TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

III.6
COMPOUND HELICOPTERS A PARAMETRIC APPROACH

M. Rieugnié, D. François
EUROCOPTER FRANCE
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ABSTRACT

The purpose of this is study, financed by the DRET, was to compare the various types of compound helicopters, including the compound with compound engine and the high-speed helicopter, in the perspective of medium term development (2010-2020).

Compound helicopters with wings, and an auxiliary propulsion system such as a propeller, fan, jet engine or compound engine were modelised. A separate contract had been given to TURBOMECA to modelise the compound engines. The basic missions selected for the evaluation of the different types of compounds were combat missions, with an objective of a maximum speed of 400 km/h for all the compounds and helicopters studied.

It was found that two solutions merited an in-depth optimisation: compound with a mechanically driven auxiliary propeller and compound with compound engine. However, the latter solution finally appeared too heavy and with too low an efficiency to compete with the mechanically driven propeller. A compound with an auxiliary propeller can be significantly lighter than a helicopter. However, when the safety requirements (autorotation) are integrated, the weights become similar, and the major advantage of the compound remains a better manoeuvrability at speeds above 220 km/h. A parametric evaluation of the costs showed that the production and operating costs of the compound and of the helicopter would be very close.

The characteristics of the compound could be interesting for escort and anti-helicopter interception missions. However, up to a maximum speed of 400 km/h, the compound does not have a clear advantage over the helicopter. At higher speeds it is better adapted, but the convertible could become a competitor.

1. PURPOSE OF THE STUDY

This study was carried out in the framework of a contract financed by the DRET (Research and Technology Management).

We were asked to determine the utilisation range of the compound helicopter, defined relative to that of the helicopter, pushed to its limits. A compound helicopter is defined as being a helicopter equipped with a wing and an auxiliary system providing thrust, with the aim of improving the performance at high speed.

As there are numerous types of compound helicopters, it was necessary to make a comparison between the different types of compound. In particular, we were asked to study the compound with compound engine. A compound engine is defined here as being an engine which supplies both thrust and shaft power in variable proportions.
The study of the compound engine, which was the subject of a contract given to Turbomeca, will not be detailed here.

2. DIFFERENT FORMULAS

Among the numerous formulas of compound helicopters having flown or having been studied for 40 years now, we selected four. All these compounds are equipped with a wing. These four formulas were modelised.

The propeller compound helicopter was selected as it seems to be the auxiliary propulsion system which offers the best efficiency at the speeds envisaged for the compounds. In addition, the only compound to almost enter series production (Cheyenne) possessed this type of system.

The different variants of the formula were examined, according to the propeller drive system and position.

The fan compound helicopter (shrouded propeller with a high pressure ratio) was also selected as a standby solution if the propeller was found to have too large a diameter during dimensioning.

The jet compound helicopter was added as numerous prototypes have already been built with this type of auxiliary propulsion, which seems easy to derive from an existing helicopter. It was necessary to study the compromise between weight and consumption by testing several jet engines with different by-pass ratios.

Finally, the compound engine compound helicopter, little studied, offers obvious advantages in terms of aircraft architecture. Though the fan of a compound engine has inherently a lower efficiency than a propeller, the overall dimensioning could be more advantageous.

3. MODELIZATION

To optimize the compound helicopter, we used an energy method model. In the framework of this study, it was necessary to extrapolate the helicopter polars to the higher speeds. This model is coupled to a parametric modelisation of weights which enables the general dimensioning of an aircraft. This type of model is commonly used for the reliability pre-projects in order to dimension the aircraft rapidly, using the general specifications consisting of a mission and some performance points.

In the framework of the compound helicopter study, it was necessary to develop the modelizations associated with this type of aircraft: propeller, wing, jet engine, compound engine, and the management of the power limitations in the different possible configurations. The models were kept as simple as possible. The models for the jet engine and the compound engine were carried out with the assistance of Turbomeca.

The model for the compound helicopter was validated using the data at our disposal concerning the Cheyenne.

4. MISSION AND DIMENSIONING CRITERIA

We decided to optimise the compound around an escort mission for a tactical lift helicopter on a troop-landing mission (Fig 1).

