Recent Development of Rotorcraft Configuration

Yihua Cao*, Dong Li, Qiang Zhang and Hang Bian

Beijing University of Aeronautics and Astronautics, Beijing 100083, P.R. China

Received: August 22, 2006; Accepted: October 14, 2006; Revised: October 19, 2006

Abstract: In view of the flight theory of rotorcraft, breakthroughs in the field of rotorcraft configuration during recent twenty years are described in this paper. From the traditional configuration (including the single main rotor with tail rotor, tandem rotors, side by side twin rotors, coaxial rotors and crossing rotors) to the recent ones (including ducted tail rotor, non-tail rotor helicopter, hingeless rotor, bearingless rotor, tilt-rotor, tip-jet rotor, reverse velocity rotor system, the compound helicopter and rotor/wing transition helicopter), the great progress on rotorcraft configuration have been revolutionarily made. These new technologies have an effect on the rotorcraft performance in high speed and super-maneuverability and high-agility flights. In light of advancing blade transonic shock and stall of retreating blade at high angle of attack in forward flight for helicopter conventional layout, the new progress in rotorcraft configuration in recent years show the potential to exceed maximum flight speed limit for current helicopters, and even to be greater than the cruise speed of propeller aircraft. At the same time, maneuverability and stability in forward flight have been improved. With the increased rotor efficiency, overload capability and good flight performance, these new types of rotorcraft have good maneuverability and lower vibration/noise level, and avoid ground or air resonance. Owing to the introduction of the new types of rotor configuration, the reliability and maintainability as well as survivability of the rotorcraft can be improved significantly. Therefore, their service life has been prolonged. In short, the rotorcraft with new types of configuration will become the more economical, effective and rapid vehicles for air traffic transportation in the future.

Keywords: Rotorcraft, configuration, ducted tail rotor, non-tail rotor helicopter, hingeless rotor, bearingless rotor, tilt-rotor, tip-jet rotor, reverse velocity rotor, compound helicopter, rotor/wing transition helicopter.

I. INTRODUCTION

The ideas of rotorcraft can be traced back to early Chinese tops, a toy first used about 400 BC. In Italy, the Renaissance visionary Leonardo da Vinci’s sketch of the "aerial-screw" or "air gyroscope" device is dated to 1483 and it shows what is a basic human-carrying helicopterlike machine. In 1907, about four years after the Wright brothers' first successful powered flights in fixed-wing airplanes at Kitty Hawk in the United States, a French bicycle maker named Paul Cornu constructed a vertical flight machine that was reported to have carried a human off the ground for the first time. During the first thirty years in 20th century, several experimental rotorcrafts had come into being. From then on, the rotorcraft configuration had shown its diversity. Due to the trim problems, these early rotorcraft need to compensate antitorque among several rotors. Through continuous practice and cognition on the technical condition of the day, only the coaxial and tandem rotorcraft could survive. In Russia, the Russian Boris Yuriev had also tried to build an initial helicopter around 1912[1]. This machine had a looking like single main rotor with tail rotor configuration. Tail rotor torque in opposite direction can compensate the main rotor antitorque. This configuration had become the mainstream of rotorcraft, and 95% helicopters are of this layout. As an important branch of the aircraft family, nowadays tens of thousands of helicopters have been widely used in all fields. However, traditional configuration have their own limitations including forward velocity limit caused by advancing blade transonic shock and stall of retreating blade at high angle of attack in forward flight, vibration/ noise and ground or air resonance and bad riding qualities. In recent years, inventors have always tried their best to find solution schemes through changing rotorcraft configuration.

A look at patents of the rotorcraft configuration during the last 20 years shows inventors’ creativity and consideration about all kinds of rotorcraft configuration with new and original layout. Simultaneously, some professional aviation manufacture and research enterprises devote a plenty of resources to developing interrelated technology for the configuration evolution. From the traditional configuration (including the single main rotor with tail rotor, tandem rotors, side by side twin rotors, coaxial rotors and crossing rotors) to the new configuration (including ducted tail rotor, non-tail rotor helicopter, hingeless rotor, bearingless rotor, tilt-rotor, tip jet rotor, reverse velocity rotor system, the compound helicopter and rotor/wing transition rotorcraft), a series of patents and new technologies have been introduced in this paper. In some respects, it reveals the scientists’ effort to search the solution. As a significant reference about the development of future rotorcraft configuration, the introduction to new rotorcraft configuration can be helpful to other inventors and engineers for studies in depth.

Most related patents come from the databases in Ref. [2] established by European Patent Office sine1985, where most US, European, Japanese, French, Swiss, UK, Germany, WIPO (World Intellectual Property Organization) patents can be searched. In the preliminary searches, the nine key

*Address correspondence to this author at the Institute of Aircraft Design, Beijing University of Aeronautics and Astronautics, Beijing 100083, P. R. China; Fax: (86)(10) 82316100; Tel: (86)(10) 82339537; E-mail: yihuacs@yahoo.com.cn

1872-2121/07 $100.00+.00

words in the abstract were used as the search terms. These search items are ducted tail rotor, no tail rotor, hingeless rotor, bearingless rotor, tilt rotor, tip-jet, reverse velocity rotor, compound helicopter, rotor/wing transition. Title lists of nineteen (19), four (4), seventeen (17), nine (9), twenty-four (24), four (4), two (2), fourteen (14), and thirty-six (36) items are produced for the respective search terms. However, there are a lot of repeated patents in each list because one invention was ever filed in different country. Firstly, only tens of patents were fit for this subject after filtering. Secondly, patent title page illustrations are used to present some short description of patented inventions that may be of general interest. Thirdly, due to their complexity, the patented inventions would require extended amounts of descriptive text for introduction. In this review paper the main body arrangement is presented in the introduction, and researches for nine kinds of rotorcraft configuration are followed in the subsequent sections. Among all kinds of rotorcraft configuration mentioned here, six of them are classified as the other configuration because of their own unique characteristics.

II. DUCTED TAIL ROTOR

When the engine drives the main rotor rotating, rotor antitorque is created and it tends to cause helicopter body to rotate in a direction opposite to that of the main rotor. In order to overcome this antitorque, the conventional helicopter uses a configuration of one main rotor with one tail rotor. The tail rotor of a single main rotor helicopter is a small diameter rotary wing with the function of balancing the main rotor antitorque and providing yaw control, which is achieved through the action of the tail rotor thrust on a longitudinal arm about the main rotor shaft.

In order to keep the flight safety in low level or NOE (Nap of Earth) flight, a new antitorque system (i.e. ducted tail rotor) is adopted. Because the tail rotor is ducted, and this ducted tail rotor system can prevent the tail rotor blades from accidental contact with a passenger or other objects on the ground. Furthermore, in the flight near the ground, the ducted tail rotor blades are prevented from accidental contact with trees or buildings. As for the performance of ducted tail rotor, both the fan and duct can yield thrust. Thrust of the duct is generated through negative pressures developed on the duct inlet. Maximal thrust of the duct is about 50% of the total thrust generated by a ducted tail rotor. Furthermore, as compared with helicopter conventional tail rotors, ducted tail rotors have a higher aerodynamic efficiency, small size and high security.

In order to decrease an axial length of the duct, it is required to shorten a chord of the rotor blade. Therefore, in order to obtain a required total area of the rotor blades determined by the horsepower absorbing capacity of the tail rotor, the number of the tail rotor blades is necessarily increased. The number of the ducted tail rotor is generally 8 to 13. On the other hand, the higher the peripheral tip speed of the blade becomes, the better its performance becomes. The rotational speed of the tail rotor for small- and medium-size helicopters can reach 2,500 r.p.m. to 5,000 r.p.m.. High-frequency noises of 300 Hz to 900 Hz are generated because the tail rotor rotates at such high angular speed. The noise from the tail rotor is considered as the main source of the rotorcraft high frequency noise. In addition, due to its increased weight and complex structure, it is not convenient for maintenance.

Alain Vuillet [3] described a tail rotor with multiple blades located in a duct (Fig. (**1**)). Fixed radially-directed blades, located inside the duct downstream from the rotor, recover energy of rotation from the airstream at the outlet of the tail rotor, thereby increasing thrust produced by the rotor.

The arrangement comprises a plurality of fixed blades disposed inside of the tunnel, which generate a transverse air flow and recover, in the form of axial thrust, the energy of rotation of the air flow at the outlet of the rotor. The arrangement can increase the thrust of such a rotor that already exists, without increasing the power.

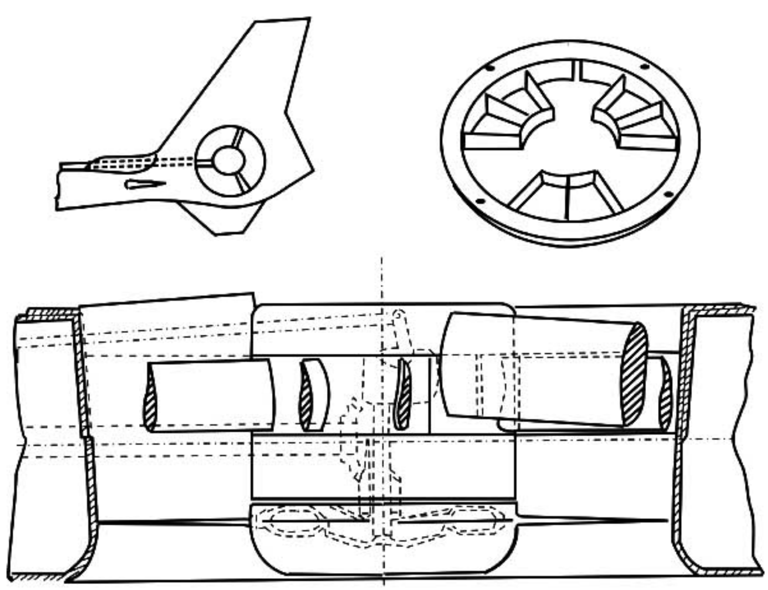

Fig. (1). Ducted tail rotor arrangement with increased thrust for rotary wing aircraft.

Mouille and Rollet [4] showed a helicopter tail rotor mounted in a transverse aperture formed in a fairing slanted with respect to the vertical by an angle between 0 deg. and 45 deg., and "V" empennage fixed to the top of the fairing. The two aerodynamic surfaces extend dissymmetrically with respect to the vertical plane passing through the top of this fairing (Fig. (**2**), Fig. (**3**)). The whole device can provide simultaneously the antitorque function and the static and dynamic stabilities of the aircraft about yaw and pitch axes. The faired antitorque rotor with 45 degrees slant participates in the general lift, and its power gain in steady flight is about 5%. In addition, "V" empennage can reduce the radar signature, which is advantageous for modern military helicopters.

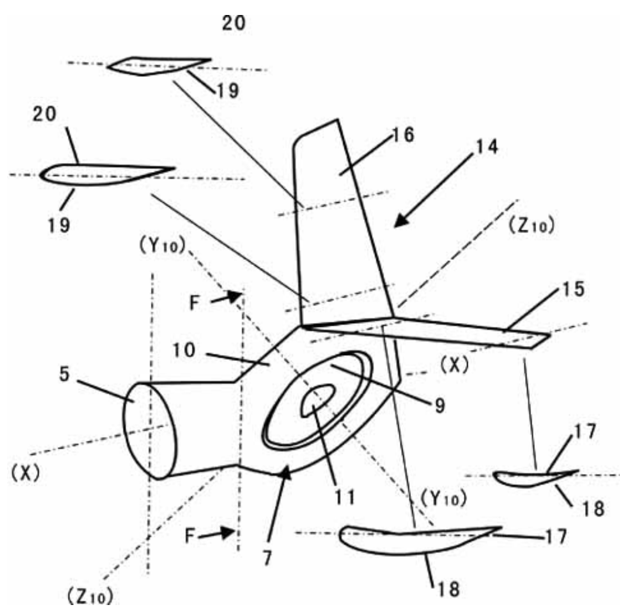

Fig. (2). Directional and stabilizing device having a faired and slanted antitorque rotor and "V" empennage.

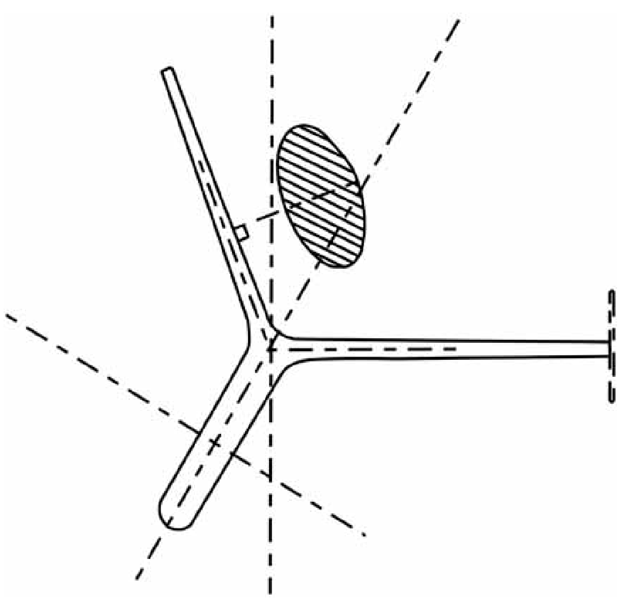

Fig. (3). Directional and stabilizing device seen from the front.

A new ducted tail rotor for rotorcraft was invented by Bandoh[5], which can sufficiently reduce a noise level without reducing the blade tip speed (that is, without deteriorating the performance) and without inducing a structural problem with the mounting of rotor blades, and in which a high-frequency sound is converted into a low-frequency sound.

In 1994, Desjardin [6] offered a ducted rotor with fewer blades than normally used to produce equivalent thrust. The drive scissors, rotating control ring, stationary ring, and bearing in the conventional rotor system, which mutually supports the ring for relative rotation, are not required in this invention. Instead, a unique assembly including a pitch beam and flexure extending from the pitch beam to each pitch shaft preferably converts axial movement to pitch displacement and eliminates the conventional pitch links. The tail rotors can produce aerodynamic thrust of variable magnitude to alter and stabilize the yaw position of the aircraft.

In 1996, Dequin [7] improved the counter-torque device for helicopter, which is similar to the Bandoh's design. The invention's characteristic is that its rotor is supported within the duct by a stationary flow-straightener with vanes connecting the wall of the duct to a central body housing the mechanism for driving the rotor (see Fig. (**4**)).

