the fixed wing aeroplane, and so given an uninterrupted period of a few years for the logical sequence of development these potential sources of trouble can be eliminated

The views presented in the paper are the speaker's personal opinions, but he is indebted to the Chief Executive of the Air Registration Board for permission to deliver the paper at the symposium

Acknowledgement is made to the report on "The failure of Metals by Fatigue" (Symposium at Melbourne 1946) for information contained in the paper on contributory causes to stress concentration in materials

Discussion

Mr R L Lennox Napier *Member*, (Cierva Autogiro Co) After the very comprehensive remarks of previous speakers I have little to add, except to emphasise one or two points which appear to require it

First, the designer has a good deal more to consider than many others in this field He has to cover not only the vibrations which are merely uncomfortable or awkward from the point of view of the customers, but also, right from the start, he has to differentiate between these and the vibrations which are dangerous to the structure Roughly speaking, most others concerned in this field have to deal with one or other of those general groups of vibrations, but not both, and they have quite enough difficulty in doing that It is in design that the biggest effort has to be made in dealing with the vibration problem

This involves a great deal of early paper work on fatigue, especially in regard to the transmission system, and in many cases it requires quite a quantity of ground instrumental tests and investigations Recently we have had a ground oscillation investigation in progress, and I may add a little to what Mr SHAPIRO has already said concerning our findings in connection with this particular vibration difficulty It is rather embarrassing in a way that the designer of a flying machine should have to concentrate a major technical effort on a fault which is present only when the machine is on the ground, although many other pioneers have had this same sort of trouble We have to make quite a substantial effort to ensure that the machine is safe while turning its rotors on the ground , many machines have literally disintegrated, due to unstable oscillation or ground resonance—in some cases the one type of vibration and in some cases the other

At Cierva's, now Saunders-Roe Helicopter Division, we have investigated recently a trouble of this type on the W 14 " Skeeter," and it appears to be quite clear at the moment that it can be overcome by a three-fold attack First, ground resonance vibration testing is performed on the full-scale aircraft with the rotor replaced by an equivalent mass, the machine being oscillated by a mechanical vibrator , then a series of calculations, involving some assessment, are made to convert the results of that first test to the equivalent of running conditions , and finally there is the test we can never avoid, that of running up right through the whole r p m range from zero to maximum overspeed on the full-scale machine, with all the combinations of parameters in rotor blades, drag dampers, oleo legs and tyres and even ground surface stiffnesses, which are likely to be met in practice This final test must be done, but a great deal of the risk involved with a new machine can be removed by the previous two stages I have indicated, which warn of the possibility where present, of explosive oscillation, and indicate the methods of avoidance

I may be permitted one or two remarks on instrumentation as applied to vibration I agree very closely with what has been said already concerning the danger of giving too much attention to subjective impressions, *i e*, human reactions to vibrations, when we are concerned primarily with vibrations dangerous to the structure It is our experience that on frequent occasions the subjective impressions have been completely at variance with the results indicated by instruments In that connection there is one point which I think has not yet been stressed sufficiently, it is that in our rather crude *human* "instrumentation" we respond to certain combinations of outside influences in a complex way which we do not understand ourselves, and this may give rise to some very erroneous impressions when we are relying on our own reactions to external conditions such as sound and vibration In particular, the impression one obtains of the intensity of vibration in a helicopter is largely affected, I think, by the ambient sound level occurring simultaneously I have myself noticed this effect quite clearly on the "Air Horse" during autorotation tests, and I have seen some reference to it elsewhere It seems to me that it requires quite heavy emphasis that, broadly speaking, the customer will be much more alarmed by what he calls vibration when it is accompanied by appreciable noise than he will be if that noise is effectively soundproofed out of the passenger compartment If we can ensure that the passenger is subjected to only a comparatively low sound level he will not complain much about vibrations up to the established critical levels, and I think a good deal can be done from the passenger's point of view along these lines Any one who is inexperienced in these matters, and who is beginning to follow up what has been done already, should bear in mind the danger of assessing the vibration level when the sound is mixed up with it, we must separate them, and the only way to do this is by adequate instrumentation, ignoring our own reactions almost entirely

