Helicopter Transmission Systems

By KENNETH WATSON, A F R Ae S

A lecture presented to the Helicopter Association of Great Britain, on Saturday, 26th February, 1949, in the library of The Royal Aeronautical Society, 4 Hamilton Place, London, W 1

Introduction by Mr C G Pullin

Mr Chairman, Ladies and Gentlemen

It gives me great pleasure to introduce the lecturer this afternoon, particularly as I have known him for the past 16 years and, better still, we have been associated in the development of rotating wing aircraft during most of that period

Mr Kenneth Watson, who is a Founder Member of the Helicopter Association and an Associate Fellow of the Royal Aeronautical Society, is also Chief Mechanical Engineer to the Cierva Autogiro Company

Mr Watson served his apprenticeship with Messrs G & J Weir, Glasgow, and joined the Aircraft Department of that firm in 1933, which was then under my control His designing ability was quickly appreciated and he was entrusted with the design of some of the major components, such as rotor hubs, transmission systems and control organs I think I am right in saying that the Cierva Autogiro Company and their Licencees, Messrs G & J Weir, have designed more prototype rotor systems than any other firm engaged in the art, and in 1936 no less than five rotor hubs were made and tested within seven months Mr Watson's first introduction to helicopters was the Weir W 5 machine in 1937, subsequently followed by the W 6 and later by the Cierva Company's W 8, W 8, W 9a, W 11 (Air Horse) and W 14 " Skeeter " Mark I In view of this considerable background of design and practical experience, the lecturer will be able to submit a paper of unique interest which should appeal, in a very large measure, to those members of the audience of mechanical rather than scientific attainments All those engaged in the art will appreciate the necessity for the highest class of mechanical design, which is just as essential to the success of the helicopter as the underlying scientific data associated with the generation of lift and the attainment of forward flight and control

Finally, I would not suggest that you ask Mr Watson to design a flat belt transmission, as this is, I think, the only instance wherein he has failed to meet requirements, being unable to coax the belt to remain on the pulleys , the transmission was finally rebuilt with spur gears

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MR KENNETH WATSON

Mr Chairman, Members of the Helicopter Association

Ladies and Gentlemen, I wish to thank you for the invitation to talk to you on the subject of Helicopter Transmission Systems When confronted with writing a paper on Helicopter Transmission Systems, I got together all available data on the subject, collected over a number of years, and realised that considerable time and space would be required to present this and not a talk In the circumstances therefore, I trust that I will be excused for confining this talk mainly to —

(1) Early efforts at driving rotors
(2) What does a purely mechanical transmission consist of and what is expected of it
(3) A brief description of the CIERVA " AIR HORSE " transmission and some of the problems in connection with it
(4) Some thoughts for the future, particularly with regard to multi-engine and multi-rotor power distribution and the possibility of a fool-proof speed change gear

During the past few years there have been important developments in connection with transmissions for use with the internal combustion in its application to the helicopter For a long time previously, aircraft engineers had directed considerable efforts towards the improvement of aero engines, with the result that the helicopter engineer is faced with the formidable task of catching-up with, and of necessity, surpassing the reliability of the modern power unit Acceptance of the helicopter implies for safety's sake, its safe descent as an Autogiro in the event of a power failure but may not apply in the event of a transmission failure, since usually the transmission has functions other than that of transmitting power from engine to rotor In the circumstances, therefore, it is absolutely desirable for the future of the helicopter that its transmission has the utmost reliability

HELICOPTER TRANSMISSION

In dealing with the present day helicopter transmission or drive, it would seem appropriate to go back a few years and view early attempts and the means employed to turn the rotors on early autogiros

Up until 1937 a considerable number of Autogiros were constructed of varying types, size and characteristics, but they were primarily research or experimental machines in which little or no attempt was paid to secondary requirements In particular, the problem of initially starting the rotor had been left in abeyance and the rotor was generally started by a number of men pulling on a rope which had been wound round the rotor hub Alternatively, the rotor could be started by towing the machine along the ground at progressively increasing speed as the rotor speed was increased Such methods, of course, formed a serious handicap to the practical utility of the autogiro and various alternative methods were tried

In 1930 a jet reaction starter was built for the Air Ministry in which the products of combustion of compressed air and oil were discharged from jets at the blade tips This system, while it gave promising results, was not proceeded with on account of the weight and complexity The first practical starter system to be used on machines was arranged in such a way that the slipstream from the engine airscrew was deflected upwards through the rotor by suitably inclining the tail structure The obvious device of gearing the engine to the rotor hub for starting purposes, originally tried in this country, was first perfected in mechanical detail by the Autogiro Company of America and this system displaced all other methods of rotor starting Attempts were also made at having the rotor driving gears separated in flight, the engagement only taking place during revving up of the rotor By this means the rotor was relieved of the necessity of driving the high speed pinion together with the possibility of a pinion bearing seizure In one case the pinion was mounted on a cam which on being rotated by a hand mechanism engaged it on the crown wheel The driving torque held the pinion in engagement during running up, it was subsequently thrown clear by the over-drive upon the release of torque There was also an attempt at holding the separated gears in mesh by hand during the run up In this case the driving pinion was mounted on the pylon structure and the crown wheel on the tilting hub, so that by pressing the control column well forward the gears were engaged and held in engagement until the control was pulled back This simple scheme was not successful on account of the control and structural rigidity being unable to look after the gear tooth separating forces For the same reason, the cheap but cumbersome looking friction come arrangement was not a success on account of being unable to build up sufficient contact pressure for the friction drive, so that the constant mesh pinion and crown wheel was retained with the autogiro starting system

It can be said that while the autogiro was a stepping stone to the ultimate development of the helicopter, so also was the autogiro rotor drive system an important step towards the helicopter transmission In helicopter transmissions the duties are more exacting, but nevertheless, the autogiro contained more or less the elementary and the practical experience required for the driving of a large articulated rotor

Turning now to the subject of this talk, it can generally be agreed that the helicopter transmission or drive requirements are clear The first essential is a power unit The choice here is a limited one since it confines itself to the adaptation of an approved aircraft engine Unfortunately, the differences between helicopter and aircraft power requirements are so varied, that it is hoped that eventually suitable power plants will be available The aircraft engine is essentially constant speed while the helicopter requirement is for a power speed combination which do not align themselves with the characteristics of the internal combustion engine The helicopter rotor requires a low tip speed for maximum hovering efficiency and a high tip speed for high speed flight so that the engine should be capable of developing take-off power at lower r p m than the cruising r p m This short coming of the engine can, however, be overcome by the use of a speed change gear in the transmission Again, since the helicopter engine develops its maximum H P at zero forward speed, means have to be provided for blowing air over the cylinder fins in the case of an aircooled engine, or through a suitable heat transfer unit in the case of a liquid cooled engine, also, since the power plant is usually submerged within the airframe, the problem of exhaust cooling requires careful attention

The next essential is for an engagement clutch so that the engine can be started without the encumberance of the rotor and run up independently of

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the rotor The engaging clutch should of necessity be of the slipping type and need not have the full torque capacity of the drive since it can be engaged at low rotor pitch and speeds The engagement can be either by hand operation or responding automatically to engine r p m , so that the rotor or rotors can be accelerated to the desired r p m , without undue shock

In addition to the engaging clutch, it is essential to have a free-wheeling or over-riding device in case of sudden engine failure There are various types of over-riding clutches but the one that finds most favour is jamming-roller type, it is simple and reliable and has the advantage of being more or less dead-beat in operation The small amount of rotational movement between engagement and dis-engagement prevents the building up of high inertia loads in the drive system due to rapid angular acceleration

In most transmission layouts and in particular the multi-rotor transmission, the engine is usually separated from the rotor or rotors by a considerable distance and since the power has to be transmitted over this distance the drive shaft is an extremely important component in the drive mechanism and demands that, in addition to being capable of transmitting the required torque, that the shaft length and supporting bearings are such that the critical speeds of all shafts be outside the range of permissible engine speeds under idling, power-on, autorotating and over-speed conditions Due to the deflections of the structure in which the shafts are mounted, flexible couplings are required which will give a degree of angularity These couplings are usually of the Hooks Joint type where large degrees of angular displacement are required, or of the rubber bush type where the angularity is of a smaller order The rubber type coupling has the added advantage of absorbing the high peak torques of the aircraft internal combustion engine It is essential that some form of damping mechanism is incorporated adjacent to the engine output shaft in the event of there not being sufficient flywheel mass available otherwise the effects of peak loads on clutches, shafts, couplings and gears will require consideration

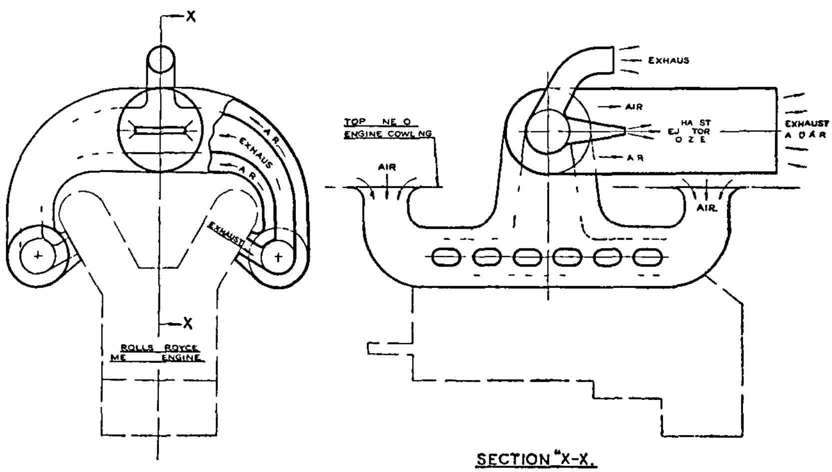

Fig 1 Diagram of air-cooled exhaust system

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Since the speed of the power unit is usually many times that of the rotor, a speed reducing gear is required The choice of a reduction gear in itself is a rather perplexing one due to the power and speed characteristic of the rotor in its various regimes of flight

In addition to the requirement mentioned, it is desirable to have low mechanical losses, adequate cooling of gear boxes and in general, mechanical simplicity and reliability combined with good accessibility

THE " AIR-HORSE " TRANSMISSION

The power plant consists of a Rolls Royce Merlin Mark 24 engine developing 1645 h p at take-off, with a single stage two-speed supercharger The standard 42 to 1 reduction gear is retained The engine fuel and oil system are conventional and the cooling system follows modern practice except that the radiator employs a light alloy matrix in place of the conventional copper one

The exhaust system constituted a major installation problem Liquid cooled jacketed manifolds were tried in the first place but were abandoned in favour of the aircooled manifold on account of penalties of considerable increase in radiator size, increased fan h p and the possibility of long term development The liquid cooling was, however, remarkably effective and a manifold of this type did many hours on the test bed

The air-cooled cross-over type exhaust manifold (Fig 1), was developed in collaboration with Rolls Royce The exhaust gas is collected from the

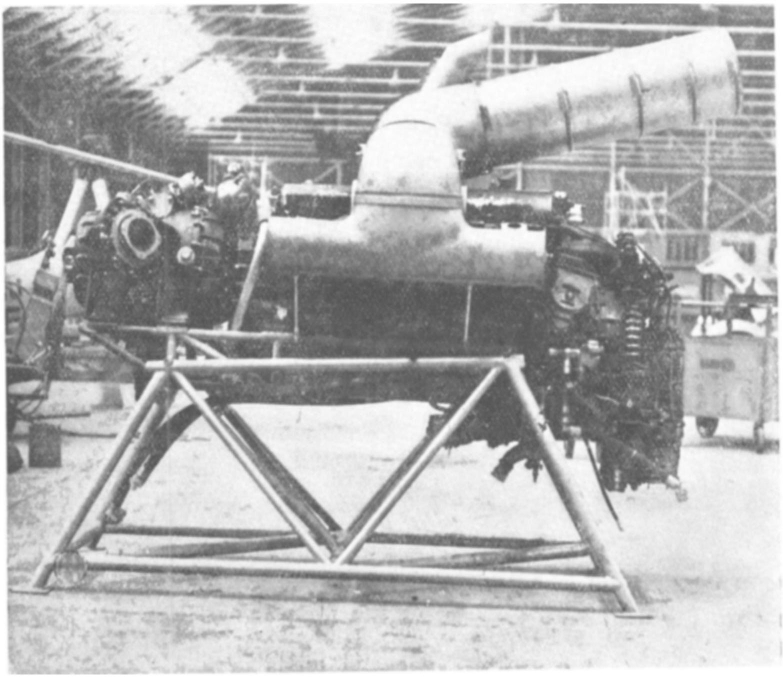

Fig 2

centre of each manifold bank into a cross-over junction which results in a high order of silencing due to the matching of the impulse orders on either bank Each manifold, together with cross-over pipe and junction, is surrounded by a jacket through which cooling air is drawn from the four open ends of the manifolds by the ejector action of the exhaust gas The

