Discussion

The **Chairman,** in opening the discussion, thanked the member who had demonstrated the slides, and put to the Author some questions submitted by Sq /Ldr GELLATLY (*Member—A & A E E*), who, unfortunately, had been unable to attend The questions concerned —

(1) What was the future of the shaft drive Assuming it had a future, what development did the lecturer foresee firstly, for the piston-engined aircraft with two-speed gears, and secondly, in connection with the turbine engine and its surge problems

(2) What were the lecturer s thoughts on constant speeding, constant torque devices which were of interest in helicopter design, clutch design in relation to normal operating conditions, the anti-drive system—rotor brakes, and, built-in torque-meters not only for test purposes but for operational uses

(3) Finally there was the general question of maintenance and inspection

The CHAIRMAN said it had been a most interesting Paper, which showed a very careful thought in the design of these mechanisms, a thought which might sometimes be missing from helicopter design He suggested that the first part of the discussion should keep to the problems of transmission and away from the question of whether transmissions were necessarily good things

Capt A G Forsyth (*Member—Fairey Aviation Co Ltd*) congratulated the author on his paper which contained many interesting features, and as the drive is one of the most important features of the helicopter, his remarks on efficiency, lubrication, etc , backed up by his experience, would be of value to designers He thought it was a pity that the author had confined his description to gearing only, as most of the troubles experienced in producing satisfactory drive systems were encountered in the design of the clutches, free-wheels and high speed shafting

Referring to Diagrams 1, 2 and 3, these cover driving the rotor head by spur gearing and bevels There is nothing unusual in the assemblies, and the design of the gears is straightforward The troubles to be expected in this assembly would be to harness the turbine satisfactorily at 10,000 r p m to the final drive at 195 r p m to cope with the starting problems, narrow power band of the turbine, compressor surging, etc He thought that Fig 1 was apt to be misleading, as it would be essential to introduce a clutch or a free turbine between the turbine and the first gear The same remarks apply to Figs 2 and 3

Dealing with efficiency, the author states that in his opinion nothing under 1% is acceptable Capt Forsyth thought that this figure was too low, and in practice is was more likely to be 1½% or 2% It is possible to obtain 1% on ground spur gears but when bevels are introduced this low figure is not possible in normal assemblies He recommended the figure of 2% for general use

He referred to Fig 3 which incorporated a large bevel for the first stage of reduction, 10,000 to 1,215 r p m In his opinion the introduction of a bevel of approximately 3 ft diameter would be difficult and the use of a Mitchell pad to support the rim would localise the heat It would be practically impossible to balance the thrust between the deep groove thrust bearing shown and the Mitchell pad, due to expansion in diameter and depth when hot He also criticised the assemblies of the bearings taking the thrust of the smaller bevels, as they were too far away from the bevels

The side drive assembly was satisfactory but he thought that the lower bevel driving the side shaft was too far away from the thrust bearing located at the lowest point of the assembly

The top gearbox is not mentioned by the author Capt Forsyth, however, asked how it was proposed to assemble the main gear to ensure that the teeth were in line Was it proposed to assemble the rings on the centre hub and to grind after assembly ? How are the rings assembled inside the top and bottom flanges of the hub ? Did he think that the three bearing assembly would be satisfactory ? Capt Forsyth referred to the gear failure shown at Fig 9 , he thought that the gear could be improved by paying more attention to rounding off the ends of the teeth instead of chamfering, and to eliminate the sharp corners at the root of the teeth He was surprised that the bottom of the teeth were not half round and stub teeth There was obviously some reason for this ? He thought it would be a good thing to replace the chamfer on the lightening holes by finishing half round

Referring to Fig 10, the author said that internal gears showed obvious advantages , it would be interesting to know what efficiency was obtained from this assembly, and the method of forming the teeth No oil squirts were shown but presumably there were some

