A CONCEPTUAL STUDY OF HIGH SPEED ROTORCRAFT

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Abstract

A study group of future rotorcraft is formed in JAXA with participants from a wide spectra of organizations in Japan. Taking the helicopter market in Japan as a study case, four potential high speed rotorcraft (VTOL aircraft) missions are discussed. When a capability of hovering is required, compound helicopter is concluded as the most suitable design configuration. A simplified conceptual design process for a compound helicopter is described where a wing and propellers are added to a single rotor helicopter. A compound helicopter concept for high speed EMS (Emergency Medical Service) is proposed. The result of the conceptual design is compared with a conventional helicopter and the cost expense is illustrated. If also considering the cost to maintain a base hospital, a high speed rotorcraft with significant higher cost is acceptable which covers a much wider area providing effective first aid to critical patients.

1. INTRODUCTION

Conventional helicopter uses the main rotor for lift and propulsion at the same time. Because of its relatively simple mechanical design and high capability to perform vertical take-off and landing (VTOL) and missions during hovering flight, it has found a wide spectra of applications, both military and civil, and become a irreplaceable aircraft nowadays.

However, there are several shortcomings in the conventional helicopter design: the maximum flight speed limitation, low efficiency of cruising flight, high vibration and noise levels, etc. Among them, it is well known that the flight speed limits comes from the sonic barrier at the advancing side and stall at the retreating side of the rotor. Generally, the conventional helicopter cruising speed is around 125 knots, with several modern models reaches 150 knots and more. It is widely accepted that remarkable speed increase comparable to a fixed wing airplane is hard to achieve with the current helicopter configuration.

Designers have long been working hard to break the speed limitation of helicopter with numerous inventions. Tiltrotor converts the rotor for lift at hovering and low speed flight into a set of propellers and use wings to generated the lift at high speed flight. Literally, it converts a helicopter into a fixed wing aircraft at cruising flight. Even a certain degree of compromises have to be done between an optimal rotor for hover and an optimal propeller at high speed, and despite the difficulties has to be overcome during the conversion process, it was successful to develop this type of aircraft and led to quantity production and deployment for military purposes in US and Japan recently. It is reported that a civil model of tiltrotor is under development although the type certification process has been taken for an unexpectedly long period. The performance of the V22 Osprey is heavily depends on the operational gross weight and the maximum speed of 275 knots at sea level and 305 knots at 15,000 ft are proved. The cruise speed at sea level is set at 241 knots which is nearly twice of the cruise speed of a conventional helicopter. [1-3]

Other efforts to improve the maximum speed of the helicopter are mainly based on the idea of adding a propeller or propellers to the existing helicopter designs. Two types are tested so far. One is adding propeller(s) to a conventional single main rotor helicopter. [4] Generally, a wing is added to share part of lift during cruising flight. The technology demonstrator X3 flown by Airbus Helicopters (then EuroCopter) is a successful sample of this type. The maximum speed record at level flight of 255 knots was achieved on June 7, 2013 and a speed of 263 knots in a descent was also achieved. [5]

Another design which uses a coaxial main rotor and a pusher propeller, utilizing the lift generated on the advancing sides of both rotors at high speed flight so a wing is not a necessary. Although the mechanism concerning the main rotor is much complex, a more compact aircraft design is possible. A demonstrator X2 by Sikorsky set the previous helicopter high speed record of 250 knots in 2010. [6]

Japan is a narrow island country and has high mountains along the central areas of the islands. Nearly 800 helicopters are operated in Japan which is nearly the same number of the fixed wing airplanes. Considering the ratio is about 1:10 in the US, we can see that Japan is suitable for the helicopter operations. Currently, the emergency medical services (EMS) by helicopter are based on the local hub hospitals, but it is hard to realize the 15 minutes requirement to reach the scene after the severe bleeding accident is reported everywhere in the country. A high speed helicopter can find a good market for the EMS operations and a conceptual study is performed.

