

Technical Publications

Periaerofoil (a.k.a. Flying Saucer) Concept and Theory

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Table of Contents

ISSUE RECORD.....	2
INTRODUCTION.....	3
CONCEPT OUTLINE.....	4
SUMMARY.....	5
DESIGN OUTLINE.....	6
THEORETICAL ADVANTAGES.....	8
LIFT FACTORS.....	9
Profile.....	9
Chord length.....	9
Length.....	9
Pitch.....	9
Air velocity.....	9
Aerofoil height and position.....	10
BASELINE CALCULATION.....	11
Air velocity and lift force in free air.....	11
Comparison with commercial product.....	12
THE VENTURI.....	13
Back pressure calculations.....	13
Checking for compliance with Bernoulli.....	14
Ground effect.....	15
Breakdown and conclusions.....	16
Variation with distance.....	17
THE AEROFOIL.....	18
General calculations.....	18
UPSCALING.....	19
FURTHER WORK.....	20
TESTING.....	21
Measuring motor thrust.....	22
Measuring exit air velocities.....	23
REFERENCES.....	27
Online resources.....	27
Constants.....	27

ISSUE RECORD

19/04/26 Initial report
07/09/26 Added section "Further work" and minor edits
12/09/26 Clarifications

INTRODUCTION

One of society's most useful aeronautical projects has been the, now common, helicopter. More recent and more common variations on this basic design are such things as quad-copters and octo-copters, aka "drones".

- Helicopters are used extensively for operations such as surveillance, medevac and search-and-rescue where land-based or fixed-wing vehicles are impractical, including hostile environments.
- Drones are increasingly used for light-load transport and overhead surveillance over comparatively short distances. This type, being less complicated and less hazardous in the event of failure, lend themselves more easily to remote control and even autonomous operation.

However these vehicles have significant limitations on their operation:

- They are very noisy.
- They create significant downdraught.
- For hostile environments the larger vehicles are difficult to protect.
- Compared with fixed wing aircraft, helicopters are not fuel efficient.

Those who live near helipads would testify to the nuisance and sometimes alarming "thumping" vibrations created synchronously at ground level by overhead helicopter rotors, even at heights of hundreds of feet. And for military operations it is difficult to approach a conflict area without giving plenty of warning to those who are intended to be taken by surprise.

The downdraught of helicopters can cause serious hazard to the immediate ground environment, which necessitates "standing off" at some height during medevac (especially at sea) and other operations where it is not acceptable to land. This necessitates using winching facilities that can take a long time in urgent situations, impacting on the overall response efficiency.

It is therefore of interest to investigate the possibility of developing a vehicle that has the flexibility and agility of rotary-wing vehicles while substantially reducing some of the above disadvantages and restrictions. To be of practical interest such a vehicle would need to be comparable in fuel efficiency to helicopters although, especially when moving slowly or over short distances, could not be reasonably expected to compare with fixed-wing aircraft or ground-based transport on favourable surfaces.

It should be noted that an invention known as the "Discopter" was patented in the USA in 1944 by Alexander Weygers, but was never developed into a viable product. The Discopter used multiple propellers to produce downdraught in similar fashion to modern drones, except that they were enclosed in an overall disc structure and had adjustable ported outlets to control attitude and direction. This is supposed to have stimulated the imagination of so-called "flying saucers" featured in science fiction themes.

The concept of using downdraught as a means of aerial suspension was later developed into helicopters and other vehicles, as mentioned above. However, this project does not create significant downdraught and therefore differs fundamentally from the earlier invention and its derivatives.

CONCEPT OUTLINE

In order to suspend a vehicle in the atmosphere, at an arbitrary distance above ground and without any physical means of support, there are limited possibilities.

Given that no suitable electromagnetic or electrostatic field is available, which would require either an adjacent vehicle or substantial local ground infrastructure, the only apparent option is to use the air itself.

Daniel Bernoulli, a Swiss mathematician and physicist of the 18th century, presented a theory that calculated a change in fluid pressure when flowing through a pipe with a changing cross section area. This theory was later extended to account for the change in pressure experienced by a flat surface in moving air.

From this, aerodynamic theory was developed and remains the basic mechanism by which all aircraft, whether fixed-wing or rotary-wing, remain aloft. It governs not only the wings of a fixed-wing aircraft but all propeller blades and the rotors of a rotary-wing aircraft.

This project does not attempt to find an alternative means of support, but considers a totally different application of the same principle.

SUMMARY

This project, as far as it goes, is not intended to produce a laboratory machine that could actually fly. This for several reasons, not the least of which is that a laboratory test apparatus would necessarily be encumbered with structural variables for testing the proposed theories and which would compromise the aeronautical performance.

This report describes and analyses an experimental project that considers the possibility of developing a vehicle in the form of a so-called flying saucer. By using an annular aerofoil about a circular airframe this project combines the aerodynamic principles of rotary-wing and fixed-wing vehicles, together with what may seem to resemble an industrial ventilation system.

The provisional name for the project is derived from the classical Greek words for “around”, “air” and “blade”

An experimental design is presented that employs commercially available components within an original airframe design concept. The potential amount of lift is estimated from theory, measured experimentally and compared with rotary-wing devices of similar power.

The control systems necessary to stabilise and direct the attitude and rotation of the vehicle are not considered here although some design ideas are presented for further investigation. This report is therefore confined to discussing the basic consideration of whether such a device could actually fly.