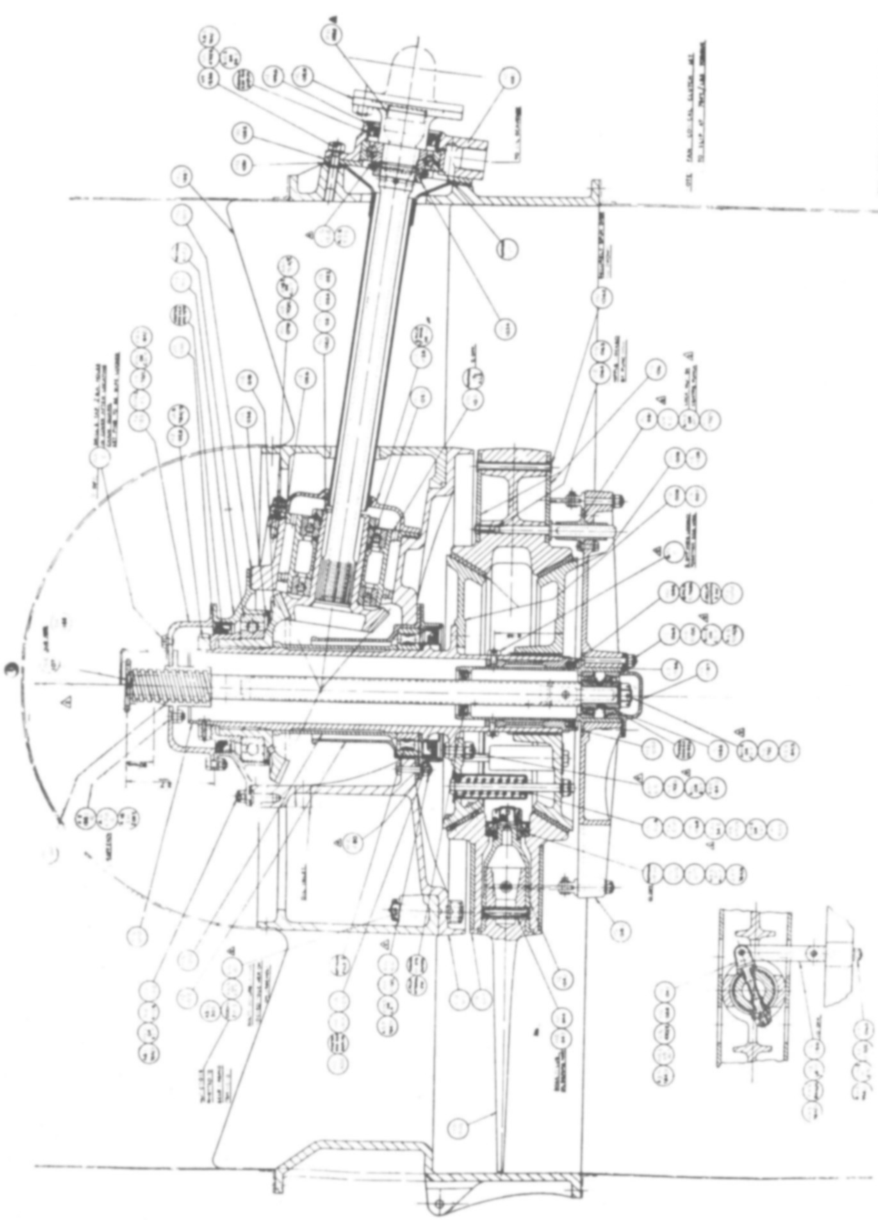

Fig 3 Arrangement of variable pitch fan

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cooling air and exhaust gas come together at the mixing pipe and are ejected to atmosphere, only a percentage of the exhaust gas is used for pumping, the remainder is ejected from the stack pipe on top of the cross-over junction box Fig 2 shows the manifold mounted on the engine

The coolant radiator, engine oil and the separate transmission oil cooler receive a flow of air from a horizontally mounted variable pitch fan (Fig 4), drawing air from above and ejecting it down through the radiator and oil coolers

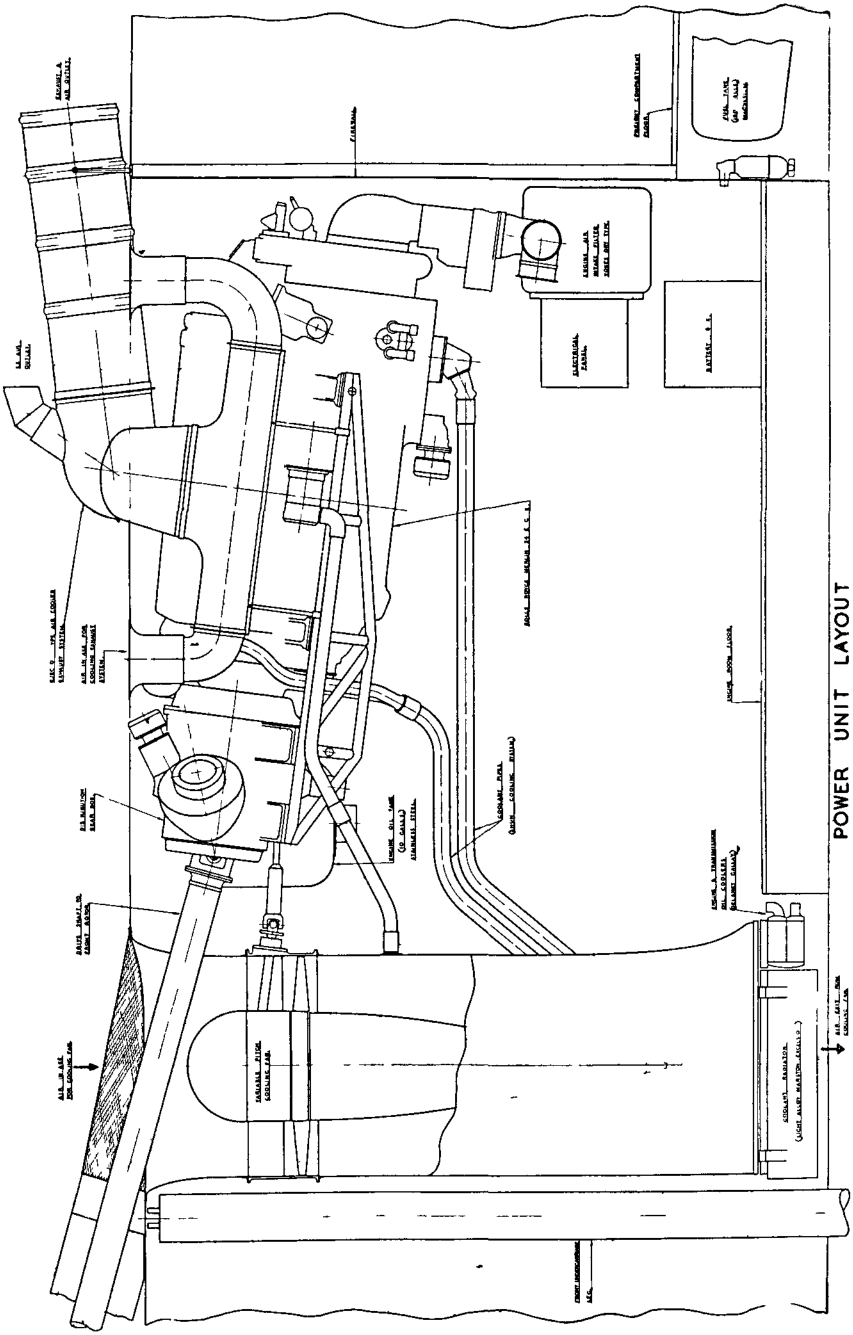
The cooling fan is geared direct to engine and is driven from an extension shaft on the distribution gear box It absorbs approximately $1\frac{1}{4}$ per cent of the engine power and since the normal driving torque is low in comparison to the relative inertia of the fan, means are provided whereby the drive elements are relieved of high torque loads due to rapid acceleration or deceleration of the engine when the main rotor system is not engaged (Fig 3) The fan hub is mounted on the opposed cone clutches which provide for both axial and radial location The light alloy cones have moulded Ferodo linings riveted to them and are spring loaded to one another to slip at a predetermined torque The fan hub is a magnesium casting and the clutch friction faces are formed by a process of spraying cast iron on to a prepared magnesium surface Ten cast magnesium alloy blades are located in the hub in plain bearings with the thrust loads taken on ball bearings and are connected in pitch by means of lever and rods to a spider which in turn is operated by a hand wheel in the pilot's cockpit Variation of pitch on the blades give a very precise and effective means of temperature control

Fig 4 also shows the mounting of the engine and distribution gearbox on a common cradle which is connected in the airframe on a four bolt pick-up The whole unit is inclined at an angle of $7\frac{1}{2}°$ This, combined with an 8° universal joint angularity allows in effect a direct drive between engine and the front rotor reduction gearbox

The Merlin engine is a standard unit except for one or two very minor modifications After some considerable investigation it was decided to retain the engine 42 to 1 reduction gear as the primary reduction since it was found that the resulting simplification of the gearing more than off-set the clutch, shafting and structural difficulties associated with the higher torque of the engine propeller shaft

The coupling (Fig 5), between the engine and the distribution gearbox is enclosed within the gearbox and consists of an alloy steel member which is splined to fit the propeller shaft, carries on its outer flanges the pins for fifteen Silentblock oil resisting rubber bushes The light alloy outer housing into which the bushes are pressed forms part of the clutch bell housing

Crankshafts of internal combustion engines vibrate tortionally, in which case, unless specially catered for within the engine, the output shaft instead of turning at uniform velocity alternately accelerates and decelerates in rapid succession If this fluctuation is transmitted unaltered, it gives rise to load reversals in the transmission To damp out the tortional vibration it is necessary to introduce an elastic member in the system in such a way that the torque will be transmitted through it The torque variations which accompany tortional vibration will cause the elastic member to yield and rebound alternatively and the resilient motion must be accompanied by the absorption of energy either within the resilient member or by surfaces which slide upon each other as a result of the resilient motion The energy



POWER UNIT LAYOUT

Fig 4

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thus absorbed tends to damp the tortional vibrations No damper can however, completely suppress tortional vibration because it begins to function only when the vibration starts but if properly proportioned it can hold the amplitude of vibration down to a minimum

The coupling in the " Air Horse," in addition to its damping qualities, has the additional advantage of looking after inaccuracies in alignment between the engine and gearbox due either to assembly or to subsequent deflections under load, axial expansion due to heat, and to greatly reduce the inertia shock at starting

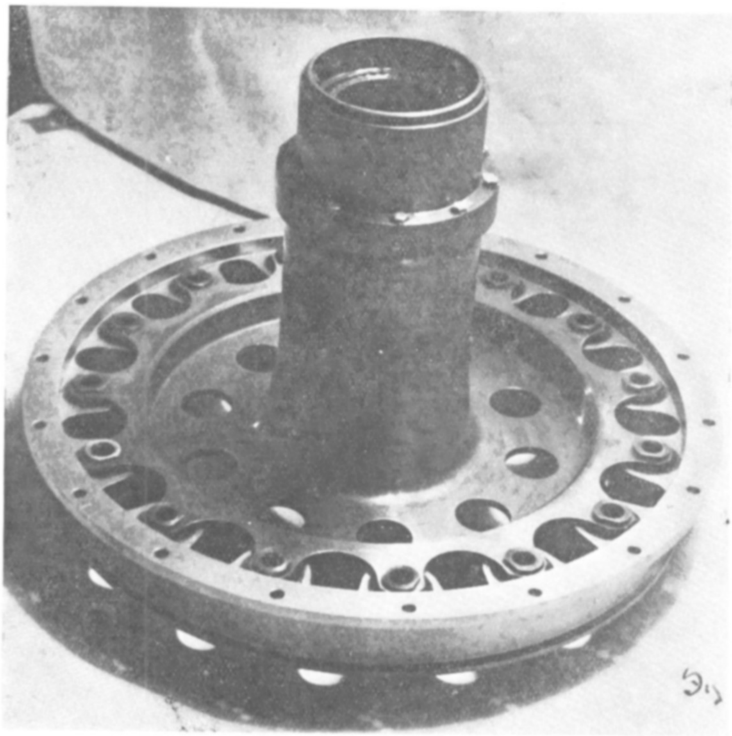


Fig 5

The function of the distribution gearbox (Fig 6), is to divide the engine power into the proportions required by each of the three rotors and to provide in the event of a power failure that the three rotors remain permanently geared together It also contains within its magnesium alloy casting the previously mentioned coupling, a slipping clutch for engaging the rotors, a combined free-wheel and positive clutch in parallel with the slipping clutch, a rotor brake, the cooling fan drive, an extra power drive and a lubricating oil pressure and scavenger pump for the entire transmission right out to the rotor hubs In addition, it also provides drives for a hydraulic pump for controls, separate rotor and engine r p m , generators, and provision for other accessory services