A loosely arranged study group led by Prof. Kawachi (one of the authors) is formed with participants from the three representative helicopter manufacturers and interested professors and researchers from the universities and institutes and helicopter operators in Japan. Studies and discussions were concentrated to answer the following seven questions:

1) What are the technology issues for current helicopters?

2) What are the technologies need to be addressed for future rotorcraft?

3) What are the new missions that can be found with future rotorcraft?

4) What are the suitable rotorcraft configurations for the new missions?

5) How to build an advanced design process for future rotorcraft?

6) What are the competitive advanced technologies for the future rotorcraft development?

7) What is the conceptual design for the future rotorcraft?

While a number of technology issues, such as variable rotor speed, de-icing, low noise blade design, applications of advanced smart structures and health utility monitoring systems (HUMS), are raised for the current helicopters, it is agreed a breakthrough to dramatically increase the flight speed performance under the current conventional helicopter design seems difficult.

For the future rotorcraft technologies need to be addressed, considering the development activities of new tiltrotor and compound helicopters in the US and Europe, high speed rotorcraft is focused and it is believed there will also be a large civil market for high speed rotorcraft besides the obvious military needs.

The answers to question 3 through 7 are illustrated in following sections.

2. POTENTIAL CIVIL MARKETS FOR HIGH SPEED ROTORCRAFT

The potential missions for the high speed rotorcraft in the civil market of Japan are divided into four types:

1) There are needs of high speed EMS helicopter in Japan. In emergency medical aid, the golden hour (also known as Cowley curve) refers to a time period lasting for one hour following traumatic injury being sustained by a casualty or medical emergency, during which there is the highest likelihood that prompt medical treatment will prevent death. [7] For an likely frequently occurring traffic accident accompanying massive bleeding, from Figure 1, the death rate grows fast after 15 minutes, so that an effective EMS operation is required to reach the site within 15 minutes. As shown in Figure 2, currently, there are about 40 hospitals operating doctor-helicopters in Japan. It is only possible for the conventional helicopters to cover 60% of the main area excluding the isolated islands. If a high speed helicopter which can fly twice the cruising speed of current conventional helicopter, the coverage rate can be increased up to 90% without increasing the number of base hospitals. Considering the high operating cost for each base hospital, it is considered that introducing a helicopter with larger coverage area is a more cost-efficient means to finally realize 100% EMS coverage in Japan.

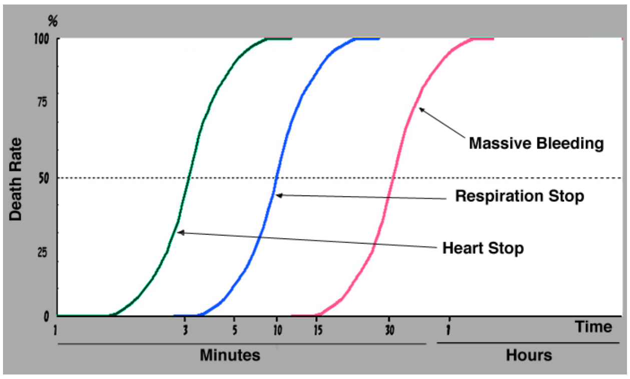
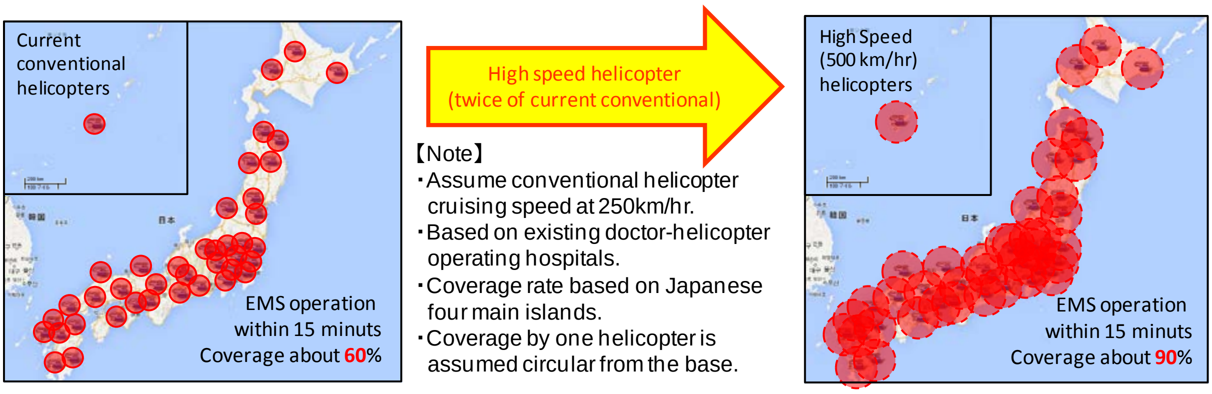


