The Fatigue Problem with Emphasis on the Airworthiness Aspect

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The previous papers delivered at the symposium and the discussion up to now leads naturally to the subject of fatigue of component parts of the helicopter, due to fluctuating loads and stresses arising from the various modes and frequencies of vibration already discussed, and also due to induced aerodynamic loads These latter loads mainly on the blades cannot strictly be covered by the term " vibration," but it is essential to discuss the resulting effect of such loads on the helicopter in such a discussion as this one

This subject of fatigue of course has been worrying the structural designer in many engineering fields for a long time The designer of railway rolling stock has been worried for years by the failure of axles and rails, and more recently the fixed wing designer, especially the designer of civil aircraft who contemplates that his aeroplane may be in service for at least 10,000 hours or so Unfortunately, when so little is still known about the fundamental nature of the fatigue of materials and the extreme difficulty of ascertaining the effect of varying external loads on a structure, the helicopter designer is presented with the problem of fatigue at his doorstep even at this comparatively early stage in helicopter development

In this paper the problem will be dealt with purely from a qualitative angle and no attempt is made to suggest that certain numbers of hours of testing should be carried out under particular ground and flight conditions

There are fundamental reasons why fatigue tests are necessary whether on the full scale helicopter on the ground or in flight and on component parts In the first place the impending fatigue failure of a critical component may not be obvious by inspection, since after the initiation of a fatigue crack at the surface this can develop into complete failure of the component in a very short space of time between inspections, and in any case for parts such as the rotor blades frequent inspections and stripping is impossible

In addition, even if the external loading condition is known with some accuracy, stress analysis or static test of a component may not indicate the possible source of fatigue trouble since the fatigue failure may not of necessity occur at the section corresponding to the highest static stress

The fatigue testing of a helicopter or its component parts must of necessity be costly in time and money so that at every stage in the development a sensible balance must be struck between the risk of proceeding to the next stage of development on the one hand, and the probable futility of prolonged testing on the other hand There is a limit to the testing period beyond which it would be a waste of time to carry on, since no more can be learned at that particular stage

It is most important, however, that everything should be done within reason and without too much emphasis on safety aspect to the detriment of other possibly quite as important considerations for helicopter development in order to avoid an accident resulting from fatigue failure The principle must be established that having determined the range of stresses under all possible ground and flight conditions, then the *service* life of each critical component should be so determined as to ensure continuous safe operation—the service life being well below the fatigue life of the component

For a comparatively simple treatment of the fatigue problem the critical parts of the helicopter can be subdivided into

(*a*) Those rotating parts such as the gears and other parts of the transmission up to the rotor head, but excluding the engine

(*b*) The rotor blades themselves

Parts such as gears are subject to normal working loads giving rise to cycles of stress variation quite independently of vibrations as such, and these parts can be cleared for indefinite life by tests on a ground rig in the normal development stage

Other parts of the transmission, rotor head and rotor blades will be subject to variations of stress of certain frequencies and magnitudes about a mean due to ground and flight conditions During its service life the helicopter will spend proportionate times in these particular ground and flight conditions

Thus there are three logical steps to take

(1) To obtain a cross section of the stress variation for critical components under all possible ground and flight conditions

(2) To obtain a knowledge of the absolute frequency of these stresses by estimating the relative time spent in each of the manoeuvres

(3) To determine the fatigue strength characteristics of components, either by full scale tests of the helicopter on the ground or by carrying out laboratory tests to determine the well known S-N curves at various stress levels

The various flight conditions to be covered are too numerous to state here, but, for example, in the

Power On Condition

The helicopter will probably spend 80% of its service life in the level flight condition but this will be split up into various speed bands

Then 5% in Hovering ,
8% in Turns, etc ,

and in the *Power Off Condition* in Autorotation about 2% of its life

The most critical flight conditions giving rise to maximum stress variation will probably be pull-outs both from power on descent and from autorotation, but the estimated hours spent in such critical flight conditions will be exceedingly small Thus if these conditions override the others the service life based on these conditions will be correspondingly large

Ground conditions can also give rise to critical load conditions, such as rotor starting in gusty conditions, engine surging and clutch engagements Here only a few load cycles are involved but the load variation can be of a high magnitude and could so damage the critical components as to produce failure in subsequent flight

The question of what form the testing of the components shuld take is a most contentious one I will not venture an opinion but just state the three alternatives

(*a*) A " slave " machine could be used in flight to simulate day by day a representative cross-section of manoeuvres, ground, take-off, climb, level flight, descent and landing with a few interspersed autorotations This is of course the best form of fatigue testing but economically may be out of the question

(*b*) Ground testing of a complete machine where the control movements are so adjusted to simulate as nearly as possible the stress variations induced in the flight manoeuvres Of course it is extremely difficult and may not be possible to simulate the stresses with any degree of accuracy, and in any case the vibration characteristics will be altered appreciably from flight conditions

(*c*) The third method which is not really a full alternative to the first two methods, but may be regarded as an essential step in the design development stage, is the laboratory testing to be carried out on components or sections of components Such coupon tests are of great importance in any case even if the full scale tests are carried out, because there is nothing more annoying and such a waste of time than to have to redesign a small part during the full scale test when the design of that part could have been rectified by the easier preliminary laboratory test Laboratory tests, however, suffer from certain disadvantages in that the conditions of service life cannot be of necessity properly simulated

(i) In service the temperature conditions are different from the laboratory and the atmosphere may deposit corrosive substances which have a weakening effect on the fatigue strength

(ii) There is always a substantial scatter on laboratory tests of the fatigue life of apparently identical specimens tested under identical stress conditions

