of attack at the tips would reduce to a mere $\pm 4^\circ$, thereby regaining a more favourable range of $0$–$12^\circ$ for dynamic operation; a trick not unreminiscent of the variable pitch propeller. An even more sophisticated development of this idea would be warping. Notice that a split, variable-pitch device has the added benefit of eliminating the imbalance in lift about the rotational axis, the adverse roll previously referred to. It also has the potential for an initial torque favourable to the rotation itself. One potential problem with such an approach is that if one does not know the exact airspeed, one will always undercompensate for the angle of attack on one side and overcompensate on the other. This is, once again, not a good idea just below the stalling angle.

Notice that all examples, as well as Eq. (2), recommend a control strategy in which the device is never rotated at maximum deflection. The examples highlight stabiliser span and low airspeeds as limiting factors in its use.

## 5 Conclusions

This work sets out a design for the control of a rotatable stabiliser which, it is proposed, might augment, or fully replace, the conventional mechanisms for pitch and yaw in aircraft. The anticipated advantages of such a device are around 25% less drag, for a capability which ranges between equivalent, to greater than twofold that of the conventional tail. One, anticipated handicap is a restriction on the speed of rotation, due to the potential for the aerofoil to stall, from its tips, inward, during rapid rotation. The deviation in the angle of attack, $\Delta \alpha$, brought about by a rapid adjustment is readily calculated according to the formula

$$\Delta \alpha = \arctan \left( \frac{\text{revolutions per second} \times 2\pi \times \text{radius in m}}{\text{airspeed in km h}^{-1} \times \frac{10^3}{36}} \right),$$

in which the radius referred to is the distance along the aerofoil from the point of rotation. A strategy in which the device is never rotated at maximum deflection is obviously recommended.

Convention then dictates that, in the absence of any lateral displacement of the joystick, the orientation of the stabiliser and the deflection of its control surface should correspond to those of an horizontal stabiliser and its elevator, respectively. The function of the joystick traditionally assigned to the control of ailerons is otherwise replaced by that traditionally associated with rudder pedals. This means that for purely lateral displacements of the joystick, the orientation of the stabiliser and the deflection of its control surface correspond to those of a vertical
stabiliser and rudder, respectively. From this topology it follows that small and continuous adjustments of the controls should cause the stabiliser to rotate in a direction opposite to that of the joystick (when viewed from aft) and the deflection of the hinged control surface is proportional to the radial displacement of the joystick from its centred position. For what, in terms of that protocol, would amount to large and contradictory rotations of the device (e.g. rotations of $90^\circ$, or greater) movement of the device can be more efficiently effected by regarding its original orientation to differ by $180^\circ$ and its original deflection to be the negative of what it actually is. Such a mode of control obviously implies the use of a symmetrical aerofoil, such as the NACA 0015, which has an almost identical performance to that of the NACA 2412 (Jacobs et al., 1933), the latter being the preferred choice in most of the Cessnas. The particular control protocol outlined above also serves to illustrate the potential the device has to be controlled reflexively and in an elementary and intuitively obvious manner. It is contended that the mapping between states of the device and the position of a two-axis controller (e.g. a joystick) is the most logical that can be formulated. Notice that the only difference between the aft, or tail implementation and the canard-wing type implementation is that the deflection of the hinged control surface is in the opposite direction.

The danger of a large-span stabiliser stalling, from the tips, inward, at low airspeeds during rotation, make the device ideally suited to high speed aircraft and missiles; all craft in which a short tail-span and fins are preferred. The tendency of drones not to engage in rapid aerobatic manoeuvres allows for slow rotation, making them just as likely candidates for the application of such a device. In a manned aircraft the response of the normal tail configuration is instantaneous, at least in so far as the human input is. In a remotely controlled aircraft one relies on servos etc. anyway.

Clearly, there would be a fundamental loss of continuity in the movement of the device and therefore the control of the aircraft, were a tilting, as opposed to a rotating device to be used. In the case of a $90^\circ$-tilting device, for example, one cannot effect a continuous transition between a nose-up to nose-down input, while simultaneously maintaining a yaw input, as this results in a lateral inversion of the yaw.

References

[1] S. Childs. *Swivelator*. Provisional patent 2004/7616. 2004.

[2] S. Childs. *Swivelator*. Provisional patent 2004/10179. 2004.

[3] S. Childs. *Swivelator*. Provisional patent 2005/05287. 2005.

[4] E.N. Jacobs, K.E. Ward, and R.M. Pinkerton. The characteristics of 78 related airfoil sections from tests in the variable-density wind tunnel. Technical Report 460, National Advisory Committee for Aeronautics.

[5] T. Thom. *The Aeroplane – Technical*, volume 4 of *The Air Pilot’s Manual*. 1993.