are imposed on the blade root Flexible blades have the effect of increasing the effective drag hinge offset

The analysis has been taken a step further by incorporating damping in both the hub constraints and about the blade hinges This analysis may be useful in judging the amount of damping required for low frequency oscillation, but in practice much of the damping is so erratic and subject to various influences and drift, that the use of damping to mask really dangerous conditions is inadvisable

To obtain the dynamic parameters, analysis can be used in simple cases but mostly ' ground resonance ' tests are essential In such tests the machine is excited at the hub by some form of exciter and the response is measured In ground resonance tests the blades are replaced by concentrated weights

Unstable blade motion We are here concerned with the unstable motion of articulated blades about their flapping hinges Such instability has been observed and/or analytically predicted in unusual designs of articulation under normal conditions or in normal designs under abnormal conditions

Flutter It can be said that a high order of torsional stiffness is inevitably desirable Perhaps a good practical rule is that the natural frequency of the blade in torsion should not be less than 3rd rotor order

From the practical point of view it is important that resonance tests simulating flight conditions in which the collective control system is excited and the response measured whilst the rotor is rotating can be carried out on the ground By this means the approach of flutter can, it is hoped, be reliably judged

DISCUSSION

W Stewart, B Sc (*Member*), *Aero Flight Section, R A E* We have just heard two excellent lectures on different aspects of vibration I would like to congratulate both authors on the presentation of their lectures and open the discussion with a few comments on both papers

Mr McClements in his " Operational Aspects " pays equal attention to noise and to mechanical vibration This is a much wider interpretation of vibration than is normally anticipated, although there is no doubt that noise can cause annoyance to the passengers and contribute to the fatigue of the crew Discussing the mechanical vibrations, the results of the B E A flight tests on the S 51 helicopter brought to light a very interesting phenomenon, *viz* the measurement of vibrations at less than rotor frequency It is difficult to appreciate how such a vibration could arise and, consequently, it is equally difficult to deal with it It may be that it represents some short period oscillation in the stability of the helicopter and which is very rapidly damped While it is not apparent in handling tests it is measurable at vibration level Alternatively, it may be some form of oscillation in the stability of the blade itself Finally, in relation to the allowable limits for passenger comfort, may I draw the author's attention to the work of Gerstenberger of the Sikorsky Company

Turning to Mr Shapiro's paper on the sources of vibration I have one general comment to make I would like to have seen much more information on the relative importance of the various vibration phenomena It seems to me that helicopter vibrations can be divided into two groups Firstly, there are those due to lack of symmetry in parts, errors in manufacture or assembly, etc These mechanical vibrations can be (or should be) reduced to an acceptable level by careful dynamic balancing, tracking, etc, and by subsequent proper maintenance Secondly, there are vibrations inherent in the characteristics of the helicopter, *e g*, due to blade motion about the flapping and drag hinges, blade stalling, etc These are fundamental and must be avoided by proper selection of design parameters and by appropriate limitation of the flight envelope They are, in fact, at present, the most serious limitations in helicopter development and consequently I feel that they are the most important, especially from the point of view of the research necessary to develop helicopters with higher forward speed and more economic operational capabilities

Dr J A J Bennett, F R Ae S (*Founder Member*), *Fairey Aviation Co, Ltd* Mr Chairman, ladies and gentlemen, I shall limit my remarks this afternoon to cover a trend of development with which the future of the helicopter industry in this country is most closely associated Ever since the helicopter emerged from the purely experimental stage, its unique uses have been exploited at the lower end of its speed range and attention has been diverted from the basic limitation of flight dissymmetry The intended operation of helicopter airliners between city centres, which may be as far distant as several hundred miles, forms a new challenge to the helicopter designer and the search for a solution to the fundamental problem of vibration in forward flight can no longer be postponed

Operation of the retreating blade close to the stall, causing the lift of each blade to fluctuate from a minimum value in each of the two lateral azimuths to a maximum in the fore and aft azimuths, has been an inherent barrier to the improvement of forward speed No matter how much power was available, the full use of the available power was limited by vibration

Both the frequency and amplitude of the vibration are dependent primarily on the number of blades Obviously the more blades there are in the rotor of a helicopter, the better the fluctuating loads are distributed The frequency increases with the number of blades and the amplitude decreases As I have shown elsewhere (Ref 1), the physical effect of forward flight dissymmetry is to cause a simultaneous displacement of all the blades In the flapping sense, for example, the vibration is caused by a periodic upward displacement of the tip-path plane and not by periodic tilting of this plane The axial components of the several blades due to the periodic tilting neutralise one another Hence, the first design requirement of a helicopter subject to the forward speed limitation is to have as many blades as possible