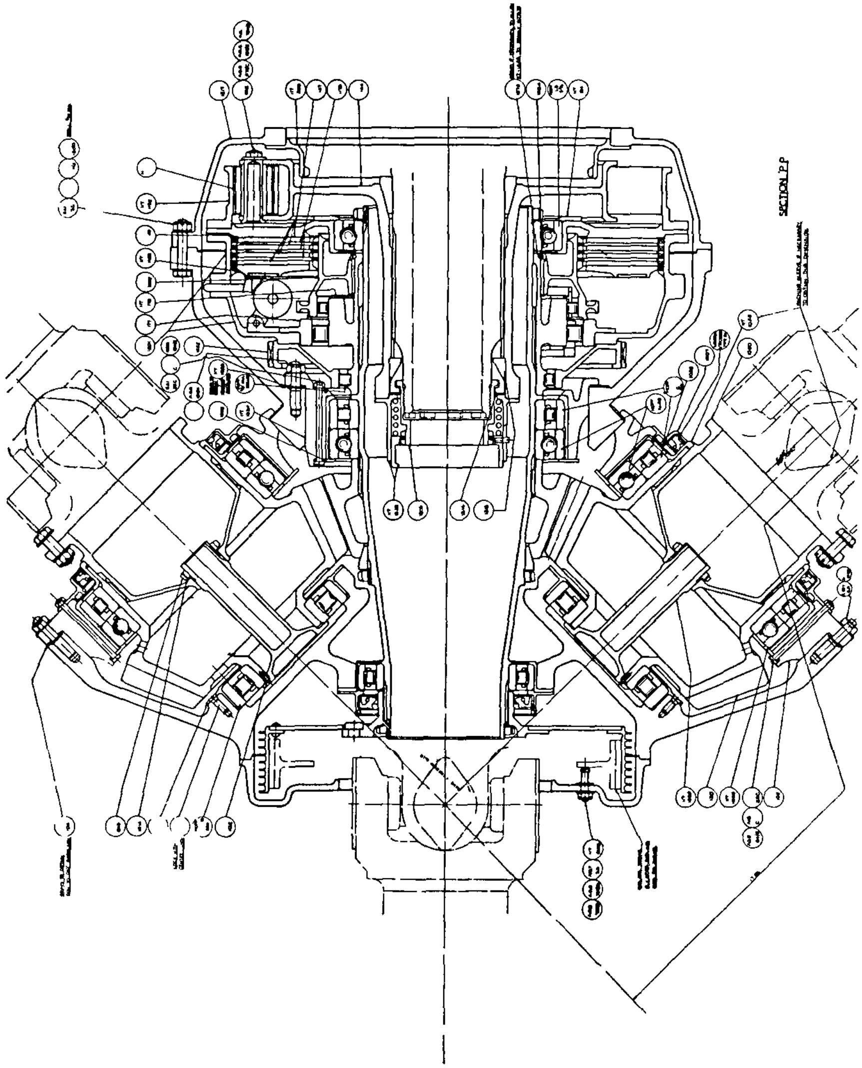


Fig 6 Distribution gear box

The propeller shaft torque is transferred back into the engine by a splined coupling which acts as the torque-wise location between engine and gearbox The three external shaft torques almost cancel one another by virtue of their planwise displacement and direction of rotation, so that for the case of the torque being split equally between each of the rotors there is only 16 per cent residual to be taken by the engine mounting to fuselage The amount, of course, varies depending on how the power flow varies as from rotor to rotor

In most helicopters today the rotor engaging clutch has the full torque capacity of the drive, whether the engagement is by hand operation or responding automatically to engine r p m Since such a clutch is required to slip during engagement only, its capacity at starting is over determined It requires very skilful manipulation if the hand operated type otherwise the transmission and in particular the rotor blades, are liable to severe damage if the clutch is misapplied This also applies to the centrifugally operated clutch if not fitted with a cut-out to look after the possibility of rapid engine acceleration at starting In view of the hazards the solution appears to call for an engaging clutch with sufficient torque capacity to allow the rotor blades to be accelerated up to say half-speed at low incidence after which a positive locking type clutch is engaged for the remainder of the duty The elements of such a positive locking clutch are already existing in the free-wheel and over-riding clutch which is essential in the case of a power failure, and it only remains to provide means whereby this clutch will not take up the drive until such time as the engine and rotor speeds have been synchronised With such a combination only a very limited amount of torque can be applied at starting and during acceleration up to the positive clutch engagement speed

Such a clutch combination (Fig 6) has been applied to the " Air Horse " It is very flexible in its smoothness of engagement on account of the " oil wetted " friction surfaces, although when starting from cold it takes a little time to accelerate the rotors to the positive clutch engaging speed Since, however, this takes place during the warming up period, there is no time lost in actual fact Estimating the torque capacity of the slipping clutch requires very careful consideration The rotor torque can be estimated reasonably accurate but the torque due to mechanical drag when cold requires very careful consideration particularly in a multi-rotor configuration

The clutch bell housing in the " Air Horse " is machined from an aluminium alloy forging It is connected to the flexible coupling outer housing and located radially and axially to the gearbox shaft by ball and roller bearings The outer bore is splined to pick up with mating splines cut direct on the outer diameters of four Ferodo discs Sandwiched between each Ferodo disc is a high carbon thin steel plate each having specially cut radial slots to ensure them remaining flat under variations in temperature Each plate is splined internally and connects to the roller clutch hub containing the wedging tracks for the primary and secondary free wheel clutches Torque from the slipping clutch is transferred to the rotor shafts by the secondary free-wheel This has the advantage of immediately freeing the clutch drag from the rotors, otherwise, with the system of two-stage clutching employed there would be a possibility of the rotors trying to drive the engine on the over-drive This peculiar state of events only happens when the slipping clutch and free-wheel clutch are arranged to work in parallel It does not arise, however, when the clutches are arranged in series

The pressure for engaging the clutch plates is obtained from the centrifugal action of eighteen heavy alloy (Tungsten) bob-weights (Fig 7), pressing on a light alloy pressure plate When the clutch is at rest the bob-weight toggles are in-operative When, however, the engine commences to revolve the clutch housing, the bob-weights links tend under centrifugal force to fly outwards causing the rollers to move away from the centre of the clutch using the link abutment to force the back-plate more and more into engagement In order to overcome the possibility of engagement due to rapid engine acceleration at starting, each bob-weight toggle is held by a trigger to its disengaged position This allows the engine to be run up to full r p m and to be idled at a smooth speed for " warming up " without fear of engagement Engagement is achieved by allowing the trip-roller to trip each trigger as it passes and ensures a progressive application of the bob-weights to the pressure plate The trip roller is connected to the rotor brake operating lever in such a way that the first part of the lever movement disengages the rotor brake and the latter part trips the clutch for engagement The opposite sequence applies for engagement of the rotor brake, for as soon as the engine

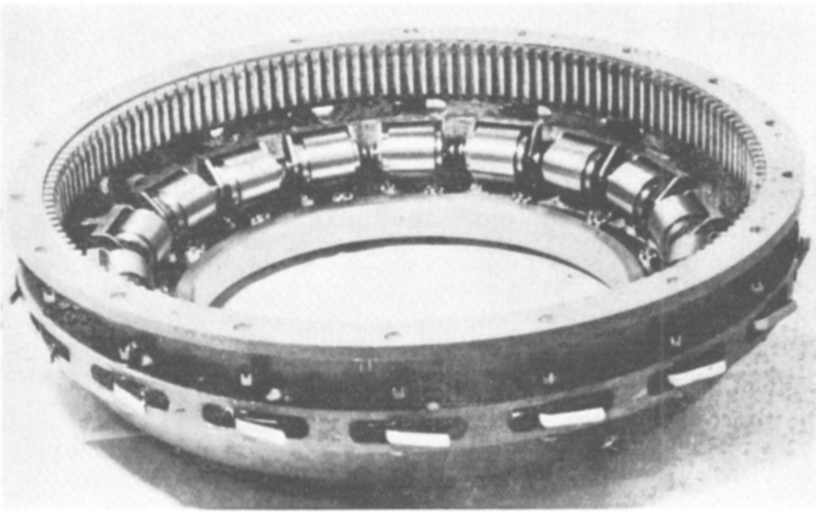
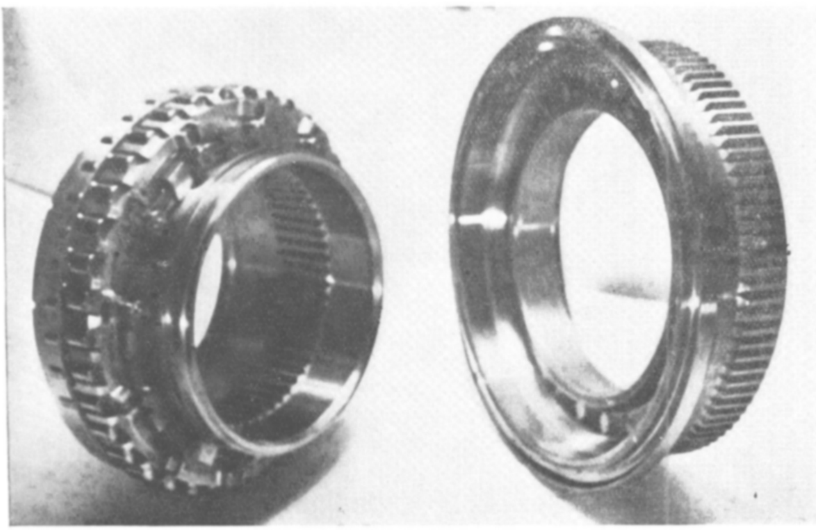


Fig 7

Fig 8



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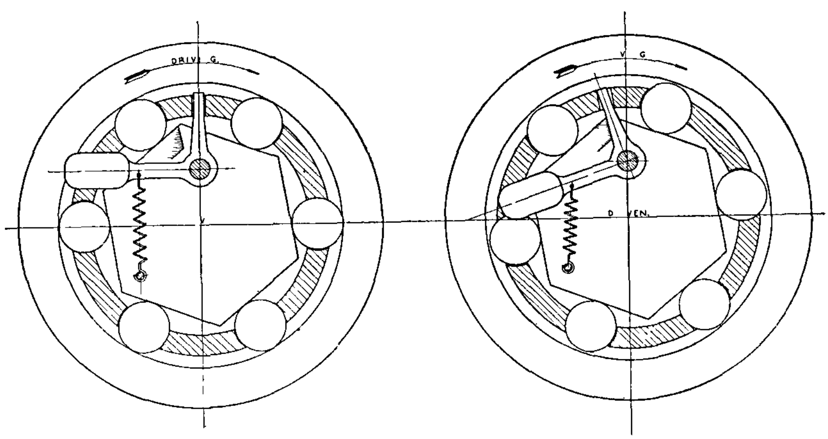
is stopped the bob-weights are returned to their neutral position by springs allowing the triggers to click back and lock the toggle levers in the disengaged position ready for the next start

The main free-wheel and clutch lock (Fig 8), is of the jamming roller type in which the hardened steel rollers are contained in a light alloy cage which is rotated in the direction of roller engagement by the centrifugal action of a series of fly-weights which are connected to the driven member and pick-up on slots in the cage The fly-weights are held to their inner-most position by coil springs In this position the roller cage prevents the rollers contacting the wedging surfaces so that at starting the clutch is completely free in the driving sense until such time as the slipping or starting clutch brings the rotors up to a predetermined speed When this speed is attained the centrifugal effort of the fly-weights acting on the roller cage overcomes the spring effort and rotates the cage into position for the rollers to take the drive Further opening of engine throttle tends to slip the starting clutch causing the rollers to be wedged more firmly between the roller tracks to take the full driving torque In this position the rollers are still free to over-ride in the event of an engine cut

Fig 9 shows the principle of the roller clutch " lock-in " and " lock-out " action The outer or driving member has a plain cylindrical track concentric with its axis and the driven track has a series of flat wedge shaped surfaces In operation, each roller contacts with one cam surface and with the smooth cylindrical surface of the outer ring A tangent at the point of contact between the roller and the cylindrical surface makes a small angle with the cam surface This angle, which is termed the wedging angle, is of great importance in connection with the successful operation of the clutch The wedge angle ϕ must not be greater than twice the friction angle otherwise the roller will be squeezed out and the clutch will not take hold It is also obvious that the greater ϕ (within this limit), the smaller will be the stress



ROLLER CLUTCH. LOCK IN. ROLLER CLUTCH. LOCK OUT.

