# A NOVEL CONCEPT FOR HELICOPTER ROTOR DRIVES

## 3RD EUROPEAN CONFERENCE FOR AERO-SPACE SCIENCES

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## ABSTRACT

The REDT (Rotor à Entraînement Direct par Turbine – Direct Turbine Driven Rotor) is a new concept for helicopter rotor drives developed by Sagita in Belgium. It works without any mechanical link between the engine on one side and the rotor drive on the other side. It uses a fuselage-mounted compressor that powers two contra-rotating rotor-mounted free turbines. These free turbines drive a pair of contra-rotating rotors that are fitted with rigid hingeless main rotor blades. This novel rotor drive eliminates the need for either mechanical transmission or a tail rotor. The aim of the REDT concept is to lower the maintenance costs and the accident rate, as well as to extend the flight envelope towards much higher airspeeds compared to classical helicopters.

## 1. INTRODUCTION

Current helicopter technology covers only a small part of the general aviation market. The factors restricting a widespread use of helicopters are technical complexity, difficult handling and the high pilot skills required, operating cost, low speed, discomfort due to noise and vibrations and the risk of a failure of the tail rotor. The latter is responsible for a large number of helicopter accidents. The autogyro avoids some of these drawbacks, yet it lacks the essential qualities of the helicopter that is hovering flight and vertical take-off and landing. Several solutions have been suggested to avoid helicopter drawbacks:

1. Suppression of the tail rotor by blowing air or gas jets at the blade tip: the rotor is thus powered without coupling to the fuselage. This also reduces the mechanical complexity of the helicopter.
2. Suppression of the tail rotor by balancing the torque on the fuselage with another rotor turning in the opposite direction.

Examples of solution 1 are the MC Donnell XV-1 convertiplane, Aérospatiale SO-1310 and Djinn or the Fairey Rotodyne. Examples of solution 2 are the coaxial Kamov or the Piasecki-Boeing helicopters with tandem rotors. The prototype Sikorski X-2 demonstrator should also be mentioned, as it is equipped with the Advancing Blade Concept (rigid hingeless blades on two contra-rotating rotors), which aims at achieving high flight speeds through the distribution of lift on the advancing blades of each rotor.

The REDT concept presented here combines the advantages of both solutions. It consists of two coaxial contra-rotating rotors that are driven by two contra-rotating turbines, powered by pressurized air or gas.

## 2. DESCRIPTION OF THE REDT CONCEPT

In the REDT design (Figures 1(a) and (b)), the pressurized air generated by a fan (1) is not ejected at the tip of the blades (14,15) but at the rim of a lenticular shaped cupola (2) through concentric and contrarotating turbine stages (21,22).

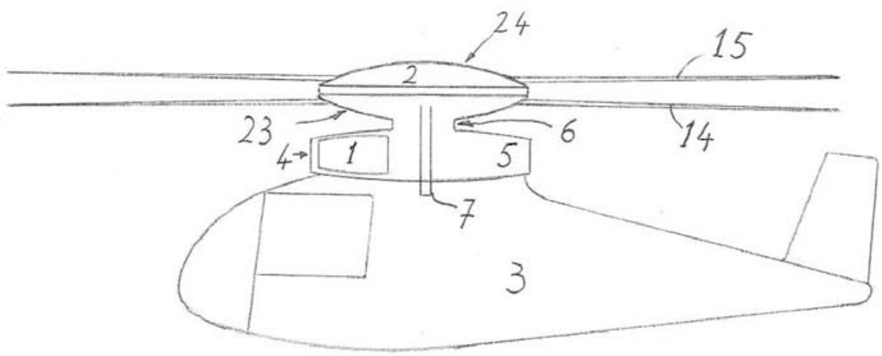



Figure 1(a) - A Schematics of the REDT concept

Each half cupola includes a rotor that is fitted on its rim with the turbine stages that power it.