Capt Forsyth favoured the use of epicyclic gears for the final stage as by this means it was possible to produce a compact assembly Spur gears produced high bursting loads in the casings whereas with epicyclic gears the loads in the gearing were self-contained

Spur gears have to be used in cases where the control is by means of a spider mounted on top of the head as in the case of the Bristol 171 The author has put forward a case for squirting the oil into the teeth after the gears have come into contact There are two schools of thought on this subject , in fact reduction gears have been made to try out both, with conflicting results For slow speed gears it is best to use Fig 11 and for high speed, Fig 12 In Capt Forsyth's opinion the most important point to consider in gearbox lubrication was not the squirt position but to ensure that the squirts were delivering oil to the gears not froth

It pays dividends to pump the oil from the box through a cooler before entering the squirt , do not let the gears dip in the oil bath, and provide adequate breathing

Referring to the " L " section gears (at Fig 10), this practice is used where a thin box is required as it allows the bearing and housing to be accommodated inside the gear In Capt Forsyth's opinion, these can only be considered for lightly loaded applications as when highly loaded, the rings deflect and cause fatigue to be set up between the teeth on the unsupported side He had found it an advantage to form a rim inside the open side similar to that shown inside the main gear Fig 14, to prevent the rim from flexing

Capt Forsyth thought that the choice of flanged joints (Fig 16) would depend upon the space available The drive by friction had an advantage where one could use a flange wide enough The fitted bolts offered a weight saving as the flanges could be scalloped between half the number of bolts

In conclusion he said that to do full credit to the designer, the finish of all components should be of the highest possible standard, as more trouble was experienced due to bad finish than to any other cause

He hoped that Mr Norton would be able at some future date to cover the other types of drives which can be applied to helicopters

Mr J Wotton (*Member—Percival Aircraft Ltd*) thanked the Lecturer for the pleasing and direct way in which he had dealt with the subject With a background of experience gained in the design of the Brabazon and the Princess coupled units and of the clutch and free wheel system used on the original Bristol helicopters, it was to be expected that the lecture would be of considerable interest Whilst there were varying opinions about the eventual use of tip jet drives for helicopters, especially for the larger sizes, it was generally accepted that the application of free turbines to helicopters would enable the shaft driven type to hold its own for some years to come

They were all aware of the vital importance of the transmission system and of the need for sound, yet economic, design The clutch and free wheel mechanism which must accompany the use of reciprocating power units gave rise to an additional anxiety on the part of the designer, for a fierce clutch or jumping free wheel might well severely damage or wreck expensive rotor blades

The Author's reference to friction drive and the desirable features in the transmission lubricating system were of particular interest and no doubt of educational value to many of them

Mr Wotton said he had expected the Paper to give a lead as to choice of gear types for various running speeds and configurations and he wanted a little more information in this connection The diagrams showed fairly simple gear trains giving overall gear ratios of approximately 50 1 With current expert opinion and stringent A R B requirements tending to favour four-engined machines for inter-city operation, ratios of up to 100 1 must be considered for large aircraft and more complex gear arrangements might be forced upon them As an example, a single rotor driven by four engines of 1,000 h p would run at very little over 100 revolutions per minute for they would power a machine of some 35,000 lb all-up weight, whilst engines of this size would probably run at some 20,000 r p m

The compactness and low installed weight of turbine power units indicates that in order to make the most economic use of the main cabin of the aircraft their location should be adjacent to the rotor head, probably with their axes at right angles to it

Such an arrangement had been suggested in some of the illustrations shown during the evening

Incidentally, Mr NORTON had not touched on the advantages to be gained when a free turbine was used and it was possible to have a torque variation of something like plus or minus 10 per cent There was something in the free turbine system for which they had been searching for a long time—and this was no doubt in Sq /Ldr GELLATLY's mind—in that they had an infinitely variable ratio over a fairly wide margin They were able to operate in the hovering case with the rotor running at a fairly low speed but with the engine at max r p m , whilst in forward flight it was possible to increase rotor speed whilst the engines were allowed to run at a more effective and economical speed