Figure 1: The Golden hour principle [7]



【Note】
- Assume conventional helicopter cruising speed at 250km/hr.
- Based on existing doctor-helicopter operating hospitals.
- Coverage rate based on Japanese four main islands.
- Coverage by one helicopter is assumed circular from the base.

Figure 2: Requirement of high speed doctor-helicopter in Japan to realize 15 minutes EMS operations

The mission requirement for a high speed EMS helicopter is to cover a 100km radius area within 15 minutes with a patient on a stretcher, a doctor, a nurse, an accompanying person and two flight crews onboard. It also needs to carry a pack of medical equipment weighing about 50 kg. Currently, the radius is about 50 km using a conventional helicopter assuming its cruising speed of 250 km/hr. Usually, helicopters with gross weight in the 3,000 - 4,000 kg are used. Currently, as of January of 2014, there are 43 EMS helicopter operated from 36 hub hospitals throughout Japan.

Another need for high speed helicopters comes from the requirement of rapid disaster relief activities. If we can reach the main areas in Japan from Tokyo within two hours, it will be less than half the time of present situations. It is desirable to start rescue activities immediately after disastrous earthquakes, which frequently occurs in Japan. A range of 1,000 km with cruise speed about 500 km/hr is required to satisfy above need. The main use will be transportation of emergency rescue members and supplies, and the rescue activities will consist of a lot operations in hovering flights. Major disaster relief helicopters currently used are mainly in the range of 8,000 - 10,000 kg. The number of public helicopters for fire-fighting and disaster relief is about 80 in Japan.

Japan is consisted of four major islands together with several thousands of small isles. Some remote isles are nearly 2,000 km away from the nearest main island. Vast areas of the maritime territories and the exclusive economic zones are patrolled and controlled by the Japan's Coast Guard which is operating 46 helicopters and 27 airplanes together with 446 boats. Fast cruise rotorcraft are crucial for most of their activities, especially for rescues from the wrecked boats. Mainly, a range of 1,500 km with gross weight about 7,000 kg is considered as the requirement for maritime uses.

There are also needs for high speed business rotorcraft which can fly long distance above the weather. The civil tiltrotor AW609 under development is believed to fill this niche.

There are also needs for high speed VTOL commuters to carry a large number of passengers. But considering the higher operating cost compared with the fixed wings, its long endurance range cannot be fully utilized. Only a relative short haul from a vertiport into a hub airport is considered as a possible civil transportation applications.

3. APPLICABILITY ASSESSMENT OF VTOL AIRCRAFT CONFIGURATIONS

The above-mentioned mission requirements for high speed rotorcraft can be plotted in Figure 3 and 4, where the achievable limts for four configurations of VTOL aircraft: the conventional helicopter, compound helicopter, tiltrotor and tiltwing, are also indicated. For a high speed EMS helicopter, from Figure 3, the filght range requirement is within the limit of a conventional helicopter and the cruise speed requirement can be achieved by configurations of compound helicopter, tiltrotor and tiltwing. But from Figure 4, because the mission also needs a certain degree of hovering capabilty, only the compound helicopter seems suitable for this mission. The missions of high speed disaster relief and rescue rotorcraft are also fitted for the compound helicopter design, which has the advantages of excellent hovering capability and also high speed.