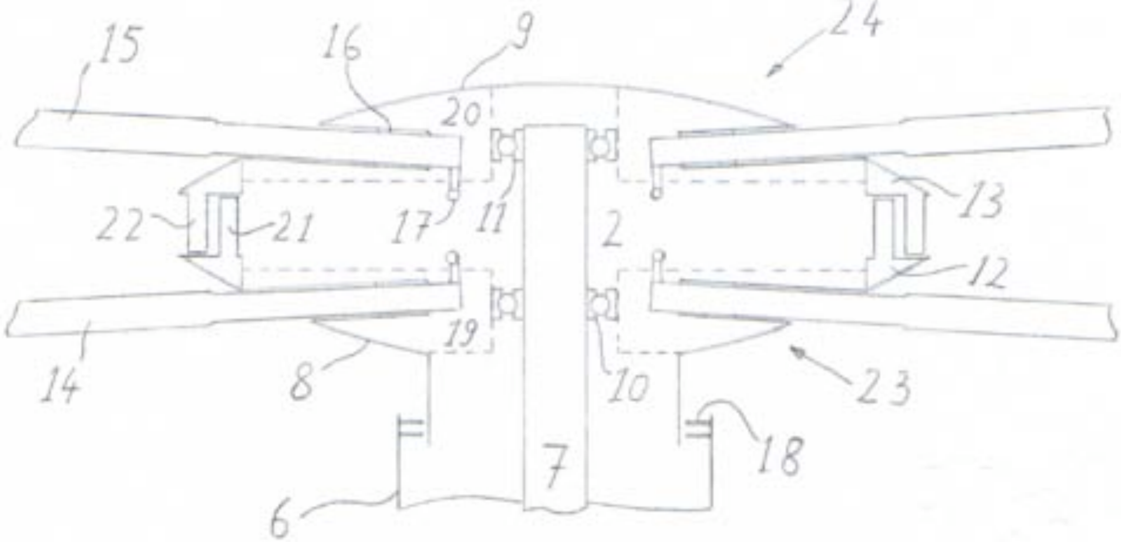



Figure 1(b) – A schematics of the REDT rotor

The turbine stages of both rotors are imbedded into each other as in the Ljungström turbines (Ref. 1). As they turn in opposite directions, their relative speed is doubled compared to their tangential speed. The power issued to each rotor is equal to the enthalpy drop in each rotor turbine, multiplied by the total mass flow rate. Each turbine has a number of stages, usually two or three, depending on the enthalpy drop: best efficiency is achieved when each stage is situated, as in the diagram by Smith (Ref. 5), around $\psi$ =1-2 and $\varphi$ = 0.6-0.8, with a reaction rate of 0.5, where $\psi = \Delta h/u^2$ and $\varphi = V_r/u$, u being the relative blade speed, $V_r$ the radial flow velocity, $\Delta h$ the enthalpy drop per stage. The enthalpy drop in each rotor turbine = $1/2\ \Sigma_i\ \Delta h_i$.

In practice, the diameter of the cupola is about one quarter of the rotor diameter and the feed pressure to the turbines is about 1.3 bar absolute. This is a compromise between high efficiency and allowable temperature. It is important that the temperature of the compressed air is not higher than 150 °C in order to avoid problems with the bearings, flight control components and seals that are located in the compressed air flow path.

The blades of the rotor are rigid, with only one feathering hinge: this simplifies the hub design and eliminates the risk of collision between blades. At a given forward speed, it is possible to switch from helicopter mode to autogiro mode by closing the rotor feed valves and opening a nozzle (5) through which the pressurized air can be ejected to the rear and produce a forward thrust.

## 3. POTENTIAL ADVANTAGES – DISADVANTAGES OF THE REDT CONCEPT

### 3.1 *Technology*

The advantages and disadvantages of the REDT concept are listed directly below; their discussion follows the listings.

*Advantages*

- Increased safety: the lack of a tail rotor and the high capacity of the rotor to overspeed reduces the “dead man’s curve”
- Well suited to fast flight: there is the possibility of autogyro flight, the advancing blades on each side eliminate the retreating blade stall problem and the rotor hub fairing reduces the fuselage parasitic drag.
- Ease of handling: there is no torque transmitted from the rotor to the fuselage.
- Comfort: no mechanical noise from gearbox.
- Performance: approximately 10% more power available to the rotor thanks to engine supercharge.
- Suited to very large helicopters: no restrictions due to gearbox output torque, size and weight.
- Reliability: no gearbox at all, hingeless blades, far fewer moving parts.

*Disadvantages / challenges*

- Heavier rotor: due to the increased number of blades and the extra mass of the turbines.
- Rigid blades are subjected to higher bending loads than hinged blades. They must be made stronger at the attachment and therefore heavier.