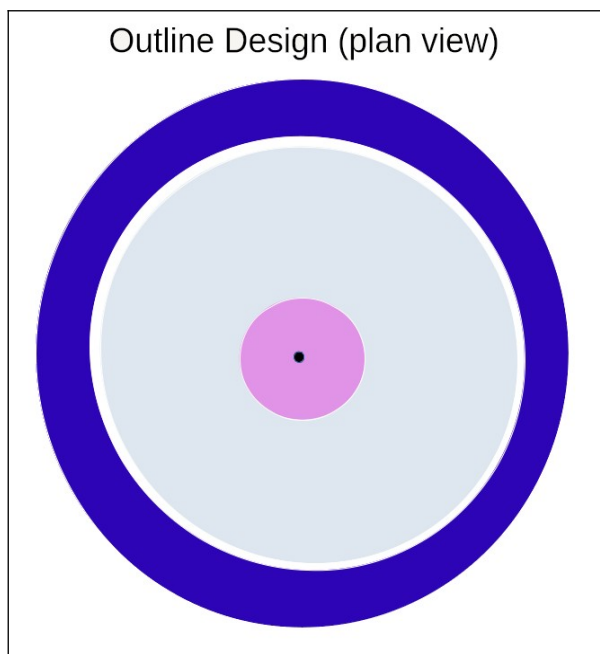
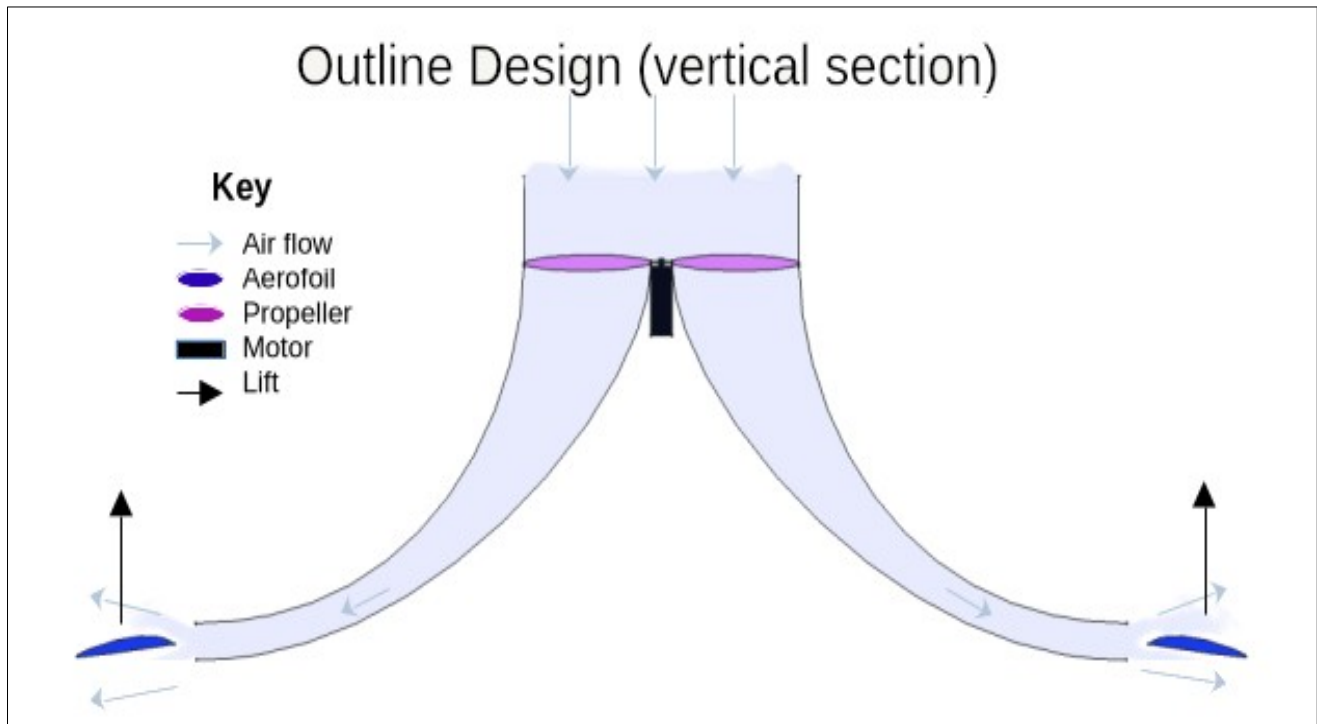
It is shown that, while the proposed design has significant limitations, a practical understanding of the relevant theory is developed which, with further experimental development, could lead to a functional design. However it is also shown that current aerodynamic theory is inadequate to determine an optimal design for which the lift characteristics can be reliably calculated.

Therefore, while this report presents a tantalising approach to a new type of aircraft it does not clearly demonstrate a functional design, so some ideas regarding further research are presented to overcome the difficulties encountered.

DESIGN OUTLINE

As shown in the vertical cross-section and plan view diagrams (which are indicative and not to scale), the experimental design uses a central downward-blowing fan or propeller, in conjunction with a conical airframe. The airflow is directed between two profiled cones that form the core of the airframe. These act as an annular venturi that smoothly redirects and confines the airflow radially.

The resulting airflow is projected outside the airframe and across an annular aerofoil that is



suspended (with minimal interruption to the airflow) from the airframe.

Being mounted outside the airframe the aerofoil produces a distributed pressure differential that acts on free space. If the aerofoil were mounted inside the airframe the pressure differential would remain inside the airframe and produce no net lift.

Through it's mountings (not shown in the diagrams), the aerofoil thus provides lift for the entire airframe in the same way as for a fixed-wing aircraft.

The aerofoil may be profiled in a similar way as for fixed wing aircraft if the airflow pattern is similar, but this cannot be assumed to be the case. However, as an initial experimental possibility established designs may provide a starting point..

Some means of controlling attitude is required.

This could be achieved by segmenting the aerofoil and changing the effective lift in parts; either by changing the pitch of individual segments, or by using trailing-

edge control surfaces in much the same way as for fixed-wing aircraft. Alternatively it may be better to use some sort of baffles inside the venturi; these could concentrate or block the airflow in different directions and achieve a similar effect with possibly less mechanical complication.

Such considerations are not within the scope of this initial study, which concentrates on the essential viability of this type of architecture as a flying machine.

The rotor would necessarily cause some rotation of the airflow inside the venturi, which would lead to a torque reaction on exit. This is controlled on helicopters by a tail rotor, and on multi-propeller drones by matched pairs of contra-rotating motors. In this design there would need to be restricting vanes within the venturi and aligned vertically in the airflow.

Adjustable elements in such vanes would allow control of overall rotation of the airframe. Alternatively some proportion of the air flow could be directed tangentially through controllable vents or “frog-eyes” in the upper surface of the venturi assembly. Additional airflow for this purpose could instead be provided by an auxiliary motor and ducting. Such possibilities have not been investigated in detail here, and would need to be considered if this project is developed for practical use.

The possibility of using multiple motors and propellers to provide redundancy, is also not considered in this report.