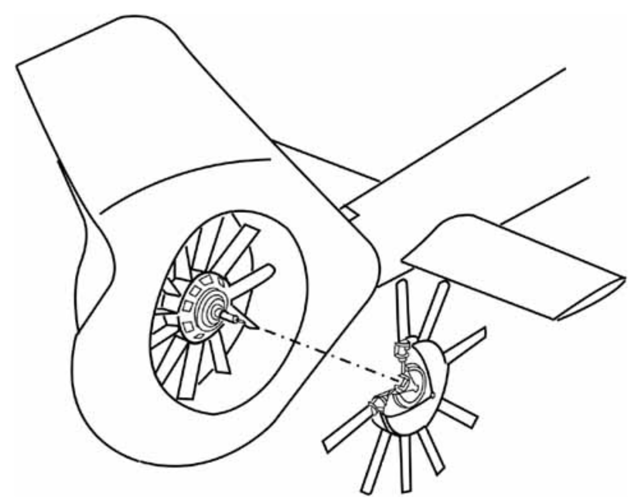

Fig. (4). Counter-torque device with ducted tail rotor and ducted flow-straightening stator, for helicopter.

At the same time, it introduces greater rigidity, which is not only an increased counter-torque thrust but a better natural frequency of the assembly enabling the level of vibration to be reduced. In addition, the greater rigidity is favorable to better coupling of the transmission arm to the rotational-drive mechanism. The improved counter-torque device facilitates the operations of maintenance, the removal and refitting of its assembly, and particularly interchangeability of the flow-straightener.

III. NO TAIL ROTOR

In addition to ducted tail rotor, NOTAR (No tail rotor) system is an anti-torque system, too. Although, tip-jet and coaxial helicopter may omit the tail rotor used for anti-torque balance, NOTAR helicopter antitorque forces are generated mainly from the main rotor downwash through the circulation control effect. Circulation control is an aerodynamic phenomenon in which the bulk flow around a body is deflected by a sheet of air ejected tangentially to the body surface. The deflection of the bulk flow causes a body force in the direction opposite the deflection. Successful force generation by circulation control depends upon many parameters including the strength of the tangential jet relative to the bulk flow, its location and direction, and its thickness. NOTAR mainly includes a variable pitch axial flow fan, a tail boom with longitudinal slots and jet cone mounted on the tail boom. The system has some advantages, such as small vibration, low noise, high maintainability and efficiency.

In 1980, Logan [8] described a kind of NOTAR system (Fig. (**5**)). The air with high pressure generated through a relatively low-pressure-ratio fan within the fuselage is discharged through the slots extending lengthwise along the tail boom. This airstream joins the downwash from the main rotor blades, so the circulation is formed. Circulation control provides the majority of the antitorque force in hover with the tail jet providing the additional trim anti-torque force as well as the maneuver force.

In 1990, Vanhorn [9] offered an improved system that increase the vortex generators in the longitudinal slots or nozzles which produce the circulation control portion of the system which combines with a jet thruster and fluid resource to replace the tail rotor (Fig. (**6**)).

The jet thruster in the tail boom is a sleeve valve assembly forming two concentric truncated cones. The inner cone is fixed and has openings to direct air either right or left. The outer cone rotates and has a constant area cutout. It can vary the jet's exit area to satisfy the requirements for both thrust magnitude and direction.

NOTAR system is popular in the helicopters produced by McDonnell Douglas Corp, such as MD-520N.

IV. HINGELESS ROTOR AND BEARINGLESS ROTOR

Articulated rotor hub was used in the traditional helicopter from 1940’s to 1960’s and its format become popular in the practice. The flapping, shimmying and feathering of the rotor can be realized by flapping hinge and shimmying hinge and feathering hinge on the hub. The disposal consequence for typical articulated rotor hub (from inner to outer) is flapping hinge, shimmying hinge and feathering hinge. Some flapping hinge and shimmying hinge are the same one. One method of burdening centrifugal pull

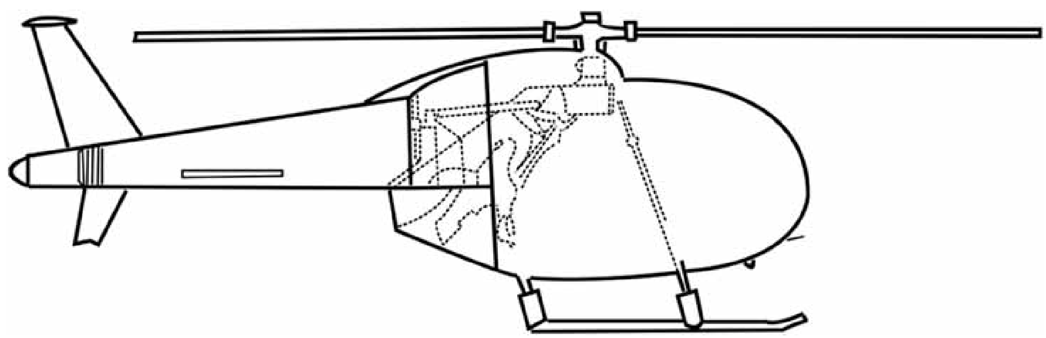

Fig. (5). US4200252 to no tailor rotor helicopter.

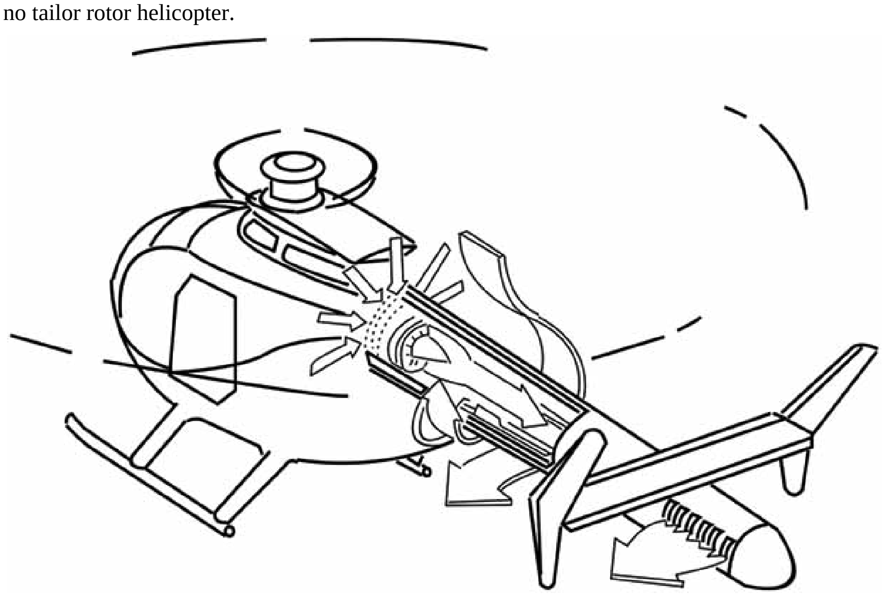

Fig. (6). US4948068 to no tailor rotor helicopter.

and feathering movement is the application of thrust bearing in axial hinge. The other one can use the elastic cell pull and twist shaft. The elasticity and torsion of the shaft must be equilibrated during feathering control, and for decreasing control force the shaft has a sufficiently low torsional rigidity.

There is a hub damper in the articulated rotor that provides the damp for shimmying movement, and it can avoid "ground resonance". But such rotor systems have a relatively complicated structure, a long maintenance time, a short fatigue life, a poor steering efficiency, and a small damp of angular rate. In order to overcome these limitations, the hingeless rotor system, such as BO-105 and WG-13 "Lynx", began to be studied in the beginning of the seventies of the nineteenth century.

The hingeless rotor system mentioned in preceding text had not flapping hinge and shimmying hinge, but still remained axial hinge for feathering. Therefore, It was not real "hingeless rotor". Because the feathering hinge bearing large moment and centrifugal pull and the structural weight were difficult to be lightened, the structural simplification was limited. In order to get rid of feathering hinge, a new rotor system, bearingless rotor system, was investigated. In bearingless rotor system, flapping, shimmying and feathering movement could be realized by the flexible element.

In this section, the patents about hingeless and bearingless rotor systems are described.

(1). Hingeless Rotor

The hingeless rotor comprises the following components: a rotor mast driven in rotation about an axis of the rotor, a hub secured in terms of rotation to the mast, at least two blades. In 1981, Weiland and Brunsch [10] studied a new hingeless rotor in which lift producing sections of the rotor blades are connected at their inner ends to a respective intermediate member (Fig. (**7**)). The intermediate members are flexible to torsional and bending loads and tension resistant, whereby the intermediate members allow blade angle movements as well as flapping and lead-lag movements. Hence, the helicopter with the hingeless rotor does not require any special rotor head, blade angle bearings, as well as flapping and lead-lag hinges. The hingeless rotor with shear resistant in the intermediate region of the support spar has an improved steering characteristics, and can operate a highly accurate, certain and safe steering behavior.

Buchs [11] offered a new hingeless rotor that has a sample structure (Fig. (**8**)). The objects of the invention are to precisely control the degree of the flexibility for the flapping movement and for the lead-lag movement, to keep the torsion stiffness in an advantageous low range and to make sure that the reset moment of the twisted cross-section of the connecting element in response to centrifugal force is as small as possible.

Another hingeless rotor equipped with a pitch-control device was invented by Legendre[12]. Pitch control is obtained by introducing reduced shear forces and moments into the torsionally rigid cuffs. The new system is reliable, durable, economical, both in terms of manufacture and in terms of assembly, and easier to maintain.

In 2000, Certain [13] built a mounting architecture of the laminated spherical support half-bearings of each oversleeve on the corresponding torsionable strip. It allows a decoupling between the operations of putting the two laminated half-bearings of each blade into compression and the operation of take-up of the pitch moment of this blade. Simultaneously, it allows an optimal sizing of the laminated half-bearings without removal of their central zone, which is essential for the take-up of the flapping forces, and their mounting in an easily accessible structure and limiting the number of parts, and allowing in this way savings in manufacturing, mounting and maintenance.

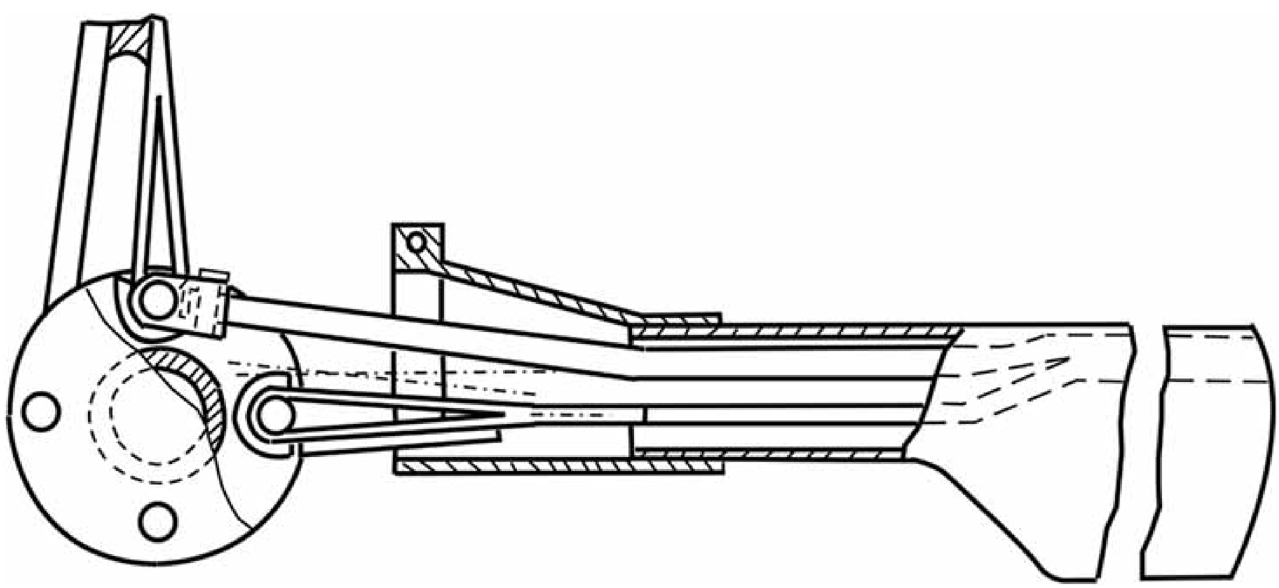

Fig. (7). US4292009 to hingeless rotor.

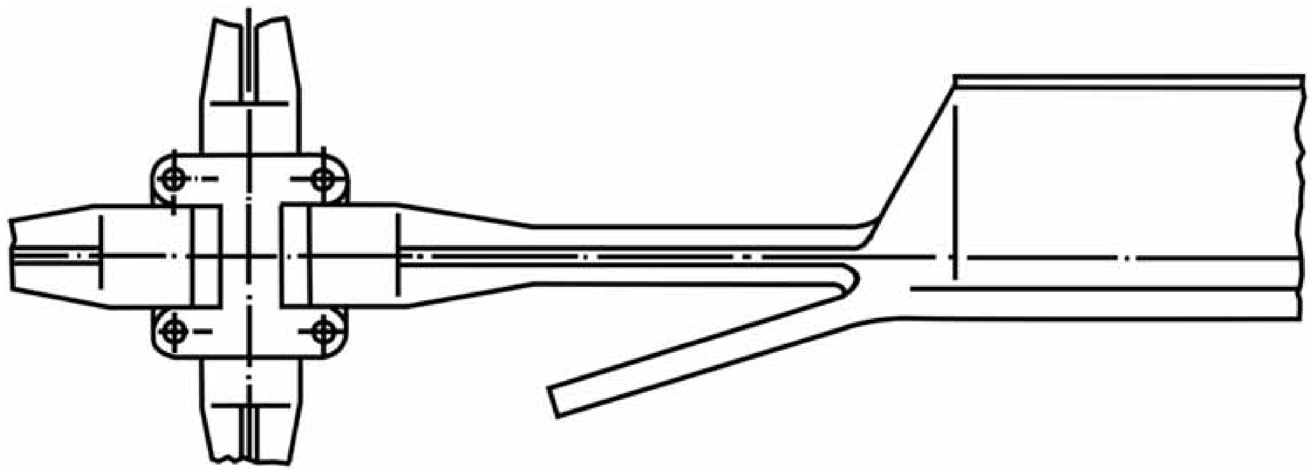

Fig. (8). Improved hingeless rotor.

