Vibration Problems associated with the Helicopter

By O L L FITZWILLIAMS,
B A, A F R Ae S

A Meeting of the Association, which took the form of a JOINT MEETING with the Royal Aeronautical Society, was held at the Library of the Society, 4 Hamilton Place, London, W 1, on Tuesday, 12th February, 1957, at 7 p m

DR G S HISLOP (*Chairman of the Helicopter Association Council*) *in the Chair*

The CHAIRMAN, in introducing the Author, said that the occasion was a very auspicious one, in that a paper was being presented by one of the founder members of the Association at a Joint Meeting with the Royal Aeronautical Society, with which the Association maintained the closest of links On behalf of the Association he welcomed the fact that a joint meeting was being held, and he welcomed those members of the Society who were present to hear a paper and discussion on a specialised helicopter subject In particular he welcomed the President of the Royal Aeronautical Society, Mr E T JONES

Mr FITZWILLIAMS, who was giving a paper on a very important aspect of helicopters, in addition to being a Founder Member of the Association had given valuable service on its Council for many years He began his professional career in 1938 with Messrs J G Weir, of Glasgow, who were specially interested in autogiros From 1940 to 1944 he had been with the Ministry of Supply, assisting in the development of rotary-wing aircraft, and from 1944 to 1946 he had been with the Airborne Forces Experimental Establishment, also on rotary wing work In 1947 he decided to move into industry and joined the Westland Company, becoming Chief Designer (Helicopters) and subsequently Chief Engineer He was therefore very well qualified to speak on the vibration problems associated with the helicopter He was also an Associate Fellow of the Royal Aeronautical Society

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The Association wishes to record its appreciation for the co-operation of Westland Aircraft Limited who arranged for pre-prints of the paper to be made in a format suitable for subsequent inclusion in the Journal

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INTRODUCTION

Although many existing helicopters vibrate to a mild extent most of the time, and to a serious extent some of the time, appreciable vibration is not an inherent characteristic of the helicopter On the contrary, it is hoped that this paper may go some way toward establishing that the helicopter is capable of development into an exceptionally smooth vehicle

Also, since the significant limits to the forward speed of a helicopter are fixed by vibration, it is one of the objects of the paper to present the results of some experiments which indicate that the helicopter is capable of smooth operation at forward speeds considerably higher than have so far been achieved

1 STANDARD OF VIBRATION, NOISE AND MOVEMENT

The standard of comfort provided in the aeroplane has increased tremendously during the past 25 years This improvement resulted from the introduction of enclosed cabin accommodation, soundproofing, positioning of the engines remote from the fuselage with the airscrews opposite parts of the fuselage not occupied by passengers, increased wing loadings, over-the-weather flying, auto-pilot control, cabin air conditioning and pressurisation, and more recently the introduction of turbine engines Because the present high standard is the natural result of a series of design improvements, of which soundproofing is probably the only one introduced solely for the purpose of improving comfort, the concept of acceptable standards of vibration, noise and movement does not seem, until recently, to have played a large part in governing aeroplane design

Even now the various standards which have been proposed do not present a coherent or complete picture Standards of internal and external noise seem to be still in an early stage of investigation, standards for vibration require additional work before they can be regarded as a satisfactory basis for design requirements, and standards for acceptable movement of the aircraft as a whole in turbulent atmospheric conditions appear to have been almost entirely neglected

The helicopter has a good deal of leeway to make up in respect of noise and vibration but anyone who has flown short haul trips at low altitude in rough weather will realise that it has an important inherent advantage for this type of operation The helicopter rotor is a natural gust alleviator and its capabilities in this direction could be further extended by suitable development of the control system

Many existing helicopters have an unpleasant wallowing motion in rough air, partly due to the manner in which their torque balance is achieved but possibly also due to the nature of their control systems which seem to encourage a faulty feed back from the pilot's control column Since the helicopter is primarily intended for short haul operation at low altitude, where atmospheric turbulence cannot be avoided, improvement in the helicopter's response to these conditions is of some importance Experiments with the Widgeon indicate that a considerable improvement is possible by closer attention to correct "feel" in the pilot's controls

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The levels of vibration recommended as acceptable by various authorities are presented in Fig 1 in a conventional manner They are repeated in Fig 2 in a handy presentation due to Gerstenberger, which illuminates the considerable discrepancies

Our experience is that compliance with Constant's curve produces an acceptable helicopter for the majority of military and civil roles at the present time Figure 3 shows, in relation to Constant's curve, all the unacceptable vibrations found in an examination of 370 vibrograph records In every case, by suitable maintenance adjustment, these amplitudes were reduced below Constant's threshold

As shown in later sections of this paper, the natural vibration of a helicopter in cruising flight can be reduced to approximately half the amplitudes indicated by Constant's curve and could, by relatively simple means, be almost entirely eliminated if necessary The latter possibility, although it may appear somewhat far-fetched at this stage of the discussion, is sufficiently real to raise a query as to whether an absence of vibration is a desirable state of affairs Enjoyment of and interest in a journey may actually be stimulated by some "sense of activity" in the vehicle so that a "band of desirable vibration" may be a not entirely unrealistic alternative to the present concept of a "threshold of discomfort"

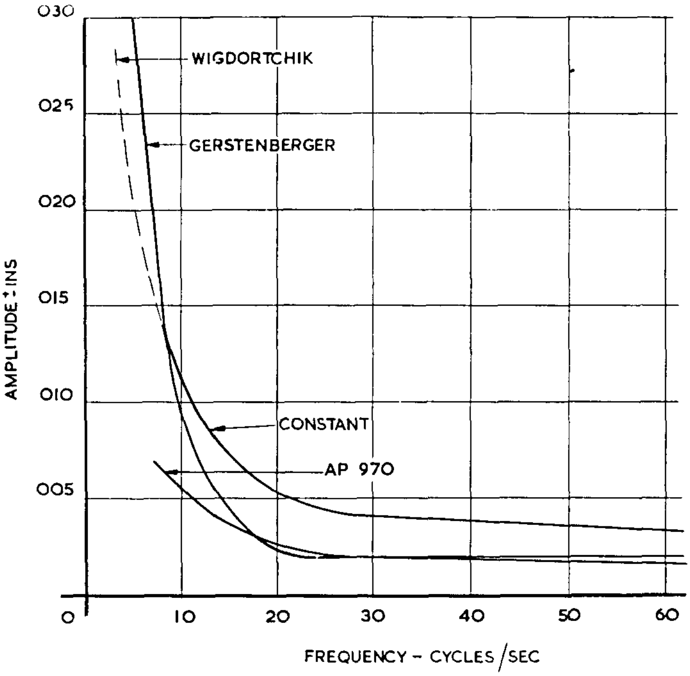

Fig 1—Vibration limits

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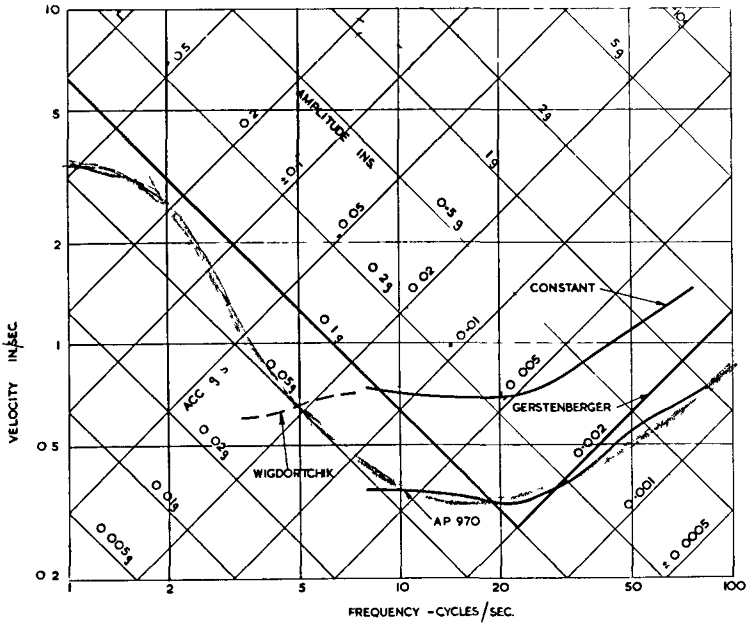