Depending on the intended application the control systems and payload could be distributed around the intake column and/or in the conical space underneath the venturi assembly. Additional cylindrical space could be made available below the venturi, which could be used to contain batteries, fuel or a heavy engine in a gravitationally balanced position.

THEORETICAL ADVANTAGES

With the propeller enclosed within the airframe this should substantially reduce the exterior noise, especially in a downward direction. Sound-proofing could be applied to the exterior surfaces of the venturi assembly, although care is required to maintain smooth surfaces for the airflow inside it.

The air is not directed downwards on exit, so the downdraught is almost entirely eliminated. This should enable the vehicle to be used at much lower elevations for medevac and other loading/unloading tasks. It also reduces the projection of motor noise downwards.

The propeller is not directly detectable from underneath or the side, so the “thumping” effect synchronous with the blades’ rotation, which is known to be a disturbing effect from helicopters at low altitudes, would be very much reduced or eliminated.

The very much simplified rotor assembly required by this design could contribute to cost and reliability in comparison with helicopters.

The underside of the airframe could be made to provide substantial protection for sensitive components against accidental or hostile damage, and while the aerofoil may be vulnerable it should, with careful design, be resilient to significant damage.

As there is no required air disturbance immediately below the vehicle, the underside of the airframe could be fitted with a “skirt”, which would allow the vehicle to float for short periods on water or soft surfaces.

Against this, there is obviously a significant radial airflow, which could be damaging at ground level while landing or taking off. However this should be no worse than that of an equivalent helicopter, as their downdraught is deflected outwards by the ground, with similar effect. For comparison with helicopters this would depend on the respective airflow volumes and speeds.

All these things considered, it remains to be shown whether such a device could actually fly. This needs to be initially established by performing some calculations and controlled experiments, which are the subject of this report.

LIFT FACTORS

In one way or another the essential underlying principle of any heavier than air flying machine is lift.

In this design as for other types of aircraft the lift is provided entirely by the flow of air over an aerofoil. Therefore, according to standard theory and empirical evidence, it depends on the following aerofoil parameters:

Profile

A number of standard profiles are commonly used for fixed-wing aircraft, such as the National Advisory Committee for Aeronautics (NACA) cambered 4-digit types used for comparatively low speed aircraft. The lift and drag characteristics of these are well known and it is assumed that the required characteristics for the annular aerofoil are closely related to these. Different profiles are suited to different speed regimes. For example, low speed aircraft usually benefit from thicker designs as they are less affected by a less favourable lift/drag trade-off.

Chord length

This is essentially the distance between the leading edge and the trailing edge (in this case measured radially). For asymmetric (cambered) aerofoils (where the lower surface may be almost flat after the cylindrical leading edge, and the upper surface is humped) the chord length is slightly longer than the direct measurement, being measured along the curved half-thickness profile. This, coupled with the aerofoil length comprises the effective surface area, which is a major determining factor in providing lift.

Length

Equivalent to the wingspan of a conventional aircraft (less the fuselage). Lift calculations are normally made per unit wing area. This is normally fairly easily calculated from the length and widths of the wings, but the calculation of effective length is a little more complicated here than for conventional aircraft. In this design the length, being in the form of a ring outside the main airframe, is greater than the overall circumference of the airframe and there is a small air gap between the airframe and the aerofoil, increasing its inside radius. Also, the effective length is somewhere inside the aerofoil, and therefore somewhere between the circumferences of the inner and outer edges.. Third, it is known from wind tunnel research that for standard profiles the median for lift is ahead of the thickest part, which may be less than halfway between the leading and trailing edges.

Pitch

This is the aerofoil chord angle relative to the air-stream. As a general rule the lift is increased with pitch until there is significant turbulence due to the sharp angle through which the air-stream is diverted. A maximum angle of 12-15 degrees is common for many designs, but it varies with the profile. In fixed-wing aircraft the wings are fixed to the fuselage at a small pitch angle that gives a balance against gravity at cruising speeds; elevators (controlled by the pilot) usually hinged to the trailing edge of the rear wings are used to adjust the effective angle of the rear wing to change the balance of lift and adjust the overall pitch of the fuselage. Flaps, usually hinged to the rear of the main wings, have a greater effect and are commonly used when approaching to land when additional lift is required at reduced airspeeds. In this design it may be preferable to adopt similar mechanisms, or it may be preferable to divert the airflow within the airframe and use a fixed aerofoil.

Air velocity

The velocity of the air flowing over the aerofoil is a major determining factor for lift. In the proposed design this is determined by the volumetric output of the propeller (which depends on the motor speed and the design of the propeller) and the area of the exit port at the circumference of the airframe (which is found from the outer diameter of the airframe and

the vertical aperture). A smaller aperture might be expected to lead to a greater velocity, but back-pressure in the venturi might compromise this. Also, complications arise because the airflow cannot be assumed to be the same as for conventional aircraft, for which the aerofoil is assumed to be moving in a much larger body of still air.

Aerofoil height and position

Another consideration not applicable to conventional aircraft relates to the position of the aerofoil vertically in the radial air stream. In other words, whether it is better to be central, or perhaps above or below the middle of the exit aperture. While it is said that most of the lift arises from reduced pressure at the upper surface, rather than increased pressure on the lower surface, it is not clear how this might suggest an optimal position in a limited height airflow. This suggests the need for some experimental measurements.

There is a similar issue regarding the radial position of the aerofoil, which is the size of the air gap between it and the airframe. The leading edge of aerofoils are known to cause back pressure (a component of drag) and turbulence. So it seems sensible to leave an air gap which is at least comparable to the leading edge diameter so that the bulk of air flow is unaffected for the remainder of the aerofoil and the back pressure has little effect on the airframe. This also needs to be investigated.

Clearly, from the above, the performance of such a craft cannot be easily predicted by established theory or by comparison with established designs. So while some familiar principles can be used for preliminary calculations, it is necessary to build and measure the performance of a representative experimental airframe.

BASELINE CALCULATION

To assess the viability of this project it is necessary to compare the performance of an experimental design with that of a commercial product using the same power. Therefore a selection of components was used that were typical of popular drones, namely a power source, motor, controller and propeller.

Before considering the internal characteristics of the airframe it was necessary to first find out what thrust and air velocity was achievable from the designated motor and propeller. Details of the experimental method and apparatus are described in the Testing section.