It is also worth providing a short discussion of the fuel consumption in helicopter mode. This discussion is based on the comparison between a conventional tail rotor helicopter (CTR) and a REDT helicopter equipped with same rotor diameter and the same engine (Ref. 4).

For the CTR, the power available to the rotor will be the engine power minus the gearbox losses and the tail rotor power: these losses account for 10-15% of the engine power in hover. The power available to the rotor of a REDT helicopter will depend on the engine fan and rotor turbine efficiencies. For typical fan and turbine efficiencies of 82% and 87%, the overall efficiency would normally be 0,82 x 0,87 = 71%. Subtracting from this 1% head losses in the ducts, the total losses would then be about 30%.
However there is a reheat between the fan and the turbine, due to the latent heat of the engine exhaust gases that are mixed with the fan air flow: this creates a Joule cycle that increases the turbine power.

The net resulting overall efficiency is 84%. The losses are only 16%, roughly the same as for a CTR. A part of the fan air flow feeds and supercharges the engine and this increases the power output of the engine by 10% if the engine can sustain it. This supercharging of the engine by the fan corresponds also to the recovery of the sea level power at a ceiling of 1000 to 1500m, for a given fan pressure ratio of 1.3 / 1 and depending on the engine: piston or gas turbine.

The U.S. Department of Transportation has published a "Basic Helicopter Handbook" (Ref. 6). One of the chapters is entitled, "Some Hazards of Helicopter Flight'. Ten types of hazard common to a typical single rotor helicopter are listed. The unique coaxial rotor design either reduces or completely eliminates these hazards. The following list indicates some of them:

- Settling with power – The REDT concept has reduced susceptibility to this hazard
- Retreating blade stall– The REDT concept has reduced susceptibility to this hazard
- Medium frequency vibrations – The REDT concept has reduced susceptibility to this hazard
- High frequency vibrations – The REDT concept has no susceptibility to this hazard
- Anti torque system failure in forward flight – Eliminated in the REDT concept
- Anti torque system failure while hovering – Eliminated in the REDT concept

The reduced susceptibility to or elimination of these hazards constitutes a major improvement in safety and is one of the main advantages of the coaxial rotor design.

3.2 *Economy*

Helicopters, due to the nature of their technical systems, are more complex and have higher maintenance costs than similar size fixed-wing aircraft. The helicopter gearbox, transmission and rotor blade systems contain many moving parts under high stress. Several of the components in the gearbox, transmission and rotor blade systems have short time overhauls and preventive retirement. Thus, the maintenance costs for helicopters are much higher than for fixed-wing planes. With fewer components, the time a fixed-wing aircraft spends in maintenance tends also to be much shorter than for a helicopter. From that point of view, the REDT, by its technical simplicity, should bring clear advantages.

The second point impacting helicopter market share is the rate of accidents. According to the EASA (European Aviation Safety Agency), passenger and Emergency Medical Service (EMS) flights are prone to the highest fatal accident levels. Other factors playing in the sequence of mishaps are human, environmental and technical elements as well as the flight phase (Figure 2). An accident is the result of a sequence of events that have occurred since the first occurrence of a failure or malfunction. A more precise evaluation of these first occurrences was made based on NTSB data and a summary is given in Figures 3 (Ref. 7). The first occurrence malfunctions can be categorized by grouping several failures of similar type. This is explained in Figure 3. It is somewhat staggering that about half of all accidents are due to propulsion and drive system malfunctions, poor handling qualities and/or control assurance, mainly due to tail rotor problems. For this aspect too, the REDT should also bring clear advantages.

Another important impact on market share that will appear as quite positive for the REDT concept will be its increased cruise speed.