(2). Bearingless Rotor

Bearingless rotor is more advanced rotor system that allows the elimination of the rotor hinges. This advance has been largely made possible by the introduction of the fiber-reinforced resin-matrix materials, which allows the stiffness properties of the rotor blade root adjacent its attachment to the rotor hub to be adjusted to suit certain optimal and desired values. Rotors having these properties are characterized by being relatively flexible in the in-plane and normal-plane bending sense and relatively stiff about the other axes and senses of structural displacement.

In 1982, Desjardins [14] invented a bearingless rotor system (Fig. (**9**)) that comprises a rotor blade that terminates at its inboard root in a bolted attachment, which joins the blade to a radially extending strap member. The strap is generally formed of fiber-reinforced composite resin-matrix materials and has its structural stiffness and strength properties arranged to satisfy particular functional requirements.

In 1985, Sampatacos [15] offered a scheme for an improvement of bearingless couplings between the blade and rotor hub. The improvement includes a planar elastic flexure which has at least a pair of elastic elements disposed between the blade and hub. The bend in each element is W-shaped, the extended ends of which are coupled between the blade and hub (Fig. (**10**)).

In 2000 and 2001, Bauer [16,17] invented two kinds of rotor blades for bearingless rotor systems, in which the first one provides particularly a separable or releasable junction between an airfoil blade and a flexbeam to allow the quickest and easiest possible folding of the rotor blade, and the other offers a simpler and more economical arrangement of damping elements in connection with a rotor blade.

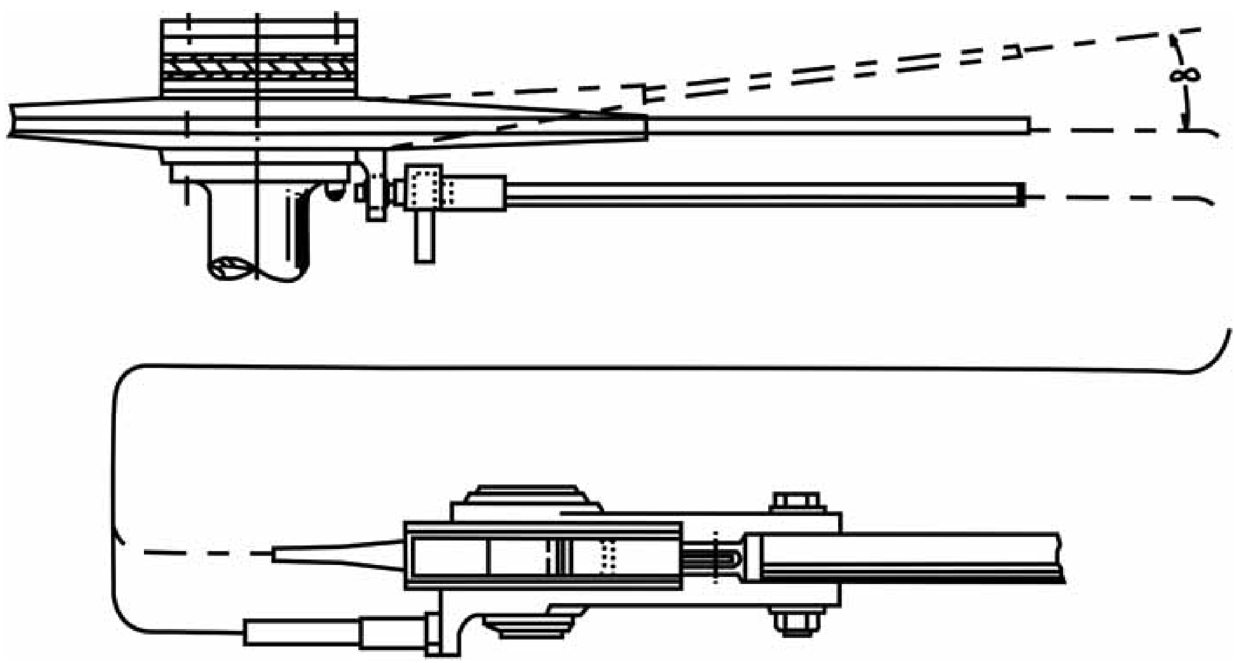

Fig. (9). Bearingless rotor.

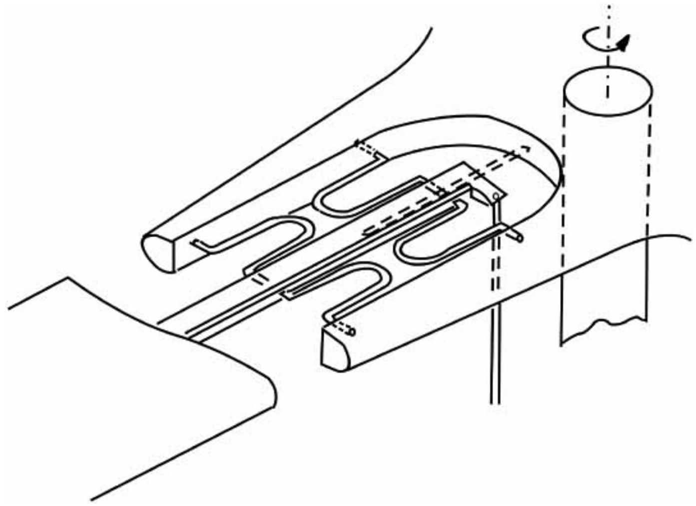

Fig. (10). Low drag, bearingless rotor head.

V. TILT ROTOR

Tilt rotor aircraft is a hybrid flight vehicle of traditional helicopter and traditional propeller driven aircraft. Typical tilt rotor aircraft has the fixed wings that terminate with convertible tilt rotor assemblies that house the engines and transmissions that drive the rotors. Therefore, tilt rotor aircraft has a forward velocity of the fixed-wing aircraft and a capability of taking-off, hovering, and landing like a helicopter. Simultaneously, comparing with the helicopter with same horsepower, the propeller driven fixed-wing airplane has a better transportation efficiency and aerodynamic quality, which prolong the air range. The most successful example of the tilt rotor is V-22 “osprey”.

The propellers can tilt about a pivot axis on a respective fixed wing, each of which is connected by a respective transmission to a respective engine supported by the corresponding wing, an inter-connecting shaft linking the two transmissions in order to drive the two rotors. However, the tilt rotor aircraft has its own shortcomings caused by the complex structural features and the aerodynamic and aero-elastic features. The structural aspects are essentially relating to the complex structure of a forward-swept wing as well as the fuel tank. The other ones are related to the fact that aerodynamic centre of a forward-swept wing is shifted forward at high angles of incidence in flight, which tends to destabilize the aircraft, on the other hand, the fact that the forward sweep tends to amplify what is referred to as "stall flutter", which may mean increasing the rigidity of the fixed wing system on this aircraft, thereby increasing the mass. During recent years, the improvements about the tilt rotor system were invented in succession.

Hager [18] built a new Variable Diameter Rotor (VDR) system for tilt rotor in 2000 (Fig. (**11**)). In hovering flight, VDR system is generally advantageous to employ a large diameter rotor to improve hovering performance by lowering disk loading, reducing noise levels, and reducing downwash velocities. Conversely, a relatively small diameter rotor is desirable in forward flight to improve propulsive efficiency by minimizing blade aero-elastic properties, minimizing blade area, and reducing tip speed (Mach number). Furthermore, when the plane of the rotor is oriented horizontally, the rotor diameter is enlarged for the improved hovering efficiency and, when oriented vertically, the rotor diameter is reduced for the improved propulsive efficiency. In the invention, a drive system for a variable diameter rotor system includes a main rotor shaft and a plurality of rotor blade assemblies with inner and outer blade segments.

Balayn [19] offered an improved tilt rotor aircraft. Its each transmission has a reduction gear unit which pivots with the corresponding rotor and is connected to a non-pivoting reduction gear rotor, in turn linked to the inter-connecting shaft as well as to the corresponding engine fixed to the corresponding wing (Fig. (**12**)). In this invention, fixed wings are the wings with a zero sweep, on each of which the inter-connecting shaft is substantially rectilinear and substantially parallel with the pivot axis but offset from said pivot axis substantially perpendicular to a longitudinal axis of symmetry of the aircraft.

In 2002, Krysinki [20] proposed a modification scheme including active control of vibrations and avoiding the significant additional masses for decreasing the excitations caused by the rotors and controlling easily roll in airplane mode. The invention simplifies the maneuvering and command means for controlling, and gives them the ability to land in airplane mode (without converting beforehand from airplane configuration to helicopter configuration). This possibility can make it descent in airplane mode and in gliding flight and to land without having to tilt the rotors into helicopter mode.

In 2002 and 2005, Roger [21,22] offered a single-tilt-rotor VTOL (vertical take-off and landing) airplanes (Fig. (**13**)) and its followon, in which large diameter helicopter-type of rotor is used for vertical lift and a small tail rotor provides antitorque. The large rotor is attached to an elongated power pod containing the collective and cyclical pitch mechanism, transmission, and engine. It may be tilted 90 degrees forward to provide horizontal thrust during cruising flight when airplane is supported by conventional wing. In term of safety, a twin tiltable-rotor VTOL airplane cannot be as safe as a single tiltable rotor design. Another

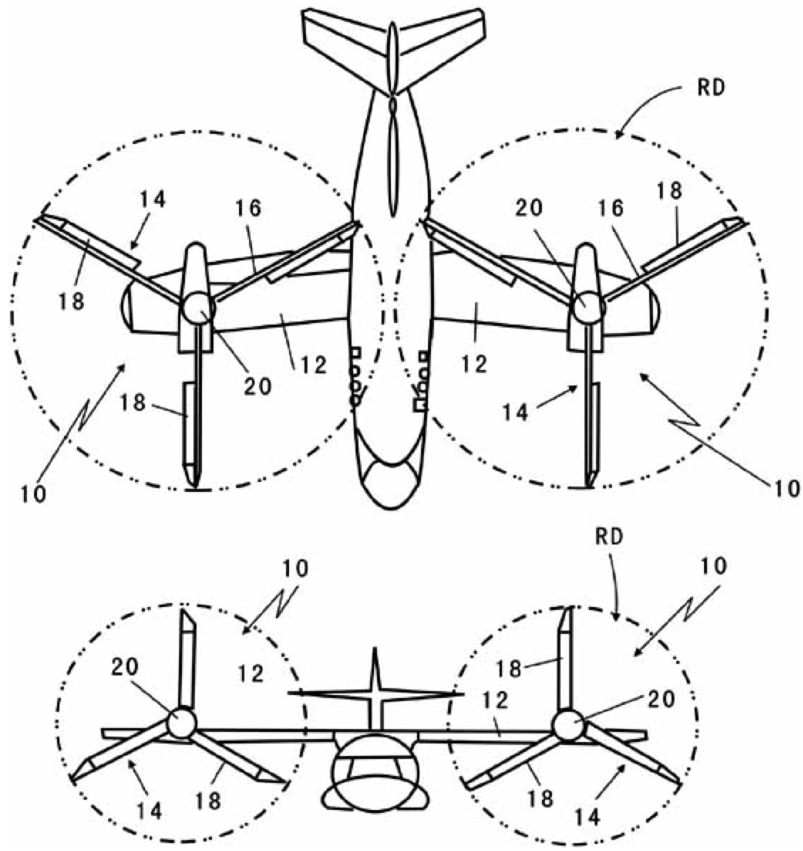

Fig. (11). VDR system.

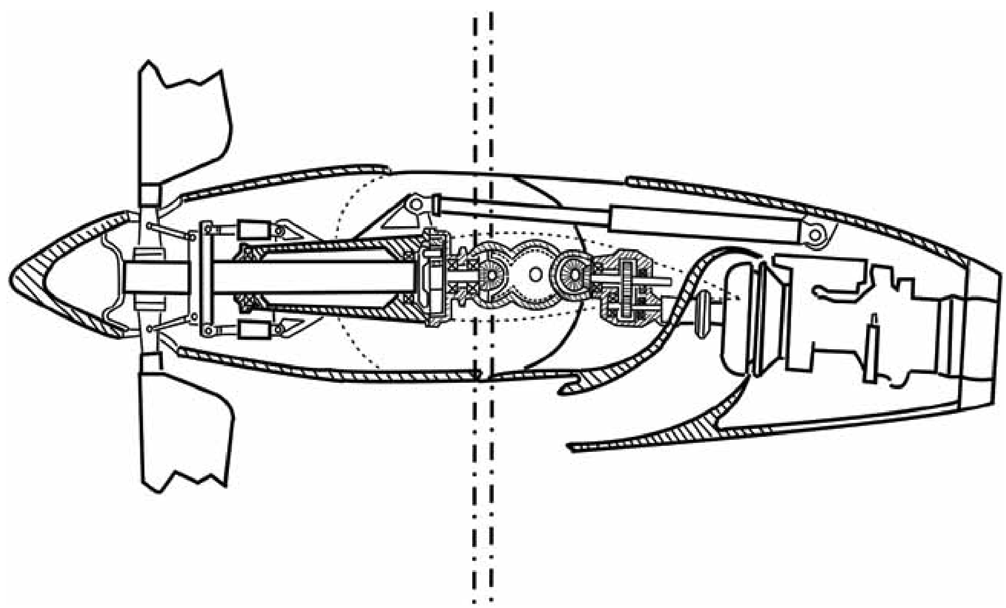

Fig. (12). Tilt rotor pod.

disadvantage of a twin-tilt-rotor airplane would be the necessity of using computer stability augmentation system in the VTOL mode, while a single rotor helicopter due to its large diameter thus more dynamic stability, can be controlled by a trained pilot without requiring stability augmentation system, thus has been proven to be much cheaper and more reliable.