Two blades may suffice for low-powered helicopters of a maximum speed below 100 m p h and three blades for medium-powered helicopters operating up to 150 m p h, but the helicopter airliner with enough power available to operate at still higher speeds should preferably have four blades

Another feature of the helicopter airliner will be the use of a small fixed wing At first sight this would appear to be a retrograde step introducing additional weight and drag which the helicopter can ill afford When it is realised, however, that the airliner would not otherwise be able to make full use of its available power because of vibration, the importance of the additional weight and drag of the fixed wing becomes quite negligible The fixed wing is provided to unload the rotor progressively with increasing forward speed in order to minimise the effect of forward flight dissymmetry

The rotor, operating at reduced lift, avoids the vibration associated with periodic stalling of the retreating blade owing to the lower pitch required by the reduced lift conditions Low pitch operation of the rotor, though not an essential at low forward speeds, becomes increasingly essential in high-powered helicopters capable of maintaining speeds beyond 150 m p h

This method of avoiding the bugbear of vibration caused by the periodic stall of the retreating blade cannot be exploited fully if propulsion of the helicopter is dependent on a forward inclination of the tip-path plane, which inclination would only be accentuated by the unloading of the rotor The gyrodyne principle of propulsion, independent of the attitude of the tip-path plane, is a practical approach to this problem and no doubt will be a design feature of helicopter airliners in the future

The requirements of the airlines set a very high standard for the future of the industry and, if vibration limitations are to be avoided, we require more blades, low pitch, small fixed wings and independent propulsion

Ref 1 Bennett, " Aircraft Engineering," May, 1940

A L Oliver, *A and A E E* In helicopter type testing at A & A E E, the vibration characteristics of a helicopter are measured practically entirely with reference to their effect on crew and passenger comfort We assume that a full investigation of rotor, engine and control vibrations has been made during pre-flight tests and development flight trials

The results of these tests are useful in indicating the probable flight conditions which will give rise to the most serious vibrations We propose to measure vibrations in these conditions in addition to those occurring in certain standard operational states These standard conditions of flight are

take-off, both vertical and normal,
climb,
hovering away from the ground,
cruising flight at various power settings,
autorotation, and
approach and landing, both normal and steep (By " normal " landing we visualise something like 10 degrees)

In addition, measurements should be made during starting and running-up The importance of this, will largely depend upon whether passengers enter the aircraft with rotors stationary or not, but in any case the crew will have to endure any vibrations which do occur

For measurement, we use Miller electronic equipment, with acceleration pick-ups of the inductance type A major snag is, of course, the subsequent analysis A graphical method is used whenever it is possible to separate out the frequencies by inspection of the record and knowledge of vibration source frequencies, but a prohibitive amount of work is involved if two frequencies are very close to one another One criticism I would like to make of the equipment concerns the frequency range The effective range which we used was from 2 to 40 c p s , a range of 0 to 100 c p s is really desirable

The positions at which we measure vibrations are all in the cabin, and are

at both crew and passenger stations,
on the controls, and
at certain special places, such as roof compass mountings, where visible vibrations would be particularly fatiguing

The condition of the aircraft throughout the tests is normal ; it takes off at its normal operational all-up weight after routine servicing, and no attempt is made to make the aircraft either abnormally smooth or abnormally rough

Tests made recently on one type of helicopter showed that, according to the standards of Constant's threshold-of-comfort curve, the control column has an uncomfortable 3-per-rotor vibration in the for-and-aft direction in all conditions of flight The worst flight conditions were maximum speed at maximum continuous power and low speed manoeuvres (less than 15 m p h) at 5-minute power, and in all cases but one the offending vibration was a 3-per-rotor ; the exception was the port side of the cabin structure, level with the passenger's seat, where there was a 1-per-engine vibration in all flight conditions Two other frequencies were recorded ; one was thought to be due to the main-rotor transmission shaft, the other, a very low frequency most noticed during high-pitch, high-power, low-speed manoeuvres, was thought to originate at the main rotor head No amplitudes could be measured, however, because of the limitations of the equipment, so that the importance of these vibrations is unknown

These results confirm the qualitative impression that, in current single-rotor types of helicopter, the nearer the centre-line of the main rotor, the better from the viewpoint of comfort

There are two points which have not apparently been fully investigated as yet Firstly, there is the possible cumulative effect of two or three vibrations affecting the same body at the same time—in the same direction, of course Separately the amplitude of each may be insufficient to cause discomfort at their frequency, yet together they could produce discomfort