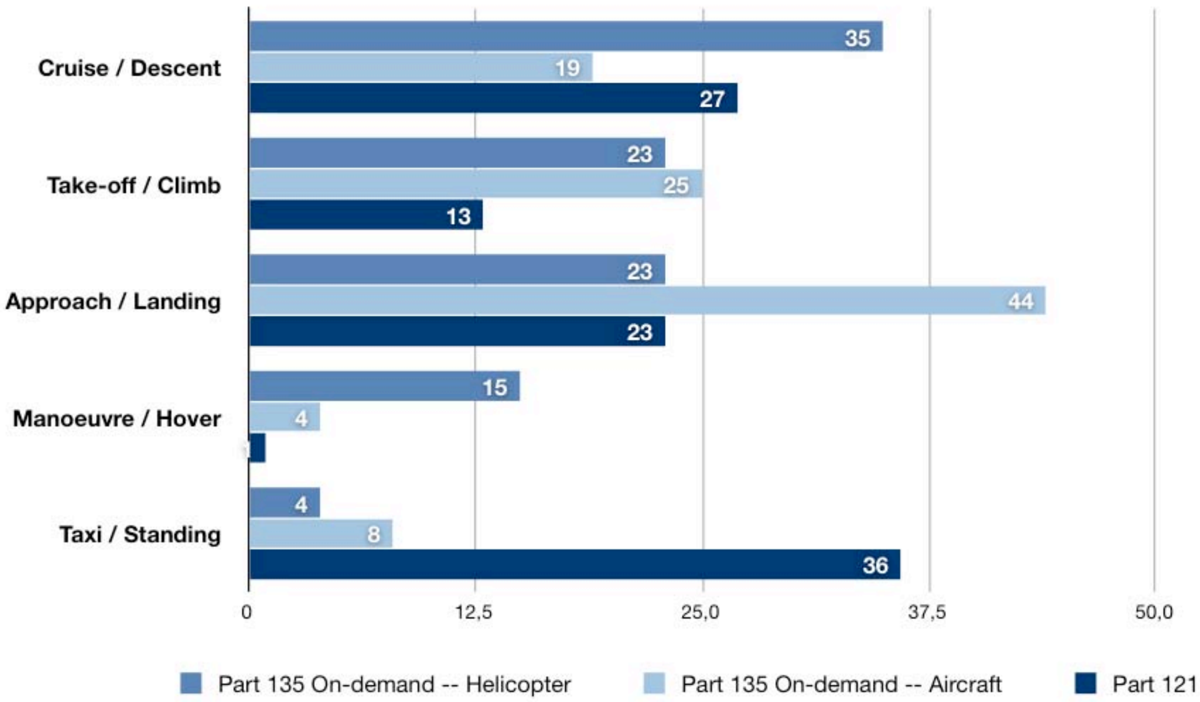



Figure 2 – Helicopter accidents per flight phase

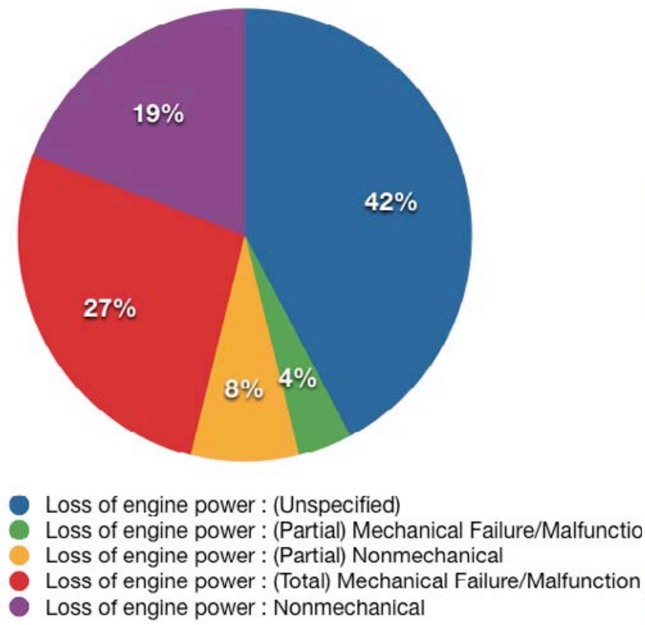



Figure 3 (a) – Engine related accidents

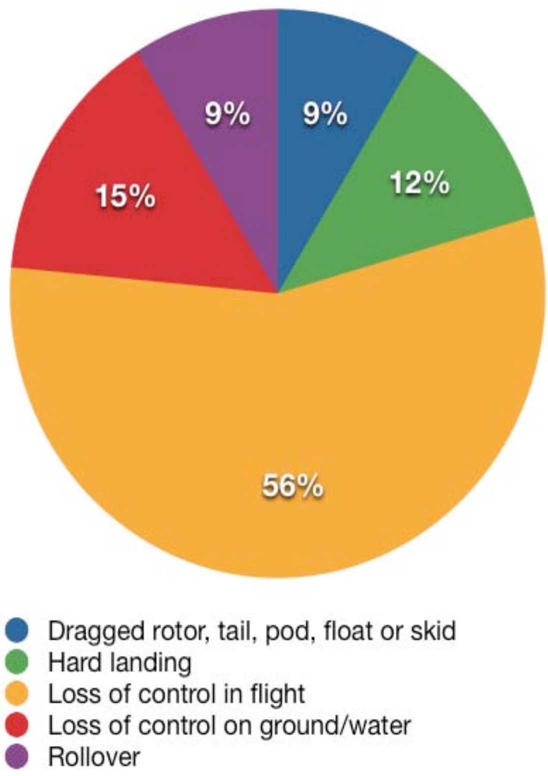



Figure 3 (b) – Loss of control related

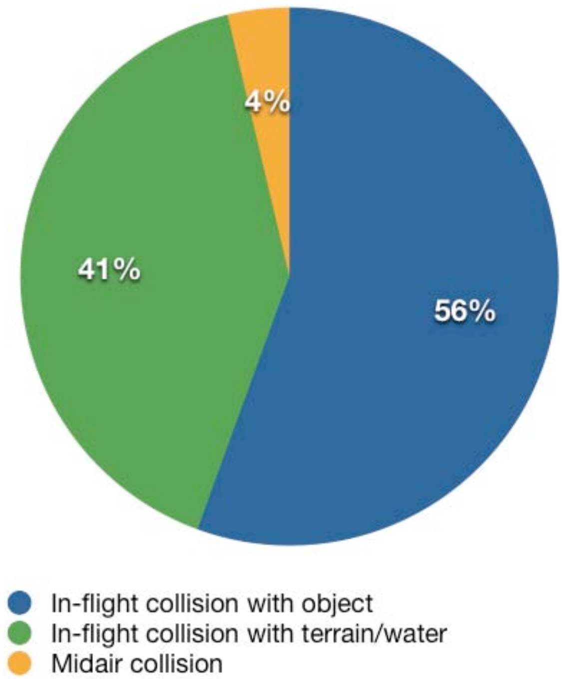



Figure 3 (c) - Collision related

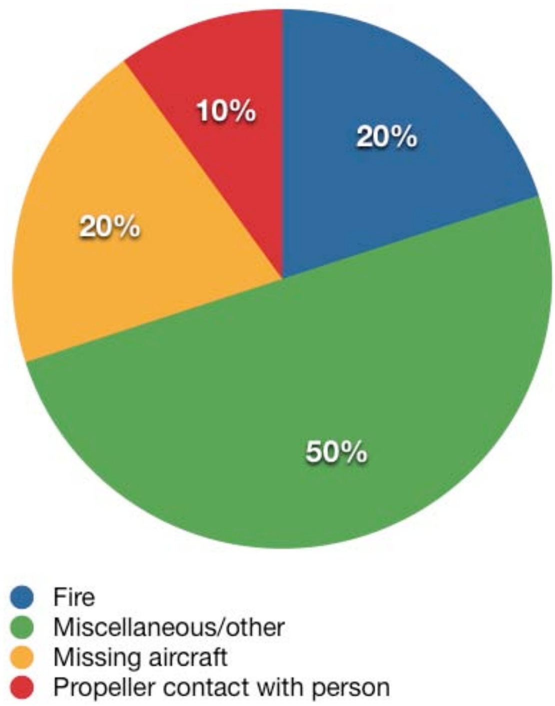



Figure 3 (d) – Miscellanous related

## 4 TEST RESULTS

### 4.1 *Ground testing*

The REDT concept is evaluated using a scale model powered by a 1,8 kW Schuebeler electric fan and Lithium Polymer batteries (Figure 4). This model is a 1/5 scale of a light two-seater helicopter to be produced as a kit aircraft. The model is mainly intended as a bench test for the mechanical design and the flight control system. The model should at least be able to hover and to demonstrate non-acrobatic flight. It is also intended to validate the full-scale aircraft's general aerodynamic characteristics.

First, the fan performance map was measured and the REDT contrarotating turbine was designed to match the best efficiency point of the fan. There is no reheat between compression and expansion on this model. The measured fan isentropic compressor efficiency is low, because this fan is not designed to recover the dynamic pressure and the losses are usually large in very small turbomachines. In order to raise the efficiency, a conical diffuser was installed behind the fan, and particular care was given to the turbine seals, which are two-stage abradable labyrinth seals.