The troop-landing mission is defined as follows. After regrouping at a rendezvous point, the first part of the transport mission is carried out at high speed and low altitude to the troop-landing zone. On approaching this zone, and during the disembarkation of the troops, the troop-landing helicopter flies in nap-of-the-earth (N.O.E.) flight. The helicopter then returns to its base in high speed, low altitude flight. This mission is carried out in European conditions (1000 m, 25°C).

ESCORT OF A TRANSPORT HELICOPTER

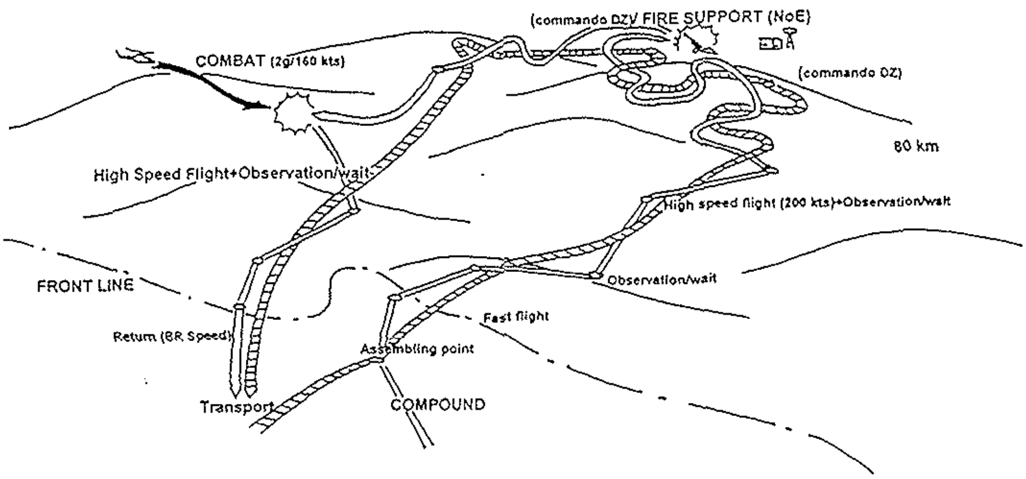

Figure 1 - BASIC MISSION

The mission of the compound centres on the transport mission. During the high-speed phases of the transport mission, the compound flies in advance of the transport helicopters, at maximum cruise speed, to verify the absence of any menace on the route of the transport helicopters, and waits for them at an observation point. Then, during the part of the mission carried out in N.O.E flight, the compound remains near to the transport helicopter in order to provide fire support against the ground or to react to the menace of an enemy attack helicopter. The compound uses its capacities for a more rapid N.O.E. flight in order to explore the ground around the transport helicopters. The mission is detailed in table 1

Additional dimensioning criteria were also integrated, all at the combat weight.

- 17 % power margin in hover flight out of ground effect (N.O.E. flight requirement).
- Maximum speed 400 km/h (210 kts).
- Stabilised load factor 2 g at 325 km/h (175 kts)

The weapons envisaged for this mission consist of a 20mm helicopter mounted gun with 400 rounds, two 68mm rocket pods, and short-range air-to-air missiles (Mistral type).

In addition, the technological level considered was a technological level corresponding to an entry into service in 2015, and therefore the results of programmes in progress for the improvement of rotor tip profiles, engine performances, structural materials and mission systems were integrated in the study.

PHASE	Nature	Duration
Take-off	Hovering OGE	5 min
Route to the rendezvous point	Level flight 260 km/h	5 min
Covering disembarkation	Hovering OGE	7.5 min
Escort (combat weight)	Level flight 380 km/h Hovering	14 min 5 min
Escort (N.O.E. flight)	Level flight 200 km/h Hovering	8 min 7 min
Escort (return)	Level flight 380 km/h Hovering	14 min 5 min
Reserves	Level flight, minimum hourly consumption	20 min

Table 1

Other missions were studied, but were not selected as the basic mission: helicopter interception, attack, combat helicopter escort. Each of these missions possesses its own specific characteristics which could sometimes favour a compound helicopter in particular. No civilian mission was chosen, given that the compound does not appear to enable a sufficient increase in speed relative to the helicopter to interest air transportation.