In his improvement, 4-blade propeller (see 12 in Fig. (**14**)) for horizontal propulsion is mounted in the rear of the cabin. It is of variable-pitch design capable of zero pitch during the hovering mode and is featherable for maximum gliding efficiency in case of engine failure. In the horizontal cruising mode, the tiltable rotor can rotate slowly at a minimum rotational speed necessary to maintain the integrity

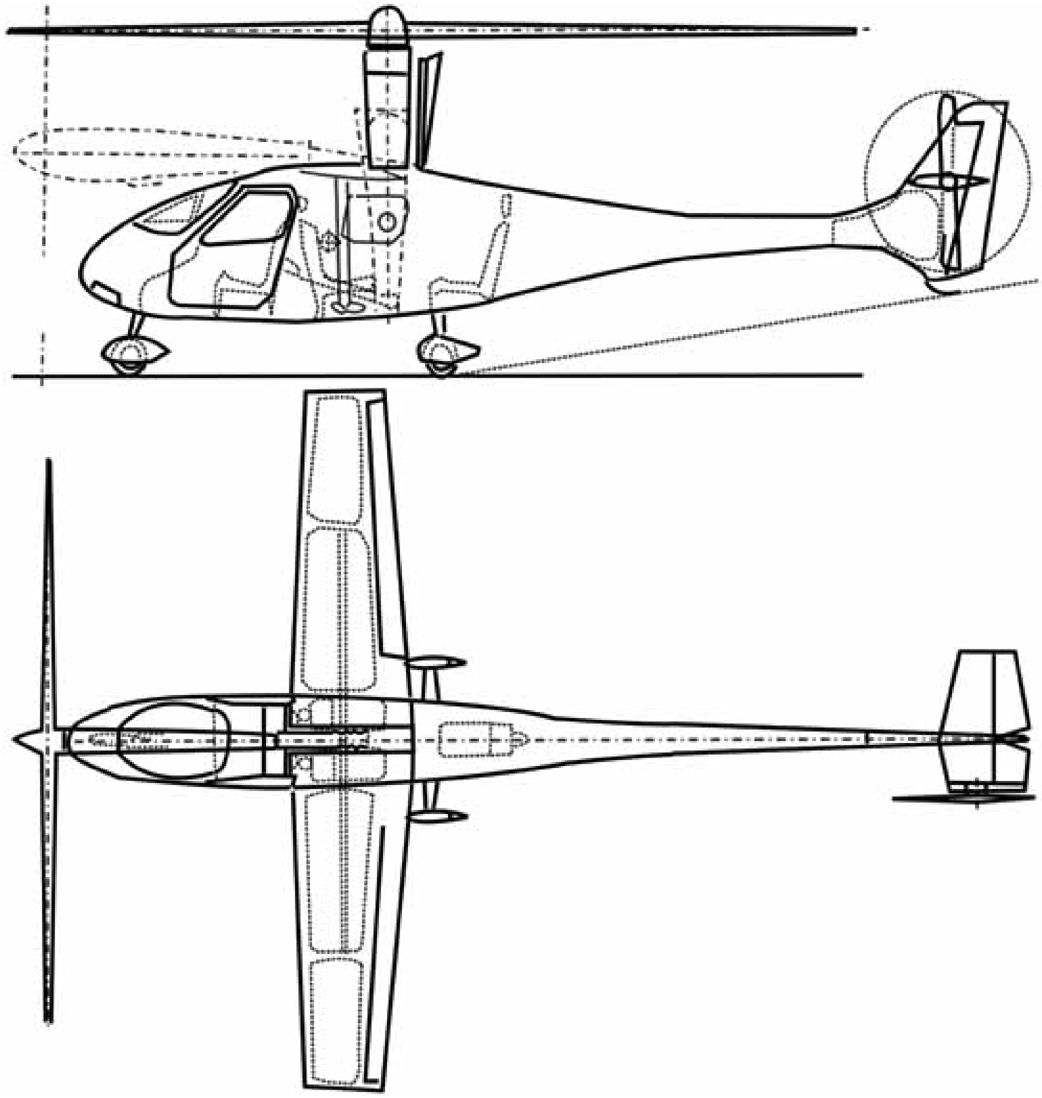

Fig. (13). VTOL airplane with only one tiltable prop-rotor.

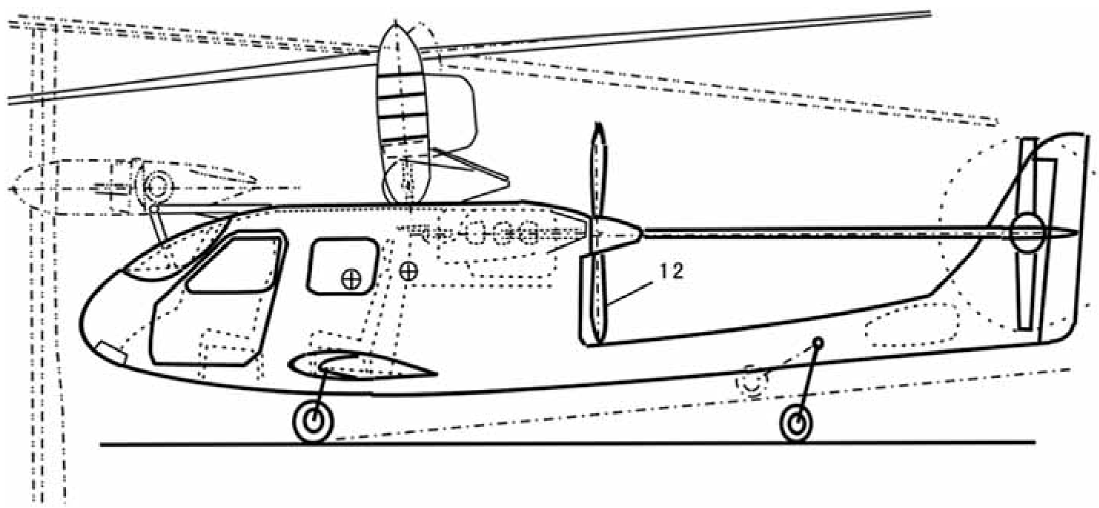

Fig. (14). US 2005045762 to the improved VTOL airplane.

of the rotor blades. A pair of high-aspect-ratio wings on both sides of the fuselage provides highly efficient lift during cruising flight with very little induced drag. Conventional horizontal and vertical tail planes are used for directional stability in the cruising mode.

In addition, Mackay [23] presented the boundary layer control device for tilt rotor configuration and Fenny [24] gave a method and apparatus for sensing preload in a tilt rotor downstop.

VI. TIP-JET HELICOPTER

In order to rotate the main rotor, conventional helicopters utilize a piston engine or a turboshaft engine having a rotating shaft mechanically linked to the rotor. The power is transmitted from the engine to the main rotor as a driving torque. This driving torque induces a fuselage torque that has the same magnitude as the driving torque, but is of opposite direction. To compensate for the induced fuselage torque, a compensation torque, created by the tail rotor of the helicopter, is applied to the fuselage of conventional mechanical helicopters. The compensation torque produced by this tail rotor is a function of the speed of rotation of the tail rotor, of its pitch and of the distance between the shafts of the main rotor and tail rotor.

Differing from the conventional driven system, tip jet driven helicopter uses the power of gases discharged through the tip of the blades of the rotor to impart rotating motion to the rotor. No torque is transferred from the fuselage to the rotor. Therefore the tail rotor may not be needed and drive system has a considerably simpler construction. Indeed, the tail rotor is a major cause of accidents and it adds complexity to the helicopter drive system. As a consequence helicopter is lighter. At the same time, some disadvantages arise from the utilization of tip jet. One major shortcoming is the low efficiency of its drive system. However, the lightened weight compensates this deficiency.

In 1950's, some commercial tip jet driven helicopters had already constructed and put into service, such as Fairey Rotodyne. In 1996, Milot [25] introduced a new tip jet driven system (Fig. (**15**)), whose efficiency can be comparable to the power transmission efficiency of mechanical helicopter with same payload. The drive system comprises a combustion engine with a hot gas exhaust outlet, air compressor connected to the combustion engine, and a rotor blade assembly including a hollow rotor hub and at least two hollow rotor blades.

Except that the compressed gas from combustion engine drives the rotor, rocket parts on wing tips can be used to generate thrust force. Japanese inventor Taga [26] invented wing tip jet gyrocopter. Rocket parts 2 on wing tips generate thrust force due to combustion of mixture composed of fuel and compressed air mixture, the lift can be obtained through rotation of rotary wings 3 due to the thrust force. As a single-seated helicopter, it is cheaper than the other type and its structure is shown as a sample (2,3 in Fig. (**16**)).

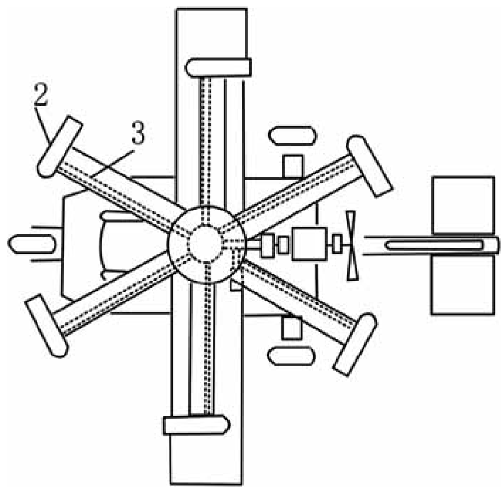

Fig. (16). Wing tip jet gyrocopter.

The recent patent improves its driven system further. A hybrid engine where the combination of ram compression and compressed air is provided by centrifugal compression is used in a helicopter rotor tip jet or for other applications. As a small two-seated ram jet power helicopter, Hiller model HJ-1 Hornet, became the first ram jet power unit to be certified in the United States and also the first C.A.A. (Civil Aviation Authority) approved tip mounted power plant.

However, tip mounted ram jets has not proven to be very useful because the ram jet is inefficient at the speeds that can

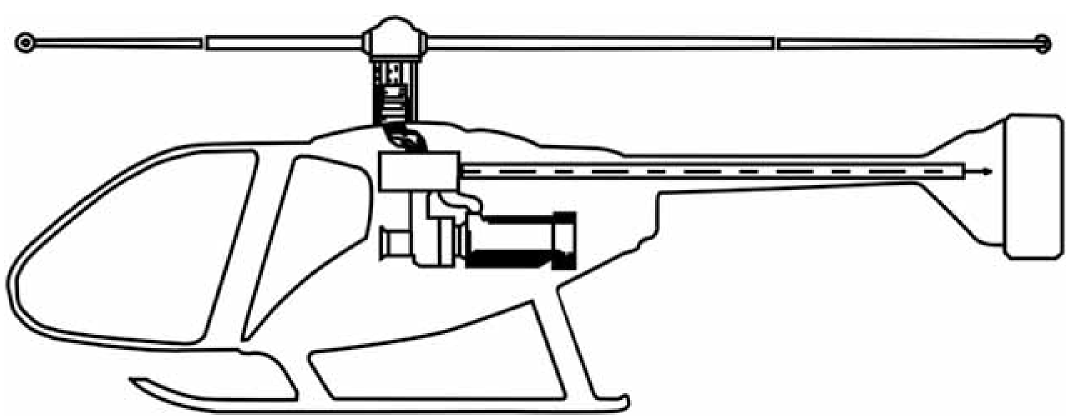

Fig. (15). Combined cycle compressed air tip jet driven helicopter.

be achieved at the tip of the blade. The speed is limited from strength and shockwave standpoints. The problem is that the ram compression has not the enough impact pressure. Greene [27] offered some means for injecting compressed air to overcome the problems. Its example is shown in Fig. (**17**).

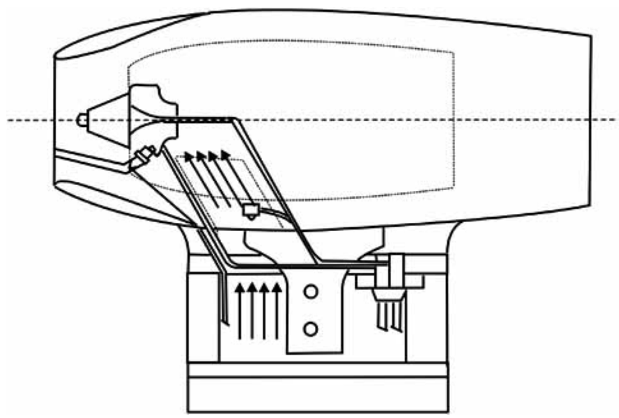

Fig. (17). Centrifugal air flow and fuel lines for supplying fuel and added air to a ram jet engine.

VII. REVERSE VELOCITY ROTOR

The forward speed of a conventional helicopter is limited by a number of factors. Among them one is the tendency of the retreating blade stall at high forward airspeeds. As the forward airspeed increases, the airflow over the retreating blade slows down, thus the blade may approach a stall condition due to the increase of angle of attack. In contrast, the airflow velocity across the advancing blade increases with increasing forward speed, which may lead to unstable. Accordingly, blade flapping and feathering means are normally used to equalize lift.

Thus, as the airflow velocity over the retreating blade decreases with increasing forward airspeed, blade flapping and feathering increases the angle of attack of the retreating blade and decreases the angle of attack of the advancing blade so as to tend to equalize lift throughout the rotor disc area. However, as the angle of attack of the retreating blade is increased further, the retreating blade approaches a stall point for a given forward airspeed.

To avoid the retreating blade stall, the rotor should be speeded up. However, when this is done the advancing blade encounters progressively higher velocities, approaching a maximum blade velocity with the accompanying power loss due to compressibility Mach number effects.

Thus, operation near the stall point on the retreating blade and near the maximum speed on the advancing blade causes the following adverse effects: (1) severe vibrations of the helicopter and controls, (2) large increase in profile-drag power requirements, (3) compressibility Mach number problems on the advancing blade, (4) sharply increased power requirements to increase speed of rotor revolution, (5) imbalance of lift between the retreating and advancing blades that causes serious rotor dynamic problems which adversely affect the blade flapping operation and the sensitivity of the blade control mechanism. In general, the control, stability and performance of the entire aircraft become impaired as the helicopter approaches its maximum forward airspeed.

In 1975 Lemont [28] disclosed the concept of the reverse velocity rotor in detail. The reverse velocity rotor can be provided for a helicopter and helicopter rotor system that substantially increases the maximum speed of helicopters, while materially reducing the above-described adverse effects normally encountered by conventional helicopters. This object can be accomplished by varying blade pitch throughout the revolution of the rotor blade, and it generates uniform positive lift in both the advancing and retreating sector of blade travel.

The reverse airflow produced across the retreating blade by the high forward speeds of the aircraft is used to generate positive lift in the retreating blade sector of rotor operation. The reverse velocity effect may be increased either by increasing the airspeed of the aircraft or by lowering the rotational speed of the rotor. Also the use of reverse airflow lift in this manner permits the use of shorter, higher solidity ratio rotors.