Fig 9

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in the material for a given torque load Unfortunately, the coefficient of friction for a given material is very indefinite It varies with the finish of the contacting surfaces with the viscosity of the lubricant and to a degree with the contact pressure Both the outer and inner rings are made from a nickel-chrome case hardening steel and the rollers from a direct hardening steel

Theoretically there is a line contact between the rollers and the engaging surfaces but in actual fact, since all materials are elastic the rollers flatten out under load together with an elastic deformation of the contacting surfaces Since the contact pressure on each roller is the sum of the tangential driving force divided by the tangent of the wedging angle it will be seen that both the inner and outer rings require considerable radial backing to avoid distortion The choice of wedging angle can be a very tricky business, 7° is a reasonable all round figure but it is influenced by the type of power unit used and the effectiveness of the torsional vibration damping system employed

The distribution gearbox employs a minimum number of power gears by virtue of the engine inclination being up towards the front rotor This type of layout shows to advantage in the three-rotor configuration since the centre of gravity of the aircraft is such that the front rotor absorbs more power than the rear rotors under conditions when the higher powers are being used, for instance, for hovering or for vertical climb The rear rotor shafts are driven by bevel gears which mesh with a common bevel gear splined to the gearbox shaft The gears are of the straight tooth type corrected to avoid tip interference Care was taken in the choice of gears to ensure adequate strength for wear, since excessive wear is not as serious as tooth breakage, because replacements can be made before complete failure occurs For helicopter transmission gears therefore, by far the most important consideration should be that of tooth strength since a failure may have serious consequences Each of the three main bevel gears are carried on two parallel roller bearings for radial location or one ball bearing for thrust location The outer track of the thrust bearing is radially free to ensure that it will take thrust loads only

The transmission lubricating oil pressure and scavenge pump is located on the distribution box It supplies oil to the complete transmission including the rotor hub gear boxes, at the rate of 18 gallons per minute at 100 p s i A feature of the gear type pump is the elimination of pressure release ports on the side faces This is done by having the pump gear teeth cut in such a way that the volume of oil trapped between the teeth is constant, irrespective of the relative position of the gear teeth The pump is situated on the engine side of the clutch to ensure that oil is circulated throughout the transmission before rotation of the rotors commences

A rotor brake is also provided, it is of the expanding shoe type and is mounted on the front end of the distribution gearbox

A rather frightening problem at first sight is the transmission shaft layout, particularly since the rotors are placed at such a long way from the junction box On the rear rotors the shaft length between universal joints is 33 5 feet and 15 feet for the front rotor shaft The front length is made up in two lengths with a steady bearing between each length and the rear ones in four lengths with a steady bearing between each length The shafts run through the centre of the outriggers and are connected to the

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distribution box and the rotor hub gearboxes by universal joints which work through an angle of approximately 7½° Each shaft length is connected by large diameter flexible steel discs (Fig 10), which look after bending—due to structural deflection and expansion of the shafts owing to temperature changes It is always difficult to establish at first the best shaft diameter

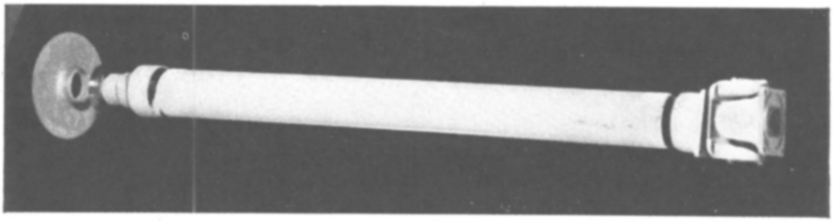

Fig 10

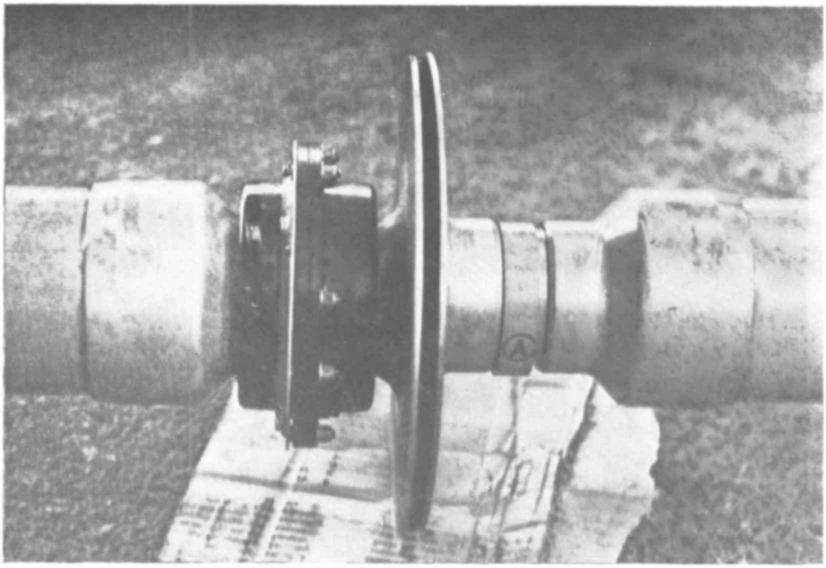

Fig 10a

since so many things have to be considered For example, on first thought the best solution appears to be for a high speed shaft which has a correspondingly low torque This type of shaft however, may demand a larger number of steady bearings or alternatively, whirling dampers together with good dynamic balance On the other hand, the lower speed shaft although looking heavier at first sight, considerably eases the problem, particularly with regard to the dimensional quality of tubes that are available

On the " Air Horse " the transmission shafts run at 42 times engine speed They are made from large diameter light alloy tubes with lengths between the steady bearings arranged such that the first order of critical speed is about 10 per cent outside the running speed range For a given shaft length the light alloy shaft showed a substantial weight saving over the steel shaft since, for example, having determined a diameter and wall thickness that would look after torque and whirling, the steel tubular shaft falls down on account of buckling The light alloy shaft shows a good balance on all scores and the resulting wall thickness is such that the ends of the tubes can be serrated to attach the coupling flanges and sockets which are shrunk on Fig 11 shows relative merits of steel and light alloy shafts of a given

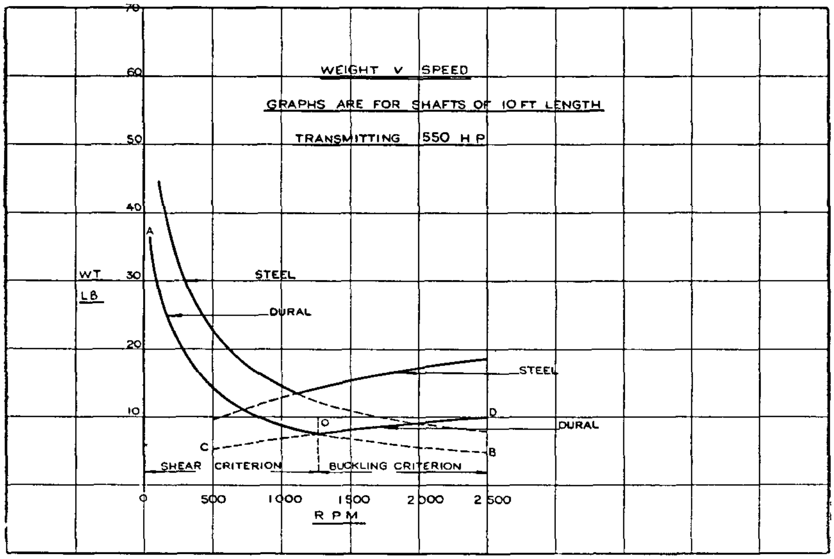

Fig 11 Transmission shafts

length, when considered on the basis of rotational speed, weight and buckling Assuming a given material there are three variables —

(1) Diameter of Shaft ,
(2) Wall thickness of shaft ,
(3) Rotational speed of shaft

and the conditions to be satisfied are,

(*a*) The shear stress should not exceed the proof shear stress of the material
(*b*) The shear stress should not exceed the permissible buckling stress of the material
(*c*) The rotational speed should not exceed the critical whirling speed

The two curves drawn satisfy conditions *a*, *b* and *c*, respectively, and show that for a given speed there is an optimum shaft weight, as indicated at point O

For speeds beyond this value the diameter of the shaft must be increased above that given by Curve A B On the other hand, it can be seen that an increase in diameter without a corresponding increase in wall thickness will bring the shaft into the region where buckling alone is critical Hence, from point O onwards, the shaft dimensions should satisfy conditions B and C, condition A being automatically satisfied, so that for speeds greater than that corresponding to point O, the optimum shaft is one which is designed to operate at its critical whirling speed and to be stressed to its critical buckling stress These conditions are fulfilled on Curve C D Point O indicates the lightest shaft commensurate with the speed at which it should operate

Another interesting and often overlooked problem in connection with shaft design is that connected with shafts coupled to cross-pin or " Hookes " type universal joints running at an angle Due to the angularity of the joint a component of the torque which gives rise to a bending of the shaft has to

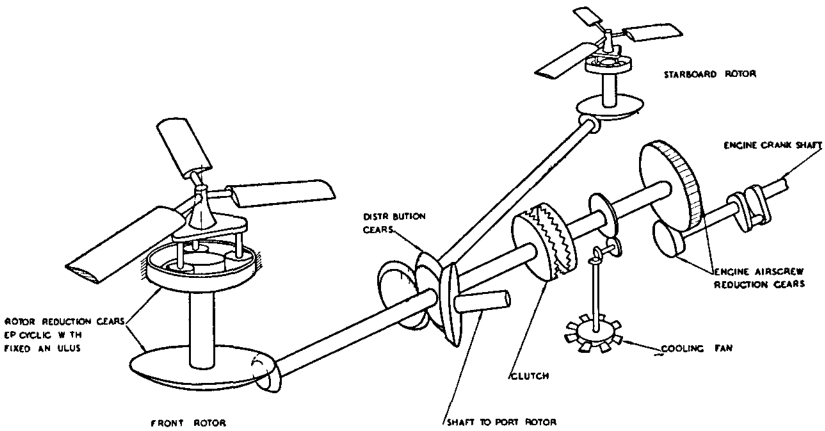

Fig 12 Diagram of " Air Horse " Transmission

be resisted In the " hookes " joint this component resolves itself into a periodic twice per rev impulse which reduces the first order of shaft critical speed to half the normal running speed, so that for shafts adjacent to universal joints to be run within their whirling speed the lengths should be arranged such, that the whirling speed is twice that of the running speed

Power is split at the distribution box and transmitted by the transmission shafts and couplings to the rotor hub gearbox without change of speed (Fig 12) Apart from the engine reduction gear a final speed reduction of 174 is obtained at the rotor hub making a total of 0733 between the engine crankshaft and the rotors The reduction at the rotor hub gearbox is obtained in two stages (Fig 13) The first by a pair of straight toothed bevel gears and the second by a train of epicyclic gears Both sets of gears are made from nickel-chrome case hardening steel and all teeth are case-hardened with the exception of the planet annulus The three planet gears are housed in a carrier which, in addition, forms the axle on to which the rotor hub linkage is mounted The three gears are carried on parallel roller bearings with the roller outer track formed as an integral part of the gear bore and the end location is obtained by a lip formed with the bore bearing on plain bronze thrust washers The planet sun gear is almost fully floating radially and is splined to one end of a quill shaft which receives the drive from the lower end of the crown bevel gear axle The top end of the sun gear is constrained lightly within a rubber backed bronze bearing

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At rest it centralises the sun gear but under load it allows the gear freedom to accommodate itself radially so as to look after inaccuracies which might occur in the manufacture and mounting of the planet train which otherwise might prevent the load from being shared equally between the planet gears

The annulus gear (Fig 13a), is spigoted and trapped between the top and bottom halves of a magnesium alloy gear casing which bolts direct on