(iii) The unsuitability of existing fatigue testing machines

(iv) It is not possible to simulate in the laboratory the exact spectrum of varying stress cycles that is estimated to occur in service life During one flight a component is subjected to a very small number of large stress variations, a bigger number of medium stress variations and quite a high number of small stress variations and this sequence will be repeated a few thousand times during the service life of the machine However, in the laboratory it is only practicable to apply all the small stress cycles first *en block* all the medium cycles next, and finally all the large magnitude cycles, or *vice versa* The sequence of application may have an important effect on the fatigue life as found by such a test

(v) The results obtained with a section of a component in the laboratory may be quite different from the results obtained if the whole component was tested *in situ*

However, even with these limitations, laboratory tests can be an extremely useful guide, not only for an approximate estimation of fatigue life but also in the design development stage for elimination of stress concentrations, etc , in components

When the strain gauge results for the flight and ground conditions have been examined and S-N curves for various stress levels have been obtained in the laboratory for the critical components, use is now made of the " cumulative damage theory of fatigue " for the estimation of fatigue life

This symposium stresses the practical approach to the problem but here is a case where by the use of a theoretical approach to the correlation of strain gauge results and laboratory fatigue tests, the practical side of the development can be expedited

For those people unfamiliar with the cumulative damage theory I would like to explain quickly what it entails

If a specimen of material, it may be steel or light alloy, is subjected to loads which are a combination of

(*a*) a steady stress (X),

(*b*) an alternating stress $\pm Y$ about X as mean,

and the application of the stress $\pm Y$ is repeated, then the material will be fatigued to some extent If failure under this repeated stress would take place after (N) repetitions of load then the cumulative damage rule maintains that each load repetition will damage the specimen to the extent of ($1/N$) and the fractional damage after (n) repetitions $= \frac{(n)}{(N)}$

Thus if it is known from strain gauge readings what stress variations about various mean levels do occur and what the estimate of the absolute frequency of these variations happens to be then it can be assumed that

$$\Sigma \frac{n}{N} = 1$$

and an estimate of the fatigue life can be made

However, the validity of the cumulative damage rule when applied to the results of laboratory tests is very suspect due to the reasons stated before concerning the disadvantages accruing to laboratory tests, *i e*, scatter of test results, unsuitability of testing apparatus, impossibility of simulating the service load spectrum

In addition very little research work has been carried out to date to substantiate the damage rule and what work has been carried out seems to indicate that the application of a number of stress cycles above the endurance limit lowers the life of the specimen under subsequent applications of a lower stress In addition, if a number of stress cycles below the endurance limit is applied then the fatigue life under subsequent applications of a higher stress is improved

Stated simply this means that the fatigue limit can be lowered by over-stressing and raised by understressing which belies the cumulative damage rule All these disadvantages to the application of the cumulative damage rule can be compensated to some extent by

(*a*) Carrying out tests on at least six specimens of each component to cover the scatter effect

(*b*) Introducing a multiplying factor for the magnitude of the stress cycle and this it is suggested should be (1 3)

(*c*) Introducing a reduction factor to the fatigue life obtained on test in order to determine the service life This reduction factor it is suggested should be (0 5)

The component is to be removed from service and replaced by a new component at the expiration of the service life It is suggested that the service life as obtained by the above method should not exceed two to three thousand hours, especially for rotor blade components

If the results of the laboratory tests indicate that the most critical factored stress cycles are all below the endurance limit of the component, then the component should still be replaced at a nominally agreed period and this period it is suggested should be in the region of four thousand hours

In addition, the results of preliminary laboratory tests would provide some confidence for using a " slave " machine in full scale flight fatigue tests

One last point on this subject concerns the different fatigue strengths of the skin and that of the spars on all metal rotor blades Comparative S-N curves for aluminium alloy sheeting whether riveted or reduxed, compared with the curves for spar extrusions (with reasonable stress concentrations) indicate that for the same levels of mean stress and fluctuating stress the fatigue life of the sheeting is only about 10% of that of the extrusion Even with the knowledge that skin joints may re-distribute loads as the yield point is reached, it may be that the skin of the blade may have to be replaced frequently before the spar and that means the blade is removed from service This is due to the fact that the appearance of a fatigue crack in the skin of a rotor blade in flight may have far more serious consequencies leading to the stripping of a blade in flight, than on a fixed wing aircraft

Finally all that has been mentioned in this paper to date leads to the inevitable conclusion that for the reduction of the possibility of fatigue failure to a minimum in helicopters there must be

First class design of component parts with special emphasis on the elimination of high stress concentrations which can have such a calamitous effect on the fatigue endurance of a structural component

These stress concentrations can be induced in various ways

(1) *By design*—sharp angles, changes of section (re-entrant angles), screw threads

(2) *Machine shop*—Rough turning, accidental tool marks on the surface Grinding cracks Identification and inspection stamp marks

(3) *Fabrication*—Slag blowholes and cracks in welded construction Press fits and shrink fits

(4) *Heat treatment*—Cracks due to hardening stresses

(5) *Manufacture of material*—Importance of surface finishing (use of shot peening process) because practically all fatigue failures originate at the surface

In addition, the workmanship and standards of maintenance and inspection on these components have to be of a very high order indeed Lately we have come to realise that the design, manufacture and inspection of these vital component parts of the helicopter, the failure of any one of which in flight may have such unfortunate consequencies, must be of a standard even higher than that for aircraft engines That is to say, much higher than the standards for the design and manufacture of fixed wing aircraft This may yet prove to be the most important of all the preventatives of fatigue failure on helicopters

Even though several helicopter designs have been flying successfully for some time, it will probably be a few years yet before the higher standard of detail design for helicopter components will have been developed and accepted as common helicopter design practice

An attempt has been made in the paper to present a balanced picture of the fatigue problem as it affects helicopters at the present stage of development, but this is still a very early stage compared with the development of 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