The reduction of rotor RPM (revolutions per minute) and rotor length also reduces the effect of compressibility Mach number problems encountered by the advancing blade. As a result, lower vibration and noise levels are encountered. Furthermore, rotor and blade dynamic problems are lessened because of the greatly reduced flapping motion and absence of blade stalling. Since blade flapping aerodynamic damping does not decay with increased flight speeds, as with conventional rotor operation, longitudinal blade sensitivity problems are avoided. Thus, the limitations of conventional helicopters and helicopter rotor systems referred to above operation are avoided by the invention of reverse velocity rotor.

In addition, the reverse velocity rotor markedly improves the rotor L/D (lift/drag) ratio. As a result the range, load capacity and airspeed of the helicopter can be substantially increased.

In the invention, a rotorcraft with reserve velocity rotor (Fig. (**18**)) is designed. The pitch of the rotor blade is controlled by a two/rev. (twice-per-revolution), cam, or higher order pitch control input rather than by the conventional one/rev. input. In so doing, the sinusoidal peaks of the angle of attack variation between the advancing and retreating blades that occur with the one/rev. input are substantially reduced. Thus, cyclic pitch inputs of a properly phased one/rev. and two/rev., of a cam, or higher order are combined so as to provide the optimum blade pitch and blade angle of attack through the advancing and retreating blade sectors of rotor travel.

In addition, a short blade radius, high disc loading and high solidity ratio rotor having an airfoil shape which is adapted for reverse velocity lift is disclosed. This rotor is designed primarily for achieving optimum lift at low RPM at relatively high forward airspeeds. At hovering speeds additional lift devices such as slotted flaps or boundary layer control mechanisms may be provided to produce the

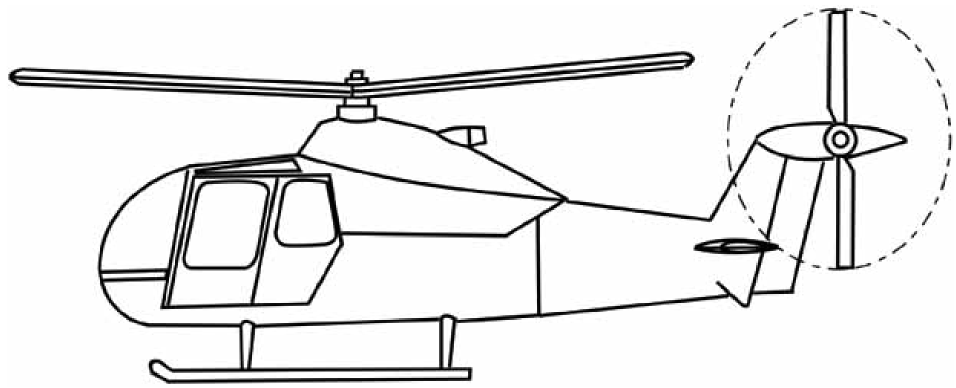

Fig. (18). US3924965 to the reverse velocity rotor.

additional lift required for the hovering operation. These auxiliary lift mechanisms are phased out of operation as increased airspeed permits.

Another feature of this invention is the use of an auxiliary twistable tail rotor so as to provide additional forward propulsion power and thereby improve lift generation by forward airspeed.

And in the following patent, Verrill [29] designed a similar design introducing reserve velocity rotor. This invention can provide an improved rotor construction for obtaining two/rev. or higher harmonic blade pitch control of helicopter rotors. Furthermore, the helicopter speed increase relies on mixing two/rev. control motion with one/rev. cyclic and collective motion through mechanical summation.

In 2001, NASA [30] designed a new rotorcraft with reserve velocity rotor system (Fig. (**19**)). The vehicle is composed of a fuselage with a ducted propfan auxiliary propulsion system located at the rear. Horizontal and vertical vanes located in the duct aft of the propfan provide thrust vectoring for lateral and longitudinal stability in forward flight and for anti-torque in hover and low speed flight. An eight-bladed articulated rotor provides vertical lift for the configuration. The flight control system provides collective and cyclic control, as well as higher harmonic cyclic control through an Individual Blade Control (IBC) system. Three turboshaft engines provide power for the configuration. Results of the study indicate that a reserve velocity rotor concept vehicle with speed excess of 300 knots is feasible.

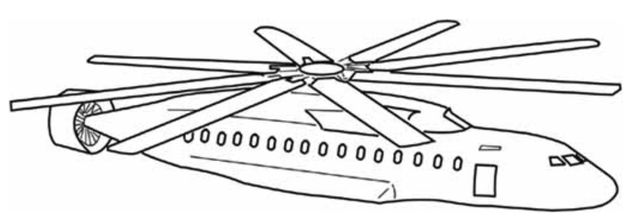

Fig. (19). NASA new rotorcraft with reserve velocity rotor system.

VIII. THE COMPOUND HELICOPTER

The compound helicopter is different from the conventional helicopter. It is requested to perform forward flight at high speed, simultaneously, and it is capable of the VTOL and hover, too. Therefore, the compound helicopter is a hybrid helicopter.

In 1986, John [31] invented a compound helicopter and its powerplant shown in Fig. (**20**). From the figure, wings 12 are added to a helicopter rotor, and a variable area final propulsion nozzle that receives the exhaust from the power turbine. Augmenter wing flaps 28 are provided on the wings and fed with air from a low pressure compressor for providing additional lift and thrust from the wings. Thus, the helicopter can take off vertically with only a very minor part of the energy. Any remaining energy could be directed to provide still further lift.

At very high speeds it will be impractical to tilt the rotor or pitch the nose of the helicopter upwards in the conventional way because the aerodynamic loads on the main lifting rotor would be too high. Decelerating the forward speed is a problem. In the invention, these flaps (see 28 in Fig. (**20**)) can move into the ambient airstream, the aircraft could be decelerated.

Zuck [32] offered a compound helicopter with no tail rotor, its tail rotor become a propeller used only for forward thrust in the rear part. The differential movement of the ailerons on the wings can control direction of the helicopter in hovering and to provide antitorque forces to counter the lifting rotor torque (Fig. (**21**)). A similar wing was invented by Simpson [33] in 2004 and can compensate for acting on the helicopter (Fig. (**22**)).

Balmford [34] presented a compound helicopter with engine shaft power output control. It includes a main rotor for hover and low speed flight, a propeller to provide the propulsion for the higher speed flight, and an engine (Fig. (**23**)). The propeller is mounted in a duct and a plurality of vertical vanes in the propeller slipstream can provide control surfaces to control forward flight direction and provide antitorque control when hovering.

In 2005 Loper [35] invented a compound helicopter. In this patent, a conventional helicopter is modified with a nose-mounted tractor propeller to provide thrust for forward flight (Fig. (**24**)). Wings are added to provide lift during forward flight. With the propeller providing thrust and the wings lift during forward flight, the helicopter rotor blades are unloaded during cruising flight to allow increased

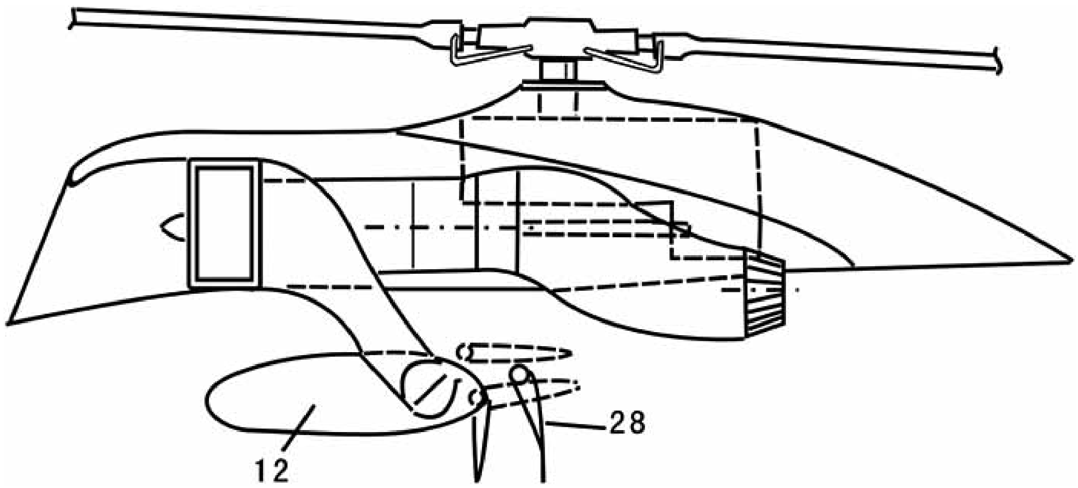

Fig. (20). US4610410 to compound helicopter.

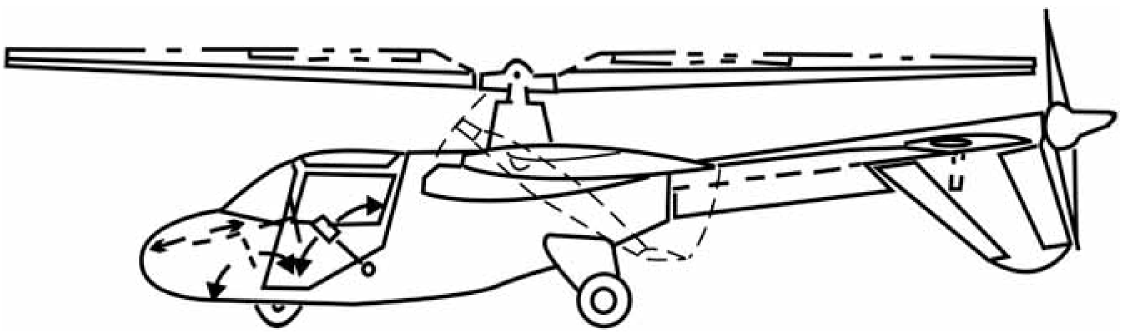

Fig. (21). US4928907 to Compound helicopter with no tail rotor.

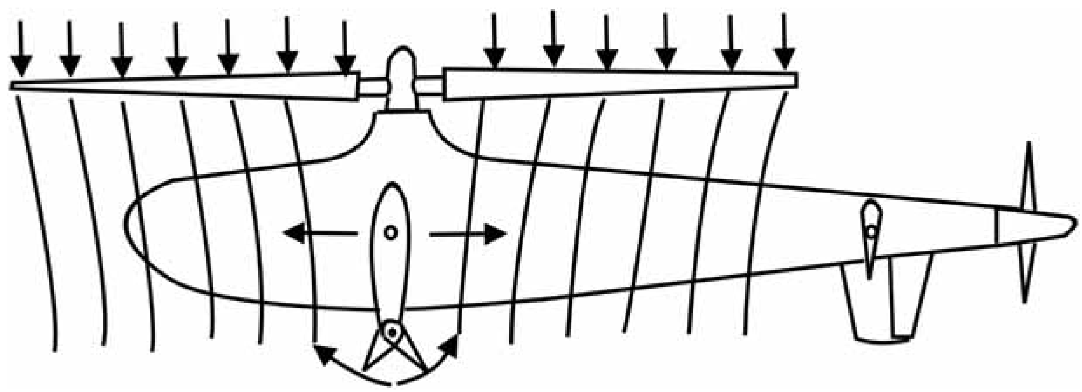

Fig. (22). Wing ailerons producing anti-torque and directional control forces.

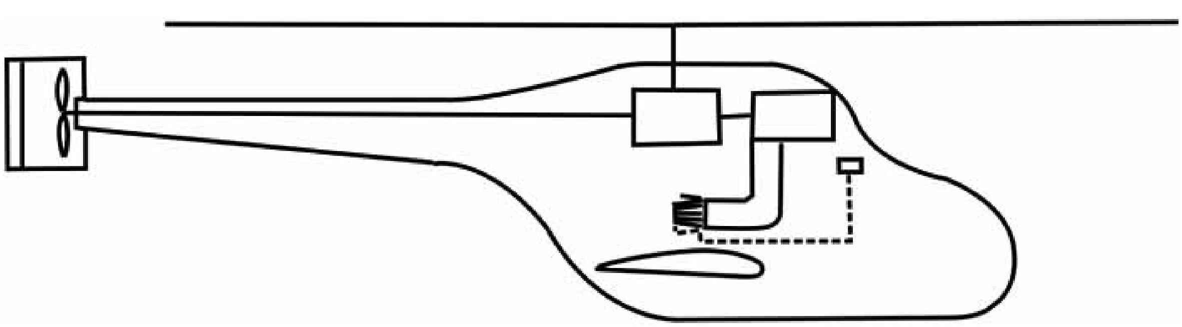

Fig. (23). The compound helicopter with engine shaft power output control.

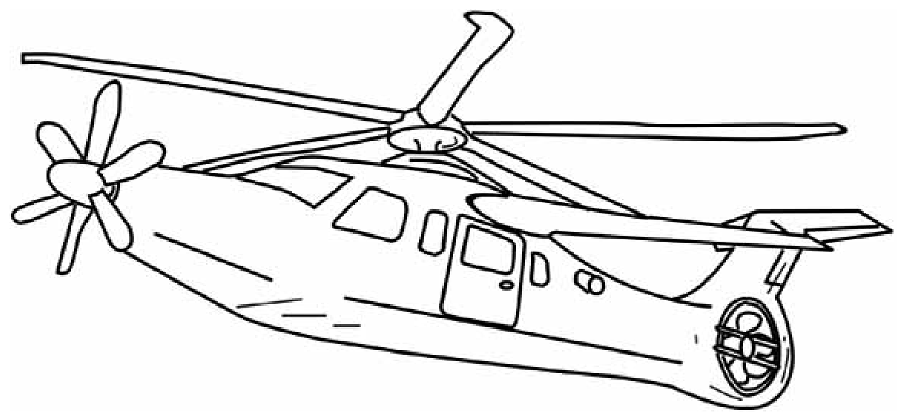

Fig. (24). US2005151001 to compound helicopter.

forward speed by avoiding limitations of conventional helicopters, including retreating rotor blade stall and maximum rotor blade tip speeds. A single powerplant drives both the main rotor and the nose-mounted propeller. The compound helicopter employs high aspect ratio wings with large flaps that may be extended to reduce vertical drag during vertical flight and hovering operations.