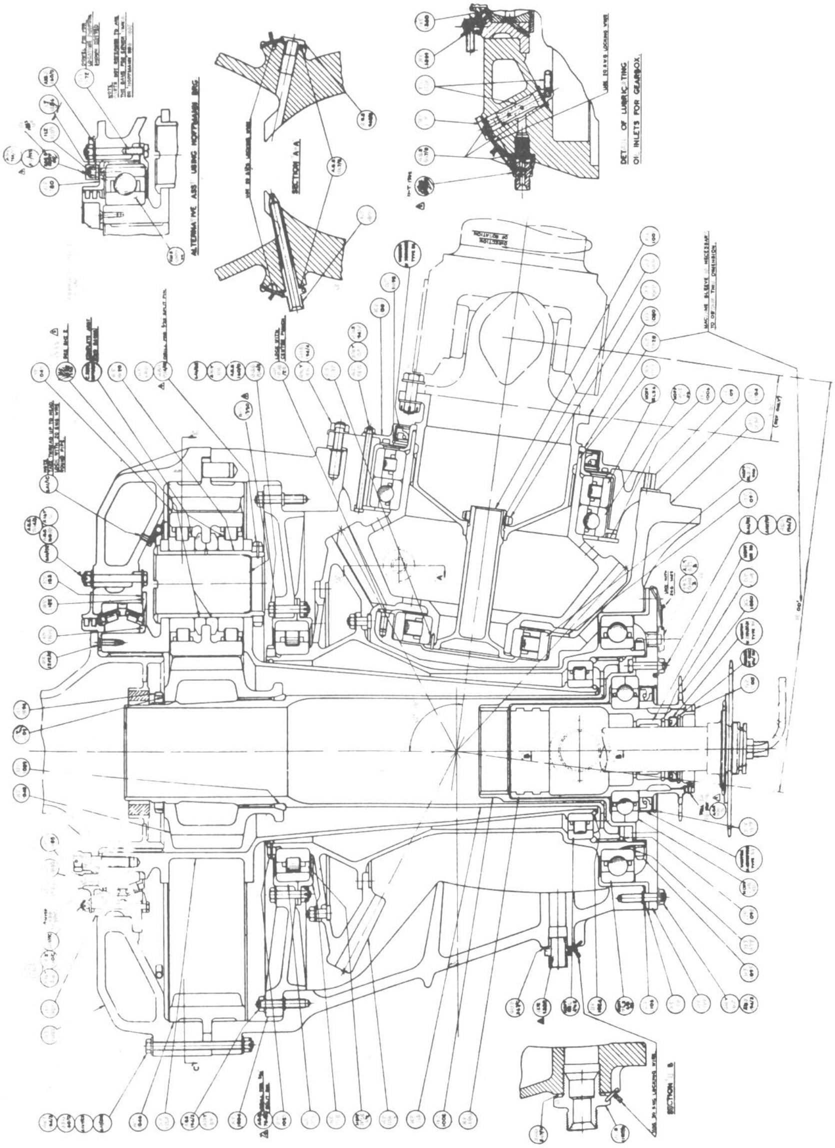

Fig 13 Rotor head reduction gear box

to the end of each of the outrigger booms The rotor lift loads are taken on a special taper roller bearing which also forms the top location for the planet carrier or rotor axle

Each of the three rotor drives is stressed to look after the possibility of a momentary flow of the full engine torque to one rotor which might occur under certain conditions of control This provision together with the safety factor called for under requirements brings the factor for each drive unit

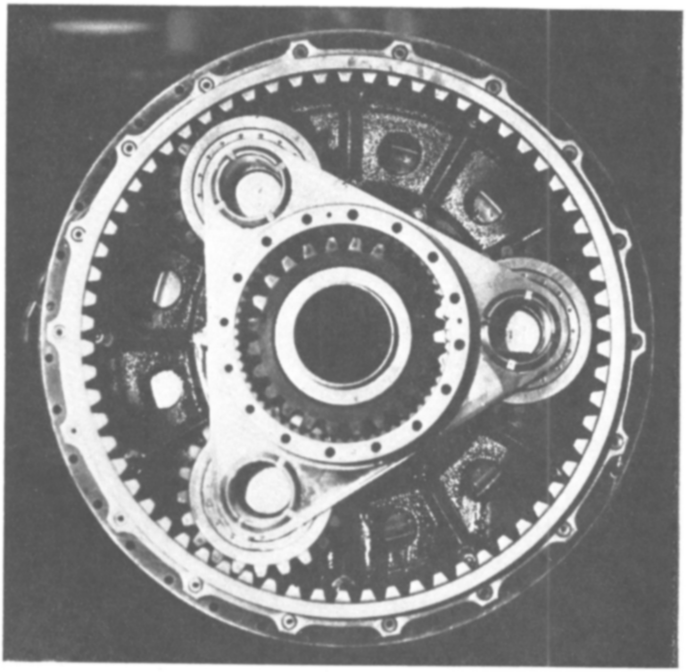

Fig 13a

under normal running conditions up to approximately 3 4 and although this bears a weight penalty, it considerably enhances the reliability and life of the transmission generally

Weights

The power unit installation weighs 14 per cent of the gross weight on the " Air Horse " This includes exhaust manifold, cooling fan and ducting, radiator, oil cooler, plumbing and accessories, etc

The transmission weighs 10 per cent of the gross weight including the transmission oil pumping system, oil cooling radiator, plumbing and the accessories which are mounted on the distribution gearbox

A major contribution to transmission weight, particularly in the multi-rotor configuration, is that brought about by the necessity of having to design around a very limited choice of ball and roller bearings Until such time as the bearing manufacturers can offer a choice of light section ball and roller bearings, particularly in the larger sizes, the penalty will have to be paid otherwise the designer will have to resort to the practice of designing "specials," a practice not to be recommended, particularly due to the high first cost of prototype bearings For example, the weight expended on ball

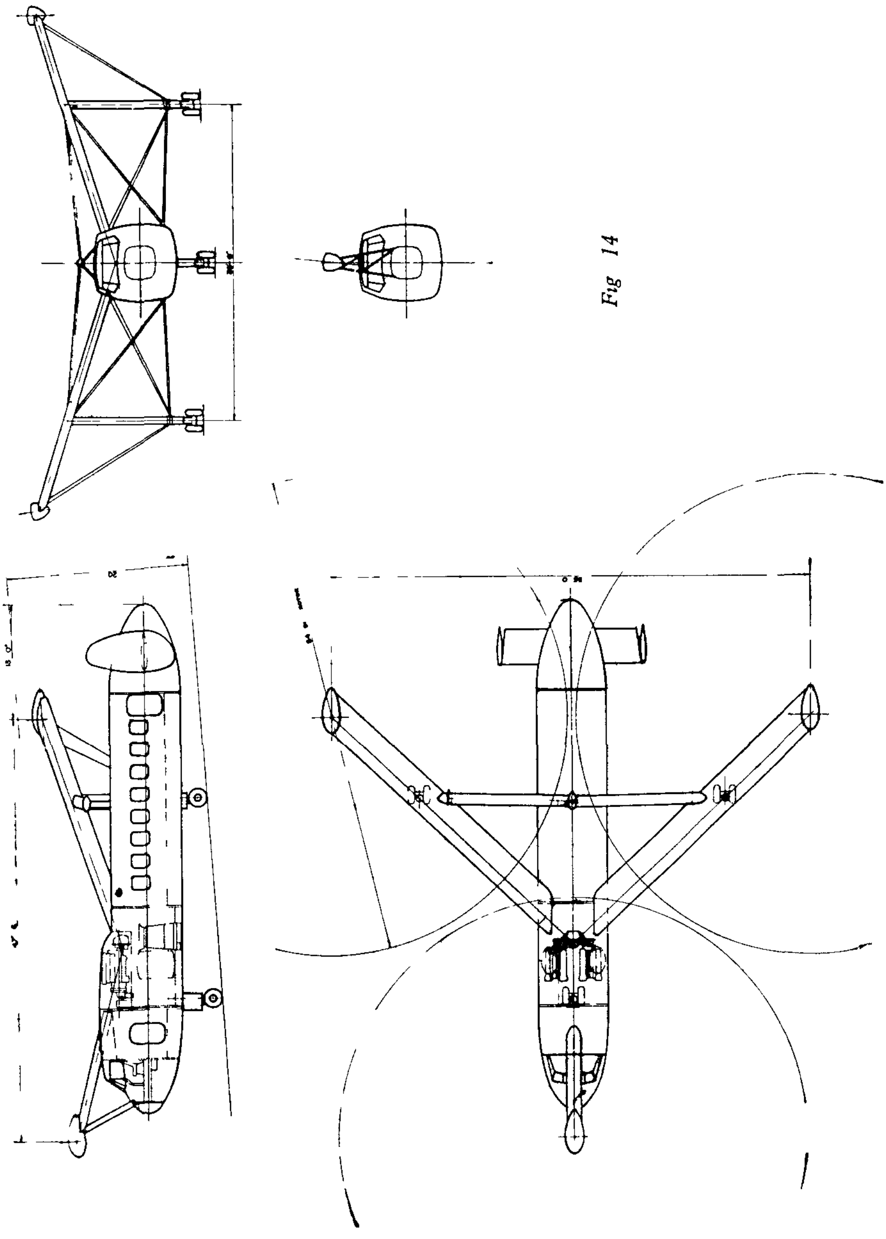

Fig 14

and roller bearings on the " Air Horse " transmission is 220 lbs or 13 per cent of the transmission weight

With the demand for twin power units for civil use together with the introduction of more rotors to absorb the larger powers, will come a variety of transmission problems to test the ingenuity of the helicopter engineer In the circumstances, therefore, it is proposed to touch briefly on some layouts and it is hoped that these will provide the student of the helicopter with some thoughts for the future

Fig 14 shows a typical three-rotor layout with twin Merlin engines with the power harnessed to a central unit which splits the power into proportions required by each of the rotors, gears all three rotors to one another and provides an over-riding clutch on the output shaft of each engine so that one or both engines can be over-riden in the event of a power failure Alternative gearbox layouts are shown and although that shown on Fig 15 is more compact and has less gears, it is, however, not as efficient as that shown on Fig 16 The question of transmission layouts that give the lowest losses must always be aimed at, particularly in the higher ranges For example, an additional 1 per cent loss on a 2,500 h p powered helicopter can be represented by a loss in payload of anything up to two passengers

The twin radial air-cooled engine layout on Fig 17 shows up well from the engine installation, maintenance and accessibility point of view but does not look so good when tackled from the transmission end

For the pure freighting helicopter, centrally disposed power units have the advantage in, that they allow complete freedom of access to a rear freight compartment particularly where the handling of heavy equipment has to be considered On the other hand, when considered for passenger handling or small bulk freight, power units located at the rear end of the fuselage give complete access between the pilots and passengers compartments, effectively isolate the fire zone and what is important for passenger carrying, considerably ease the problem of noise level, and above all, offer remarkably good access for servicing and changing of power units

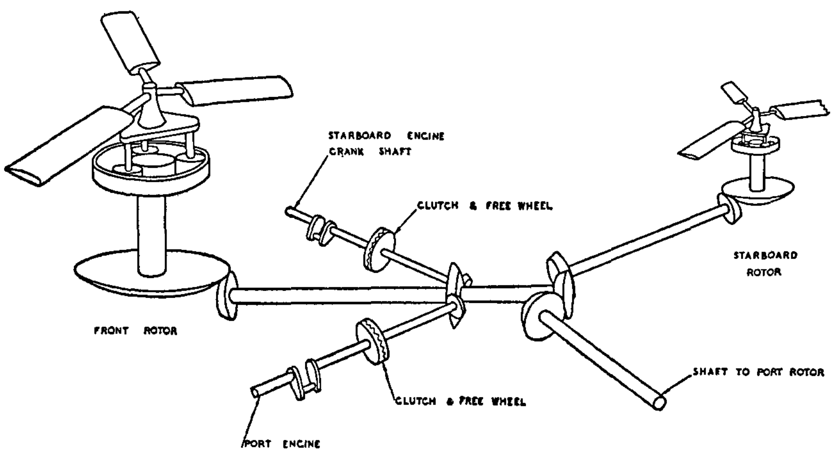

Fig 15 Diagram of Transmission, Twin-engine " Air Horse " (Scheme A)

The piston engine has now reached the stage where its performance can only be improved by the provision of better fuels and by the introduction of the ever-increasing mechanical complexity There are, however, on the other hand, indications that as the gas turbine is further developed, serious consideration will require to be given to its introduction as a helicopter power plant The greatest advantage of the turbine over the piston engine

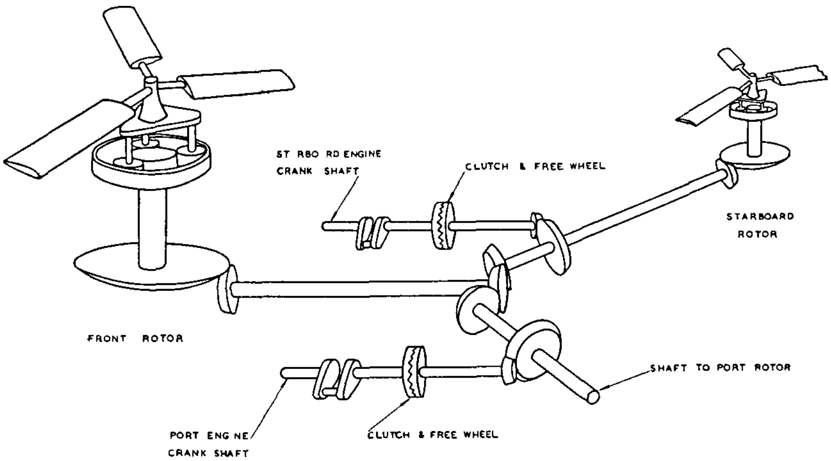

Fig 16 Diagram of Transmission, Twin-engine "Air Horse" (Scheme B)

is its simplicity With only a fraction of the number of parts maintenance is greatly reduced and therefore, apart from the question of aircraft serviceability, its introduction will reduce the number of servicing personel Once the specific fuel consumption is brought to reasonable limits for economic operation there is no doubt that it will replace the piston engine, since the turbine lends itself more readily to submerged power unit installations which are a feature of the helicopter For example, the problem of engine and exhaust cooling disappears, together with the ever attendant engine vibrations which have to be catered for Fig 18 shows a hypothetical layout for short distance passenger operation incorporating a twin " Dart " gas turbine power plant Fig 18a shows a similar layout with provision for front freight loading doors