Fig 2—Logarithmic plot of vibration limits

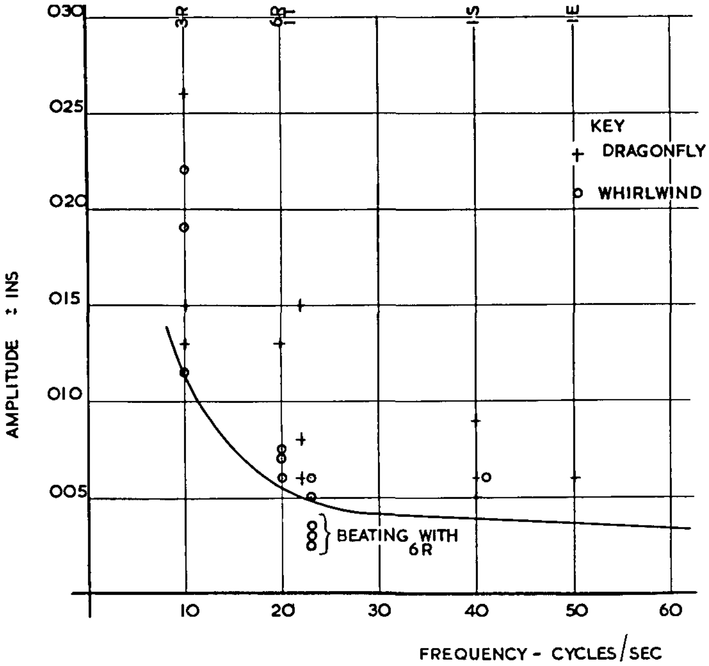

Fig 3—Unacceptable vibration levels cured by maintenance adjustment

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2 1 *Simple vibrations*

The Whirlwind helicopter is generally representative of conventional single rotor design and the main sources of excitation to be expected in this aircraft are listed in Figure 4 for the Wasp engined version Many of these excitations produce no appreciable vibration in the helicopter but those which have required attention, either during the development of the aircraft or in daily maintenance, are shown in heavy type

As would be expected, the two-bladed tail rotor gives rise to vibration at once and twice tail rotor frequency The three-bladed main rotor gives rise to vibration at once, three times and six times main rotor frequency

The engine orders listed are generally associated with torsional vibration, not felt by the occupants but important from a fatigue point of view The tooth meshing frequencies at the bottom of the list may sometimes be connected with gear fatigue troubles revealed during rig tests, or endurance trials of the aircraft, but generally attract attention only because they are one of the main sources of noise in the cabin

Some of the vibration observed in existing helicopters is due simply to inadequate development of dampers and hinge bearings or to minor design errors, for example assemblies containing seals which may bind under the extremely high pressures applied by the standard grease gun Vibration due to causes of this nature is eliminated by normal modification action during the life of the aircraft and is of little significance for the future, particularly as the majority of errors must have been made by now and one can reasonably hope that they will not be repeated!

Torsional vibrations can give trouble in rig testing of transmission assemblies, because of unrepresentative stiffness and inertia in the rigs, but they do not usually give rise to trouble in the aircraft since they are adequately covered by the design requirements for the transmission, except where resonance occurs

Torsional resonance is not, or should not be, a problem for the operator since its elimination is part of the development work required for airworthiness clearance of the aircraft The procedure is laborious, involving the calculation or measurement of the natural frequency and inertia of all moving parts of the engine and of the transmission and rotor systems, with a theoretical examination of the possible modes of vibration of the complete mechanical system It also involves elaborate torsiograph and strain gauge measurements of torsional vibration in all operating conditions in the air and on the ground Although it presents some interesting problems in measurement under difficult conditions, this work is an elaboration of established methods evolved in the development of aircraft engines Since torsional resonance cannot generally be avoided entirely, the operator is sometimes made aware of its existence by finding that operation of the aircraft may be prohibited in certain conditions outside the normal operating range

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Main Rotor Order	Vibration Order	C P M	C P S
1	**1 R**	198 6	3 31
2 82	1 Epicyclic cage	561	9 35
3	**3 R**	596	9 93
4 43	1 2nd Planet	380	14 67
5 65	½ E	1125	18 75
6	**6 R**	1192	19 86
6 3	1 Oil Pump	1250	20 8
6 98	**1 T**	1390	23 2
7 97	1 G B S	1585	26 4
11 31	**1 E**	2250	37 5
12 5	1st Planet	2480	41 3
12 56	1 S	2503	41 7
13 97	**2 T**	2780	46 3
15 4	1 Hydraulic Pump	3062	51 0
16 96	1½ E	3375	56 2
22 62	**2 E**	4500	75 0
25 12	2 S	5006	83 4
28 27	2½ E	5625	93 75
30 85	1 Generator	6130	102 2
39 55	3½ E	7875	131 2
50 9	**4½ E**	10125	168 8
61 7	2 Generator	12300	204 4
79 1	7 E	15750	262 4
90 5	8 E	18000	300
	M – 2nd Planet	18450	307 5
101 8	9 E	20250	337 5
113 1	10 E = Mk 1 2 Blower	22500	375
135 8	12 E = Mk 4 Blower	27000	450
	M – Tail gear box	37550	626
	M – Tail drive bevel	47550	793
	M – 1st Planets	52200	870
271 4	1 Fan blade	54000	900
	M – Input gear	69750	1162
	M – Intermediate gear box	80100	1336
	M – Accessory gears	110200	1837

R = Main Rotor
T = Tail Rotor
S = Tail Shaft
E = Engine
G B S = Gear Box Shaft
M = Tooth Meshing Frequencies

Fig 4—*Whirlwind Mks* 1, 2 & 4—*Noise and vibration orders at* 2,250 *engine r p m*

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The conventional helicopter contains quite massive shafts between engine and main rotor gear box and very long tail drive or interconnecting shafts supported on a large number of bearings, but provided the shafts are reasonably balanced and correctly aligned with their bearings and supports, surprisingly little vibration is felt in the airframe from these installations, even where they include Hardy Spicer joints so that the shafts are running at non-constant velocities Vibration from this cause is generally noticeable only when out-of-balance in a shaft causes a beat with some other excitation The only serious vibration of this nature in my experience turned out to be due to an unbalanced slipring assembly