There are tremendous possibilities in the way of improved instrumentation, the improvements are coming along in due course, but these developments appear to be slow from our point of view because we want them now I would mention a very crude form of seismic vibrograph which we put together rather hastily for some early tests on the "Air Horse" to keep a day-to-day check on the vibration levels in the machine I realise that I am going almost directly against what Dr G E Bennett has said about the desirability of using the accelerometer type of vibration pick-up rather than the seismic type—in other words, his preference for the use of an instrument of which the vibrating system has a natural frequency well above that which it is required to examine We managed to get some very useful, although crude, results from this instrument, which was simply a mass suspended on two springs, which restrained it from motion other than along the axis in which we were interested, and linked to a standard Askania vibrograph, this had a natural frequency of about 2 c p s and static deflection of no less than 3 5 inches, and was able to give us quite useful indications of frequencies as low as 3 c p s (the rotor fundamental), even though there was very little damping incorporated In the air it was necessary frequently to apply arbitrary manual damping to it when it was excited near its resonance

But apart from portions of records spoiled by variable damping of this nature, the instrument was giving remarkably useful and quite consistent information, especially in the higher orders of rotor harmonics, particularly the third order and above Quite incidentally, and quite accidentally, we found it was giving some usable information on normal accelerations on the machine, at below the point of its natural frequency It was thus used as an accelerometer at the same time as a vibrograph, although in a crude way The standard fixed-wing type of visual accelerometer was found to be useless, as it has a natural frequency of the same order as the rotor third harmonic

Needless to say, this is not instrumentation as the word is generally understood The order of accuracy of a crude instrument such as this is low , but much can be done in the same way by improvised instruments, in order to carry us over the gap between the present and the time in the rosy future when we shall have a vast array of effective equipment immediately to hand with which to resolve any problem that arises I emphasise the value of improvisation in this respect

Mr C W George (R A E , Metallurgy Department) We all agree that there is vibration in helicopters , if there is vibration, it must follow that there is fatigue

I think that, as one speaker has said, fatigue and vibration considerations are much less important so far as human reactions are concerned than they are in respect of the aircraft After all, a human being who is fatigued can rest and eat and recover , but metals do not recover from fatigue and, what is more, rest periods do not restore any of the damage that is done by fatigue That has been proved by a number of investigators, except that there is a suspicion that we might find a little restoration in pure iron However, pure iron is not used for the construction of helicopters

I would mention again the subject of finish , it is still not good enough We should consider that in a normal fixed wing aircraft if the engine fails there is still a very good chance of getting down to the ground safely , but if a power unit fails on a helicopter generally the result is catastrophic Therefore, we should give, if anything, far more consideration to the design and finish of anything to do with the power unit, particularly the rotor head, than in a fixed wing aircraft power unit So far, I think, that has not been sufficiently considered

There is another point about that I have a feeling that some of you think the proposed A R B Certificate testing of helicopters is somewhat severe But if you bear in mind what I have said, that you cannot afford to have power failure, then I think those proposed tests are nowhere near too severe Indeed, I think we need every one of those tests in order to be sure that we shall not have premature failures

Perhaps I may refer to the cumulative rule What Mr Williams has said is perfectly correct , in that adding up numbers of cycles at different stress levels just does not work out to 100%, for the reason that " under-stressing " and " over-stressing " are factual things Perhaps you would like a little further information on that Let us consider an ordinary S/N curve, where stress is plotted against the number of cycles It does not matter whether this relates to steel or to a light alloy This type of graph shows the safe stress line or, as some prefer, the " damage " line If you apply a number of stress levels and you start from near the bottom and climb up in periods of cycles at increasing stress levels, you can probably

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get up to the safe stress line and the specimen will not fail, whereas normally it should fail there If you go on, your fracture line will probably be at an appreciably higher stress or the life will be greater at the normal failing stress If, alternatively, you start at say 6½ per cent above the endurance value for one-fifth of the normal life at that stress, and then drop down to a lower stress and work up again in stages of increasing stress, you can probably go a little higher still before fracture occurs