The aircraft designer was sometimes faced with the necessity of taking the power through a 90 deg turn, and for this purpose Mr NORTON had in each case chosen a bevel drive Mr WOTTON put the following questions to him first, what were his views about right-angled helical gears for medium or small ratios ? Secondly, worm gears of high helix angle for large ratios, and if so, the advantage or otherwise which would follow the use of concave or " wrapped " worms with their consequent decreased unit bearing loads and improved efficiency

Thirdly, in the case of worm or helical gearing, how would his remarks about lubrication apply ?

Fourthly, when designing a drive in which power was supplied by a free turbine, would he consider a reduction in the size of the gears on account of the complete absence of shock loading ?

Fifthly, if more than one power unit was to be used per rotor, would the application of power at diametrically opposite points of, say, the final spur or worm wheel, result in improved efficiency and lower weight in that part of the drive ?

Mr E Newbery (*Member—Ministry of Supply Eng R D* 3 (*H*) added his appreciation of the very interesting lecture He was sure that if more time had been available the Lecturer would have told them even more which would have been of help to them In the early illustrations, where the turbines were shown, the reduction was in a single unit from turbine speed to rotor speed That raised a point which he would put both to Mr NORTON and to the helicopter designers—was it better to design the complete reduction in a single unit like that or would it be preferable to have the engine with its own reduction gear to an output shaft speed of 3,000 r p m ? The illustration was of a large reduction by a single pair of bevel gears—8 2 1 Although such a reduction would no doubt have theoretical advantages, would it prove the best design in practice ? Had there been any experience of such a large reduction ? Had there been any experience of the thrust pad which was illustrated ? That had intrigued Mr NEWBERY, and he said he would be interested to hear whether it had been tested and how it had stood up to running conditions

With such a large reduction, the pinion having a very much smaller number of teeth would suffer much more wear than the wheel, which might lead to maintenance difficulties The mating of the gears would also be affected by temperature, and the bigger the gear the greater the variation due to temperature, and, consequently, the bigger the difference in meshing between the two gears under, first, lightly loaded conditions and, then, fully loaded conditions

There was a divergence of opinion on oiling and cooling of gears and there were conflicting results from experience, but as the helicopter rotor reduction gears usually had the shafts vertical it seemed that there might be a case for directing the jet of oil vertically downwards along the face of the tooth rather than perpendicular to the tooth When they were getting down to the last ounce of efficiency there was a point that directing it against the driving pinion was opposing the torque and would result in a small loss of efficiency

He agreed whole-heartedly with the Author that in practice there was no such thing as dimensions being " spot on," and he agreed about the importance of tolerances These must be practical as well as theoretical and often that required very close liaison between the design side and the manufacturing of the early components Incidentally, stressing should be based on adverse limits, which, in dealing with thin sections, made a considerable difference When using a forging, the direction of the grain flow was often important and not only should this be made clear on the drawing, but when the first forgings were made one or more of them should be cut up to make sure that the required grain flow was being obtained Once the manufacturing process had been established, to satisfaction, it should be tied up with a specification

The same principle applied to any special manufacturing technique where close control was important This might seem an unnecessary precaution to some people but it was not sufficient to rely on the skill and know-how of an individual craftsman because, although he might do the job satisfactorily, someone else might have to do it later

Another feature which could not be over-emphasised was the standard of finish If, as Mr FORSYTH had pointed out, even the engine manufacturers, with all their experience, slipped up on that, how much more important was it that the finish should receive particular attention in the helicopter transmission, where a failure could be even more disastrous than an engine failure on either fixed wing or rotating wing aircraft ? Two parts could be manufactured to the same design, one could operate perfectly satisfactorily and the other could fail—simply because one had adequate, smooth radii and a good finish and the other might have a sharp corner where there should be a radius, or a tool mark which was sufficient to cause stress concentration leading to failure This was where the importance of inspection arose , not only was it necessary to ensure dimensional accuracy but it was also necessary to ensure that the standard of finish was maintained