Another interesting transmission problem is offered by the twin engined four rotor configuration with the four planwise displaced rotors arranged in two sets oppositely rotating, each of the opposing rotors being driven by a separate engine in such a way that failure of one power unit brings one pair of rotors into autorotation while the other pair remain to be driven as helicopter rotors

Speed Change Gear

Until such time as an otherwise suitable power unit is available whose characteristics can be matched with the power and speed characteristics of a helicopter rotor in all flight conditions, the installation of a change speed gear in conjunction with the conventional aero engine will considerably

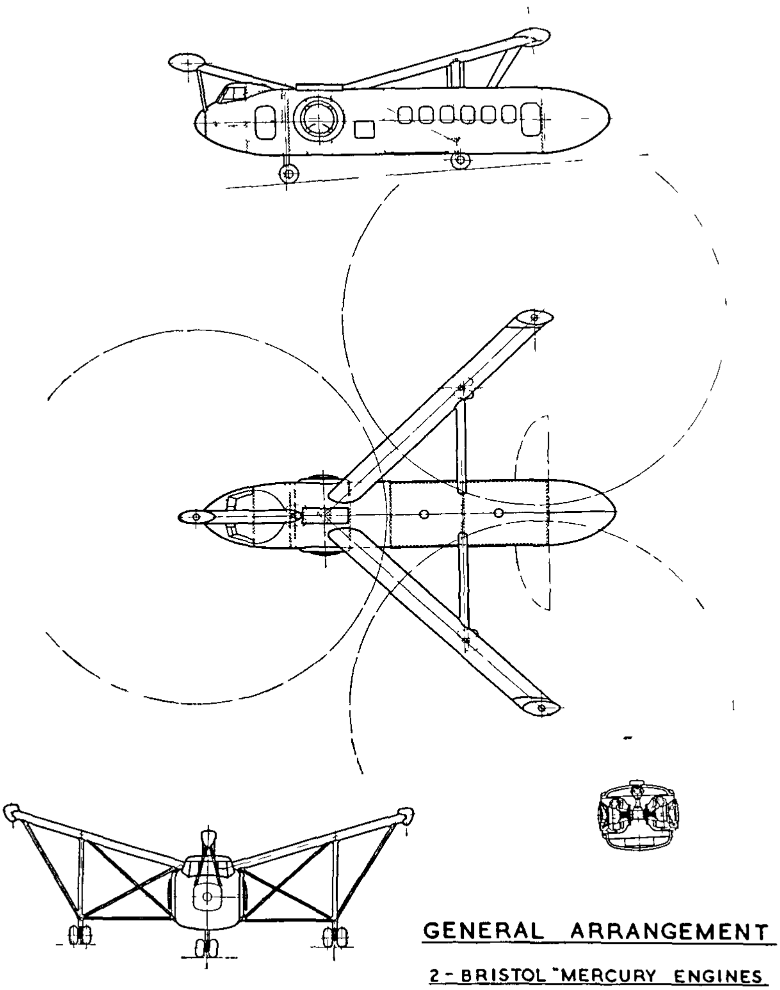

Fig 17

improve the performance of the helicopter Efficiency in hovering and vertical ascent and high forward speed requires high tip speed to delay tip stalling of the retreating blade Consequently, with a conventional aero engine and fixed ratio of crankshaft to rotor, the maximum engine power cannot be available in both these conditions , if the gear reduction ratio is great enough to give the low maximum rotor r p m called for in hovering and vertical flight, the maximum forward speed will be limited by tip stalling to a value at which the full engine power will not be absorbed, *i e* , full throttle cannot be used , but if the gear ratio will permit full throttle in forward flight, the rotor will be inefficient in hovering and vertical ascent owing to excessive r p m and too low a blade angle This is clearly illustrated in a recent article by PIASECKI and is shown on Fig 19

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Conventional change speed gears, however, are not satisfactory since the drive must be interrupted during gear changes necessitating throttling back of the engine to prevent over-speeding and re-opening of the throttle when the selected gear is engaged Such a method of gear change is unacceptable in a helicopter, for no matter how short the period of disengagement during the changes may be, there still remains a momentary interruption

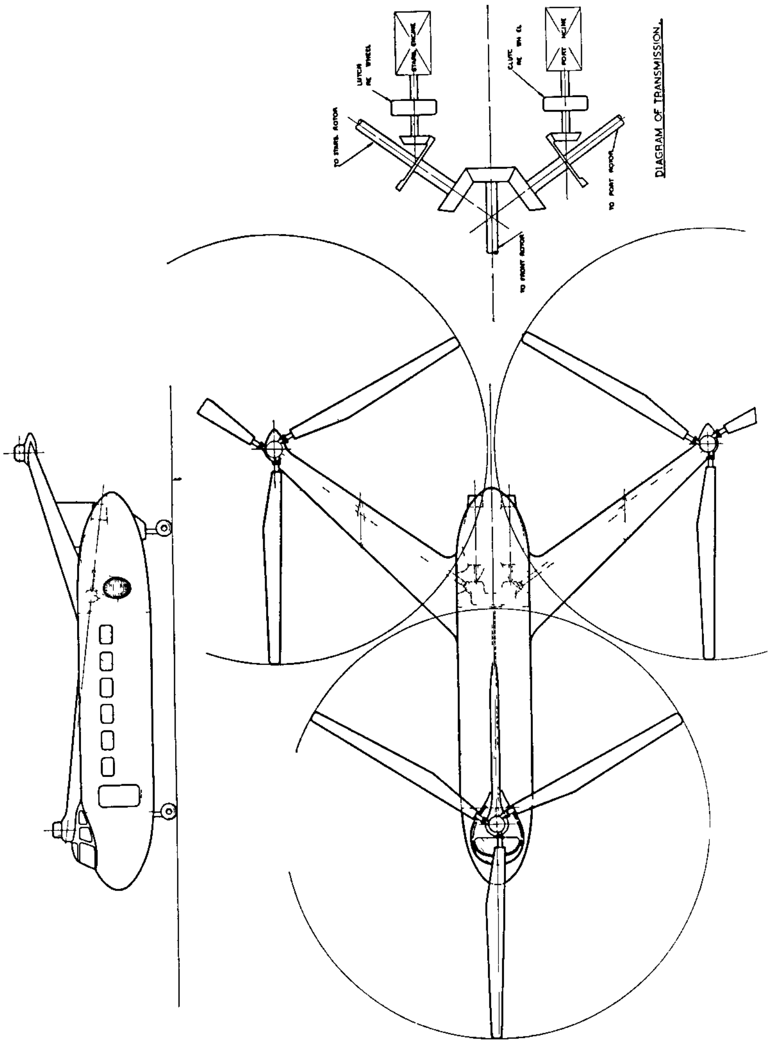


Fig 18 Three rotor passenger configuration with twin gas turbines

of power input to the rotor which should be avoided at all costs whether in changing " up " or " down " Fig 20 shows a proposed speed change gear which could be conveniently accommodated in a typical single rotor layout There is no interval of complete disengagement and therefore, no interruption

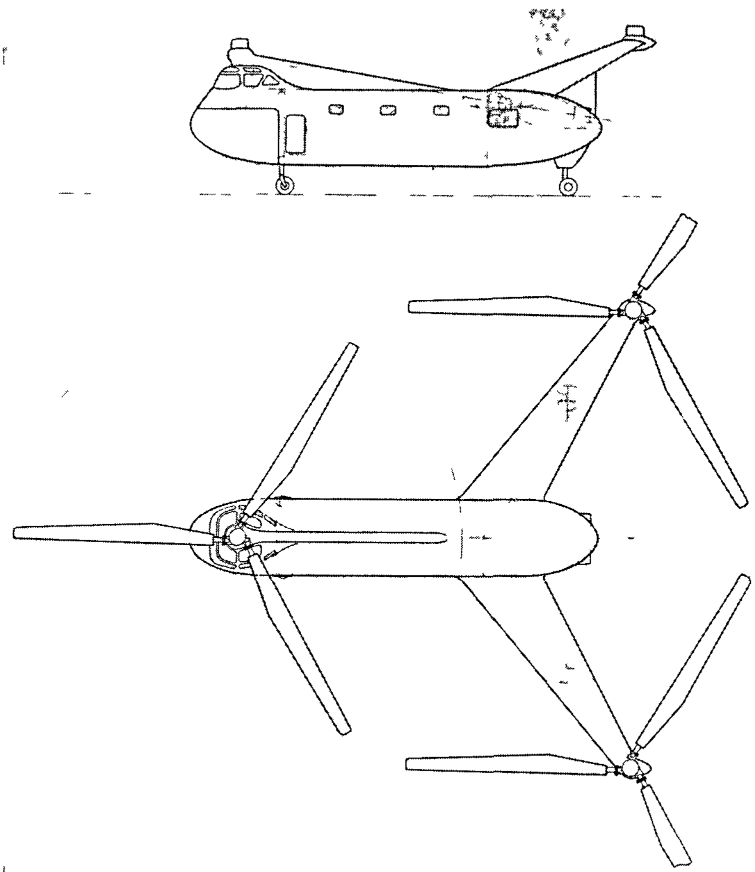


Fig 18a Three rotor freighter with twin gas turbines

of power Torque is continuously transmitted during gear changes, whether up or down

Furthermore, a change speed gear of this type incorporates as essential parts, elements which in any case have to be incorporated in helicopter rotor transmission systems, namely, a slipping clutch for starting a free-wheel clutch and a train of speed reduction gearing Consequently, a change speed gear adds little if any weight and complication to the transmission as compared with the fixed ratio system

In the " low " speed drive the friction clutch is disengaged and the power is transmitted direct from engine to rotor through the epicycle train comprising of T^1, T^2, and T^3, which gives a speed reduction between engine and rotor of $\frac{T^1}{T^3 + T^1}$

Engagement of the " high " speed drive is obtained by a gradual application of the friction clutch which speeds up the rotor shaft to give a reduction of

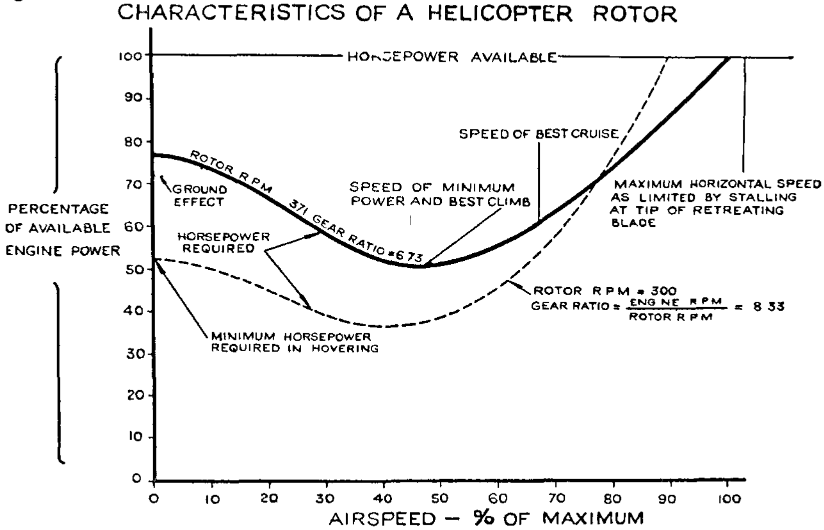
$$\frac{T^2 \times T^4}{(T^2 + T^4) + (T^5 \times T^3)}$$

between engine and rotor When engagement of the " high " speed train is obtained sun wheel (1) is over-ridden on the engine shaft through the free wheel (6) The change down is affected by a gradual disengaging and slipping of the friction clutch until the free-wheel in the sun wheel of the low speed train again picks up the drive

The speed changing clutch is also used as the rotor starting clutch The roller free-wheel clutch (6) is of the " lock-in," " lock-out " type similar to that used on the " Air Horse " so that at rest it is inoperative This allows the rotor to be started up by driving through the " high " speed epicyclic train and then slipping the friction clutch until the roller clutch (6) takes over to engage the low speed gear Provision is provided in either gear train for over-drive in the event of power failure In the " low " speed gear, the " lock-in," " lock-out " roller clutch is free to over-ride and in the " high " speed gear the free-wheel connecting the friction clutch plate to the " high " speed sun gear is also free to over-ride As an alternative to the speed changing friction clutch a " scoop " controlled fluid coupling appears to offer advantages as the change-over link At starting the coupling is normally empty The drive is engaged by " scooping " the fluid into the coupling, so that for the speed change, a progressive and smooth slipping is provided by application of the scoop control