Secondly, what importance and standards should be attached to visually-perceived vibrations ? These vibrations are not taken into account in Constant's curve, and a case would appear to exist for determining a ' threshold-of-discomfort ' for them

A question which may arouse some controversy concerns the protection of passengers and crew from the worst effects of vibrations I can conceive of no reason for not making the seats and surroundings as comfortable as possible, but I think that the controls are another matter No experienced pilot with whom I have discussed this question of whether it is a good or bad thing to completely isolate the controls from sources of vibrations said that it would be a good thing All stated that they preferred to endure some discomfort and be able to assess the behaviour of the rotor system, rather than fly in ignorance of what may be happening

So far I have been concerned only with mechanical vibrations ; in full type trials it is, of course, necessary to measure the noise level at both crew and passenger stations Unfortunately, the equipment used in fixed-wing aircraft is hardly adequate for this purpose We require a narrow-band analyser capable of covering a frequency range of 2—250 c p s , with the size of the equipment reduced as far as possible, whereas the equipment at present in use covers a range of 37 5 to 9600 c p s , has only an octave filter, and is definitely bulky The octave filter is satisfactory for broad analysis bands and high frequency work where most of the noise arises from aerodynamic sources, but is not suitable for low frequency work in which it is required to identify the exciting sources It is to be hoped that more suitable equipment will be available in the near future

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O Fitzwilliams, B A (*Founder Member*), *Westland Aircraft Ltd* The problem of vibration affects the constructor in a particularly acute manner, since he is not only expected to provide solutions for operators' troubles but he is also obliged to carry out extensive endurance flight trials for airworthiness purposes and these would be exceptionally monotonous and tiring for the pilot even with a perfect aircraft In the presence of uncomfortable vibrations these endurance runs create increasingly serious problems and focus the constructor's attention very sharply on any method of eliminating sources of discomfort, even though experience has shown that only in very special cases is there generally any direct connection between the airworthiness of the helicopter and the kind of vibration which causes discomfort to the occupants

Generally, the kind of vibration which is known directly to affect airworthiness is not obvious to the occupants and requires special instrumentation for its detection and measurement The increasing degree to which such instrumentation is being used in airworthiness investigations is, however, also giving us valuable facilities for the measurement and analysis of the more obvious vibrations, and this will undoubtedly advance our understanding in the near future to the point where we can take effective steps to improve the comfort of the helicopter in day-to-day operations

In the meantime, experience indicates that the causes of the common and obvious vibrations—which often appear and disappear in an irregular manner—are more likely to be found in the design characteristics of the particular aircraft rather than in the features common to all helicopters (such as the cyclic character of blade forces) which have often been analysed in the past Such general characteristics may become serious as speeds increase, but they seem to have little connection with present problems

The vibrations now common seem, from our experience, to result in a relatively simple manner from such things as

(1) The type of blade construction employed which is such as to encourage random distortions with atmospheric changes and service conditions—including minor damage in handling
(2) Play in control linkages
(3) Peculiarities of particular bearing and damper assemblies and, above everything else,—
(4) the bending characteristics of the fuselage

I believe it is not too much to say that the major part of the discomfort sometimes felt, particularly on long flights, could be eliminated by a change in fuselage bending characteristics, even without touching the basic causes or magnitudes of the vibratory forces Careful attention to fuselage resonance frequencies and proper siting of the occupants at or near the bending nodes seems now to be a governing consideration in the layout of helicopter airframes and fortunately goes hand in hand with solutions favourable to the elimination of c g problems

The common causes of vibration are likely to be partially or wholly eliminated by straightforward means The introduction of metal blades, the simple improvement of control linkages and the introduction of improved types of hub assembly should greatly reduce random variations in service Additionally, the introduction of servo assisted control systems will eliminate piloting discomfort at the same time as encouraging further increase in helicopter size

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The improvements resulting from these straightforward engineering changes can produce a new standard of comfort in large helicopters but must be accompanied by intensified instrumentation to detect vibration affecting airworthiness if we are to avoid giving the occupants a false sense of security The extent to which the random vibrations of present helicopters have acted as a safety measure by forcing careful inspection and maintenance is probably not sufficiently recognized

Broadly, I am satisfied that vibrations causing discomfort can be reduced to a very acceptable level by relatively simple means and that we have little to fear on this score from the more fundamental cyclic rotor characteristics, even though they will loom larger as speeds increase I am also satisfied that increasing understanding of what is important for safety will safeguard us from a false sense of security resulting from new standards of comfort

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