Using a tiltwing as a suitable commuter VTOL aircraft can be arguable because the required range is relative short so its value of high speed flight can be significantly deteriorated. As discussed in Ref. [8] by Prof. Leishman, the total transportation efficiency of a tiltwing for such a short commuter haul may be much worse than a conventional heavy lift helicopter. Tiltwings may find a suitable mission in military or business where speed together with long range have high priorities but seems like to face inevitable competions with the tiltrotors.

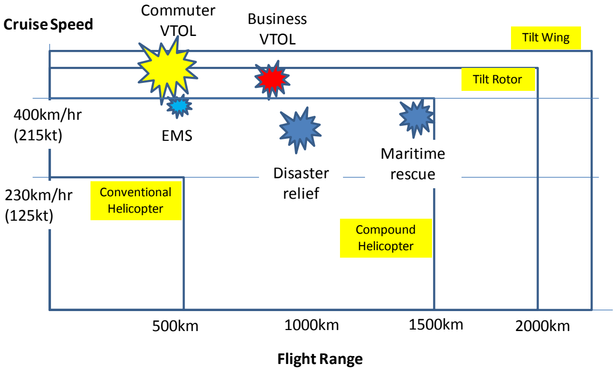


Figure 3: Mission requirement for range and speed

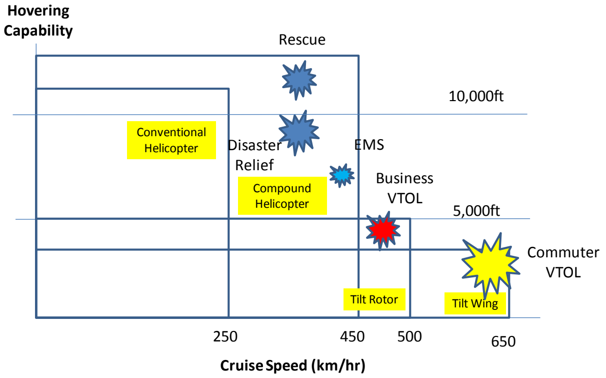


Figure 4: Mission requirements for speed and hovering capability

4. CONCEPTUAL DESIGN PROCESS FOR COMPOUND HELICOPTERS

The compound helicopter configuration is considered to fit most of the high speed rotorcraft mission requirements as mentioned in Sec. 2. For the missions require extensive operation in hover and also need to reach the site as fast as possible, a compound helicopter seems to be a right answer. With added engine power for excessive high cruise speed, the hover performance can be excellent. Also, in forward flight, using the added freedom of control of the propeller thrust and also the control surfaces on the wing and on the tail, it is possible to keep the nose-level pitch attitude, minimizing the parasite drag of the fuselage [9]. By sharing lift with a fixed wing at high speed, the vibration level could be reduced. [10, 11] There is also possibility to reduce the rotor noise by optimizing the trim and controls, especially during descent flight, where the BVI (Blade-Vortex Interaction) noise is annoying and also cause large vibration on the aircraft. [12, 13]

In this paper, an EuroCopter X3 like configuration is taken as a starting point, where the anti-torque required by the main rotor is provided by a pair of propellers on the wing-tips with differential thrust.