Figure 4 - The REDT scale model before flight-testing

Throughout the ground testing the hovering performance Out of Ground Effect (OGE) was measured, and the good functioning of the control system checked. The main parameters measured during the ground tests were the blade pitch, the lift, the rotational speeds of the rotors and the electric motor voltage. Different rotor diameters and solidities were tested.

The best efficiency was achieved when the two rotors rotated at the same angular velocity: this result was obtained when the blade pitch of the lower rotor was set to be 2° higher than that of the upper rotor. The best OGE lift was 73 N at 1400 rpm and rotor diameter 1,2 m in ISA conditions. The take-off weight of the aircraft is 58 N.

4.2 *Wind tunnel testing*

Wind tunnel tests on a 1/5$^{th}$ scale model of the REDT helicopter were performed at the University of Liège (ULg) wind tunnel. The aim of these tests was to demonstrate the autorotation capability and to analyse the flight stability of the scale model of the REDT helicopter. The ULg low-speed wind tunnel facility where the tests were carried out is shown in Figure 5.

4.2.1 Experimental set-up

The scale model of the REDT helicopter was installed in the aeronautic test section of the wind tunnel (TS1), which has dimensions 2mx1.5mx5m (Width x Height x Length). The airspeed in this test section can reach 60m/s in the closed loop configuration.

The model was installed on an instrumented pylon which allowed the measurement of lift and drag forces (Figure 6). The pylon was a simple stinger-type aerodynamic balance that was centred on the test section turntable and featured eight strain gauges. These were used to measure aerodynamic drag and sideforce. A single-component aerodynamic balance under the turntable was used to measure the lift. The data from the strain gauges and lift balance were obtained automatically through a custom-built data acquisition box and a LabTech software interface.

Figure 5: ULg wind tunnel facilities

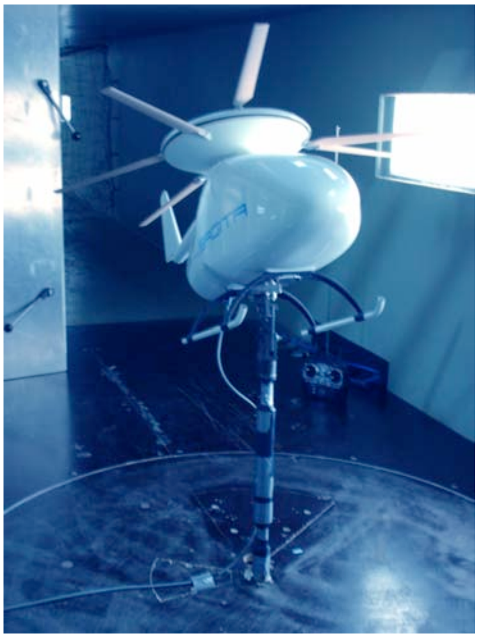


Figure 6: Scale model in the ULg Wind Tunnel

The ULg low-speed wind tunnel is a closed loop subsonic tunnel (Mach < 0,15). It features two different test sections and two interchangeable nozzles; each test section can be operated in open or closed mode.

The helicopter was also equipped with two Hall effect sensors for measuring the rotation speed of the two rotors. The data from these sensors was displayed on dedicated LCD screens. Finally, a single unsteady piezoelectric pressure transducer was used to measure the variations of the pressure behind the helicopter fuselage. The data from the sensor was acquired using a National Instruments data acquisition box.

4.2.2 Autorotation test results

The capacity of the rotor (or rotors) to operate in autorotation constitutes one of the essential safety mechanisms of a helicopter. The wind tunnel scale model showed that the REDT helicopter has good autorotation capabilities. Figure 7 plots the rotation speed of the two rotors at different fuselage angles of attack and a constant airspeed of 6.4m/s. The rotation speed of the upper rotor reaches its maximum value (1380 rpm) at this airspeed when a slightly negative blade pitch is selected on the lower rotor.

4.2.3 Rotor lift and drag measurements

Autorotation is important because it produces lift even when the engine is not operational. This initial series of wind tunnel tests performed on the REDT helicopter also aimed to measure the amount of lift and drag produced during autorotation. Several different configurations were explored in order to characterize the helicopter behaviour in various flight conditions. The aerodynamic forces acting on the model were measured at different airspeeds and angles of attack. Figure 7 shows the variation of lift and drag with angle of attack. Figure 8 contains results obtained at a constant airspeed of 6.6m/s. The figures demonstrate that the model generates significant amounts of lift during autorotation. Further wind tunnel tests will be performed on a powered model in the near future.