The layman accepts the helicopter as a remarkable flying machine that can perform many duties hitherto unknown He observes the rotors whirling

Fig 19 EFFECT OF VARIABLE GEAR RATIO ON POWER REQUIRED CHARACTERISTICS OF A HELICOPTER ROTOR



round, he hears the engine exhaust note, but what goes on between remains a mystery Here lies a vast field of intricate and interesting problems that will tax the ingenuity of the mechanical engineer

In conclusion, I wish to thank my colleagues of the Cierva Autogiro Company for help given and to thank you, ladies and gentlemen, for your attention I also wish to thank the Cierva Autogiro Company and Ministry of Supply for permission to present this paper

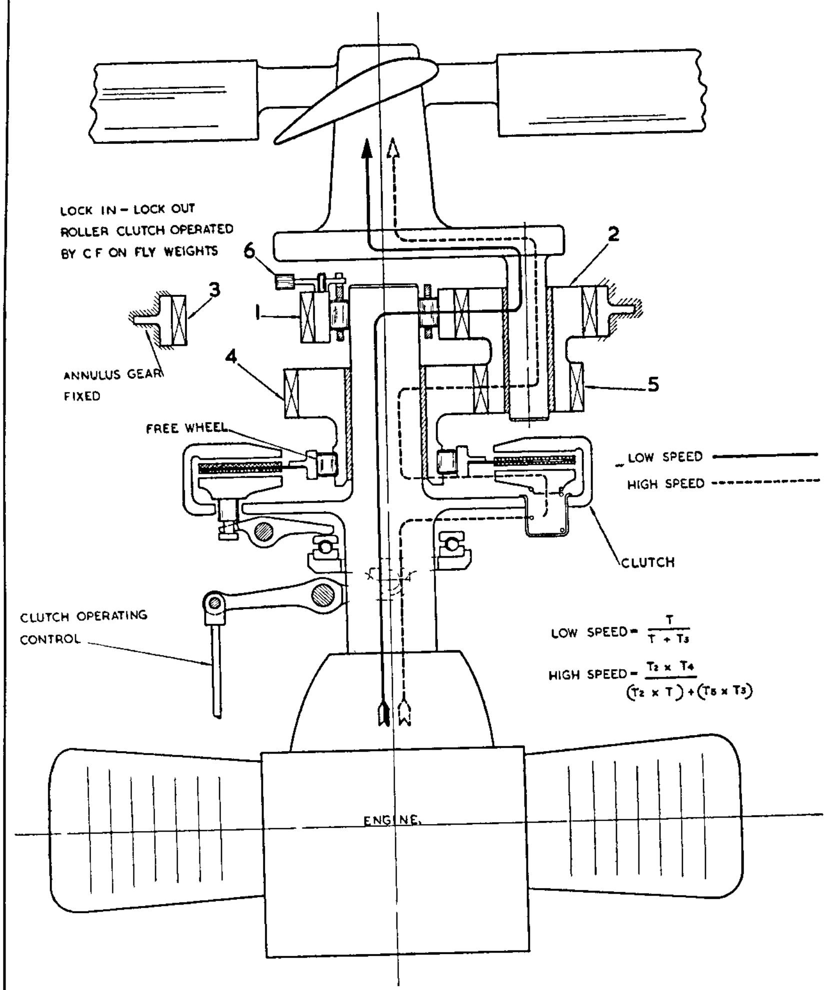


Fig 20 Diagram of two-speed change gear

Discussion

Mr G E Walker (*Bristol Aeroplane Company*) (*Founder Member*) Many papers have been read before this association giving the scientific or mathematical aspect of helicopters and I am sure many members and friends have been pleased to hear something of the more tangible problems connected with the development of this type of aircraft There must be many here besides myself who have questions to ask and observations to make, and in view of this I do not wish to take up too much time Having listened to MR WATSON'S paper, there are one or two points on which I would like to say a few words

In the first place MR WATSON indicates that to the layman that part of a Helicopter between the engine and the Rotor blades remains a mystery I must say I have more often heard it referred to as just common engineering I think that those of us who are familiar with the inside story of Helicopter transmissions will agree that although there are no such things as mysteries in engineering the problems are by no means common

I heartily endorse MR WATSON'S remarks with reference to the need for simplicity reliability—and I would add—ease and low cost of maintenance, as it will finally rest with the operators to decide whether one particular type of transmission is a success or not There must also be a tendency, as the development of the Helicopter proceeds, for transmissions to be standardized, may be not as a whole, but component by component By this I mean that as the majority of motor cars have single plate clutches and bevel gear differentials in their back axles, so the clutches, transmission shafts and free wheel units of Helicopters will by a gradual process of development become standardized in principle

It is with the idea in mind of satisfying one or all of these considerations that I put forward the following observations MR WATSON has made the suggestion that a rotor may with greater efficiency be driven through a two speed gear Now although it is agreed that a lower rotor speed is required for efficiency in hovering than in forward speed the speed change gear must add to the complication and cost of maintenance Added to this I estimate that in a normal passenger carrying service the total hovering time of a Helicopter is only 4 per cent of the life of the aircraft I would suggest, therefore, that except in the case of a Helicopter which has some specialized job where the time spent in hovering occupies a large percentage of the total life, a two speed gear would not be worth while

I was very interested in the method used in the " Air Horse " for clutching the engine to the transmission I refer to the principle whereby a small clutch is used to start the rotors moving slowly and to synchronise the speed with that of the engine, after which a positive drive of some type is moved into engagement for all powers and speeds above idling As we all know, rotor blades are liable to damage due to a sudden application of torque at starting Once they are on the move, however, they are not *nearly* so vulnerable I might add that I think it desirable to run the transmission and rotors as well as the engine during the warming up period My reason for this statement is that an engine running without load usually produces excessive vibrations On the other hand, when we have more experience of operating Helicopters on passenger services we may find it imperative to stop the rotors and keep the engine running during the embarkation and disembarkation of passengers

The next point I wish to mention is the efficiency of various gear systems MR WATSON has shown us a number of diagrams showing alternative arrangements of gearing, some of which he states are more efficient than others according, I presume, to the number of gear tooth meshings in series between the engine crankshaft and the rotor I have heard it said that one can assume a loss of 1 per cent of the power transmitted through a pair of spur gears and 1½ per cent through a pair of bevels It is inadvisable to be dogmatic about these figures as the total loss through a pair of gears may be divided into three parts (1) The frictional loss due to rubbing of the teeth , (2) The loss due to churning of the lubricating oil and (3) The loss due to friction in the bearings The friction between the teeth is quite a big percentage of the total loss It is, therefore, important that the gears should have the correct hardness and profile as well as being rigidly mounted

Of equally great importance, is the requirement for a helicopter transmission system to have a minimum number of gears in series between engine crankshaft and rotor MR WATSON points out in his paper that a loss of 1 per cent of the engine power in gear losses, etc, on a large helicopter reduces the payload by the equivalent of two passengers

We have considered this aspect of the general transmission problem, and it has been possible in all types of Bristol helicopters for the whole of the 11 to 1 speed reduction between crankshaft and rotor to be effected through two pairs of gears only

Looking at the slide showing the drawing of the distribution gearbox of the "Air Horse," I notice that there are three bevel gears meshing together It is usual when making gear adjustments for a pair of bevel gears to move both gears in or out as required along their respective axes by means of shims After two gears have been adjusted in this manner the mating of the third gear with one already fixed in position would, to my mind, present some difficulty I would like to ask MR WATSON if this is so or if special precautions have been taken to overcome the problem

I notice that Magnesium Castings are used extensively in the "Air Horse" gearboxes We have also used this material but are changing over in some cases to aluminium alloy because of the latter's higher modulus of elasticity giving smaller deflections under the high torque loads associated with rotor drives We have made a point too of carrying the weight of the aircraft in flight by steel components only, that is, the rotor is attached to the aircraft via its bearings and rotor axle so that the light alloy gearbox castings carry gear loads only

There is one final point I would like to mention with regard to the "Air Horse" transmission shafts, which I understand are manufactured from aluminium alloy tubes I note they have a universal joint at each end working through an angle of 8° This angle will cause the whole shaft to have an angular oscillation at a frequency of twice its running speed I would like to ask MR WATSON if the possibility of fatigue has here been considered and if the fitting of constant velocity joints at each end would not be an advantage

In conclusion I wish to thank MR WATSON for a very interesting paper

Capt A Graham Forsyth (*Fairey Aviation Company*) (*Member*) We have heard a very fine paper presented, including a splendid description of the "Air Horse" installation, which can be regarded as an outstanding achievement in the helicopter field I hope that future changes will not be severe, and I am certain that this Association wishes the Cierva Company every success with the "Air Horse"

Now I am in difficulties, because MR WALKER has covered many of the points I had intended to make However, a few remain One of them concerns the cooling system I note that it is recorded that 1¼ per cent of the engine power is absorbed by the fan Does this mean that the whole of the cooling is done for that 1¼ per cent, because generally the figure is somewhere about 5—7 per cent?

Another point is that cast iron has been sprayed on to magnesium castings used in connection with the driving of the fan, and I should like to know how the castings are getting on, for I feel that, judging by our experience of sprayed duralumin, quite a lot of corrosion might be set up between the iron and the magnesium

Next, I was surprised to hear what was said about the Merlin reduction gear I should have thought that if you had used the light alloys you would have achieved improvement

In connection with bevel gears a point was made about the strength of tooth, and MR WATSON said that the wear is not so important, for replacement can be made easily But I think there is some difficulty about it, because you cannot really see the extent of the wear unless you do a lot of stripping during the running period

A matter which might well be stressed is that of meshing gears You may have perfectly-made gears, giving all the required characteristics of strength, etc, but if they are very badly meshed they can fail quite soon, and in assemblies in magnesium cases and things like that you have to allow for various expansions on the assemblies It is not just a simple case of putting a pair of bevels in a gearbox, we find there must be anything up to 30 or 40 thou (0 030—0 040 in) offset before we can get the mesh properly, with the result that the gears are likely to give trouble in the early stages due to the situation at the tips

I sympathize with MR WATSON in regard to ball bearings, because if we use the standard as indicated in the catalogue it is impossible to produce a satisfactory transmission We have all worked together on this subject with a view to getting the ball bearing people to produce the right bearings for our purpose, I have been very fortunate because Messrs Hoffmann have co-operated, and I have obtained what I want

In connection with gear losses, an example has been given of 2,500 h p where a loss of 1 per cent means anything up to the weight of two passengers What percentage is lost through the transmission of the "Air Horse"?

It is obvious that helicopters of the "Air Horse size will have to be multi-engined eventually, and the various schemes put forward by MR WATSON are most interesting It appears that we are suffering from lack of suitable engines, and I emphasise that until we can get engines to suit helicopter requirements we really cannot make the best job of twin-engined installations In the case illustrated where the two Mercuries were used I think the arrangement is the best from the point of view of maintenance, and so on, and with co-operation from the engine side we can probably get the transmission through the whole length of the fuselage, instead of having to set up from the gear in the centre

The engine position in this country is very poor, and I think the only serious attempt has been the Alvis "Leonides," which enables one to produce an aircraft having the fewest number of gears between the engine and the rotor, which arrangement, as MR WALKER has said, is very desirable

There has been reference to transferring from piston engines to turbines I do not by any means agree that the piston engine is dead, and I think that for the present range of helicopters it is best that we should adhere to that type of engine We really want someone to develop a large size piston engine, for to my way of thinking the capability of the piston engine to develop its power over its whole range is very important The turbine at present has a very short speed range, and without the use of multi gears between the turbine and the rotor the stalling probability is very high and there are difficulties in connection with starting torque and running up the rotor speed Whilst I agree that two-speed gears offer many advantages, I also agree with MR WALKER that they appear to introduce unnecessary complication, especially when the turbine is used as the power unit

In connection with lubrication, the oil point is behind the clutch, so that you have the whole of the oil passing through and it is not cooled Are there any ill effects due to the rise in temperature and what is the temperature rise?

Mr J A C Williams (*Firth Helicopters Ltd*) I am appreciative of the opportunity given to us this afternoon to hear the extremely informative and well-ordered paper presented by MR WATSON May I be allowed first to ask one question on the subject of the magnesium clutch friction faces which have sprayed cast iron on them? Is it possible for MR WATSON to give further details of the process? If that is impossible, may I ask whether the powdered metallurgy process was also tried in the development of this form of friction clutch?