As shown in Figure 5, a conceptual design process for a compound helicopter with a wing and propeller(s) added can be constructed by adding the contributions of the wing and propeller to the gross weight and total required power (written in red letters in the figure). Given a required pay-load (PL) and a mission profile, where the hovering time, cruise speed and time, the loitering time and speed, and also considering the time of on-ground pre-flight check are defined, starting from zero fuel weight, at step 1, based on an empirical correlation between the empty weight and gross weight of current helicopter, the gross weight of conventional helicopter to carry the useful weight (sum of PL and Fuel) can be estimated. To design a compound helicopter, estimated weights of the wing and extra powerplant to drive the propeller(s) are then added to the estimated gross weight for a conventional helicopter.

The main rotor radius and chord length then are estimated in a same manner as a conventional helicopter in step 2 and 3 using correlation of current conventional helicopters.

In step 4, the required power for hovering flight is calculated. With a wing installed for a compound helicopter, the download caused by the downwash from the main rotor is included.

In step 5, the power required for the cruise flight defined in the given mission profile is calculated. For the rotor power at high advance ratio, formulas derived by Harris are used. [14] The tip speed of the rotor at cruise is taken as a design factor. The coefficient of the horizontal equivalent flat plate area of the fuselage against the square root of the gross weight (C_EFPA_H) is taken as a design factor also. For clean helicopters, C_EFPA_H is about 0.125 while for utility helicopters, it is about 0.25. [15] At high speed flight, drag caused by the fuselage is dominant, so to realize a remarkably lower C_EFPA_H is crucial for an efficient high speed rotorcraft design. The wing is also designed in this step based on wing design parameters such as the lift sharing ratio and wing span factor relative to the main rotor radius, etc. The lift coefficient of the wing is specified at the cruise speed, so the chord length of the wing can be calculated. The induced drag of the wing is calculated based on the aspect ratio and a wingspan efficiency factor (Oswald span efficiency factor). [16] After the drags of the rotor, fuselage and the wing is calculated, propeller thrust need to overcome these drags can be determined. Based on the design parameters specified for propeller, the diameter of the propeller and power required for the propeller can be obtained.

Engine is selected in step 6 with continuous power output higher than the largest required power calculated in step 4 and 5. For a compound helicopter, generally, the required power for cruising is higher than that for hovering. In real design, for most case, engine should be selected from a list of existing engines so the weight of the engine and the specific fuel consumption (SFC) can be found. In this conceptual study, the weight of the engine and the SFC are estimated from a correlation based on existing engines just at the maximum required power.

Finally, in step 7, fuel required for the given mission profile is calculated. Because the useful load is changed with this newly calculated fuel weight, back to step 1, a new gross weight is estimated. This cycle is iterated till convergence of the gross weight and other design parameters are attained.

During current conceptual studies, the weight of the anti-torque system is assumed equal to the existing tail rotor weight, so no additional weight and power consumption is considered.