5. CLASSIFICATION OF THE DIFFERENT FORMS OF PROPULSION

In the first stage, no optimisation of the different types of compound selected was carried out. All the compound helicopter types were dimensioned with the same group of parameters (lift coefficient in hover flight, rotor diameter, circumferential speed, lift provided by the wing, thrust provided by the auxiliary engine). During this stage, it was shown that certain compound types were significantly heavier and required much more power than others (table 2). It was therefore possible to eliminate them at this stage of the study.

	Propeller compound helicopter	Jet compound helicopter	Fan compound helicopter
Maximum weight	5200 kg	5400 kg	5550 kg
Empty weight	3300 kg	3300 kg	3550 kg
Fuel weight	520 kg	670 kg	580 kg
Engine power	1440 kW	1050 kW + 460 daN	1800 kW

Table 2

The jet compound helicopter is always a much heavier aircraft than a mechanically driven propeller compound helicopter due to its higher fuel consumption.

In addition, though the jet compound helicopter is easier to design as a derivation of an existing aircraft, it is complex to design as an original machine: each jet engine is in fact an additional motor for which the control, installation, fuel system and detectability processing must be planned.

The mechanically driven fan was also eliminated at this stage of the study. In as much as the dimensioned propeller diameters are acceptable for the installation (2 to 3 metres), the small diameter fan, which has a lower efficiency at low speeds of the compound helicopter, presents no advantage. Its weight, its consumption, and the engine power required are higher than for a compound helicopter with a large mechanically driven propeller.

The propeller compound helicopter, offering the best efficiency and the lowest total weight, was selected. It was also chosen to use a single mechanically driven propeller.

The compound engine compound helicopter was selected for the rest of the study because of the advantages it offered in terms of architecture, its global efficiency being between that of the propeller compound and the other types.

6. OPTIMIZATION

6.1 Optimization

An attempt was made to optimize the definition parameters which were fixed arbitrarily: thrust and lift ratios of the auxiliary resources relative to the total thrust and lift, rotor diameter, mean rotor lift coefficient, propeller activity factor, tip speed of the main rotor, for the minimum weight and engine power conditions.

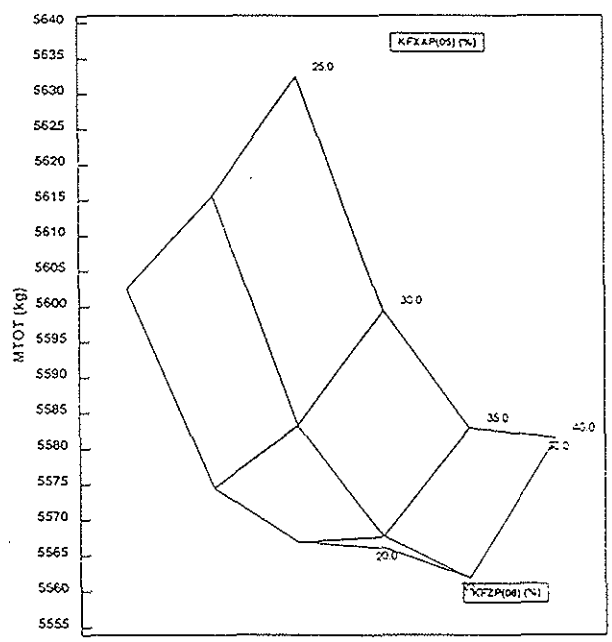

Figure 2 - INFLUENCE OF LIFT AND THRUST RATIOS ON MAX GROSS WEIGHT

It was shown that the optimum weight for the compound helicopter is located at relatively low values of the lift and thrust ratios of the auxiliary resources at total lift and thrust (Fig 2), i.e. 25 to 40 % on the dimensioning points (maximum speed point and high-speed manoeuvring point). In other words, this optimum value is produced for a small wing and a relatively small propeller, or for the compound engine, a low bypass ratio. It would be best to use the aircraft rotor, which has been dimensioned for hover flight, near to the maximum of its propulsive force possibilities in level flight.