Here he made a plea that where parts were sub-contracted the inspection should not be completely delegated to the sub-contractor The main contractor should himself undertake sufficient inspection to ensure that the standard required was being obtained, particularly in the early stages of production

The standard of helicopter transmission should be at least as good as that of the best aero-engine practice

Some of these points seem trivial and obvious, but it was necessary that they should be emphasised because it was surprising how often they were overlooked He wished the Lecturer had had more time to give the benefit of his experience in these directions

Mr Newbery added that his remarks were his own personal comments and must not be taken as necessarily representing the views of the Ministry of Supply

Mr J S Shapiro (*Founder Member—Consultant*) said it seemed necessary to redress the balance He hoped he would be forgiven for mentioning that the discussion had sounded a little like an oration on a lost cause , Mr NORTON and Mr FORSYTH had ceased to design transmissions and Mr WOTTON had never started, so, as it seemed, they were conducting an autopsy of a corpse But that did not express the real situation at all One sentence stood out in his mind among the many sensible things which Mr Peter Masefield had said—that whatever jet aircraft you take, you can always make it more efficient by putting on an airscrew If mechanical transmission retained its place in aeroplanes where they flew faster by jet, it was certainly true of the helicopter, where jet drive does not bring faster travel

He did not think the impression that the free turbine would prolong the life of the mechanical transmission gave the right emphasis The mechanically driven rotor was there to stay and who knew which would outlast which ? Let them first of all agree therefore that the question of designing a drive would always be a most important task and, as they had seen from the Paper, a very great challenge, because it demanded some of the highest creative abilities of a designer

So much for the general aspect of the matter, but he did not think that the general choice of rotor driving systems was the subject of Mr NORTON's Paper Mr NORTON had wanted to communicate certain experiences which he had done very ably, and his experiences were most interesting Once more, however, it might be necessary to redress the balance and remind the audience that most helicopters in operation today had planetary gear transmissions This touched on one of the Lecturer's statements with which Mr Shapiro did not agree a planetary or epicyclic transmission cannot by its very nature be as efficient as a straight bevel, certainly not as a straight spur, but it is lighter and in helicopters they could not dissociate weight from efficiency The two factors must go hand in hand, and any process of optimising must connect the two

They had not perhaps discussed enough the tested and tried transmissions in the hundreds of helicopters which were in operation

He wanted to ask the Author some questions about the Michell block He could not understand how this could be both effective and also avoid loss of efficiency, because surely it could not offer as little friction as a bearing in the middle of the gear

The Author had expressed no opinion on the question of the spiral or straight tooth either in spur or bevel gears It had been suggested in the discussion that the turbine, by eliminating all shocks, made gear design very easy In fact, it had taken many years before a shaft turbine was safe enough to be useful in an aeroplane, and that was because the combination of very high speeds and high frequency vibrations was a new set of conditions which it took designers many years to master Mr Shapiro was very sceptical about whether it would be possible for helicopter designers to take over a turbine without the first gear reduction, as they knew it in the aeroplane shaft turbine

Why was it necessary to dispute the merits of the oil jet before and after tooth contact ? Why not have both ? It did not seem a very great burden, and all they had to do was to meter the appropriate quantity at each end

Finally, on the use of rubber, his experience was that rubber was always disappointing in as much as they had to face the fact that ageing was faster and less predictable than was any fatigue phenomenon

Replies in Discussion

Mr Norton (*in reply*) stated that he had been presented with a phenomenal list of questions, and that he would start with the last question and then work backwards hoping that there would be insufficient time to answer the earlier and more difficult questions !