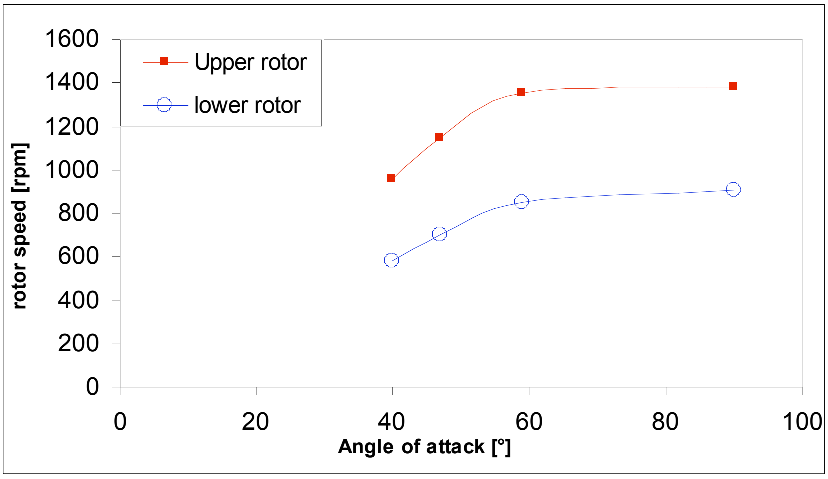



Figure 7: Effect of angle of attack on rotor speed

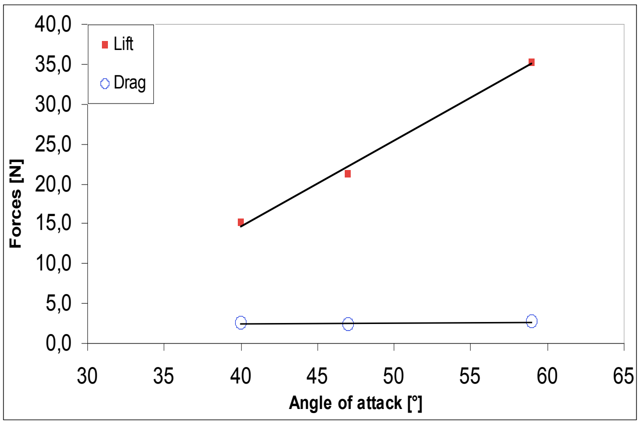
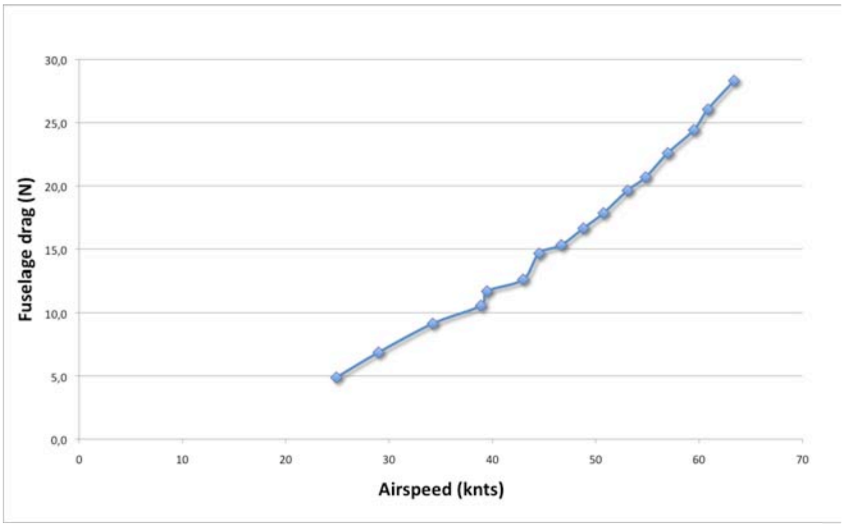