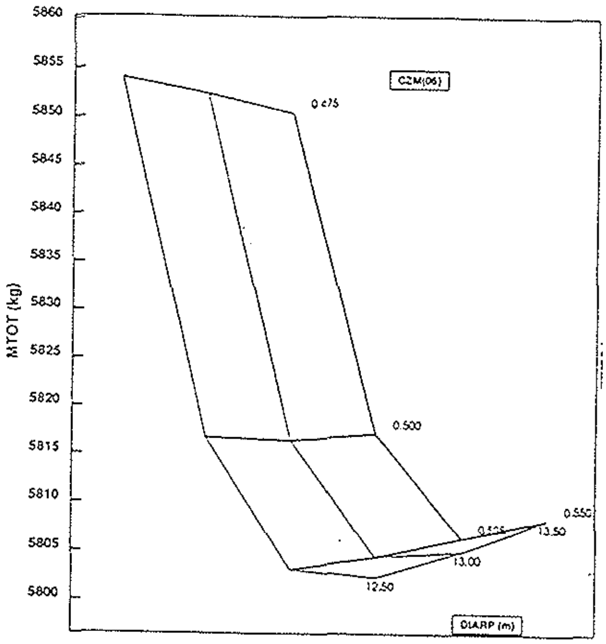

Figure 3 - INFLUENCE OF LIFT COEFFICIENT AND ROTOR DIAMETER ON MAX GROSS WEIGHT

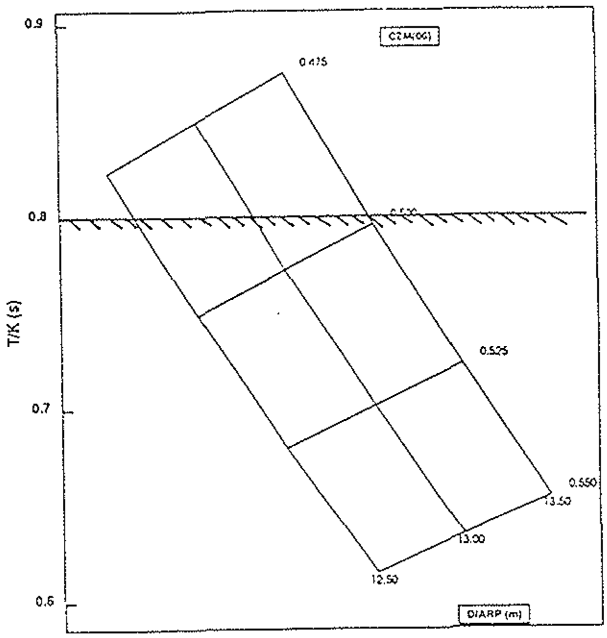

Figure 4 - INFLUENCE OF LIFT COEFFICIENT AND ROTOR DIAMETER ON AUTOROTATION INDEX

The presence of high-speed performance points and of part of the mission carried out at high speed leads to the dimensioning of a rotor which is relatively loaded in hover flight in comparison with the present helicopter rotors, with also a slightly smaller diameter. The mean lift coefficient thus obtained is 0.525 instead of 0.45 to 0.475 for a conventional helicopter (Fig 3).

However, flight safety requires that autorotation is taken into account for the dimensioning of the rotor (Fig 4). The rotor thus dimensioned is larger and less loaded, engendering a larger aircraft.