It is conventional to design drones to be able to hover at half throttle. This gives a margin for reduced available power, manoeuvring and additional payload. So measurements on the test apparatus were taken consistently at half throttle for helpful comparison.

It needs to be understood that drone motors usually use synchronous motors, where the rotation speed is proportional to the control setting. And, theoretically, the thrust (and the effective motive force) is proportional to the square of the rotor speed. This theory is based on the Bernoulli-derived aerofoil performance, where the lift is proportional to the square of the air velocity. Therefore, theoretically, the half throttle setting should correspond with a quarter of the maximum available thrust.

The results shown in the Testing section indicate that the quarter throttle setting achieved approximately half the thrust of the the half throttle setting, which is not what the foregoing theory predicts.

The following presents the relevant theory with which the thrust and air velocity can be calculated from experimental data for the test apparatus.

Air velocity and lift force in free air

For this analysis it is not necessary to consider any difference in air speed with radius, as the air is afterwards used in bulk. Therefore the necessary calculation need not consider radial variations.

The relation between air velocity and propeller lift force can be expressed as an energy equation, where the kinetic energy of the air is provided by the displacement force acting over a distance by the propeller:

$$1.1 \quad E = \delta m v^2 / 2 = F_r(r) \delta d$$

where:

E is total energy (Nm)

δm is the mass of a thin slice of air that is propelled (kg)

δd is the thickness of that thin slice (m)

$F_r(r)$ is the required total force (N), which varies with the rotation rate r

The mass can be expressed:

$$1.2 \quad \delta m = \rho A \delta d$$

where:

ρ is the air density (kg/m³) which is assumed not to change significantly

A is the active annular area of the propeller (m²)

So

$$1.3 \quad \rho A \delta v^2 / 2 = F_f(r) \delta d$$

Which allows us to find the air velocity (in free air) produced by the propeller, given a lift force.

$$1.4 \quad v^2 = 2F_f(r)/\rho A$$

The lift force (in Newtons) is found from the change in measured weight by multiplying by the local gravitational constant (N/kg). So, from the measured change in weight and the local gravitational constant we can now calculate the total lift force and the air velocity:

$$1.5 \quad F_f(r) = W(r)g$$

The applied power (in Watts) can be found from the force and the air velocity. The actual electrical power to the motor would be slightly higher, depending on it's internal efficiency, and there would be some aerodynamic drag induced by the leading edge and surfaces of the blade that would consume more input power.

$$1.6 \quad P_m = F_f(r)v$$

Comparison with commercial product

The Testing section describes the apparatus and experiments used to find the air pressure and velocity created by the motor and propeller used in the experimental airframe.

The results show that, at half motor power, the lift was 128g, using the 2-blade propeller. These results can now be used as a reference to compare the performance of the proposed design with the performance of a typical drone having a similar power supply, motor and propeller. But it must be considered that a drone typically has four such mechanisms to support it's own weight and that of it's payload (e.g. a camera).

For comparison, a popular model of quadcopter (the DJI mini 3) was selected. It uses four propellers and motors slightly less powerful than the one used on this project. It is rated at 249g overall weight (to meet current license exemption regulations) and a lift rate of 5m/s.

The equivalent weight of the vertical motion can be calculated at 5g of it's stationary weight, which gives a total effective usable weight of $1.51 \times 249\text{g}$, which is 376g. Split between four propellers this gives a lift of 94g each.

This is, as expected, a bit less than the above results obtained under test, which gives some confidence that the calculations accord with commercial expectations. It is important however that for this project only actual measurements taken for the project are used.

The testing section compares the efficiency of different propellers, and it was decided that for improved efficiency a 3-bladed propeller would be used for further testing.

THE VENTURI

Back pressure calculations

If the venturi did not introduce back pressure it would be expected that the exit air velocity would be determined simply by inverse relation with the intake and exit apertures, maintaining the same intake airspeed.

However, at the exit of the venturi there will necessarily be a pressure differential over atmospheric which propels the air outward. Also, due to the Bernoulli effect, there will be a pressure differential created by the movement of air through the conical venturi airframe. These two things will be added and reflected back to the propeller, and can be expected to reduce it's flow rate.

Therefore it might be expected that as the exit aperture is reduced there will be an increase in exit airspeed, but in less proportion than that determined simply by the ratio of apertures. But this assumes that the propeller produces the same displacement volume (and speed) regardless of the back pressure. But this is not the case, as the following calculations show.

The exit air pressure p_e can be calculated from 1.4 and the exit velocity v_e

$$2.1 \quad v_e^2 = 2F_e/\rho A_e$$

where F_e/A_e is the exit air pressure p_e

so

$$2.2 \quad p_e = \rho v_e^2/2$$

But for the Bernoulli effect from the narrowing cone this would be the same as the pressure at the intake and would balance the pressure created by the propeller. But it is interesting, and unintuitive, to discover that this is essentially independent of the aperture. So if the propeller creates a constant pressure, related to it's fixed design and rotation rate, the exit velocity is essentially the same regardless of the aperture. A narrower aperture thus results in a smaller volume of air being displaced.

However a pressure difference is created due to the Bernoulli effect. This would result in reduced airflow as the exit aperture is reduced. This can be found from the difference in air velocities due to the change in area.

$$2.3 \quad v_e^2 - v_i^2 = 2(p_i - p_e)/\rho$$

so

$$2.4 \quad (p_i - p_e) = \rho(v_e^2 - v_i^2)/2 = \rho v_e^2(1 - v_i^2/v_e^2)/2$$

The velocities, assuming that there is no significant change in density or temperature, can be expressed as a ratio of their apertures.

So

$$2.5 \quad v_i/v_e = A_e/A_i$$

The ratio of apertures is a significant design determinant, so for brevity we can define

$$2.6 \quad A_x = A_e/A_i$$

so

$$2.7 \quad (p_i - p_e) = \rho v_e^2 (1 - A_x^2) / 2$$

So the total effective back pressure resulting from the airflow at the exit can be found.

$$2.8 \quad p_i = \rho v_e^2 / 2 + \rho v_e^2 (1 - A_x^2) / 2 = \rho v_e^2 (2 - A_x^2) / 2$$

The effective force acting against the propeller F_b is this pressure acting over the intake area, and for the system to remain in balance this back pressure must balance the thrust from the propeller. So if we assume the propeller delivers constant thrust at any particular speed, rather than constant velocity:

$$2.9 \quad F_b = F_i(r) = \rho v_e^2 (2 - A_x^2) A_i / 2$$

From 1.4 the force in free air is given by

$$2.10 \quad F_i(r) = \rho A_i v_f^2 / 2$$

so

$$2.11 \quad v_e^2 = v_f^2 / (2 - A_x^2)$$

If the exit aperture is the same as the entry aperture ($A_x=1$) the entry and exit air velocities will be the same, and the exit air velocity is the same as for a propeller in free air. This formula doesn't work for very small apertures because the the large back pressure could significantly increase the air density and invalidate the above formula.