As these are real things, the adding up of the various numbers of cycles at different stress levels just does not work out to a constant value From tests we have made we find that if you start with a very high stress you will finish on the left side of the normal damage line, and if you start with a low stress you will finish on the right hand side of that line

There are one or two things which have not been mentioned, but which you may like to know One is on the question of finish Say that you polish a specimen to ½ micro-inch, and call that 100 per cent If you finish another to about 1½ micro-inches, you have dropped 8 percent of its fatigue strength, *i e*, you have only 92 per cent If you have one finish-machined to 12 micro-inches you can easily drop 25 per cent in fatigue strength , and with rough machining—which means something like 36 micro-inches—you gave lost 35 per cent of the fatigue strength

I stress that because some recent German work by Glaubitz has shown that it is really worth while to take the trouble to polish important parts, particularly as it so often happens that you are not quite sure what the real fatigue stresses are

A number of people still believe that there is some correlation between elongation value and fatigue strength I never have believed it because I do not see what connection there is between the elongation value on a single tensile test, and the ductility, as shown by putting on a fluctuating stress very many times By figures I can show that there is no connection

I will mention the results of some American work They used an aluminium alloy extrusion of an inverted T shape with a thick horizontal member They took specimens in three directions—longitudinally along the length of the extrusion and also horizontally and vertically in the transverse directions There is very little difference between the longitudinal and the transverse horizontal, and the figures for the two transverse directions are of the following order

Ult mate Strength T/in sq	*Elongation* %	*Fatigue for* 20×10^6 T/in sq	*Fatigue Ratio*
37 5	12 5	±10 3	26
35 7	4 0	±11 2	31
36 4	12 5	± 9 0	25
34 2	3 0	± 8 8	26

(Fatigue ratio means the ratio of fatigue strength to ultimate strength) There are elongation figures of 12 5 and 4, and 12 5 and 3 , but the ratios, if anything, are higher for the specimen taken vertically than for those in the horizontal transverse direction I think that gives very good evidence that elongation does not give you low fatigue strength

If, unfortunately, in your design you have tensile stresses which are so great that they cause permanent extension of your material, *i e*, plastic flow, then good elongation matters, because if you have no elongation in the material it will break at a stress concentration without yielding as soon as that breaking load is reached, whereas if it has a really good elongation value it will stretch It has been pointed out that you cannot have a theoretical stress concentration of more than three with a material having good ductility because, as soon as you have exceeded that value the material extends and the stress concentration drops

Another thing is that there is no correlation between Izod impact value and fatigue strength or fatigue ratio Figures that I can quote show that for Izod values of 75 5 and 5 4 foot pounds respectively the fatigue ratios were 58 and 55

You should also remember that, if you have fluctuating torsional stress, you have only half the fatigue strength that you would have for that material in fluctuating tension Suppose you have a material which gives (say) $\pm$ 20 tons per sq in, fatigue strength in tension, you will only have $\pm$ 10 tons per sq in, in torsion , and for any combination of the two stresses the points will fall on a quarter elliptic curve, there being a variation in form depending on the material used

I mention this because there may be cases where you have overlooked torsion, and I believe this may be the reason why fatigue failure has occurred earlier than you would have expected

Mr J Morris (Structures Dept , R A E) I came into this story when, following a failure, one of my colleagues asked me if I could help to elucidate a point in mechanics A case occurred where all three blades of a helicopter rotor broke off at approximately equal distances from the hub—about one-third of the length of the blades—apparently by bending failure in the plane of rotation The inference was that the coupling between the engine and transmission had failed, and this, it was suggested, had given rise to a torsional impulse on the rotor system which wrecked the rotor blades I was not much impressed with this supposition It seemed to me that there would possibly be a jerk but if the rotor continued in action, against air resistance, the chances were that it would just slow down

Be that as it may, I decided to look into the problem It so happened at this time that I had been working on a claim in connection with the Salamon pendulum vibration damper, and since the blades of the helicopter rotor were articulated in the plane of rotation, I thought it might be useful to investigate the behaviour of the hub and its three blades in torsional vibration, especially as owing to the flexible shaft between the hub and the main drive we could, as a first approximation, treat the system of rotor hub and blades as separating out I did the analysis on the principle of the pendulum damper and much to my surprise I found that in the particular case there was the possibility of a resonance between the third order rotor aerodynamic disturbance and the frequency of torsional vibration of the rotor system