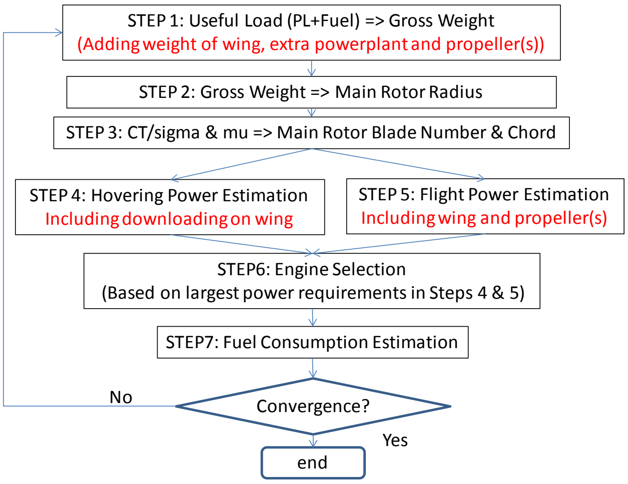


Figure 5: Compound helicopter conceptual design process

5. TECHNOLOGY ISSUES TO REALIZE AN EFFICIENT HIGH SPEED COMPOUND HELICOPTER

Technology issues to realize an efficient high speed compound helicopter are illustrated in Figure 6. Of them, low aerodynamic drag of fuselage and rotor hub design are considered most important because the required power ratio of the parasite drag is outstanding among others at high speed flight. Using a set of two electrical-driven propellers at the wing-tips to produce anti-torque for the main rotor is proposed as an application of new technologies to rotorcraft design. There are several advantages with this design: flexible layout of the wing (no need for mechanical drive-chains from the gearbox); redundancy in anti-torque system; able to stop the small propellers on-ground even the engine is running, thus improve safety to the passengers and other personals on ground. The ducts surrounding the wing-tip propellers may have no benefit for fast flight and need further studies. An aft mounted propeller provide thrust for high speed flight which can be disengaged during hovering and low speed flight, thus save power during such flight missions. The aerodynamics and dynamics of a slowed rotor at high advance ratio have been extensively addressed so far and an optimized rotor design compromising the rotor efficiency in hovering and high speed flight must be performed. [17-18]

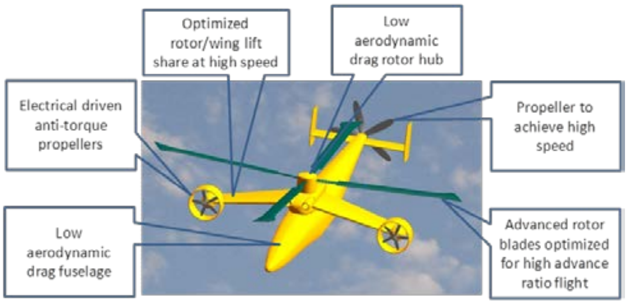


Figure 6: Technology issues for high speed compound helicopter

6. A COMPOUND HELICOPTER CONCEPT

A sketch of a proposed compound EMS helicopter concept is shown in Figure 7. As a result of preliminary concept study, defining a mission profile carrying 871 kg EMS payload and flying at 250 kt with endurance time of 1 hr, a compound helicopter with gross weight of 4100 kg is possible. The required engine power is about 2750 hp. Comparing with an existing conventional helicopter used for same purpose, the gross weight is 1200 kg heavier and use twice of the engine power. This is the expense for the 113 knots higher cruise speed. It can reach a distance of 100 km in 13 minutes after take-off, with current one in about 24 minutes. The aircraft acquistion cost will be higher and the operating cost (fuel burnt) is higher too. But it is a question of how this 11 minutes means to a human's life. Considering the costs of add two more hospitals with EMS helicopter operative capabilities and two more sets of EMS crews using current helicopters to cover the same area of a high speed helicopter, even the cost of the high speed helicopter is significantly higher than the current ones, as a unit cost combining the facility and the aircraft together, it is still much cost effective.

The analysis and design of the flight controls and trims for this compound helicopter concept is being carried out. The underlying technology issues to achieve an efficient high speed rotorcraft will be identified and studied through follow-on research programs. Simulations and tests using sub-scales are planned.

Figure 7: **A sketch of the compound helicopter concept proposed by JAXA**

7. SUMMARY

A study group of future rotorcraft is formed in JAXA with participants from a wide spectra of organizations in Japan. The discussions are concentrated on the answers to seven questions. Taking the helicopter market in Japan as a study case, four potential high speed rotorcraft (VTOL aircraft) missions are discussed. The mission profile limits are compared between configurations of tilt-rotor, tilt-wing, and compound helicopter. When a capability of hovering is required, compound helicopter is concluded as the most suitable design configuration. A simplified conceptual design process for a compound helicopter is described where a wing and propellers are added to a single rotor helicopter. A compound helicopter concept for high speed EMS is proposed. The result of the conceptual design is compared with a conventional helicopter and the cost expense is illustrated. A view on the unit cost effectiveness is discussed that if the cost to maintain a base hospital is considered, a high speed rotorcraft with significant higher cost will be acceptable which covers a much wider area providing effective first aid to critical patients.

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