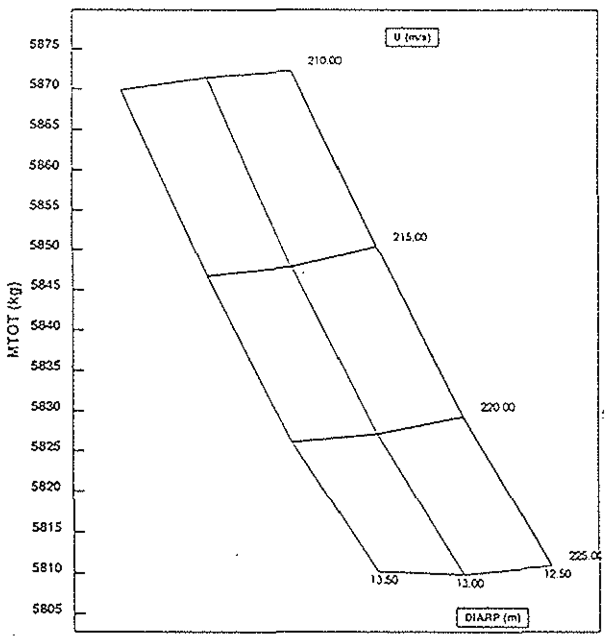

Figure 5 - INFLUENCE OF TIP SPEED AND ROTOR DIAMETER ON MAX GROSS WEIGHT

It was also shown (Fig 5) that the tip speed of the rotor must be set at quite a high value as the effects of the tip speed on the dimensioning of the rotor in hover flight are much higher than the effects of Mach on the engine power at high speed (210 kts - 400 km/h). A variable speed would result in a slight benefit.

The optimization of the propeller has little effect on the dimensioning of the aircraft. It was simply shown that it would be beneficial to have an average activity factor in order to optimise the necessary engine power. However, the safety of ground personnel and of the aircraft in hover flight requires that the propeller is protected by a shroud. The shrouded propeller will be smaller than the optimum free propeller, and will have a higher solidity ratio.

Optimization for the compound helicopter with compound engine was carried out according to similar rules. We also selected a type of compound engine. TURBOMECA proposed several types of engine. All these engines comprise a fan driven by the free turbine. Three solutions were proposed around a free turbine core: an engine with variable inlet guide vanes on the cold flux, an engine with variable inlet guide vanes over the entire height of the airflow, an engine with a variable pitch fan. This third type of engine was the one selected.

The compound helicopter with compound engine is approximately 3 % larger than the compound helicopter with auxiliary propeller (Table 3). This is due to the weight of the variable pitch fan system on the engine itself. More in-depth research is required into the variable thrust system of the compound engine for it to become competitive with the propeller solution.

	Propeller compound helicopter	Compound engine compound helicopter
Maximum weight	5830 kg	6050 kg
Empty weight	3540 kg	3725 kg
Fuel consumption	535 kg	580 kg
Rotor diameter	13.5 m	13.5 m
Rotor chord	0.475 m	0.6 m
Circumferential speed	225 m/s	225 m/s
Wing surface	8.5 m²	8.5 m²
Engine power	1415 kW	1370 kW
Propeller diameter	2.25 m	
Activity factor	200	

Table 3

6.2 Architecture

A preliminary study of the general architecture was made (Fig 6). For obvious reasons of drag and radar signature, the landing gear is retractable and part of the weapons can be carried in a hold. Also for reasons of radar signature, the fuselage has a general diamond shape, attenuated to reduce drag.

A ducted tail rotor is also used: this type of rotor has the advantage of requiring less power than a conventional tail rotor in level flight, and is also better for detectability considerations. For a propeller compound helicopter, the interaction between the ducted tail rotor and the propeller must be studied with precision in the different flight phases, taking into account the thrust required at each phase, but this is outside the framework of this study. It should be noted that a propeller is a disadvantageous element for the detection of the aircraft by radar.