I did not wish to be dogmatic , there was the possibility of a resonance, but its effect depended on how powerful was the aerodynamic disturbance , the rotor worked at a speed which was not very high, whereas in propellers working at very high speed one does get aerodynamic disturbances which operate more or less similar to mechanical forced vibration and produce undesirable and on occasion destructive resonances

It now seems a possibility in the case of the helicopter rotor I was interested to note that Mr SHAPIRO, when I discussed it with him, seemed to absorb the idea in a few seconds, and he worked it out for a particular case in my presence in very neat handwriting

One general impression I have of the papers presented today is that they set a very high standard, they have been very interesting and I have learned quite a lot from them My mind goes back to a paper presented in 1914, I think, by LEONARD BAIRSTOW, on stability in aviation The Chairman of the meeting at which it was discussed made some concluding remarks, and one of them was mis-printed as "This is a case where theory and experiment checked one another" We have seen today how in helicopter vibration, theory and experiment checked one another The extent to which we are now getting an insight into these problems is remarkable Not everything that has been said is gospel, and it cannot be expected to be, but I want to congratulate all the speakers and to say that I have thoroughly enjoyed this afternoon's proceedings

Dr A P Thurston (*Member*) In the development of fixed wing aircraft one noticed that all vital members were duplicated as far as possible. I should like to ask whether steps have been taken to duplicate the highly essential and vital parts of helicopters, particularly the controls

I would also ask whether you have any tell-tale, which has a certain wavelength, so that when you put it in certain parts it will "tell tales" about the occurrence of vibrations which may be dangerous

Mr Shapiro (*Member*) It has been suggested many times, of course, that duplication could be the remedy for incomplete airworthiness But I think, with regard to blades and articulation, that it is the wrong approach However, for the time being it is a matter of opinion You might favour a machine having two concentric rotors and duplicated motors, or even a machine with four rotors, in which case you could have a whole rotor shot away and you could still get away with it I do not say that that is impossible or undesirable, but all these things unless supported by other considerations mean complications, more weight which can be employed more effectively in other ways to promote airworthiness

With regard to tell-tale devices, I think the case in which one such device actually caused an accident is well known in helicopter circles, it tripped a clutch prematurely, when the pilot was unprepared So that such devices are not completely virtuous Sometimes they are good and sometimes they are bad However, I would mention an article on fixed wing aircraft by D Williams, in which it is suggested that the fact that there is a very large number of identical members in a wing is in itself a safeguard against fatigue The inevitable scatter of fatigue results does give a warning where otherwise there would be none so that scatter is actually utilised as a tell-tale device Whether or not that is practical I do not know

Mr J Wotton (*Member*) The papers which have been presented today represent a worthy contribution to the high standard which we have now come to expect at meetings held under the auspices of this Association

The subject matter which forms the basis of our discussion on this occasion is one which is the immediate concern of all who are in any way connected with the design, development or operation of helicopters

As was to be expected, the various speakers have dealt in the main with conventional machines having shaft drives and torque reaction rotors, the rotors being of the fully articulated type, where blades are free to flap, teeter and feather

It is noteworthy that no mention has been made of the twisting blade system, as exemplified by the American Kaman helicopter, and only passing mention of the semi-rigid rotor used on the Dorman machine I should have liked to have heard how much, in the opinions of the lecturers, these simplified types suffer from or are immune from excessive vibration

It is well known that the freedom of blade movement, originally introduced to reduce fatigue stresses, is responsible for a considerable proportion of the vibrations which are so difficult, not only to reduce in the original design, but to keep down to a reasonable level by subsequent maintenance Is it not possible that in our anxiety to reduce the effects of possible fatigue and the rotor stresses generally we now find our rotor systems infested with "gremlins" which defy all attempts to neutralise or eliminate them ?