The use of rubber

As regards the use of rubber this had to be done with discretion , its use could circumvent quite a number of minor troubles, particularly where high frequency vibrations were concerned but rubber should not be regarded as a panacea for all vibration troubles He had, on several occasions in the past, used rubber as a flexible medium in a drive for the purpose of changing the torsional vibration picture so that no dangerous resonances occurred in the normal running range

Friction

He realised that the design of a shaft coupling based upon friction as a torque transmission medium would give rise to considerable controversy but in his experience it was invariably the case that where (at least for aero-engine purposes) the design of such a joint did not take friction into account then, in operation, fretting troubles were the rule Such modifications to bolt sizes and/or bolt tension which overcame this trouble resulted in the design of the coupling conforming to the friction design theory

Oiling

The vexed question as to whether oil should be introduced into the engaging or disengaging side of the teeth, does depend to a considerable extent, upon the duty of the gears In his lecture Mr Norton confined his remarks to *high duty* gears since, for aircraft purposes, all gears of any importance are of necessity high duty gears since light weight is essential If the gear application is a low duty one then there is no particular urgency in removing the " heat charge " from the tooth surface immediately after it has formed (even if this were possible) Further, the mass of a low duty gear is high and there is thus ample material to soak away the heat of inefficiency of tooth meshing for subsequent dispersal without incurring high tooth or wheel temperatures In instances where the *lubrication* of the teeth is proved to be in doubt there is a case for supplying a carefully metered oil feed to the tooth faces prior to meshing In his opinion, however, such cases are few and far between

The suggestion that oil jets be directed across the plane of the gears is not regarded as very sound If the jet were a weak one, *i e* , the oil pressure not great, the windage from the teeth would sweep the oil to one side, whereas if of high velocity the jet would pass straight across to the other side of the gear box In neither case would the jet do more than introduce oil into the casing in a more or less random fashion If the duty of the gear train is sufficiently high to warrant the use of oil jets then why not be logical and arrange these so that the cool oil streams do their work in the most efficient way possible ?

Mr Newbery had raised a novel point This was that an oil jet opposing the direction of rotation of the wheel would reduce efficiency , in fact it would turn the latter into a turbine ! Mr Norton had never really given this serious thought If the oil pump were individually driven would the questioner expect this effect to causethe rotor to run backwards ? It would be an interesting exercise to calculate how much horse-power was lost this way but it would be much too small to measure in practice

The remarks on the introduction of oil to gears applies to spur and bevel gears both of the straight and helical tooth varieties As regards the application to worm gears Mr Norton said he had had very little experience and suggested seeking the advice of the specialist

2-Stage Rotor-Drive Gearbox

Mr Norton emphasised that the proposed layout for this drive (Fig 3) was a preliminary layout only and he could spend quite a long time discussing visible features of that design which are capable of improvement One of these features concerns the location of the ball journal bearings relative to the bevel pinion producing axial thrust Normally it is preferable to locate the ball bearing as near to the bevel as possible A further point which was raised, is that of alignment when more than two bearings support one shaft In the case of the main input shaft in Fig 3, the thrust bearing is permitted a limited amount of radial movement thus preventing it from taking journal load In this case, therefore, the question of alignment does not arise In general, however, for this class of engineering it is possible to maintain a degree of accuracy in alignment, such that loads imposed by the minute residual mal-alignment are quite small, bearing in mind the limited degree of rigidity inherent in highly stressed components This state of affairs would be expected to exist in the rotor gearbox final drive as shown in Fig 3, thus the use of 3 bearings in this case is permissible As for expansion troubles in bevel drives, the greater the distance, that is to the larger the bevels, the greater the relative movement between mating teeth and that point must be watched However, *the greater the ratio* the less the influence of expansion on tooth meshing At infinite ratio and therefore infinite wheel radius, the wheel teeth become rack teeth, therefore, movement due to differential expansion would not affect meshing There was thus some measure of easement, from the point of view of expansion, with a bevel drive of high ratio Mr Norton had not yet had first hand experience of such an extreme form of drive as that shown but he would certainly aim at the highest possible ratio, bearing in mind machine tool limitations He emphasised that he regarded the use of a small thrust block backing up the rim of the wheel as a *must* The lubrication of this pad should not prove to be difficult since, first of all, the load (in the example shown) was of the order of 650 p s i only and secondly, the block would be supported in such a way as to ensure the formation of a hydrodynamic lubricant wedge As in all bearing problems an adequate supply of lubricant would be necessary