Checking for compliance with Bernoulli

The intake air velocity will depend on the available thrust, after deducting back pressure.

If the propeller thrust is unchanged from that in free air this gives a nett intake force F_i :

$$2.12 \quad F_i = F_i(r) - F_b = F_i(r) - \rho v_e^2 (2 - A_x^2) A_i / 2$$

$$2.13 \quad v_e^2 = 2 F_i(r) / (\rho A_i (2 - A_x^2))$$

So, from equation 1.4, if the free air velocity is v_f we have a clear relationship with the aperture ratio.

$$2.14 \quad v_e^2 = v_f^2 / (2 - A_x^2)$$

Which, while arrived at by a different route, is the same as 2.11.

This seems counter-intuitive, but the propeller, unlike a bicycle pump, does not transfer a fixed volume per cycle, but maintains a fixed pressure difference; so the volume of air that flows is determined by the difference between the back pressure and that maintained by the propeller.

The equations show that the maximum exit velocity is never any greater than the free air velocity while the exit aperture is smaller than the entry, although it can increase if the exit aperture is larger ($A_x > 1$). This effect is used in ducted systems, such as some helicopter tail rotors.

These calculations do not consider any other losses due to, for example, obstructions, turbulence, or surface drag, and are limited to systems where there is no significant increase in pressure causing volume compression. In this case the propeller is producing no more than 100Pa, which is the greatest pressure in the airframe, and which is about 0.1% of atmospheric pressure, so it cannot be significant.

The test section describes how the exit air velocities were measured for several apertures, and compares the results with the above calculations.

The results, as shown in the Testing section, were not at all as expected.

A calculated airspeed of 10.05m/s was found to be only 7.87m/s, which could not reasonably be accounted for by turbulence or surface drag within the venturi. Altogether about 39% or more of the available thrust (and corresponding squared airspeed) was somehow unaccounted for, which is a factor that directly affects aerofoil lift.

So it was necessary to find out what could account for the differences.

Ground effect

Helicopters are known to be affected by the proximity of the ground when taking off, where back pressure induced by the ground provides additional lift. In this apparatus the airflow is similarly redirected from the vertical to the horizontal, but the "ground" is now part of the airframe itself.

So it is necessary to see whether and how the redirection of the airflow can result a net vertical internal pressure on the airframe, which could in effect deduct from the vertical thrust of the propeller and thereby reduce the airflow.

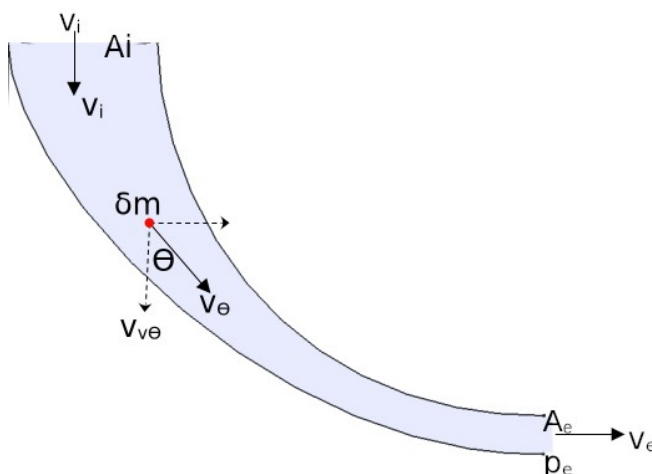
Standard theory presenting Bernoulli's calculation of air flow and pressure does not take into account the curvature of the flow path or the dynamic effects of a high mass flow rate. Conventional analysis assumes that the path is a simple cross-section, such as a round pipe, the radius of curvature is sufficiently large compared with the diameter as to be insignificant and the mass flow rate is not high.

These assumptions have to be questioned for the proposed airframe design.

The vertical intake pipe has no significance as any differential lateral forces would balance out across the airframe. Similarly the bottom flat flanges are equal in area and would not account for any differential forces. So any differential effects acting with a vertical component can be found entirely from the two curved sections and the air pressure over their surfaces.

The diagram shows a cross section of the relevant part of the venturi.

Momentum Analysis



To calculate the nett vertical force on the airframe, the principle of conservation of momentum is used. This can be used with Newton's law that equates a linear force to a rate of change of momentum M . So

$$3.1 \quad F = \delta M / \delta t \text{ or } \Delta M = \int F \cdot \delta t$$

The total mass of air m entering the venturi per second is found from the intake velocity and the intake aperture area.

$$3.2 \quad \delta m / \delta t = \rho v_i A_i$$

The rate at which vertical momentum enters the venturi is the mass multiplied by the velocity

$$3.3 \quad \delta M / \delta t = \rho v_i^2 A_i$$

In a stable situation this remains unchanged continually. So

$$3.4 \quad F_g = \rho v_i^2 A_i$$

But as the entire vertical momentum is lost this force is the total sustained vertical reaction to the redirection of the airflow within the airframe, equivalent to an apparent “ground” force. There is also a lateral force creating the horizontal velocity but this is balanced out across the airframe and does not contribute to the “ground” force.

The vertical force is a function of the angle of flow at any time because it changes as the direction of flow changes from 0 to $\pi/2$, so it is not evenly distributed through the venturi. However we are only interested in the total vertical force and not the distribution.

We can measure the exit velocity but not the intake velocity. Therefore we need to convert v_i to v_e .