Where the combined amplitude of two small vibrations exceeds the threshold of discomfort, and is thus the cause of a complaint, a careful analysis of the beat as recorded by vibrograph enables the offending frequencies to be pin-pointed with great accuracy Thus in the Whirlwind it is possible to make a quite definite distinction, for example, between half engine and six main rotor, or between once tail shaft and twice tail rotor frequencies This ability to spot the source of a vibration on careful examination of the vibrograph record has often enabled us to achieve a quick cure of vibrations which could not have been traced on the basis of reports rendered by the aircraft crew For effective maintenance of existing types of helicopter there is no doubt that a hand-held vibrograph, properly used, is a very considerable help

2 2 *The "Twitch"*

One of our earliest experiences of the value of vibration measuring equipment occurred in connection with a phenomenon which became known as the "twitch" This was a peculiarity of the Dragonfly, first reported from a Naval Squadron and subsequently found to exist in varying degrees on practically all aircraft of this type To an occupant of the aircraft it appeared as a sudden strong twitching in the yawing plane, occurring at random intervals in most conditions of flight It resembled the motion which might be expected in the event of a momentary slipping of the clutch, or sticking of a damper Although the amplitude was mild compared with the tail twitching experienced on some well-known transport aircraft in rough weather, it caused alarm until the nature of the associated airframe deflections had been established and the stresses involved found to be within safe limits

This trouble occurred at the end of the early period in which our method of dealing with faults in the aircraft consisted of getting me to go for a ride and pronounce on the cure I had some interesting rides but none of my suggestions had any effect The majority of my colleagues then joined in and the aircraft was fitted with bracing wires, strengthening members, telescopes for viewing the tail rotor and many other elegant and ineffective modifications Between us we wasted, for several months, a large part of our slender development resources

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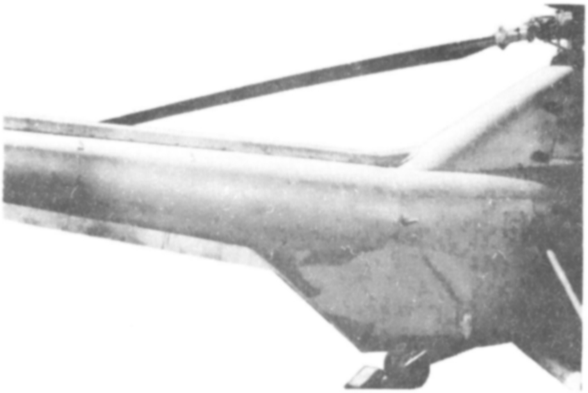

Fig 5—Sharp-edged fin surfaces on tail cone and fuselage rear end

In the end, shake tests of the airframe were carried out and vibration measuring equipment applied to the aircraft From the results it became obvious that the "twitch" was not at all the sudden and random occurrence which had previously been supposed It was a beat between a normal third rotor excitation, with a small additional component of second main rotor order, and another excitation of varying amplitude at the natural lateral bending frequency of the airframe This beat existed in most flight conditions, but occasionally the airframe excitation became larger than usual and the combined amplitude exceeded the threshold of discomfort, giving the subjective impression of a sudden twitch, followed by a rapid subsidence Since the third main rotor order excitation was of normal amplitude, and the second very small, it was obvious that a cure could only be effected if the source of the lateral airframe excitation could be traced, and eliminated or reduced

At the time it was thought that the airframe excitation was probably due to some kind of vortex street shed by the tail cone, or by the rear portion of the centre section of the airframe Sharp-edged fin surfaces were therefore added to the tail cone and rear fuselage as shown in Figure 5 Needless to say this modification also had no effect

It has since been suggested that the airframe excitation may be due to disturbances, originating in the low energy region around the rotor head, which might be considerably reduced by suitable modification of the upper pylon fairing The "twitch" still persists in Dragonfly helicopters and it would be interesting to find an opportunity to try this suggested cure, especially as the same source of disturbance may be responsible for some of the yawing motion observed on many helicopters in turbulent air conditions

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An accelerometer trace of the "twitch" is shown in Figure 6 and the significant variation of twitching amplitude with rudder pedal position is illustrated in Figure 7

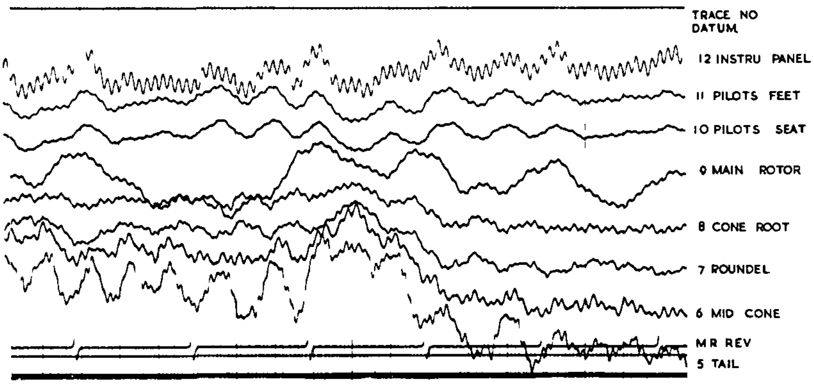

Fig 6—Dragonfly lateral vibration

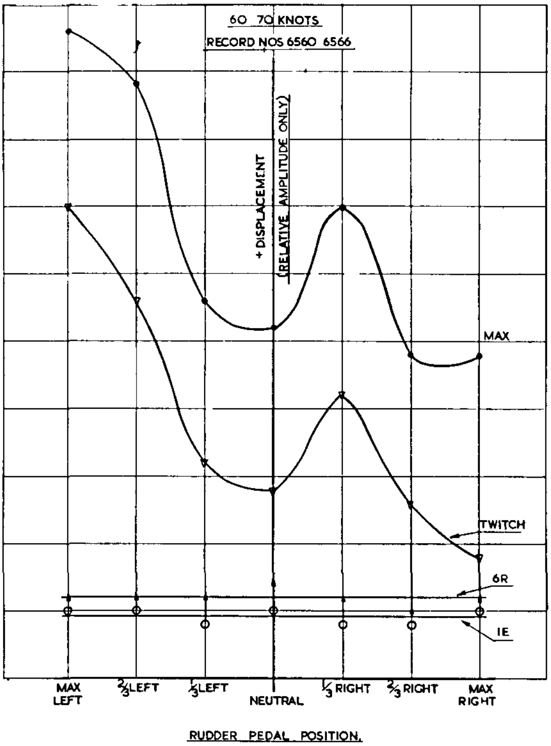

Fig 7—Lateral vibration vs Rudder pedal position

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2 3 *Airframe response*

Avoidance of resonant response by the airframe to the large number of potential excitations is important for the comfort of the occupants, the serviceability of instruments and equipment, and for the freedom of the structure itself from fatigue failure A last-minute major alteration in the natural frequency of a structure can be an extremely expensive undertaking so that structural frequencies repay careful study at the beginning of a design

The r p m range in many helicopters is very wide in autorotation but only a small proportion of flight time is spent in this condition Generally the r p m range in cruising flight is extremely narrow With the introduction of free power turbines the r p m range in the cruise condition may be noticeably widened and this may give greater likelihood of resonance and fatigue troubles until the new conditions are firmly established, although such troubles should be revealed by the standard shake tests for airframe and controls