Gears

Captain FORSYTH had raised the question of gearing efficiency Mr Norton confirmed that an efficiency loss of 1% per tooth engagement was certainly obtainable both with straight or with helical teeth Where both lubrication and tooth cooling requirements were satisfied the biggest factor was in getting the oil *away* from the gears Much efficiency was lost through oil churning and even with the " floor " between the teeth of semi-circular (or rather semi-cylindrical) form, the clearance volume quickly shrank with consequent rapid pressure rise in any trapped oil This effect was very serious from the point of view of efficiency

As regards large overall reduction ratios Mr Norton repeated that this should be provided by the minimum number of gears, that is to say, by the maximum ratio per stage If the power to be transmitted was very high, then machine tool limitations were likely to obtrude but from the point of view of wear there is little to be lost The pinion will always wear more than the wheel but materials and treatment must be chosen to give the longest possible life before measurable wear occurs Wear, as understood by the general engineer, is not acceptable for the form of application under discussion since loss of accuracy of tooth profile occurs with a consequent drop in efficiency, increase in noise and a deterioration of the torsional vibration picture and in fact in reliability too

It was impossible to generalise on the relative merits of straight teeth versus spiral teeth for bevel drives There are, however, many advantages to be gained by the use of spiral , for example tooth grinding was a well established process In the case of spur wheels it was normally impossible to grind a double helical wheel , for this reason double helicals were usually made in halves bolted together Sometimes this resulted in fretting between the contacting faces

The advantages had been mentioned of a free running turbine drive from the power transmission point of view As regards weight saving in gears, little had in fact materialised for various reasons, some of them obscure One would expect that the peak torque loading from a piston engine would demand the use of larger gears than with a free turbine drive As far as Mr Norton's experience had indicated, which was not really very far, there were often high frequency vibrations in the turbine drive which were difficult to cope with because they were not always fully understood Any reduction of size, therefore, should not be contemplated without a very complete background of experience on this form of prime mover

General

Mr Norton realised that the type of drive discussed cannot be said to have a very promising future since it is very severely challenged by rotor tip-installed engines, with particular reference to the ramjet However, the lecture specifically discussed the gear type of drive to the exclusion of rotor tip drives If the helicopter designer decides that a two-speed drive is needed then the transmission designer will certainly rise to the occasion However, the use of the free turbine should, to a large extent, mitigate against such a demand

Surge should not occur in the turbine engine If the engine design is such that surge is a possibility, then the engine controls should be designed to prevent this occurring

The advantages of the free running turbine, particularly for helicopter use, are well known The use of a fluid coupling in conjunction with older forms of engine can at least confer some of these advantages, particularly for initial rotor acceleration A small coupling together with a suitable spur gear drive can be used for speeding-up while a dog clutch can be engaged for subsequent operations

Mr Norton expressed the opinion that built-in torquemeters were highly desirable Not only was this the case during helicopter development but also during subsequent service , no less on helicopters than on fixed wing civil aircraft If engine torque as well as r p m were known, a continuous observation of engine power and fuel consumption would be possible and this is essential for efficient vehicle operation

The **Chairman** said he was sure Mr Norton would have recognised, from the questions, the interest which the Paper had aroused That was probably the best compliment he could have His answer to the discussion had been surprisingly complete It had been an interesting evening, and the CHAIRMAN asked that thanks be shown in the usual way Thanks were accorded by acclamation

The proceedings then terminated