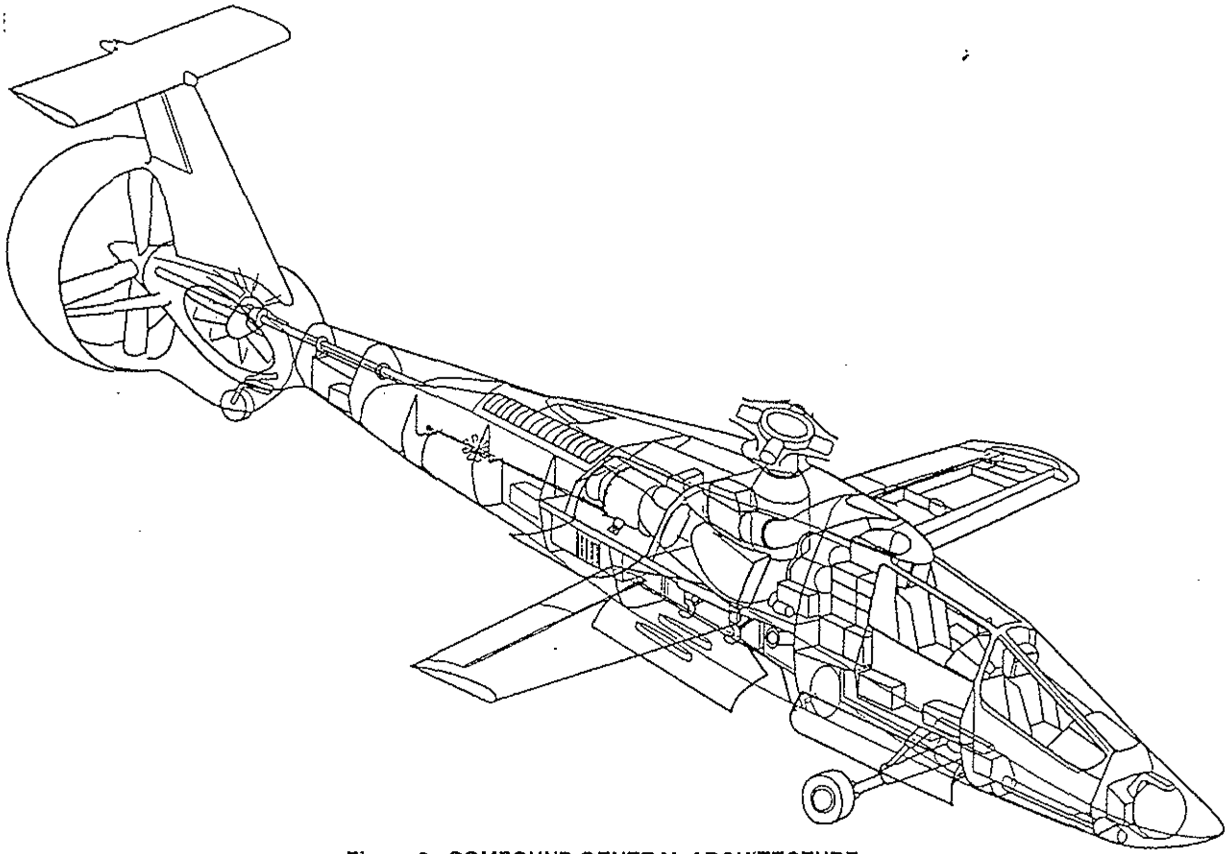

Figure 6 - COMPOUND GENERAL ARCHITECTURE

7. COMPARISON WITH A HIGH-SPEED HELICOPTER

7.1 Dimensioning the helicopter

A high-speed helicopter was dimensioned on the basis of the same mission as for the compound helicopter. The same speed requirements used for the compound helicopter were imposed on the high-speed helicopter. However, the maneuverability requirement was adapted: a maneuvre margin of 2.25 g was imposed on the minimum power speed.

The helicopter characteristics were then optimised in terms of engine power and maximum weight. The maneuverability requirement leads to a rotor with a high solidity, coherent with the blade surface required at maximum speed. The engine power is dimensioned by the high-speed point. The OGE hover performance is no longer dimensioning.

Optimisation was achieved in a manner similar to that of the compound helicopter, and led to a 5-blade rotor with a diameter of 13 metres. The optimum tip speed from the point of view of the aircraft weight remains high, though this is not the case from the point of view of the engine power, due to the significant increase of the profile drag of the blades at high speed.

The general dimensioning of the optimised helicopter is located at a maximum weight identical to that of the propeller compound helicopter after the safety constraints have been taken into account, and at an engine power 9 % higher (Table 4). The fuel consumption is also slightly higher than that of the compound.

We therefore have two approximately equivalent machines in terms of overall dimensioning for which the performance was compared.