Shake tests for helicopters require only slight adaptation of the standard methods used for aeroplanes They are carried out with exciters mounted on the control column, in the case of the control system resonance investigations, and on the rotor head and tail cone during the examination of airframe response Figure 8 shows the resonances revealed in a shake test of the S 51 airframe in vertical bending Similar tests in lateral and torsional modes would be needed on any new helicopter

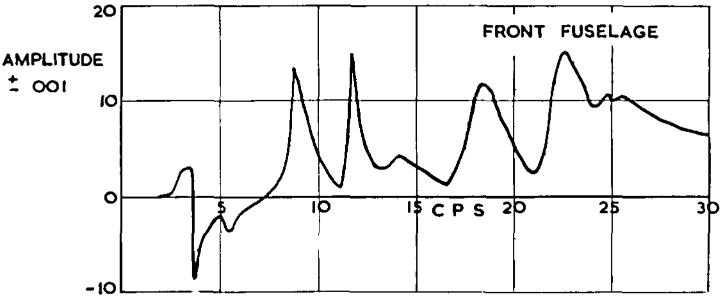

Fig 8—*S* 51 *airframe typical shake test response to out of balance excitation*

2 4 *Anti-vibration mountings*

The problem of anti-vibration mountings has been a considerable plague in helicopters up to the present time In the case of instrument panels, if the mountings are soft enough to attenuate piston-engine vibrations they will generally amplify lower frequency vibrations arising from the rotor, sometimes to the extent of making the panel unreadable Since there is no entirely satisfactory practical solution the final choice is usually a compromise based on trial and error Those with experience of this problem will not be surprised that in experimental work the most satisfactory mounting is often a block of wood! Since much radio and other standard

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equipment is fitted internally with anti-vibration mountings having a natural frequency of 600 cycles per minute, which happens to be approximately third rotor order, one can only express surprise at the robustness of this equipment in standing up to the beating it must sometimes receive

The mounting problem for a piston engine is essentially the same as that for an instrument panel If the mountings are soft enough to attenuate engine vibration in the airframe, they will generally amplify vibration of the engine in response to rotor excitation The problem is further complicated by the lack of flywheel inertia in helicopter piston-engine installations and sometimes, in spite of the weight penalty involved, such inertia has to be added to control engine movement within acceptable limits

In three versions of our helicopters we have installed American engines and have been fortunate in being able to obtain the American mountings, so that we have at least preserved the same standard as that achieved on American helicopters having a very large background of practical operating experience

In the case of the small Leonides engine in the Dragonfly we have had satisfactory results from extremely hard dynafocal mountings, although these transmit a large amount of engine vibration to the airframe In the case of the Leonides Major we have tried to be somewhat more scientific and have achieved quite a satisfactory result when the helicopter is airborne We have, however, had a great deal of trouble with vibration of the engine in test running with the aircraft tied to the ground This problem has been somewhat alleviated by providing a single point tie down for ground running which allows the aircraft freedom in pitch and roll

The introduction of the turbine will eliminate the problem of anti-vibration mountings for the engine and simplify some problems in the mounting of instruments and equipment It will remove a great deal of harsh and unpleasant vibration from cockpit and cabin

2 5 *Control vibration*

In looking to the future one is tempted to dodge the subject of control vibration This problem will obviously disappear with the introduction of fully duplicated power controls, but the subject is still of some importance since experience with the majority of existing helicopters has left a strong impression that control vibration and high control forces are unavoidable features of the helicopter

As to whether it is possible to design a direct mechanical control linkage giving satisfactory characteristics without power assistance, one can only say that experience up to the present time overwhelmingly indicates that power assistance will be required in all future helicopters except perhaps in the smallest sizes

In the conventional helicopter the important control forces and vibrations arise primarily from friction in the blade pitch change assemblies and compressibility effects at the blade tips Both can be greatly reduced, if not entirely eliminated

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Frictionless blade pitch change assemblies have been a feature of many helicopters, most notably in the form of the tension-torsion rod assemblies which characterize Mr Hafner's designs Compressibility effects which cause trouble in the control system appear to be avoidable by a relatively small increase in rotor solidity

Even where these reductions are achieved, the servo-assisted control system is unlikely to have acceptable characteristics since opinion is generally hardening against any deterioration of control characteristics in the event of a servo power failure, so that full duplication of power controls is already a necessity in the larger helicopters Reduction of the primary causes of control force and vibration is therefore tending to become a straightforward design problem aimed at the saving of weight in control linkages and hydraulic systems, rather than a problem affecting the handling qualities of the aircraft

It would be a considerable advantage if some really effective form of aerodynamic servo could be developed for rotors having more than two blades, with a standard of safety equal to that of the rotor itself so that duplicated hydraulic or electric power systems could be avoided A development of this kind seems, in principle, to be perfectly feasible and should receive urgent attention

3 *TRIALS OF A FOUR-BLADED DRAGONFLY*

Stalling of the retreating blades and the motion of the blades in the presence of second harmonic flapping are the two major sources of those vibrations which are generally considered peculiar to the helicopter Although each could be considered separately, they are in practice so closely linked that it is convenient to present a discussion of them in the form of an abbreviated account of some trials carried out with a four-bladed rotor fitted to a Westland Dragonfly

The object of these trials was to demonstrate that stalling of the retreating blade does not constitute a true limit to the forward speed of a helicopter, provided that the rotor design is such as to eliminate major vibrations arising from the flapping motions of the blades

Operation at forward speeds beyond the onset of retreating blade stall implies that the rotor thrust is generated mainly in the fore and aft quadrants of the rotor disc From the performance point of view this amounts to a reduction in the effective span of the rotor and hence an increase in induced drag In this respect the pure helicopter can be compared with the compound helicopter in which, at high forward speed, a large proportion of the lift is transferred to a fixed wing, usually of smaller effective span

The increase in forward speed of the pure helicopter which might result from successful operation at high tip speed ratios beyond the onset of retreating blade stall can be indicated by reference to the Pitcairn PCA-2 Autogiro, which was flight tested in 1933 at a tip speed ratio of 70% For a helicopter having a conventional tip speed of 550 f p s , this would correspond to a forward speed of approximately 230 knots, probably in excess of any real requirement for short range transport aircraft with vertical take-off and hovering ability

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3 1 *Blade flapping and retreating blade stall in a four-bladed rotor*

The arguments leading to these trials were formulated toward the end of 1950, but the programme, the expense of which was shared by the Ministry of Supply and the firm, was conducted on very low priority so that it was not until March 1956 that the results were collected into a report having limited circulation The argument presents a very much simplified picture of rotor behaviour under the conditions appropriate to high speed flight, but in spite of over-simplification it corresponds reasonably well to the actual behaviour of the rotor and illuminates a difficult subject in an easily understandable manner, as will be seen from the following summary

In a rotor operating at a tip speed ratio μ, the instantaneous centre of rotation lies on the axis of the retreating blade at a distance μR from the rotor centre, when the retreating blade is at 90° to the direction of flight The maximum lift and drag forces which can be developed by the working portion of the blade, between the instantaneous centre of rotation and the tip are then reduced to approximately $(1-\mu)^3$ times those which the whole blade could develop in vertical flight