IX. ROTOR/WING TRANSITION ROTORCRAFT

Conventional helicopters have high hovering efficiencies due to their low-disk-loading, but forward speed is limited to about 250 miles/hour. Speed is limited by the advancing (upwind) rotor blade tip speed, which cannot approach or exceed the speed of sound without incurring unacceptably high drag. Rotor/wing transition rotorcraft designs attempt to have both qualities: efficient hovering and high-speed forward flight. During the lifting or hovering mode rotor/wing transition rotorcraft are driven by one or more rotors, like a helicopter. But during forward flight in certain height it flies by the wing, like a fixed-wing plane. In some places, it resembles the tilt-rotor rotorcraft, whereas, its rotors is fixed in the fuselage.

Early in 1974, Girard [36] offered VTOL Rotor Wing Drone Aircraft. It is capable of vertical take-off and landing and high speed cruising flight, which utilizes a combined rotary and fixed wing. The wing has a large center body with three radial arms. They are pivotal and controllable in the manner of helicopter rotor blades in the wing rotating operation, and incorporate spoilers to minimize center of pressure shift during transition between rotary and fixed modes. In fixed position the wing is stopped with one arm forward in a modified delta configuration, the lateral arms being movable for roll control in cruising flight. Propulsion is by means of a turbojet providing cruising thrust and also wing rotating thrust through tip nozzles in a beam 54 mounted below the wing. In stopped position, the beam is streamlined in alignment with the forward arm, and for rotary wing mode the beam rotates relative to the wing to clear the movable arm. Gas produced by turbojet engine is conducted to nozzles at opposite ends of the beam, which provides rotational power for the wing. In the forward flight, the thrust power is driven from exhaust gas out of the tailpipe (54 in Fig. (**25**), Fig. (**26**)).

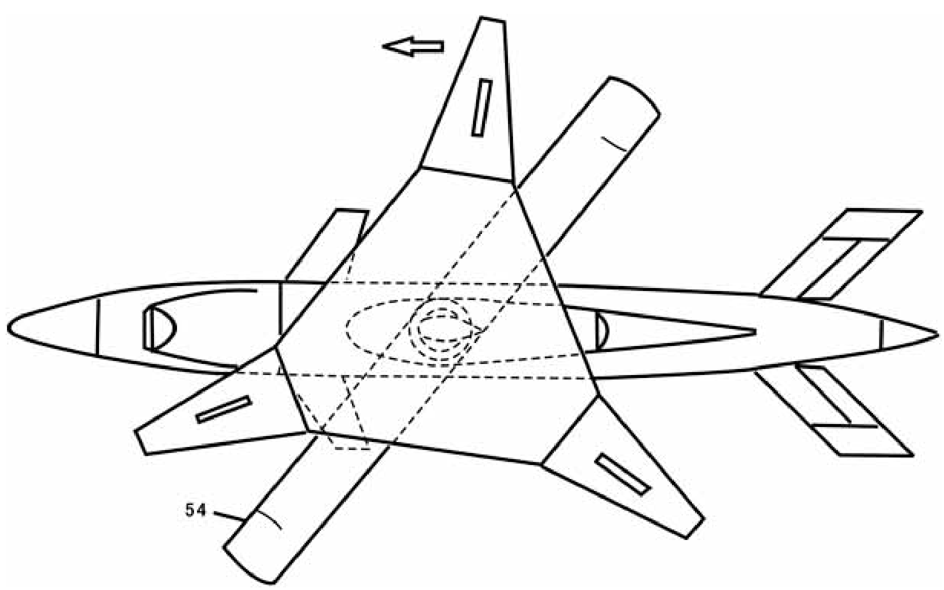

Fig. (25). VTOL rotor wing drone aircraft.

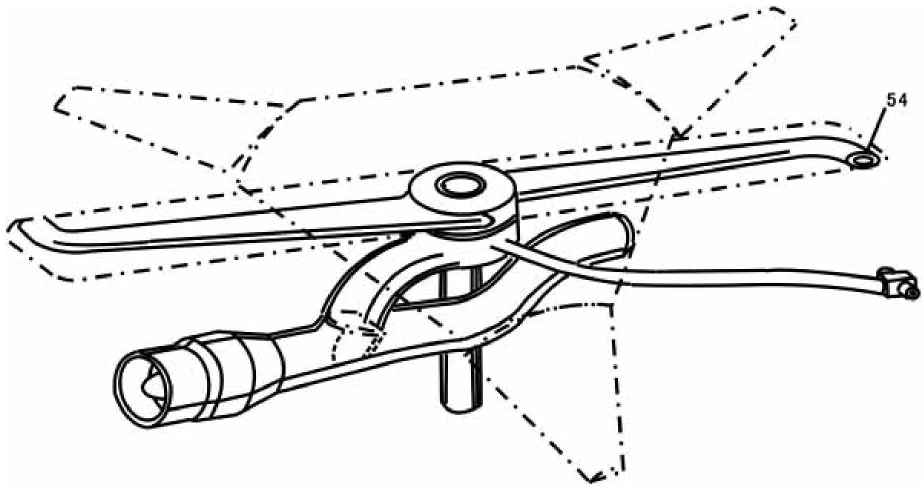

Fig. (26). Perspective view of the propulsion system.

In 1974, the origin of the X-wing rotorcraft was provided by Girard [37], named as VTOL Aircraft with cruciform rotor wing (Fig. (**27**), Fig. (**28**)). The aircraft can be configured for various uses, but is particularly adaptable to use as a small remotely piloted vehicle (RPV), or drone. Similarly, a diverter valve directs exhaust gases from the turbojet tailpipe, either to the nozzles for wing rotation power, or to a rearwardly directed cruise propulsion nozzle. The wing has a center body with four radial arms in a cruciform configuration, the tip portions of the arms being pivoted about radial axes to vary their pitch angle in the manner of helicopter rotor blades. In fixed wing position the wing is locked with two arms longitudinal to the fuselage and the other two extending laterally. The nozzle housing is streamlined along the top of the pylon in stopped position. To slow down wing rotation in transition from vertical to cruising flight and stop the wing in proper alignment, the tip portions may be provided with selectively operable air brakes. A portion of the exhaust gas is diverted to a nozzle assembly for directional control at low speed and for power modulation of the rotating wing without the need for excessive use of engine speed adjustment.

Subsequently, Girard [38] described a new rotor/wing transition rotorcraft, entitled aircraft with Retractable Rotor Wing (Fig. (**29**)). Similarly, its power with direct thrust for the forward flight is provided through a turbojet engine. For rotary wing drive, the jet exhaust is diverted to a rotating drive beam having tip jets for propulsion, the drive beam being mounted on the opposite side of the airframe from the wing. The separation avoids aerodynamic interference between the wing and the drive beam, and keeps the hot exhaust gases clear of the rotating wing mounting and its associated control system. The drive beam is coupled to the wing by a telescopic drive shaft within the wing supporting mast. In the fixed wing position, a folding landing gear 22 is stowed longitudinally in the airframe and enclosed by doors for minimum drag (see 22 in Fig. (**30**) Fig. (**31**)). On the

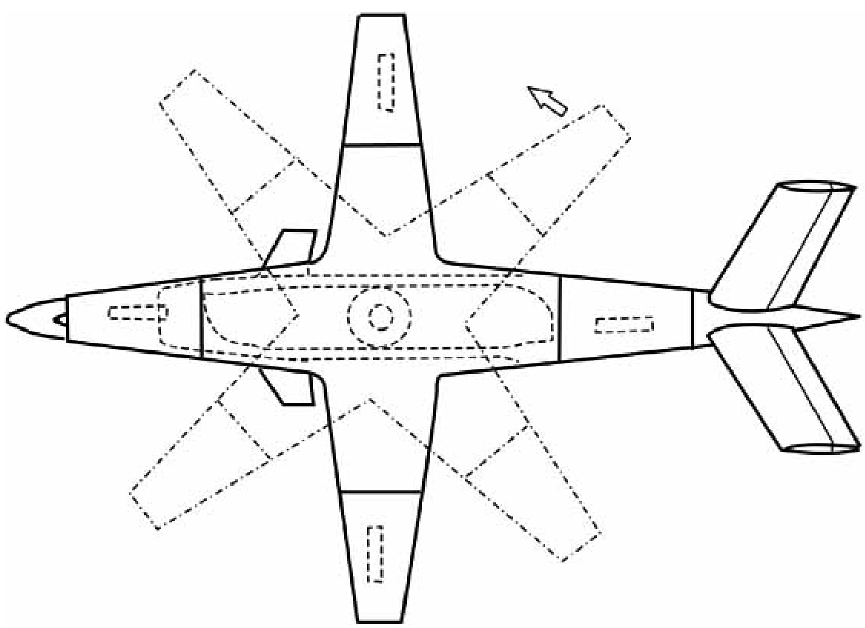

Fig. (27). VTOL aircraft with cruciform rotor wing.

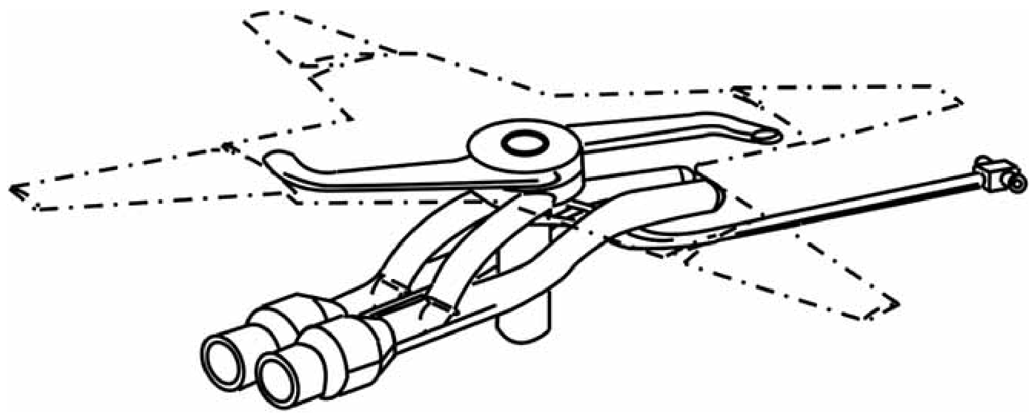

Fig. (28). Perspective view of the propulsion system.

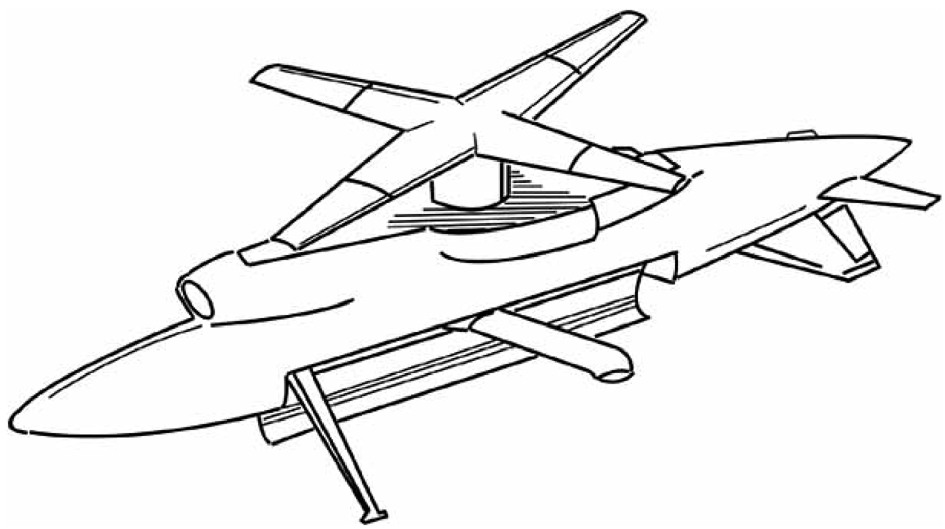

Fig. (29). Rotorcraft with Retractable Rotor Wing.

other hand, the wing 10 rests on the basic airframe and is aerodynamically faired into the structure in a fixed position for high-speed forward flight in the retracted position (10 in Fig. **32**). In the extended position, the wing 10 is rotated for powered lift, the wing tip portions being movable in the manner of a helicopter rotor (10 in Fig. (**30**) Fig. **31**).

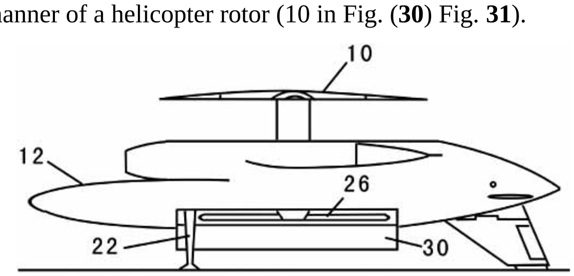

Fig. (30). Landing.

A manned rotor/wing transition rotorcraft invented by Binden [39] provided a single seat rotorcraft having the capabilities of vertical takeoff, landing and hovering operations utilizing the X-Wing as a conventional helicopter rotary wing. After transition to forward flight following takeoff, the rotating wing is stopped and becomes a fixed wing of "X" configuration (Fig. **33**).

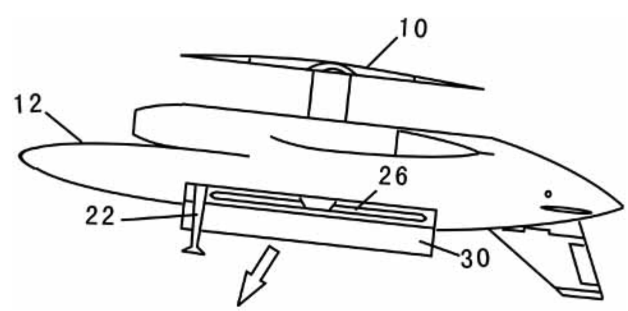

Fig. (31). Vertical flight.

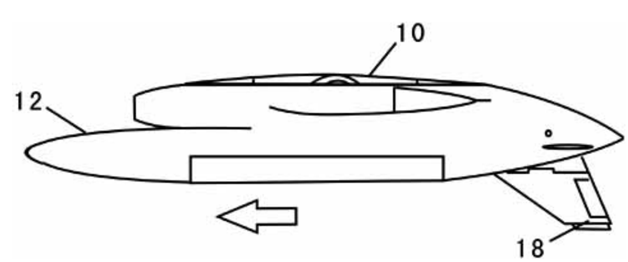

Fig. (32). Forward flight.