	Propeller compound helicopter	Helicopter
Maximum weight	5830 kg	5800 kg
Empty weight	3540 kg	3490 kg
Fuel consumption	535 kg	560 kg
Rotor diameter	13.5 m	13 m
Rotor chord	0.475 m (4 blades)	0.51 m (5 blades)
Circumferential speed	225 m/s	225 m/s
Wing surface	8.5 m²	
Power of one engine	1415 kW	1545 kW
Propeller diameter	2.25 m	
Activity factor	200	

Table 4

We also examined what effect a maximum speed of 450 km/h (245 kts) had on the dimensioning of a propeller compound helicopter and a high-speed helicopter. In these conditions, the propeller compound has a clear advantage over the high-speed helicopter for which the lift provided by its rotor collapses completely at these speeds. It would therefore appear, that for the missions and sizes of aircraft studied, the limit between a dimensioning which is advantageous to the helicopter or to the compound is located at a speed slightly lower than 400 km/h. However, we arrive at empty weight/total weight ratios greater than 0.65 and at engine powers greater than 2000 kW.

7.2 Performances

The hover performance of the high-speed helicopter, with a rotor dimensioned by the maneuvre point and the engines dimensioned by the maximum speed point, is extremely impressive. However the general specifications used renders the compound helicopter entirely acceptable in this field; equivalent to a good combat helicopter of the present generation.

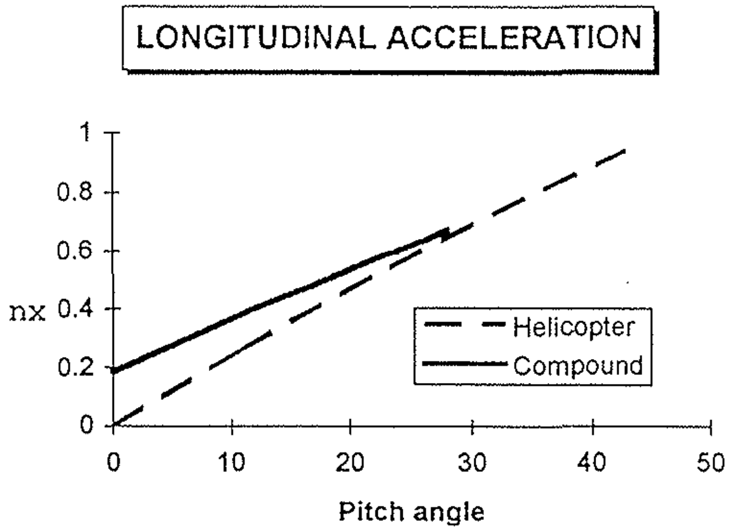

Figure 7

The longitudinal acceleration capacity is often given as being one of the strong points of the compound helicopter.

It would seem that this assumption should be qualified. A helicopter to which a propeller and more powerful engines are fitted will have an acceleration greater than that of an identical helicopter which is not equipped with these characteristics. Here, the rotor of the high-speed helicopter is larger and the engine power identical to that of the compound helicopter. Inclining a large helicopter rotor will give more thrust than increasing the pitch on a propeller. It was therefore shown that the stabilised longitudinal acceleration of the high-speed helicopter is greater than that of the compound (Fig 7).

The compound has the advantage of being able to maintain an attitude lower than that of the helicopter at the same acceleration, which may be important for keeping the sight axis for a combat helicopter.

The capacities of an aircraft to decelerate should not be neglected as they define the possibilities of maneuvre in N.O.E. flight just as much as the acceleration capacities. The propeller compound helicopter can use its propeller to decelerate by reversing the pitch. It should be noted that a compound with a compound engine does not have this possibility.