It is somewhat surprising that we have heard nothing of the torqueless tip jet-operated helicopter , while this type is not yet an accomplished fact in this country, it is no secret that design studies are in progress in more than one quarter here Even if in such types we do not depart entirely from the articulating rotor head, the need for drag hinges immediately is non-existent, while the absence of mechanical drive makes possible and even simple the replacement of the normal flapping by a spherical bearing type of tilting head, still using the optimum three-blade configuration

The additional stresses invited by reverting to a rigid system will be more than compensated for by the removal of a number of factors which are themselves responsible for many of our vibrational and, through them, fatigue and stressing problems

Cyclic feathering of the blade, we know, is responsible for much of our vibration, to resist which the blades must be accurately manufactured and matched

By no means has the last word been said as to the best means of obtaining differential lift, and cyclic feathering may yet give way to some better means which is less susceptible to vibration-producing tendencies This aspect of the helicopter rotor is open to considerable research and experiment

The jet-driven machine is peculiarly free from the multitude of imposed and super-imposed vibrations, and of the overlapping frequencies of engines, drive shafts and torque reacting devices which are the bane of the shaft-drive addict !

The smooth running of tip jet reaction driven rotors has been established on the Continent and in America, and the eventual evolution of such machines, with their lower first cost, simplified maintenance and perhaps, above all, freedom in large measure from unpleasant vibrations, must be a logical conclusion

This is not the time to suggest possible lines of development, but it may well be that the jet-driven machine holds many of the solutions to our vibration problems

The Chairman Perhaps Mr SHAPIRO would organise what might be a joint answer to the points raised I think the last speaker has raised some very interesting points

I was very much impressed by Mr MORRIS's concluding remark, in which he said the time has come when experiment checks with theory , coming from the abundance of his experience and ability, I felt that that was very comforting for us all, because during the afternoon we have concentrated attention on a vital subject for the helicopter, and we have concentrated our attention to such effect that we might have scared ourselves to death That is the sort of thing that happens, I think, when one comes to survey part of a whole It is true in this case that it is a most significant part of the whole , the subject is vast, and there is a great deal we do not know On the other hand, I think we have gone a long way To start with, we have had the courage as an Association to face up quite openly and in public to this major problem, and we have had a most illuminating and frank discussion In view of the time limitation, the subject has had to be treated very sketchily in certain aspects, and I think that sooner or later the Association must return to it But the fact is that we have a number of successful helicopters flying the world over , so that, by and large, we have found practical solutions for many of the problems with which we have been faced It is perfectly true that we have not full knowledge of many things on which we urgently need research

Vibration due to blade stalling has been mentioned by several speakers as a major factor We do not know precisely what are the aerodynamics, and how near we can get to the nominal stalling angle of the blade before the onset of serious vibration A certain amount of work has been published in American papers, but I do not think there has been much work done on this side of the Atlantic

In regard to the fatigue of metals, we are not the only people who are in trouble It is a problem on the fixed wing aircraft side, just as it is on the helicopter side, and we should go forward together , it is very useful for us to have a man such as Mr GEORGE here, for he has a knowledge of both sides Whilst we have heard a great deal about this problem, the very many sources of vibration that exist in the helicopter, the snags and difficulties we may run into on the fatigue side, the general problems which the authorities see in getting an aircraft to the airworthy stage and so on, I do not think we should feel that we have enormous difficulties ahead and that it will take us a very long time to solve our problems However there clearly are problems and the deduction is that we must concentrate our brains and attention on certain critical points which we have to think out quite clearly, so that we can make a major attack on them

VOTE OF THANKS

Mr FITZWILLIAMS, who was invited to express the thanks of the meeting to the contributors of papers, said I wish that I had had notice of this opportunity to express appreciation of this afternoon's discussion All I can say is that I am entirely in agreement with Mr ROWE concerning the courage of those who have discussed this matter in public here this afternoon After all, we have to remember that many of them represent firms having a great deal of money and so forth at stake , it is not lightly that they discuss the faults of their own products Those who have spoken in that way have received in return a good deal of advice and knowledge from others, particularly from those representing the R A E and the A R B , and I think they will find that the information given from such sources will be considered a very adequate return

The whole meeting has been most successful and worth while , and I think the Association, whilst congratulating itself, is glad to be able to express very genuine thanks to the contributors

(The vote of thanks was warmly accorded , and the meeting closed)