When the tip speed ratio is small the lift and drag forces developed by the retreating blade are large, so that in this condition discontinuities associated with stalling generate large vibrations in the helicopter When the tip speed ratio is large the lift and drag developed by the retreating blade are small, so that discontinuities associated with stalling are no longer a serious cause of vibration of the helicopter

In symmetrical vertical flight the blades of an articulated rotor exert about their flapping hinges a constant lift moment independent of azimuthal position and the blades therefore revolve about the rotor centre in the surface of a cone, the tilt of this cone with respect to the rotor shaft axis being the first harmonic of flapping As forward speed is increased the blades, while passing through the retreating quadrant of the rotor disc, become progressively unable to generate a lift moment sufficient to maintain their motion in the surface of a simple cone When this occurs to a significant extent at low tip speed ratios it is generally due to stalling of the working portion of the retreating blades At high tip speed ratios it will inevitably occur to a significant extent simply through inadequate relative air velocity over the working portion of the retreating blade, irrespective of whether the blade is stalled

Loss of lift moment on the retreating side of a rotor constitutes an unbalanced condition, which would cause a nose-up precession of the rotor disc if it were not for the pilot's instinctive reaction in moving the control column forward in the cockpit This movement of the control reduces the lift moment generated by blades on the advancing side of the rotor disc, until the lift moments on both sides of the rotor are again in equilibrium It will be evident that the new condition of equilibrium is characterised by a reduction in the lift generated in the lateral quadrants of the rotor disc and a corresponding increase in the lift generated in the fore and aft quadrants

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In the above condition each blade is subject to a twice-per-revolution variation in lift moment about the flapping hinge This excitation is at a higher frequency than the natural flapping frequency of the blade (approximately once-per-revolution for rotors with small flapping hinge offsets), and it follows that the upward flapping displacement will be greatest where the lift moment is least (i e laterally) and least where the lift moment is greatest (i e fore and aft)

If we consider a two-bladed helicopter operating in the above condition at a low advance ratio, it will be evident that the two blades will be "coned" upward to the greatest extent when athwartships and to the least extent when fore and aft Thus the helicopter will be subjected to a vertical vibration due to the second harmonic of blade flapping, in addition to a vibration at the same frequency due to discontinuities in lift and drag caused directly by stalling of the retreating blade As the forward speed of the helicopter increases, the vibration due directly to stalling will be reduced but that due to the second harmonic of flapping will increase A helicopter of this type may therefore be expected to suffer increasingly severe vibration as the forward speed is raised beyond the onset of stalling

A four-bladed rotor may be considered as two two-bladed rotors arranged so that when one pair of blades is "coned" up (athwartships) the other pair is "coned" down (fore and aft) Thus the two pairs of blades are balanced against each other, so that a helicopter fitted with a four-bladed rotor is not subject to any vibration due to the second harmonic of flapping When a helicopter of this type encounters stalling of the retreating blade it will therefore experience only that vibration which is due directly to discontinuities of lift and drag caused by stalling Also the maximum severity of this vibration will be the less the higher the tip speed ratio at which the onset of stalling is encountered Moreover, as the forward speed of the helicopter is increased appreciably beyond the onset of stalling, the severity of the resulting vibration will be reduced until, at a sufficiently high tip speed ratio, it will become negligible

3 2 *Test equipment*

The main equipment used for the trials was a standard Westland Dragonfly fitted with four sets of standard Dragonfly blade, sleeve-spindle, flapping link and damper assemblies carried by a specially designed four-armed hub, provided with a special blade rest assembly to carry the four droop stops

From experience gained during the first few flights it was clear that the results of the trials would be of little value unless airspeed and rotor speed could be measured with an unusually high degree of accuracy The test aircraft was therefore flown, in all conditions in which measurements were taken, with an S F I M (Hussenot) A 23 recorder receiving a rotor speed indication from a microswitch mounted on the lower control swashplate, with a marker cam attached to the upper (rotating) swashplate Airspeed indication was simultaneously recorded from a trailing airlog

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Vibration measurements were taken at positions at the top and port side of the control tunnel immediately in front of the observer who was seated in the central position behind the pilot The measurements were recorded either by hand-held Kelvin Vibrograph or by S F I M accelerometers bolted to the structure and connected to the A 23 recorder, the results being substantially the same by both methods

3 3 *Test conditions*

Throughout the trials all tests were conducted at a take-off gross weight of 5700 lb, this being about the maximum for acceptable general performance in view of the extra drag of the fourth blade at normal rotor r p m and the greatly reduced engine power available at the low r p m used under test conditions

The modified hub and extra blade add 130 lb and 135 lb respectively to the tare weight of the aircraft and the above gross weight was also about the minimum at which an acceptable fuel reserve could be carried in addition to the observer, the necessary instrumentation and the forward ballast (minimized by installing the aircraft battery in the cabin) required for maximum airspeed

The maximum engine boost obtainable under most conditions at 165 rotor r p m was 0 lb /sq in and all tests were based on this nominal setting The flight path varied from a slight climb at low speed to a relatively steep dive at maximum speed

A maximum tip speed ratio $\mu = 0\ 42$ was attained at corrected aircraft and rotor speeds of 109 5 knots and 168 r p m respectively, with an estimated 1 2 degrees of second harmonic flapping, and an estimated retreating blade tip angle of attack of 23 degrees In view of the subsidence of vibration experienced at high speed, these results appeared to justify the initial assumptions

A specially marked and tufted blade, photographed by a camera on the rotor head, was therefore installed to provide direct confirmation of blade stalling and of the estimated blade motion and retreating blade tip angle

3 4 *Vibration measurements*

Two sets of vibration measurements were obtained, one with the hand-held vibrograph and the other with accelerometers linked to the A 23 recorder Lateral vibration in the aircraft was small throughout the trials

Vibrograph measurements of vertical vibration at a nominal rotor speed of 165 r p m are plotted in Fig 9 At first the points plotted on this graph caused concern as it can be seen that a single line drawn through all the points would give the impression of a large vibration persisting at the top end of the speed range, with an amplitude less than the peak value but with no indication of subsidence at increasing speed

A vibration of this character might be explicable on the assumption that each blade was being disturbed by the tip vortex shed by the preceding blade According to Meijer Drees[1] such a condition is possible at high speed within a very narrow band of operating conditions at low power, but this explanation would imply that vibration due to blade stall was substantially negligible throughout

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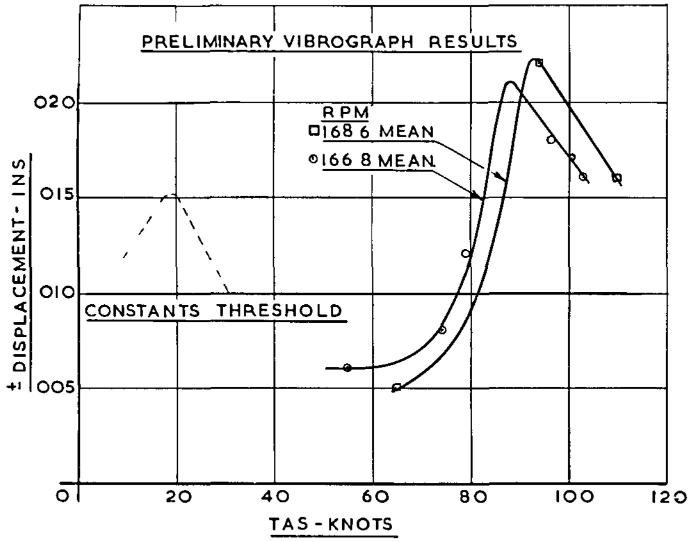