Assuming the density does not significantly change, the intake and exit velocities are simply related by their respective apertures. So (as per 2.5 and 2.6)

$$3.5 \quad v_i/v_e = A_e/A_i = A_x$$

and

$$3.6 \quad F_g = \rho v_e^2 A_x^2 A_i$$

This requires a correction to the previously calculated available thrust, and therefore the airspeed (see 2.9 to 2.11).

$$3.7 \quad F_i = F_f(r) - \rho v_e^2 (2 - A_x^2) A_i / 2 - F_g = F_f(r) - \rho v_e^2 (2 - A_x^2) A_i / 2 - \rho v_e^2 A_x^2 A_i = F_f(r) - \rho v_e^2 A_i (2 + A_x^2) / 2$$

so

$$3.8 \quad v_e^2 = 2F_f(r) / (\rho A_i (2 + A_x^2))$$

So, from equation 1.4, if the free air velocity is v_f we have a clear relationship with the aperture ratio.

$$3.9 \quad v_e^2 = v_f^2 / (2 + A_x^2)$$

Breakdown and conclusions

From the measurements taken for the different apertures (see Testing section) the components of pressure can be individually identified. By separating the exit pressure, Bernoulli back pressure and the “ground effect” pressure it may help to identify possible improvement opportunities in the airframe design.

Breakdown of air pressures Half Speed Three Blades

Ai m²	0.0184	ρ kg/m³	1.225	Diam m	0.2	Thrust N	1.746	
H_e mm	v_e m/s	V_e² m²/s²	A_e m²*10⁻³	A_e/A_i	P_e N/m²	N/m²	P_g N/m²	PTot N/m²
5	5.413	29.298	3.142	0.171	17.95	17.42	1.05	36.413
10	6.250	39.064	6.283	0.341	23.93	21.14	5.58	50.644
15	7.439	55.341	9.425	0.512	33.90	25.00	17.79	76.686
20	7.865	61.852	12.566	0.683	37.88	20.21	35.34	93.438

The exit airspeeds should be compared with the free air speed measured earlier of 12.45m/s (see Testing section).

The table clearly shows that with large air volume movements (higher exit speed and larger exit aperture) the “ground effect” increases enormously; by a factor of nearly 35 for the experimental airframe.

For the 20mm aperture the ground effect added to the Bernoulli effect amount to 55.55 N/m², which accounts for nearly 60% of the propeller thrust of 93.4 N/m², leaving only about 40% at the exit. The air velocity squared is proportional to the pressure, so this would result in a corresponding reduction of the square of the ratio of the free air velocity and the measured exit velocity, which can be seen from the above figures to be close to 40%, which matches the calculations very well.

Perhaps the most important things that can be determined from these calculations and test confirmations are:

- Using a vertical input flow and diverting it to a horizontal outflow is less efficient than using a horizontal input flow and eliminating the internal “ground” effect. This would be particularly relevant for the high air velocities required to achieve lift with a peripheral aerofoil. This could perhaps be achieved using a centrifugal impeller instead of a conventional propeller.
- For a circular exit aperture of small height compared with its diameter, the Bernoulli effect could be reduced by using a horizontal input thrust aperture of similar height. This could be achieved by using a centrifugal impeller of a height well matched to that of the exit aperture.
- Little, if any, relevant research seems to have been published for impellers suited to this application, so it seems this project would benefit from further investigation into impeller design, and a suitably redesigned airframe.

Variation with distance

The test results for exit velocities show that the velocity drops off substantially with distance from the airframe.

This indicates that a standard aerofoil profile, which is based on the assumption that the ambient relative airspeed is constant over the depth of the aerofoil, will not perform according to conventional lift calculations, and adapted designs are required for greatest efficiency. This is examined further in the Aerofoil section.

THE AEROFOIL

General calculations

The lift from an aerofoil is determined by three principal factors:

- The relative air velocity and density.
- The lift coefficient C_l , determined by the cross section shape and the pitch angle.
- The surface area, assuming the airflow is laminar and orthogonal to the leading edge.

Thus, according to standard theory

$$3.1 \quad F_l = C_l \rho A v^2 / 2$$

where

C_l is the lift coefficient for the given cross-section and pitch

ρ is the air density (kg/m^3)

A is the surface area (m^2)

v is the relative air velocity (m/s)

The optimum airspeed for the experimental airframe was obtained for a triple-blade rotor at half motor speed and a 20mm exit height aperture (see Testing section). This gives a total lift of

$$3.2 \quad w * 0.2 * \pi * 101 * 1.6 * 1.225 / 2 = w * 62.2 \text{ N}$$

Where w is the annular width of the aerofoil.

For an aerofoil of radial width 60mm this gives a total lift of 3.73N. This should be compared with the lift measured earlier as a drone, which was 1.746N, and suggests that the design may be a competitive alternative to the common drone/helicopter configuration. This calculation assumes that the airflow over the aerofoil would be the same as for a fixed-wing configuration.

But it has been found that for this design (see the Testing section) the airspeed is not constant over the width of the aerofoil (i.e. the distance from the airframe). For the experimental airframe the square of the airspeed dropped off by 35% over 10mm and by 70% over 20mm, which would be reflected in the surface airflows over the radial depth of the aerofoil. Therefore the actual lift over the surface of the annular aerofoil can be expected to be substantially less than that obtained with a constant airflow, as found when moving through a volume of static air.

This being beyond standard theory and empirical knowledge it would be necessary to develop a new theoretical approach, validated with experimental evidence, to determine the lift produced for a variety of profiles. This would result in an optimised aerofoil configuration for the airflow patterns produced by this type of aircraft.

UPSCALING

Considering the possibility of constructing a similar design, but with four motors and propellers of the same type, the lift can be compared with the single engined design.

If they are arranged in a square the overall horizontal dimensions would be slightly more than doubled. So from 1.4, the intake force from the propellers would be multiplied by four. But so would the intake area, so the intake internal air velocity would therefore remain the same.

As an approximate guide, from 2.3, while the intake area is multiplied by four, the exit area (given the same height) would only be doubled, as for the perimeter. So the exit air speed would therefore be doubled, which would produce four times the lift for the same aerofoil.

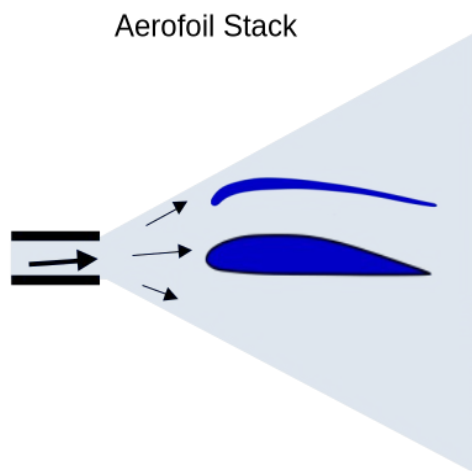
At the same time the surface area of the aerofoil, given the same depth, would also be doubled as for the perimeter of the airframe.