Considering the paper as a whole, Fig 11 shows an interesting comparison between the relative weights of steel and dural shafts, but the comparative figures for magnesium are not given In view of the fact that magnesium has been used extensively in other parts of the transmission system in the "Air Horse,' why was not the use of a magnesium shaft investigated in this connection? Or was it? Is it that magnesium shafts have certain disadvantages which are not mentioned, or merely that the supply position was such that the magnesium type shaft could not be used?

As an interesting comment on the use of magnesium-zirconium for these long shafts, such a shaft has been used on the Planet "Satellite" to transmit 250 h p at some 2,400 r p m Up to the present time it has given satisfactory results over a long period of ground running and, therefore, I would suggest that further weight-saving could be achieved on long transmission shafts by the use of the latest type magnesium-zirconium tubing This in itself may affect to a quite considerable extent the use of high or low speed shafts

Under present requirements a weak link must be provided in the transmission system, and that in itself seems to me to present a very knotty problem, in view of the fact that a weak link is essentially dependent upon the strength of the link component, for it must be assumed that other parts are jamming The strength of the weak link will obviously vary with the type of fatigue load imposed, the form of the f *versus* N curve for the material Steel has a fatigue limit, aluminium has not a strict fatigue limit so far as I know, and magnesium lies somewhere between those two in respect of fatigue limit Therefore, the strength of the weak link itself will vary quite a lot according to the number of hours run by the component If such a weak link fails in normal running service, it probably means the loss of an engine, unless special governing devices are fitted May there not be a case for considering wet type clutches in this application, for I believe the probability of their seizing is virtually zero ?

The paper has dealt with the extremely intricate problems of the transmission on a large helicopter, which in some ways are similar to those in the smaller type helicopter, except that in the latter there are certain problems which arise purely from the restriction in size In illustration of that I would mention that in the " Air Horse," for instance, there is an axial flow type fan , with that type of fan, in order to secure high efficiency, there must be proper diffusion of the air flow after passing through the fan blades and stator system But that requirement is virtually ruled out on the small helicopter, and a centrifugal type fan must be employed This has the advantage that it does not appear to be susceptible to dimensional accuracy to the same extent as does the axial flow type For example, in the latter type a considerable amount of efficiency can be lost by large tip clearance The axial flow type fan must be run at a higher tip speed than the centrifugal type for a given air pressure differential across it in most applications Therefore implicit in the design of the axial flow fan is a larger diameter, which means a larger flywheel inertia for a given weight

The question of scaling helicopter size, especially in transmission, is an extremely vexed one Doubtless you will be familiar with the Landgraf type of inclined rod transmission, which Mr Landgraf evolved during the last war, because of his inability to get any gears cut for a normal type transmission This form of transmission seems to have worked well in his prototype machine, and on the present Firth helicopter its use is being extended to a higher torque It is debatable whether or not a more conventional system might be designed for the larger Firth machine for the same weight , but a conventional system would be more complicated and would have a smaller safety factor In this type of transmission the resolved tension in the wire is sufficient to offset the load from the lift in each rotor It has a somewhat unique feature, in that, so far as can be seen, no true resonant frequency exists in the individual wires, as the tension in the wires, and therefore the frequency, is varying cyclically

Mr A McClements (*Chief Development Engineer, British European Airways*) (*Founder Member*) I do not propose to say anything about the design aspect of transmission systems because there are many people here today far better qualified to do this than I am However, I have had the opportunity of being associated with regular helicopter operations on a modest scale and it might be of some interest if I mention a few of the things about transmission systems of certificated helicopters which we have learnt during regular usage Firstly, we find that in spite of all they are called upon to do, transmission systems are basically reliable, *i e* , if properly maintained they do not suddenly stop functioning However, they do give some trouble and quite a high percentage of the overall defects experienced by us were found in the transmission This can be appreciated by noting that during some 1,400 hours flying, about 50 per cent of the defects thrown up appeared in the transmission systems (When referring to the transmission system, I mean everything required to convey the power to the blades up to and including the rotor hubs) Notable among the parts of the transmission which gave trouble were the main and tail rotor heads which amounted to 50 per cent of the defects, the gearbox which amounted to 20 per cent , the clutch (12 per cent), and the rotor brake (10 per cent)

Another aspect of the transmission of vital interest to the operator is the effort which he has to expend on it Here we find that during important inspections about 80 per cent of the work required is done on the transmission

I have mentioned these figures because I think they do indicate on which parts of the transmission improvements can be introduced most fruitfully Also to appreciably lower maintenance costs and increase utilization, transmission improvements are the obvious thing to aim at

If we look at the types of defects which have arisen we will find that these are largely associated with wear of such parts as clutch shoes, needle bearings, rotor brake shoes, and indeed the majority of the parts at fault could have had their lives assessed before ever they reached the operator Indeed it would seem that the whole transmission system lends itself to life assessment under laboratory and rig conditions, and I believe if this were done extensively and care taken to make component replacement easy and servicing simple, the manufacturer would go a very long way towards cheapening maintenance and increasing utilisation

Mr Raoul Hafner (*Member*) The question which interests me mainly is that of the design of gears MR WATSON has said that it would be a good thing to design gears for strength rather than for wear I am rather inclined towards Mr Forsyth's view, that we should balance the requirements, that we should make them equally good from the points of view of both wear and strength, because we want to extend the periods between general overhauls as much as possible Again, in this case there is no means of inspecting the surfaces during service, and if those surfaces are allowed to deteriorate there will be, not only wear, but eventually fracture

Another point of interest to me is that of shafts MR WATSON has exhibited a graph showing the merits of steel and aluminium shafts I do not think the factor of limiting fatigue strength has been mentioned But the light alloys have a low limiting fatigue strength, and I cannot help feeling that the light alloy shaft is ruled out

A further point of interest to me is that of elastic couplings MR WATSON has pointed to their damping properties , I feel rather that elastic couplings in transmission are there to provide elasticity Our job is to ensure that the exciting frequencies fed into the system from the driving or driven end are outside the various modes of oscillation in which this system can move, and that we introduce these elastic couplings—and I stress the elasticity of the couplings—to vary the natural frequency of the systems I do not think the damping feature is an important one

I should like to hear what MR WATSON has to say on these matters

Mr J S Shapiro (*Cierva Autogiro Company, Ltd*) (*Founder Member*) Perhaps I may first make a comment on Mr Hafner's remarks Some time ago I had occasion to stress the importance of speaking in numerical terms I can assure you that light alloy shafts are about 50 per cent better in respect of fatigue than are steel shafts , we can only assess the matter on general grounds—in other words, on fatigue values as we know them—but I think the assessment is fairly reliable

Magnesium shafts are not suitable, for their fatigue limit is worse than that of steel shafts That situation may be altered in the future, and indeed, we have some indications of it, but so far we cannot use magnesium shafts with any reliability

With regard to axial flow fans I would like to say that even in small sizes they can be made efficient, and that they do not need all the extras which render their use impossible in small installations

I disagree with MR WATSON with regard to turbines If the piston type internal combustion engine has not very desirable characteristics in association with the rotor, the turbine is even worse But we may not have any choice in the matter, and I think the turbines must be regarded by the helicopter designers as a fresh calamity which must be accepted

Mr Kenneth Watson (in reply) I should like first to refer to the remarks of Mr Walker and Mr Forsyth in connection with the use of the two-speed gear, " with all its attendant difficulties," and so on Such a gear need not introduce any further complications to the system As I have said, the elements which constitute that gear are already a necessity in the typical helicopter system of transmission, and only by suitably re-arranging the components can such a gear be used without the penalties involved in extra weight

I agree entirely with MR WALKER that a very small percentage of the total life of a helicopter is spent in hovering But during that very short percentage of time the helicopter has to be lifted from the ground, and it is in lifting that I am sure the two-speed gear can be of considerable value, it should make possible increasing pay-loads, and so on

The next point, which both MR WALKER and MR FORSYTH mentioned, is that of the difficulty of gear meshing, and MR WALKER referred particularly to the meshing of three bevel gears I admit that that seems to be quite a problem when one looks at it, but present day precision methods of cutting gears, meshing them, and so on, brings the possibility of the solution of that problem well within practical scope In the particular example I mentioned, that of the "Air Horse" distribution gearbox, we have three gears which are more or less identical That solves the problem of inaccuracies in tooth dimension The difficult factor was the gear casting itself, the bores for the output bevels, and there were compound angles However, that did not appear to offer great difficulties to the manufacturers Having personally meshed many gears in my time, and having seen the mesh of that particular set of gears, I can say that I have not seen anything better anywhere, so that the difficulties associated with such a problem can be overcome by good machining and the maintenance of accuracy

Then MR WALKER mentioned the problem of the universal joints on the ends of the long transmission shaft, and the possibility of fatigue due to the torsional variation twice per rev arising from the double angularity This was considered carefully The fatigue set up by such variation is well within the capability of the materials, and the possibility of incorporating constant velocity joints is rather frightening, for in the first place the cost will be much heavier, and an additional bearing is demanded

Reference was made by MR FORSYTH to the unusually low percentage of power required for driving the "Air Horse" cooling fan I can assure him that the power required to drive that fan *is* only $1\frac{1}{4}$ per cent of the engine power

As to the spraying of cast iron on to aluminium or magnesium, the first attack on that problem was made by the Cierva Company in the case of a clutch some years ago In a standard automobile clutch the components normally made in cast iron were made in aluminium alloy, and the clutch rubbing faces had a close-grained cast iron sprayed on to them I do not know from the technical point of view what goes on between the two metals in the way of corrosion, but the particular case I have mentioned is probably about three years old by now and there is no outward indication of any such corrosion occurring

The spraying of cast iron on to magnesium is a different problem, and in that case I cannot give any answer now because insufficient time has elapsed since the application of the cast iron But the material on the cooling fan of the "Air Horse" has been sprayed on for about 18 months now and it has not shown any signs of deterioration

Another question is that of the gas turbine having a very narrow band of the power range, as compared with the piston engine I am sure that the introduction of the two-speed gear with the turbine will considerably expand that range in so far as the application of the turbine to the rotor is concerned

I think MR SHAPIRO has answered MR WILLIAMS' question concerning magnesium shafts, and also MR HAFNER'S in connection with the merits of light alloy as against steel shafting

On the question of gear strength and wearing qualities, mentioned by MR HAFNER and MR FORSYTH, I still maintain that gear strength should be given preference over wearing qualities One is given no indication that a tooth will fail, it just happens On the other hand, wear can be detected without stripping the components, simply by measuring the backlash Thus it is my experience and my firm view that strength should always have preference over wear

In reply to MR FORSYTH'S query regarding lubrication the temperature rise was about 20° and the oil was passed through a cooler afterwards

In conclusion, I thank you for your attention and for your contributions to the discussion

WRITTEN CONTRIBUTION

J A C Williams (*Firth Helicopters Ltd*) I cannot agree with MR SHAPIRO on the subject of magnesium alloy fatigue strength and can only assume that his conclusions were drawn before the figures given below were obtained The fatigue strength for the latest type of magnesium-zirconium alloy based on 50 million Wohler type reversals are —

	Unnotched	Notched
Casting DTD 721 (heat treated)	± 5 5 tons/sq in	± 5 5
Extrusion DTD 733	± 9 5 tons/sq in	± 5 75

We can take ±11 5 tons/sq in for the fatigue strength of double heat treated aluminium alloys in the unnotched condition The specific gravities can be taken as 1 80 and 2 80 for magnesium-zirconium and aluminium alloys respectively and the comparative weight-factored fatigue strengths of extruded magnesium-zirconium would be —

Unnotched ± 14 8 tons/sq in *Notched* ± 8 95 tons/sq in

on the aluminium alloy basis These figures suggest that the magnesium-zirconium alloy is equal to, if not superior to, the highest strength aluminium alloy

MR WALKER has said that a change to aluminium from magnesium has been made on certain castings due to deflection troubles Surely this needs specific qualification and probably refers to a case of size limitation Designing on a weight basis most people change from aluminium to magnesium castings in order to decrease deflection

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MR A McCLEMENTS' VOTE OF THANKS TO MR WATSON

MR McCLEMENTS It gives me very great pleasure to thank Mr Watson for having devoted the time and effort necessary to prepare his paper and to come here to present it He has been associated with helicopter development for a long time and has specialised on one of its most important aspects, namely, transmission systems, the conception and engineering of which call for skill and ingenuity of the highest order Such qualities have been manifest in the projects with which Mr Watson has been associated, and particularly in the " Air Horse," which I understand is the world's largest helicopter I think you would all wish me to congratulate him and the Cierva Company on the magnificent progress made with the " Air Horse " and to wish them continued success with it , I do so on your behalf (Hear, hear)

From the paper presented today it is obvious that Mr Watson has contributed information of major importance to the records of our Association It remains only for me to thank him and to ask you to signify your approval

The vote of thanks was heartily accorded, and the meeting closed