Fig 9—Vertical vibration in cabin (Vibrograph)

The positioning of the points is explained in a more acceptable manner by the spread of rotor r p m during the tests The rotor speed and airspeed measurements were determined with considerable precision so that they can fairly be divided into two groups represented by the twin curves of Fig 9 which are plotted for average rotor speeds of 166 8 r p m and 168 6 r p m respectively The twin curves show the expected subsidence of vibration combined with the expected shift of vibration to higher airspeed with increased rotor speed They also support the expectation of decreased maximum severity of vibration with the onset of stall at higher tip speed ratio (lower rotor speed)

The vibrograph measurements thus appeared to support the assumptions underlying the trials programme but the number of measurements was too small to be conclusive Confirmation is, however, available from the entirely independent accelerometer measurements These also showed a wide scatter of rotor speed about a mean value of 169 7 r p m but points within plus or minus 2 r p m of the mean value, plotted in Fig 10, show the subsidence of vibration in an unmistakable manner

The simultaneous recording of r p m and vibration ensured accuracy of the rotor speed in these measurements but in the case of the accelerometer readings the periods of measurement were too short for precise recording of airspeed which is subject to an error due to pendular swing of the airlog The points plotted in Figs 9 and 10 are also subject to an error not exceeding ± 001″ in the measured displacements, the two sets of error limits being sufficient to reconcile the rate of subsidence of vibration shown in Fig 9 with the steeper rate indicated in Fig 10

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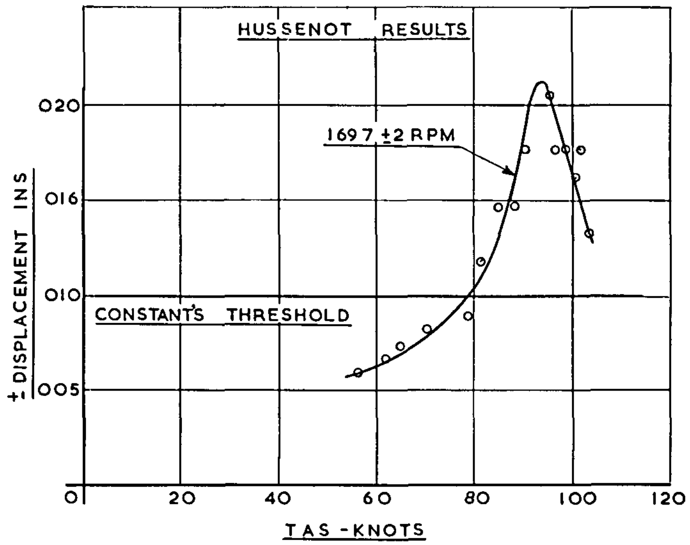

Fig 10—Vertical vibration in cabin (Accelerometer)

3 5 *Results of the trials*

The results of the trials consisted essentially of repeated flights sufficiently far beyond the onset of retreating blade stall to demonstrate that the vibration caused by the stall should be considered as a "hump" to be got over, or suppressed in the design of the rotor, rather than as a firm barrier to large increases in the forward speed of the pure helicopter

The high tip speed ratios which were attained, in spite of the low maximum forward speed of the test aircraft, were made possible by the addition of a fourth blade The extra blade weight preserved a normal coning angle at the low rotor speed used during the trials (165 r p m as compared with the 188—195 normal cruise r p m of the standard Dragonfly) while the extra blade area was sufficient, at this low rotor speed, to delay the onset of stalling to a tip speed ratio $\mu = 0\ 31$ The ability of the test aircraft to fly through and beyond the region of maximum vibration is due to the inherently balanced characteristics, with respect to the second harmonic of flapping, of a rotor having four blades

In addition to generally confirming the expected behaviour of a rotor in conditions simulating flight at high forward speed, the trials provided some interesting factual information of which the following points help to complete the picture of rotor behaviour under these conditions

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3 6 *Stalled area of rotor disc*

Tufting of the special blade provided a check on the areas of stalled, disturbed and reversed air flow over the blades The stalled area of the rotor disc was very large as shown in Fig 11 which is a conservative interpretation of the photographs taken during one revolution Since the condition of equilibrium requires that the lift moments be equal on advancing and retreating sides of the rotor, it follows that an abnormally small amount of lift was being developed on the advancing side of the rotor to balance the large stalled area on the retreating side Hence it follows that the lift was being developed mainly in segments at the front and rear of the rotor area

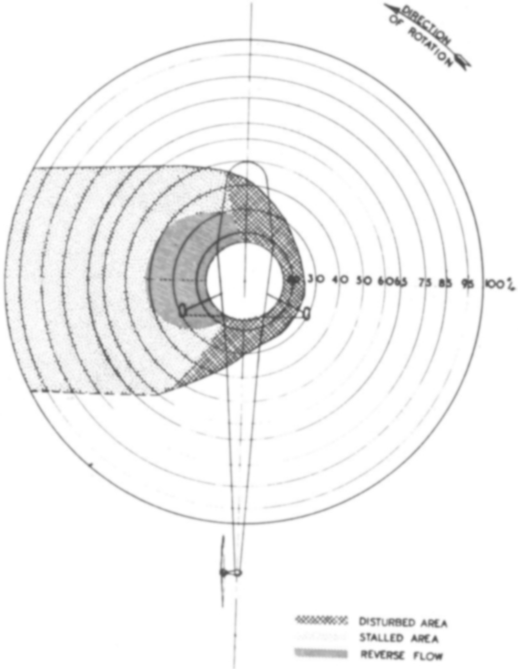

Fig 11—Airflow characteristics over blade

It should be noted that although the position of the control column in the cockpit, under these test conditions, was uncomfortably far forward and displaced to starboard, the response of the aircraft to control movements was, as expected, normal in all flight conditions This must obviously be the case so long as the advancing quadrant of the rotor disc and substantial portions of the fore and aft quadrants are free of blade stall

3 7 *Retreating blade tip angle of attack*

Due to instrumentation difficulties the A23 recorder was not available for the flight during which the accompanying photographs were taken The photographs therefore relate to an indicated air speed, corrected for position error, of 104 knots and a rotor speed, from tachometer indication subsequently checked from the film, of 170 r p m The error limits for these measurements are believed, however, not to exceed ± 1 knot and ± 2 r p m respectively

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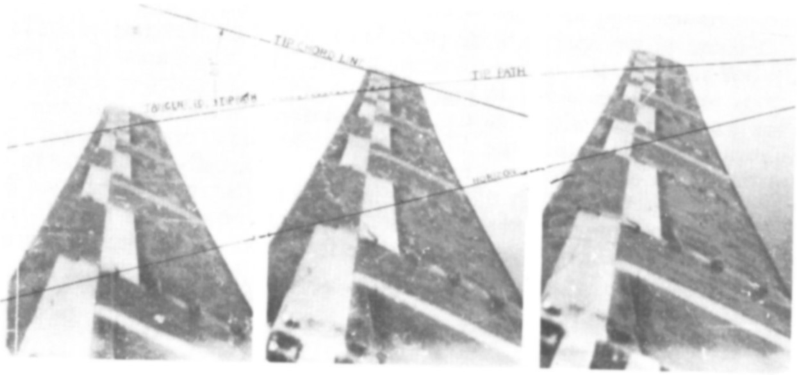