So from 3.1, where the lift, given the same aerofoil profile and ambient air pressure, is proportional to the square of the velocity as well as the surface area, this would result in eight times the lift.

FURTHER WORK

The foregoing theory and experimental evidence indicates that the experimental design used here is by no means optimal in exploiting the theoretical possibilities. However it leaves several interesting questions unanswered, and a variety of promising possibilities unexplored. The following suggests two aspects that have been specifically identified so far.

To progress this concept further it is necessary to design a suitable centrifugal impeller. Such things are commonly used in ventilation systems and in turbochargers commonly found in motor vehicles. The theory for these is not well known and would need to be developed so the required mechanical design can be determined from parameters such as size, rotation rate, exit dimensions and required exit velocity, any or all of which will change according to the functional requirements of the vehicle being designed.



Standard aerofoils in their usual configuration would not be best suited to this type of aircraft because they require a laminar airflow within the operating envelope (i.e. without excessive pitch).

The airflow provided by this design is very different, being divergent, and therefore needs to be reconsidered from first principles. Not only to determine the best cross-section shape, but whether it could perhaps be best to have "stacked" aerofoils or multiple apertures. Or even to have some sort of flow "guides" attached to the airframe to concentrate the airflow over the aerofoil, without themselves creating significant downward forces.

The diagram shows how standard aerofoil designs might be combined to make better use of the available airflow. Each aerofoil would interact with the effects of its neighbour, so the overall performance would be difficult to predict with established theory.

Both of these areas would benefit from recent developments in multi-physics simulation software, which is unavailable to the author, as well as a flexible approach to unexplored possibilities.

TESTING



The illustrated commercial equipment was used to provide experimental data and was used in the construction and operation of the experimental airframe

The propeller motor, as illustrated, is rated at 2200KV, which means that it provides up to 2200 rpm per volt on a three phase synchronous supply on a light load. The maximum speed of the motor is proportional to the supply voltage, but rotation is determined by the supply frequency. This motor, like many others used for similar applications, has 12 magnetic poles, and each cycle of the supply provides a two-pole rotation. Thus, one complete rotation requires 6 cycles and the rotation speed (rpm) can be calculated from the supply frequency cycles per second (cps):

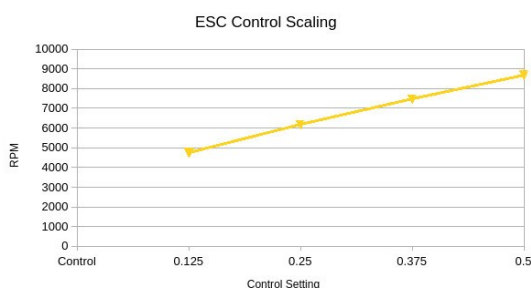
$$\text{rpm} = \text{cps} * 60 / 6 = \text{cps} * 10$$

Three different types of propeller were used, for which the thrusts were separately measured for comparison. They had respectively two, three and four vanes. They were all of the same outer diameter.

To support such motors Electronic Servo Controllers (ESCs) are normally used, and the one used in this project is illustrated. These take in a power supply (in this case a 7.4V LiPo battery) and an input from a manual control unit or radio receiver, and provide a 3-phase motor output sufficiently rated for the maximum power required (in this case 30A). The unit used here also has a 3-wire cable that provides a low power 5V supply for the support electronics and takes in a single line digital control signal.

Unlike mains three-phase power lines these ones are not colour coded at the ESC. Therefore as the direction of rotation of the motor is determined by the phase order it has to be found by experiment. Having done so, the wires were marked to match the clockwise direction of the motor (conventionally observed as counter-clockwise when looking into the output shaft!). With the propellers in use this provided vertical lift.

The digital control signal to the ESC may take several forms, from a simple Pulse Width Modulated (PWM) signal to a more versatile numerical code (DSHOT). The former restricts rotation to one direction (which can be reversed by swapping over any two of the wires); the latter allows reversing and telemetry during operation.



To keep things as simple as possible a commercial manual controller was used with a proportionate rotary control using PWM, as illustrated. In conjunction with the ESC this provided a linearly variable output frequency to the motor, and it was calibrated in 25% steps on a card fitted under the control, using an oscilloscope on the ESC input.

The chart shows the scaling measured for the equipment used.

This can be used as a reliable measure of rotation speed because if, due to excessive load, the motor is unable to keep up with the demanded frequency it "stalls" and an irregular motion becomes obvious.

Measuring motor thrust



The motor thrust was calibrated by measuring the apparent loss of weight when fitted with the intended operating propellers, and used in the same way as a typical drone.

Where a propeller is close to the ground the downdraught is compressed by the ground and this provides additional lift, which would in this case compromise the measurements.

It is generally accepted that this "ground effect" is significant at heights up to about the propeller diameter. Therefore, for measuring the propeller output at calibrated speeds the motor was mounted, as illustrated, inside part of the airframe structure atop a 14" length of plastic pipe. This raised the propeller to more than twice its diameter above the supporting surface to ensure the ground effect was insignificant. The battery and supporting block were only 2.5" high and would have had no significant effect.

The illustration shows the test equipment used for the 2-bladed propeller. The same arrangement was used for each of the other propellers. Sticky tape was used to ensure stability of the support on the digital scales and, as the lift approached that of the test rig for some measurements, a weight was used to hold down the body of the scales

The scales measured the reduction in weight as the motor was driven at 25% and at 50% power in this configuration. It being conventional to rate the power of a drone such that it can hover at half power, this will be used to compare the lifts obtained for a conventional “drone” and the proposed design. As the device does not actually move during these measurements it was not necessary to compensate for movement. The speed was controlled by the unit on top of the battery in the illustration. A piece of white card had been calibrated for the quarter speed positions, as seen in the photograph. The control could be operated without disturbing the apparent weight of the apparatus.