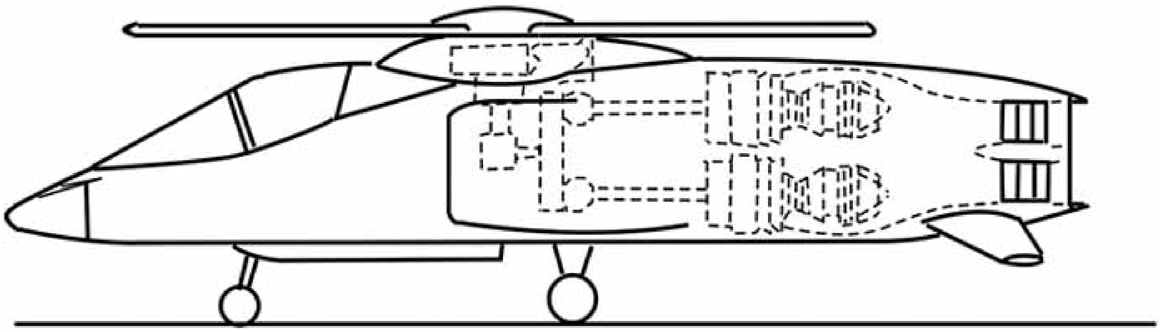

Fig. (33). X-wing helicopter.

The aircraft utilizes two engines within the fuselage, one engine being positioned vertically above the other along the longitudinal axis of the aircraft, the particular arrangement of engines allowing aircraft size and weight to be substantially reduced. The engines drive an air compressor to provide the compressed air in a controlled manner through slots formed on the blades of the X-wing, and provide the propulsive force for the aircraft. Fixed wing surfaces are provided for additional lift capability and for external stores carriage.

A unique rotor/wing transition rotorcraft was disclosed by Rutherford [40], named as "Canard rotor/wing"(Fig. (**34**)). The rotorcraft includes a rotor for propulsion during low-speed flight and hover, which is stopped and locked to function as a fixed wing during a high-speed flight. Also included are a canard and a high-lift tail, which together function to provide substantially all of the lift for the rotorcraft during the transition between low and high-speed flight, so that the rotor may be unloaded while starting and stopping. From Fig. (**35**), the driven system of the rotorcraft is similar to the prior Pat. US3794273 [36], the rotation of the rotor is tip-jet driven. As the rotors become fixed-wing, the thrust is driven from the jet engine.

Due to more efficient lifting surface, canard wing reduces both skin friction drag and induced drag. Additionally, the inventive configuration removes the conversion lift requirements from the rotating frame, eliminating any possibility of center of lift oscillation feeding into the vehicle dynamics. Using the canard and horizontal tail surfaces allows a smoother conversion feature. Flying as a compound helicopter, with the rotor unloaded reduces rotor-induced vibration as forward speed increases. This also significantly reduces the induced power required in hover. Efficiency in fixed-wing flight increases due to the reduced lifting area associated with this concept. An additional ability to vary the sweep of the wing allows efficient low-speed airplane flight with a high aspect ratio wing. High-speed flight is achieved by rotating the wing into an oblique position to delay the drag divergence Mach number. The improved canard rotorcraft is described in Fig. (**35**).

Pande [41] offered a flipped airfoil X-wing rotorcraft (Fig. (**36**)). Its rotary wing flight mode is similar to a helicopter; it utilizes an antitorque tail rotor to cancel main rotor torque. Main rotor airfoils rotate with leading edges into the oncoming airstream (neglecting forward motion) to provide lift. In the fixed wing flight mode, including

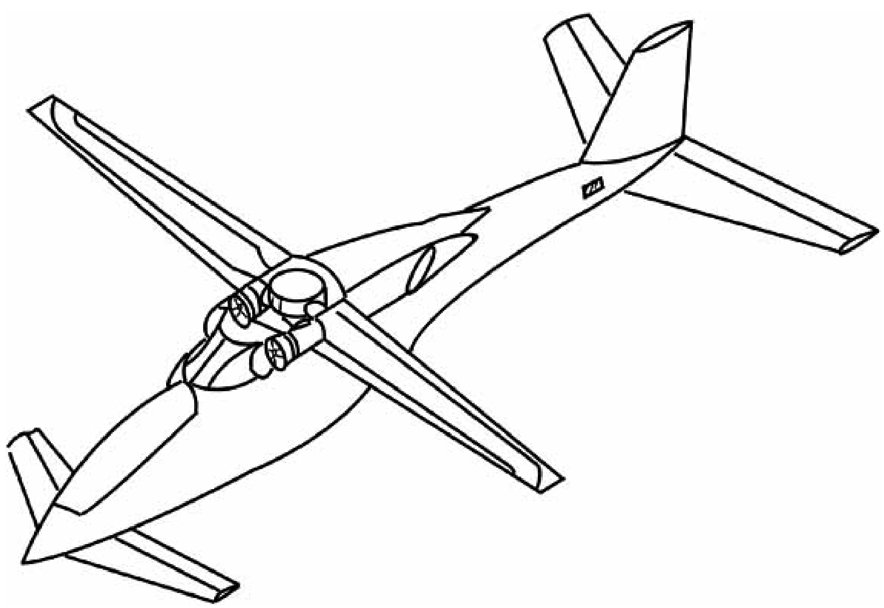

Fig. (34). Original design of canard rotor.

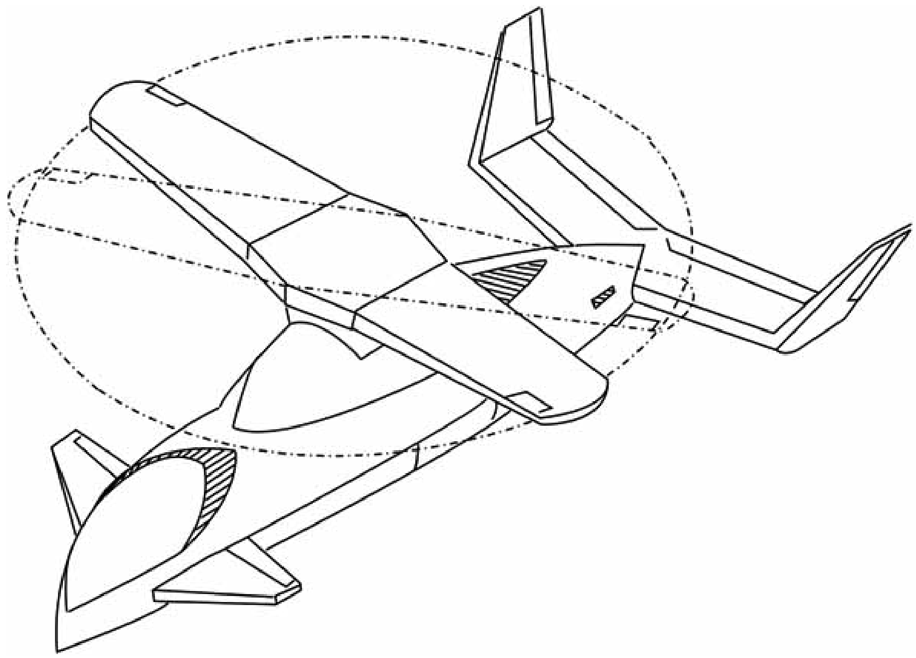

Fig. (35). Modified design of canard rotor.

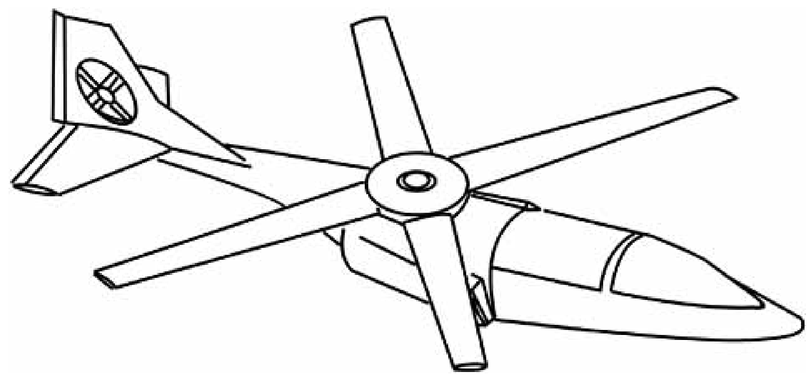

Fig. (36). Stopped rotorcraft utilizing a flipped airfoil X-wing.

supersonic flight, it utilizes all stationary main rotor airfoils for primary lift, such that all airfoil leading edges are positioned forward, meeting the oncoming airstream generated by forward aircraft motion. For the purpose of rapidly starting or stopping airfoil angular rotation without applying adverse torque to the aircraft fuselage, rotating flywheel and flywheel clutch are mounted in the rotorcraft.

In 2000, Bass and Mitchell [42] offered a dual-flight mode tandem rotorcraft (Fig. (**37**)). A plurality of tandem rotors can produce propulsion and lift, and transitional lift wing 16 enables lift on the fuselage during off-loading lift of the plurality of tandem rotors (16 in Fig. (**37**)).

X. OTHER CONFIGURATION

Some rotorcraft can be hardly classified as the above configuration. They are often of hybrid modes. Furthermore, it does not belong to the compound helicopters. Therefore, these special cases will be described in this section. Some of them can be entitled "ducted type configuration", a fuselage with a ducted rotor system that provides translational flight, as well as vertical take-off and landing capabilities.

In 1988, GeldBaugh [43] designed a new rotorcraft (Fig. (**38**)), known by the denomination "rotor aircraft". Its laterally placed dual rotors rotate in opposite directions with the axis through the center of the rotors being transverse to the longitudinal axis of the fuselage. Between the two rotor hubs a wing structure is placed above and below the blades with the two wings joined together. It forms a sheltered wing structure. A compressed gas ejection system would aid in the transition of the blades from operating in free air to operating within the sheltered wing structure. A louver system in the upper and lower wings would operate to allow air to flow freely through the wing during the lifting or hovering mode.

The sheltered wing over a portion of the rotors will allow the retreating mode of the rotor blades to rotate out of the air stream when the aircraft is in horizontal flight. Therefore, the speed limit of existing helicopters can be broken due to avoiding the shortage of retreating blade flight characteristic. In addition, it is less complicated to construct, more free maintenance. The entire assembly of the wing structure and the rotors can be maneuvered as a unit so that the flight characteristics would be similar to a helicopter.

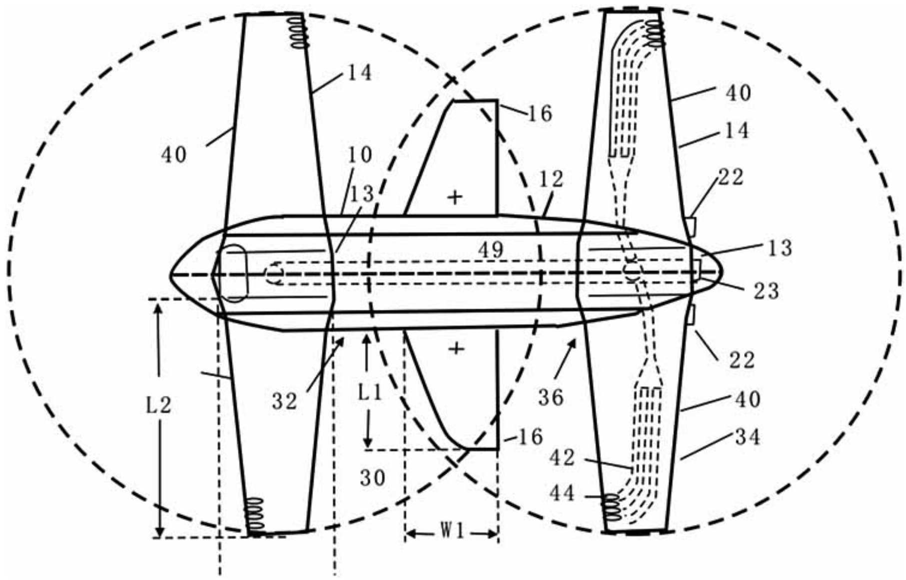

Fig. (37). Dual-flight mode tandem rotorcraft.

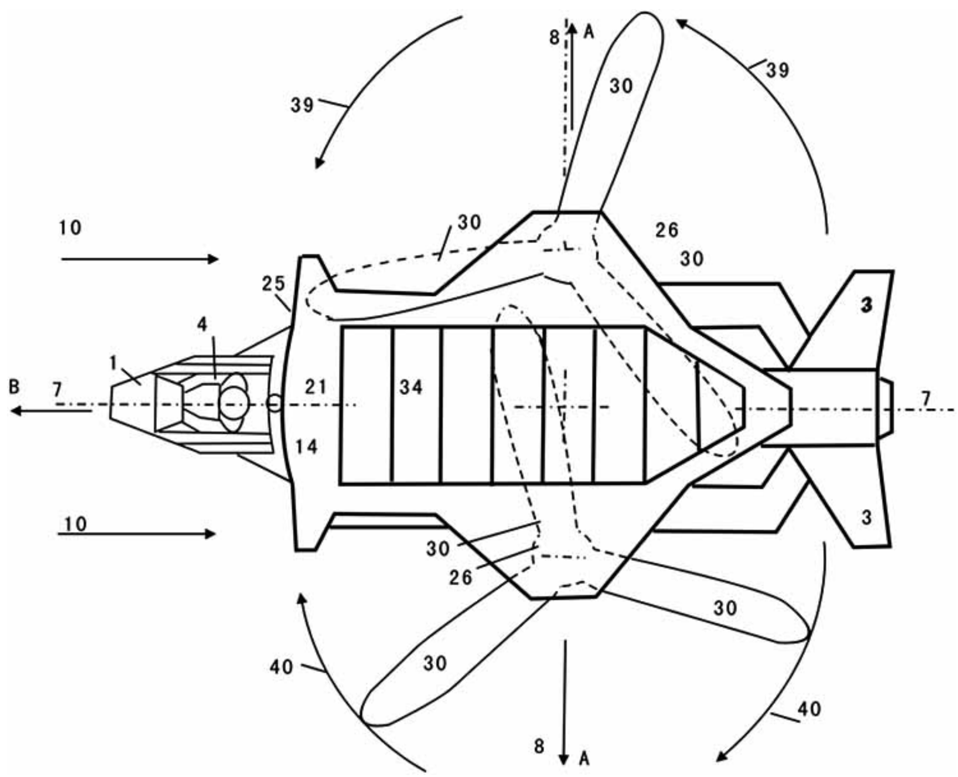

Fig. (38). US4771967 to rotorcraft.