Figure 8 – Effect of angle of attack on induced forces

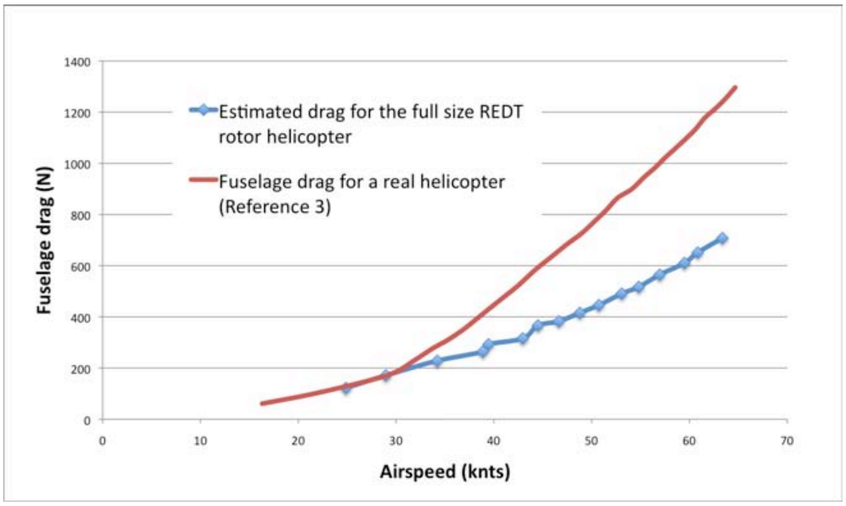
### 4.2.4 Fuselage drag measurements

To measure the fuselage drag (parasite drag), the blades were removed from the rotors and the angle of attack of the fuselage was set to zero. Figure 9(a) shows the increase in the model's fuselage drag as a function of the airspeed.

The parasite drag measured on the model was used to estimate the drag of the full-scale aircraft. The scale of the model being 1/5$^{th}$, the full size drag was scaled with the factor $5^2$ (Mach scaling, Ref. 2), as shown on Figure 9(b). The estimated drag for the full size REDT rotor model is compared in Figure 9(b) with data given in Reference 3 for a real full size CTR helicopter, for which the only known characteristic is its weight, 950 kg. It can be clearly seen that the drag of the REDT helicopter is significantly lower at airspeeds higher than 30knts. Evidently, the geometries of the REDT helicopter and the Ref. 3 full size CTR model are not identical, but the aim of the comparison is to estimate the order of magnitude of the fuselage drag for the full size REDT rotor concept. It is implicitly assumed that the two helicopters have approximately the same size. The weight of the full size REDT rotor helicopter has been estimated at 650 kg, which is quite lower than the 950 kg of the Ref. 3 full size helicopter. However, a considerable weight saving should be obtained with the REDT concept compared to a traditional helicopter due to the absence of a mechanical gearbox and a tail rotor.




(a)




(b)

Figure 9: Fuselage drag as a function of the airspeed

4.3 *Flight Tests*

The same 1/5th scale used in ground and wind tunnel tests was employed in the initial flight testing programme (Figure 10). The craft has a double swashplate, one for the upper rotor, and the other for the lower rotor. The swashplates can tilt for pitch and roll control, and rise for the collective setting of the feathering angle on both rotors. There is no need to have a differential collective setting, since the rotors cannot transmit any torque to the fuselage, being mounted on ball bearings. The swashplates and the control levers are enclosed inside the cupolas. The blades are rigid; there are no lagging or flapping hinges, only feathering hinges. A vane situated at the tail end can direct a jet of air to the left or to the right, thus enabling yaw control. This vane is coupled with a rudder for better yaw control in forward flight. As is typical for a rigid rotor, the roll and pitch responses are quite crisp, while the yaw control can still be improved for more efficiency in hover.

The flight tests are in progress, the first step being to achieve a stable hover, for which a flight stabilisation device is needed, usually through a gyroscope connected to the flight control system. Take-off power is attained, the helicopter takes off quite easily, but the flights are relatively short due to engine overheating issues. This problem is currently being addressed.


Figure 10 – The scale model during flight tests

## 5 CONCLUSIONS

The REDT design can be defined as a thermopropulsed double coaxial rigid rotor helicopter. The aim of the development is to produce a simple and reliable helicopter rotor drive that would decrease the maintenance burden and improve mechanical reliability. An obvious way to achieve this is to reduce the number of moving parts, i.e. to connect directly the power turbine to the rotor. The limited circumferential speed of the turbine will dictate the available enthalpy drop. With an adequate combination of turbine stages and mass flow rate, enough power can be developed by the counter-rotating turbines to drive any helicopter rotor, even a large one for a heavy transport helicopter.

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