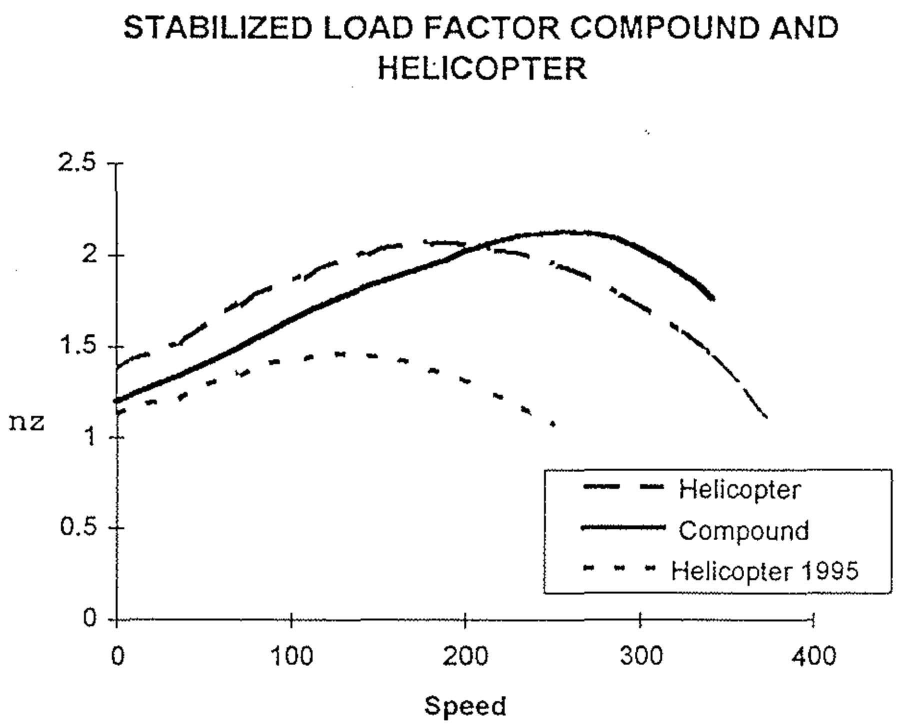

Figure 8

The high-speed helicopter possesses high maneuvre capacities at low speed. However, its performance rapidly decreases when the speed exceeds 300 km/h. The compound helicopter, whose possibilities at low speed are hardly better than those of present helicopters, gains the advantage over the high-speed helicopter at a speed greater than approximately 220 km/h (120 kts) due to its wing (Fig 8).

On the transient load factor limit, the helicopter maintains the advantage at a higher speed, up to approximately 260 km/h (140 kts). However, due to its wing, the compound helicopter retains the same load factor limit up to its maximum speed.

7.3 Costs

A cost analysis was carried out using a parametric model. However, the reliability of a cost analysis at this stage of a project, and at the target horizon, is not certain. It was shown that the production costs for a high-speed helicopter and for a compound helicopter, and their operating costs, would be quite close.

The greater complexity of a compound appears to be compensated by the fact the helicopter sub-assemblies which are dimensioned larger than those of the compound are also sub-assemblies which will cost the most: rotor and engine.

The development costs are harder to evaluate. We can however assume that the experience of a major helicopter manufacturer is easier to apply to a high-speed helicopter than to a compound helicopter.

We can therefore consider that a compound helicopter dimensioned for a speed of approximately 400 km/h is only penalised relative to a high-speed helicopter by its development costs.

8. CONCLUSION

The compound helicopter solution which appears to be the best is that of a compound helicopter with a mechanically driven auxiliary propeller. A compound helicopter with a compound engine requires more detailed study into the means of generating the variable thrust.

It has been shown that a compound helicopter dimensioned for a maximum speed of 400 km/h had limited advantages relative to a high-speed helicopter: better manoeuvrability at high speed, acceleration and deceleration in better conditions, though not as strong. In addition, it is able to maintain performances in hover flight equivalent to the present helicopter. The compound helicopter does not have a weight lower than that of the helicopter, but its installed power is 9 % lower. Given the complexity of the compound, this results in equivalent production and operating costs. These characteristics, however, limit the advantage of the compound helicopter to very specific combat missions.

The compound helicopter only gains a definitive advantage in dimensioning relative to the helicopter above a speed of 400 km/h. A dimensioning for these speeds, however, leads to very high empty weights and installed power, and the tilt-rotor can then begin to present an advantage.