A housing shaped rotorcraft (Figs. **39**, **40**) was disclosed by Franz Bucher [44] in 1994. The rotorcraft comprises a rotor with a vertical axis arranged in housing for generating lift. The housing is essentially shaped as a circular wing. A first way of guiding air is provided for controlling the air stream generated by the rotor, by means of which the position of the rotorcraft can be controlled in hovering flight. From hovering flight, the rotorcraft can be moved into a cruise flight, where the lift of the rotorcraft is generated aerodynamically through the circular wing of the housing and its forward thrust by a propeller. For the transition between hovering flight and cruise flight, a second way of guiding air is provided for controlling the pitch of the rotorcraft.

At low velocities the lift as well as the position of the rotorcraft is therefore controlled through the air stream of the rotor alone. At high velocities the lift is generated aerodynamically by the circular wing and by flaps and/or winglets. At intermediate velocities, in a transition range, the rotor air

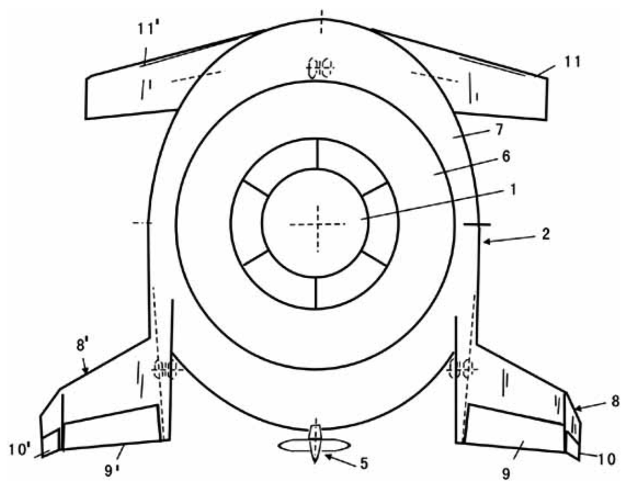

Fig. (39). Aircraft with a ducted fan in a circular wing.

stream as well as aerodynamic forces on the wings or air guiding means contribute to the lift and the control of the aircraft.

Similarly, Kinkead [45] declared a new housing shaped unmanned aerial vehicle (Fig. (**41**)). As a hybrid rotorcraft, it can provide the hover, low-speed maneuverability and high-speed forward flight. It is operable in four flight regimes: (1) the rotor generates control and lift in hover and at low speed; (2) in forward flight, lift is generated by the wings and all control is through the fixed wing surfaces (elevator, ailerons, rudder); (3) in transition up, this mode guides operation of a multiple of control surfaces when flying from hover to forward flight; (4) in transition down, this mode guides operation of a multiple of control surfaces when flying from forward flight to hover. The counter-rotating rotor can be utilized to generate lift, pitch, yaw, and roll control.

As a ducted type configuration rotorcraft, Vertical take-off and landing aerial vehicle disclosed by Plump [46] includes a toroidal fuselage having a longitudinal axis, and a duct extending along the longitudinal axis between a leading edge and a trailing edge of the fuselage, first and second counter-rotating, variable pitch rotor assemblies coaxially mounted within the duct of the fuselage, and at least one canard wing secured to the toroidal fuselage and having a leading edge positioned out of the duct of the fuselage and axially forward of the leading edge of the fuselage, where at least a portion of the canard wing comprises a control surface having a variable angle of attack. The invention provides an aerial vehicle that can take-off and land vertically, hover for extended periods of time over a fixed spatial point, and operate in confined areas. The aerial vehicle also has the ability to transit between a hover and high-speed forward flight.

Hosoda, Japanese inventor disclosed a complicated rotorcraft [47](Fig. **42**). Despite the fact it is not the ducted type configuration, it is different from other rotorcraft. It can carry out the transition flight from a helicopter mode to a fixed wing mode only by change of a collective pitch of a rotor blade and a change of a pitch of a propeller.

Another NOTAR method is using an improved helicopter transmission put forward by Aldin [48], which has

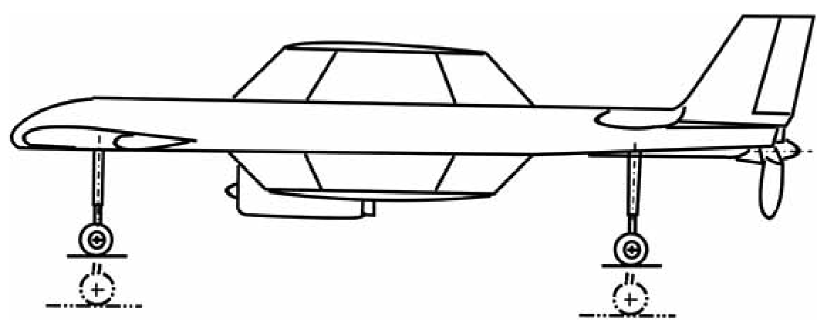

Fig. (40). Side view of the rotorcraft.

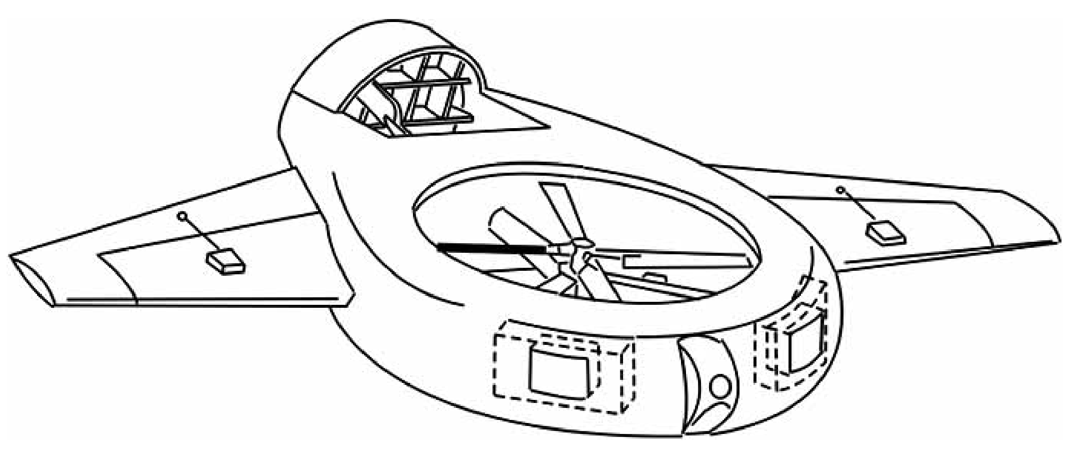

Fig. (41). US6592071 to rotorcraft.

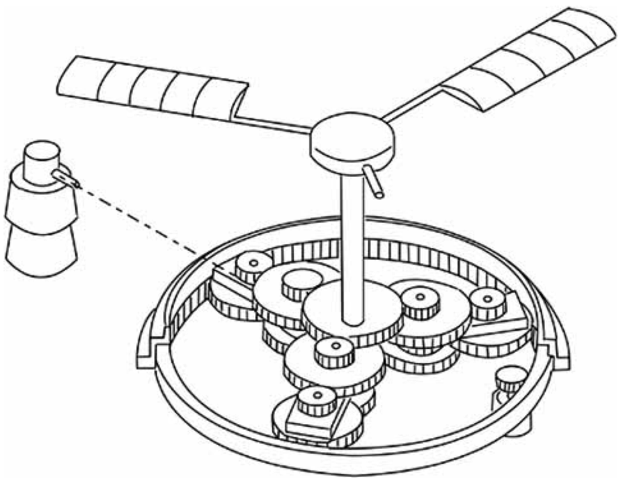

Fig. (42). Aircraft and rotating force transmitting device.

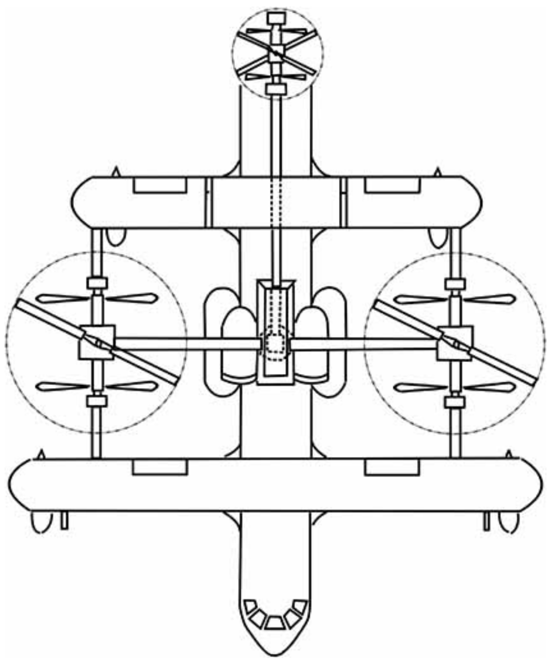

Fig. (43). Balanced torque transmission.

previously been transmitted from the engine to the main rotor comprising a pair of sun gears connected by a plurality of planetary gears which serve to transmit rotational energy from the engine to the main rotor, while completely absorbing the torque developed in doing so (Fig. (**43**)).

XI. CURRENT & FUTURE DEVELOPMENTS

With the new development in some research fields, such as reliability, economical efficiency, maintainability, super-maneuverability and high-agility, ride comfort and high velocity and long range, the inventors are trying their best to study these new configuration mentioned above in this paper. Covering aspects of the material, structure, flight control, aerodynamics and elasticity dynamics, they are improving the rotorcraft performance. Simultaneously, more advanced technologies about the fixed wing aircraft will be introduced into the field of the rotorcraft; these better features will combine with the rotorcraft characteristics. Nowadays, the traditional configuration and new ones for rotorcraft exist together. Although some of them have their own merits, they still have the shortcomings in manufacture difficulty, economical efficiency, control characteristics, and other technology.

In the future, in view of a variety of problems encountered during the development of rotorcraft, the continual arisen rotorcraft configuration will declare human exploring about the solution schemes. Simultaneously, due to the new requirements more advanced configuration will be invented to break through the limitation of the rotorcraft. Foreseeingly, more members will join in the rotorcraft family that will become the more economical, effective and rapid vehicles for air traffic transportation in the future.

REFERENCES

[1] Leishman J.G. In: Principles of Helicopter Aerodynamics, Cambridge, Cambridge University Press, 2000; 1-20.
[2] European Patent Office (esp@cenet®), available http: // v3.espacenet.com/
[3] Vuillet, A., Morelli, F.J.: US4585391 (**1986**).
[4] Mouille, R.L., Rollet, P.A.: US4809931 (**1989**).
[5] Bandoh, S., Egami, K.: US5306119 (**1994**).
*[6] Desjardin, R.A., Mccardle, F.H.: WO9302918 (**1994**).
[7] Dequin, A.M.L., Daldoss, L.J. Barquet, H.F.: US5498129 (**1996**).
[8] Logan, A.H., Moore, R.E.: US4200252 (**1980**).
[9] Vanhorn, J.R.: US4948068 (**1990**).
*[10] Weiland, E., Brunsch, K.: US4292009 (**1981**).
[11] Buchs, W., Nowak, F., Woerndle, R.: US4352631 (**1982**).
[12] Legendre, P.M.R., Manfredotti, T.P.L., Antomarchi, P.M.P.: US5788462 (**1998**).
[13] Certain, N.P.G., Jalaguier, J.-P., Ortega, E.: US20006113352 (**2000**).
*[14] Desjardins, A.D.: US4349317 (**1982**).
[15] Sampatacos, E.P.: US4541777 (**1985**).
[16] Bauer, K., Kuntze, F.-G.: US20006126398A (**2000**).
[17] Bauer, K., Kuntze, F.-G., Hausmann, G., Enenkl, B.: US20016196800 (**2001**).
*[18] Hager, L.N.: US20006030177 (**2000**).
[19] Balayn, F., Magre, E.: US20016276633 (**2001**).
[20] Krysinski, T., Ferrer, R., Klein, J.-M., Magre, E., Manfredottti, T.: EP1212238 (**2002**).
*[21] Roger, N. C.: US20026382556 (**2002**).
[22] Roger, N. C.: US2005045762 (**2005**).
[23] Mackay, J.K.L.: US5236149 (**1993**).
[24] Fenny, A.C., Darden, P.E., Builta, K.E.: US20016220545 (**2001**).
*[25] Milot, M.: WO9625328A1 (**1996**).
[26] Taga, K.: JP03189294A (**1991**).
[27] Greene, L.M.: US5934873A (**1999**).
[28] Lemont, H.E.: US3924965 (**1975**).
[29] Verrill, T.D., Ewans, J.R.: US4227856 (**1980**).
[30] Dale A, William E, Guy J.M. In: An investigation of the reserve velocity rotor concept and its application to high speed rotorcraft. Stratford. Sikorsky Aircraft Coporation, AIAA. 2002-5991 (**2002**).
[31] John, D.S.: US4610410A (**1986**).
[32] Zuck, D.R.: US4928907 (**1990**).
[33] Balmford, D.E.H.: US5174523 (**1992**).
[34] Simpon, J.: WO2004065212 (**2004**).
[35] Loper, A.W.: US2005151001 (**2005**).
*[36] Girard, P.: US3794273 (**1974**).
*[37] Girard, P.: US3792827 (**1974**).
[38] Girard, P.F.: US3986686 (**1976**).
[39] Binden, J.A.: US4711415 (**1987**).
*[40] Rutherford, J.W., O'Rourke M., McDonnell, W. R., Smith B.T.: US5454530 (**1995**).
[41] Pande, J.B.: US5405104 (**1995**).
[42] Bass, S.M., Mitchell, C.A.: US20046789764 (**2004**).
[43] Geldbaugh, G.R.: US4771967 (**1988**).

*[44] Bucher, F.: US5303879 (**1994**).
[45] Kinkead,W.D., Scott, M.W.: US20036592071 (**2003**).
[46] Plump, J.M., Gupta,N.R.: US2003052222 (**2003**).
[47] Hosoda, R.: JP2001071998 (**2001**).
[48] Aldin, E.G.Sr.: US5820073 (**1998**).