Fig 12—*Four-bladed rotor—measurement of retreating blade tip angle*

In Fig 12 the central picture shows the retreating blade at $\psi = 270°$ Neglecting the small phase displacement of the second flapping harmonic, and observing from the film that blade bending is a maximum in this position, it follows that the picture shows the blade tip at its greatest height above the mean tip path plane Hence a tangent to the actual tip path is, at this point, parallel to the mean tip path plane

In Fig 12 the tangent to the tip path is fixed from pictures taken immediately before and after the central picture, positioned so that the distances between the blade tips are in correct scale relationship The angle of the tip can thus be measured directly with respect to the tip path, and hence with respect to the parallel mean tip path plane, the angle so measured being 21 7°

From estimates in accordance with Appendix I it can be shown that the mean tip path plane is tilted forward to the line of flight by 1 3°, the inflow and induced velocities both being downward, each at 4 ft/sec, so that the total flow through the rotor is at a mean value of 8 ft/sec In conjunction with tip speed and forward speed velocities of 436 ft/sec and 176 ft/sec respectively this indicates an angle of 1 77°, between relative wind and tip path, to be subtracted from the measured angle

Thus the angle of attack of the retreating blade tip, as derived from the photographs, is approximately 20° which is identical with an estimate obtained by the method of Appendix I

3 8 *Blade bending and twisting*

Close inspection of the individual photographs of the same sequence shows no appreciable twisting or chordwise bending of the blade but there is considerable bending in the flapping plane — i e 'hogging" on the advancing side, and "sagging" on the retreating side In the cine film this motion is seen as an upward wave entering at the blade root on the advancing side and leaving the tip on the retreating side

The existence of a wave motion is incompatible with bending resonance in the primary mode and the fact that the blade is observed to bend in this manner suggests two considerations of some interest In the first place, where a bending resonance in the primary mode may be suspected the establishment of a wave motion by the use of a cine camera offers a clear distinction between resonant and non-resonant bending

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In the second place a more rigorous examination of the aerodynamic loading system on a rotor blade might show that the manner in which this loading system varies in azimuth is inherently incompatible with primary mode bending resonance in a helicopter rotor blade

Flapwise bending of the blades implies fluctuations in the vertical forces applied by each blade to the hub and may be a source of significant rolling and pitching vibration in helicopters with offset flapping hinges This might be alleviated by second harmonic control which could reduce flapwise bending at high forward speed, but is more likely to be controlled by adjustment of blade twist Vertical force fluctuations arising from each blade were substantially self-cancelling in the four-bladed rotor of the test aircraft since its flapping hinges were concentric with the main rotor shaft

Resonant bending in the chordwise plane may contribute to the vibration experienced in some existing helicopters but present techniques of metal blade design and manufacture are comparatively flexible so that it should not be difficult to eliminate resonance by straightforward modification of the blade spar proportions Although more extensive data would be desirable on the aerodynamic loading system, advanced methods of solving the relevant dynamic equations are now available, so that with the aid of electronic computors it should be possible to avoid resonance in initial design, or to eliminate resonance during development, without encountering impossible mathematical problems as might have happened before the War when the facilities available were comparatively elementary

The operating conditions experienced during these trials throw an interesting sidelight on the flutter problems discussed in Professor Collar's recent paper[2] With the entire working portion of the retreating blade completely stalled, a condition of stalled flutter involving only one degree of freedom would have been possible and the fact that it did not occur may be of some significance In this connection it should be noted that the fact that the rotor was close to the autorotative condition resulted in a more extensive stall of the working portion of the blade than would have been the case had the test aircraft possessed sufficient power to maintain level flight at high speed

3 9 *Harmonics of blade flapping*

In the cine film the bending motion of the blade obscures the tip on the advancing side, but for comparison with the estimated blade motion this is of no consequence since the estimates assume a rigid blade, i e they correspond to the actual blade motion at about 0 7R Fig 13 shows the flapping motion of the blade at 0 7R as measured from the photographs Electronic computor analysis of nine cycles of this motion yielded the following amplitudes for the flapping harmonics —

Harmonic	Amplitude in degrees
1st	5 8278
2nd	0 9850 (c f estimated 0 97 degrees)
3rd	0 1740
4th	0 0202
5th	0 0512

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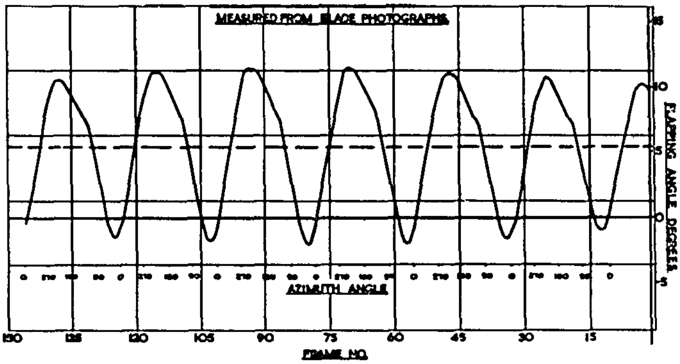

Fig 13—Flapping angle at 70% R

The phase displacements of the first three harmonics as measured from Fig 13 are illustrated in Fig 14 It will be seen that the 9° phase displacement of the second harmonic confirms the $8\frac{1}{2}$ to 9° estimated in Appendix I

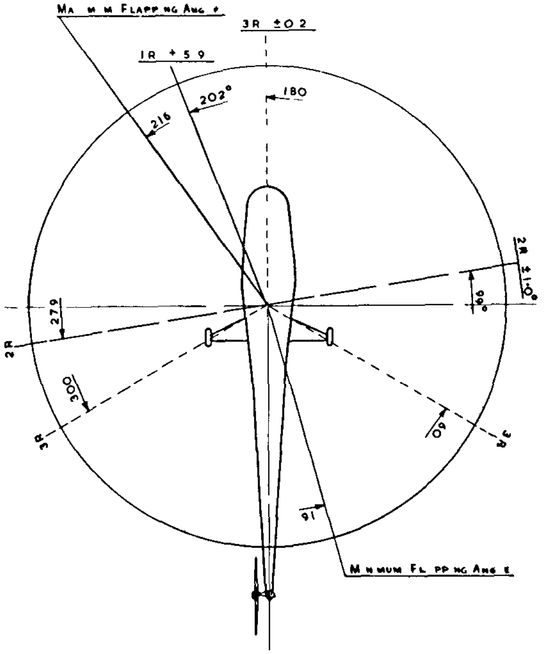

Fig 14—Four-bladed Dragonfly—Phase angles of flapping harmonics

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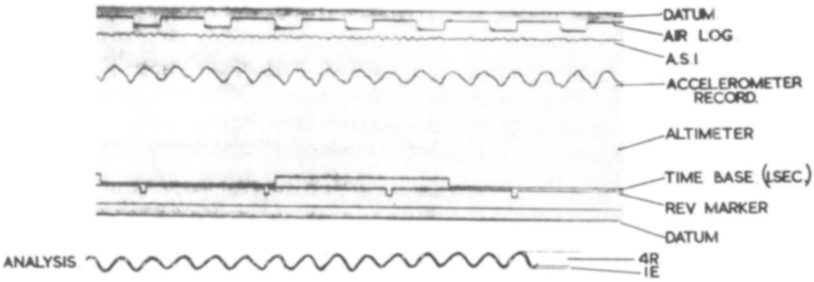
At high tip speed ratios the lift and drag discontinuities due to stalling of the retreating blades appear to have an insignificant effect on the second harmonic of flapping, so that for future high speed helicopter designs this motion of the blades can be estimated with sufficient accuracy by conventional methods which ignore retreating blade stall