Two lift measurements were taken for each propeller type using this experimental rig. The effective area of the propeller was an annulus defined by the diameters of the propeller and the motor mounting. This annulus had an outer diameter of 155mm (area 0.0189 m²) and inner diameter defined by the supporting tube of 26mm (area 0.00053 m²), which gives an effective area of 0.0184m².

The lift force and air velocity shown here were calculated according to the formulae of 1.5 and 1.4. The effective power was calculated from the airspeed and lift according to 1.6.

Motor Lift Measurements

g N/kg	9.81	ρ kg/m ³	1.225	A m ²	0.018454	
Blades	Speed %	Lift g	Lift N	v ² m ² /s ²	v m/s	P W
2	25	55.0	0.540	47.87	6.92	3.73
	50	128.0	1.256	111.42	10.56	13.25
3	25	88.0	0.863	76.6	8.75	7.56
	50	178	1.746	154.94	12.45	21.74
4	25	86	0.844	74.86	8.65	7.30
	50	170	1.668	147.96	12.16	20.29

The 25% measurements were taken to determine whether there is an approximate linearity between lift and propeller speed. Only the 50% measurements are used for performance calculations.

The above figures show that the thrust does not depend only on the number of blades. It might be expected that more blades would provide more thrust, but the thrust depends on the angle of attack and the surface area, neither of which could be conveniently measured. The above images show that the 3-bladed propellers had significantly greater surface area than the 4-bladed propellers, so the performance comparison is not unexpected.

The 3-blade propeller was specified as “6x4.5”, which means that, having a 6” diameter, a single rotation would correspond with a screw “lead” of 4.5”. The 2-bladed propeller was marked as “6035”, and the 4-bladed item was unmarked.

In each case, while the propellers looked symmetrical it made a difference of about 25% which way up they were fitted to the motor, i.e. which were the most efficient leading edges of the blades. Unfortunately they were not marked, so the best orientation had to be determined experimentally to obtain the above measurements.

It is interesting to note that the effective power is proportional to the sesquiplicate (the square root of the cube) of the air velocity, while the lift is proportional to the square of the air velocity. This implies that, for example, to double the lift it would be more efficient to use two motors/propellers than to double the speed of only one. Whether it would be more efficient to increase the rotor diameter is not investigated in this project.

Measuring exit air velocities

The illustrations show the experimental airframe: The complete assembly as used for test and measurement; the inner cone with the motor and propeller (this incorporates a propeller guard to

ensure centrality with the outer for adjusting the exit aperture); the combed supports used to



ensure precise exit apertures (stepped at 5mm intervals); and the outer cone.

The actual air exit velocity produced by the experimental airframe for different exit heights was measured using the drag force on a measured drag object placed in the exit airstream. But the velocity can be expected to vary with distance from the exit aperture, so it was necessary to find some means of measuring the force without allowing the drag object to move significantly.

The images show the apparatus used. It comprised a two-column support frame on which is pivoted a three-armed Z-crank. The lower end of the crank supports a 5mm x 20mm square bar used as the drag object, and the apparatus is placed to align this object with the airstream. The top end supports a drop bar that rests on the platform of the scales, which claim a precision of 0.01g. The drop bar is pivoted at the top to prevent any lateral pressure at the lower end that may confuse the scales.



When pressure is applied by the airstream to the drag object it acts through the crank to apply lift to the drop bar. This reduces the apparent weight of the drop bar. This variation is recorded. The arms of the Z crank are of differing lengths that effectively magnify the drag force by a factor of 2.4 to improve the sensitivity of measurement.

The weight of the drop bar was sufficient to ensure that there is always positive pressure on the scales. So within the range of the forces involved there is no perceptible movement. Thus, there is minimal movement of the drag object and the measurements can be accurately related to the distance from the aperture.

The drag force can be calculated by multiplying the measured weight loss by the gravitational constant and the Z crank leverage, as described above.

$$4.1 \quad F_d = w \cdot g / 2.4 \text{ N}$$

Where w is the measured weight loss.

The air speed can be calculated from the lateral force using the drag equation for a flat surface.

$$4.2 \quad F_d = C_p A v^2 / 2 \text{ N}$$

where

v is the air velocity

C is the drag coefficient for the shape which being square in section is taken as 2.05

ρ is the air density

A is the surface area presented by the drag object, 5mm x 20mm

F_d is the measured drag force

The above two equations can be combined to show the air velocity as a function of the measured loss in weight

$$4.3 \quad v^2 = w \cdot g / 1.2 \cdot C_p A \text{ m}^2/\text{s}^2$$

The square of the air velocity is the factor of interest as it is directly used to calculate lift.

The table below shows the measurements for different exit aperture heights (all at the same motor/propeller speed) together with the relevant parameters. A three-bladed propeller was used throughout, so the velocities can be compared with the free-air measurements tabled above.

Exit Air Velocities Half Speed Three Blades

Drag A	1.00E ⁻⁰⁴	ρ kg/m ³	1.225
Drag C	2.05	g N/kg	9.81
g/1.2*CpA	3.26E ⁺⁰⁴		
H_e mm	w g	V² m²/s²	v m/s
5	0.90	29.298	5.413
10	1.20	39.064	6.250
15	1.70	55.341	7.439
20	1.90	61.852	7.865

The velocities are calculated from the weight change according to the formula of 4.3.

When the drag bar was positioned at different distances from the aperture it was found that the measured drag dropped significantly. Approximately 35% was "lost" after 10mm, and 70% after 20mm. This arises from the divergent nature of the exit airflow.

This corresponds to a depletion in the square of the velocity, so the available lift for any aerofoil would be expected to follow the same variation. As the aerofoil would have significant depth this variation would affect the lift over the surface. This poses complications that cannot be resolved by reference to standard aerofoil theory, and would need a new approach to optimising the design.

It must be noted that, due to limitations in the available test equipment, these figures are approximate. However they serve to provide a substantial degree of confidence in the theoretical analysis.

REFERENCES

Online resources

<https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/> pp31 et seq
<https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/classic-airfoil-theory/>
<https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/airfoil-geometries/>
https://en.wikipedia.org/wiki/NACA_airfoil
https://en.wikipedia.org/wiki/Drag_coefficient
<https://www.conceptsnrec.com/blog/compressor-design-influence-of-the-impeller-exit-blade-angle>

Constants

π	3.142
g	9.81 N/kg
ρ	1.225 kg/m ³