3 10 *Suppression of vibration due to blade stall*

Inspection of Figs 9 and 10 shows that the vibration of a four-bladed rotor due to stalling of the retreating blades could be suppressed below the threshold of discomfort by postponing the onset of stall to a tip speed ratio of the order $\mu = 0$ 45, which should be within the scope of second-harmonic blade pitch control for rotors having blade loading coefficients only moderately less than present conventional values This type of control will also be beneficial at high forward speed in avoiding excessively forward trim positions of the pilot's control column, and in reducing blade stresses and the drag of the inboard portions of the retreating blades

An elegant method of dodging the vibration due to blade stall is applicable to helicopters which would otherwise have to pass through the peak vibration while accelerating to cruising speed By this method the critical speed is passed without vibration, by maintaining the rotor r p m at a slightly higher than normal value At a convenient later moment during the acceleration of the helicopter, an increase in collective pitch allows the rotor speed to fall rapidly to normal cruise r p m so that the peak of vibration causes only a momentary disturbance, comparable to changing gear in a motor-car Since the position of the peak stalling vibration in the speed scale is critically determined by rotor r p m , a clean "gear change" should quite easily be made without undue skill

Apart from some engine excitation, the only vibration present in the trials aircraft was the nearly pure simple harmonic displacement at "once-per-blade" frequency shown in Fig 15, which obviously could have been entirely suppressed by a mechanical vibrator geared to the transmission When the trials were brought to an end the aircraft was being fitted with accelerometers to establish the precise nature and orientation of vibration



NOTE THE VIBRATION RECORD SHOWS THE 4R VIBRATION WITH A SMALL AMPLITUDE OF 1ST ENGINE ORDER

Fig 15—Four-bladed Dragonfly—typical vibration record

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at the rotor head and throughout the airframe The results were expected to provide data on fuselage bending and the extent of any vibration arising from the bending motions of the blades, but especially data for the design of a small mechanical vibration absorber

Success in this programme would have provided, in a comparatively inexpensive manner, the first positive demonstration of the possibility of eliminating vibration from a helicopter in all conditions of flight, including conditions of extensive blade stall

3 11 *Blade pitching moment divergence due to compressibility*

A positive limit to the forward speed of the test aircraft was set by high control forces which, by over-riding the servo controls, caused the control column to "kick" laterally

It is now almost certain that this is due to a pitching moment divergence of the tip aerofoils in the fore and aft quadrants of the rotor disc, associated with the beginning of shock stall at high incidence Although this may constitute a true limit to the maximum forward speed of helicopters with conventional control systems, such a limit is likely to be in excess of any real requirement for short-haul V T O L aircraft Since the blade tip Mach Number increases relatively slowly with forward speed for blades in the fore and aft quadrants of the rotor disc a moderate increase in solidity would have permitted a large increase in the forward speed of the test aircraft

A moderate increase in solidity (i e reduction in blade loading coefficient) is desirable on many counts, particularly for rotors intended to operate at high tip speed ratio, where the generation of lift tends to be concentrated in the fore and aft quadrants of the disc This is obviously true for pure helicopters designed to operate beyond the onset of retreating blade stall, but it may also be of considerable significance for other types of helicopter provided with fixed wings when operating in turbulent air conditions Fortunately, this requirement coincides with the introduction of the gas turbine engine, the excellent power/weight ratio of which makes an increase in rotor solidity reasonably economical

4 *VIBRATION DUE TO BLADE FLAPPING*

4 1 *Matching of blades*

To secure smooth operation of a rotor it is obvious that the blades must be in balance and must perform identical movements in all conditions of flight For blades manufactured to normally close tolerances, balancing can be adequately achieved by adjusting the weight of the blade, and its first weight moment about the flapping hinge, to limits which are well within the capacity of normal balancing equipment

To ensure that the blades are interchangeable and perform identical movements in flight, the pitching moment characteristics of each blade must be adjusted to a standard This is done on a whirl stand by measuring the variation of pitching moment with angle of incidence for each blade, and adjusting to a common standard by chordwise positioning of a tip weight and fine adjustment of the blade trailing edge angle When this procedure is completed the blades are given a common initial setting on the aircraft

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by the usual tracking procedure They should then remain balanced and "in track" in all conditions of flight With torsionally stiff metal blades of robust construction, readjustment of the initial settings should not be necessary over long periods

In a general sense, inaccurate balancing or matching of the blades gives rise only to a mildly unpleasant oscillation of the helicopter at rotor frequency, although the condition may also be visually disturbing since it gives an unsteady flickering appearance to the motions of the blades as seen by anyone watching the edge of the rotor disc

The causes of an out-of-track condition are usually obvious and easily corrected but the subject has attracted undue attention due to the common use of two-bladed and three-bladed rotors which are exaggeratedly sensitive to the higher harmonics of flapping which accompany the basic out-of-track condition

4 2 *Motion of a three-bladed rotor with second harmonic flapping*

The typical early Autogiro built by Cierva and, under licence, by many other constructors both here and in Europe and the United States, had four blades and was fitted with fixed wings At maximum speed the wings supported approximately 40% of the weight and a result of this subtraction of lift from the rotor was that its rotational speed fell as the forward speed of the aircraft increased, so that very high tip speed ratios were attained

When the three-bladed C-30 Autogiro was introduced it was without wings so that the rotor supported the full weight of the aircraft in all conditions of flight, maintaining a substantially constant rotational speed and operating at a lower tip speed ratio, within the capacity of the three-bladed rotor The success of the C-30 rotor, operated at low tip speed ratio in conditions free from stalling of the retreating blade tip, seems to have obscured understanding of the reactions of this type of rotor in the presence of the second harmonic of flapping

Failure to maintain even distribution of lift over the rotor disc, whether due to stalling or any other cause, can excite an infinite series of the harmonics of flapping but the second harmonic is by far the biggest and most important component In the previous section we have seen how the vertical vibration experienced by a two-bladed rotor in the presence of the second harmonic can be cancelled by adding a second pair of blades so as to make a four-bladed rotor A similar argument applies to the three-bladed rotor

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The motions of a three-bladed rotor in the presence of the second harmonic of flapping are most easily seen with the aid of a model, but are illustrated diagrammatically in Figure 16 The motion is a "swashplating" or wobbling movement which is executed by the blades as if they were rigidly connected together, without change of coning angle If we consider the thrust vector of the rotor as an arrow normal to the disc, it will be seen that the motion of the rotor is equivalent to a rotation of the thrust vector in the surface of a cone having a semi angle at the apex equal to the amplitude of second harmonic flapping The rotation of the thrust vector takes place at three times rotor frequency, in the direction of rotation of the rotor

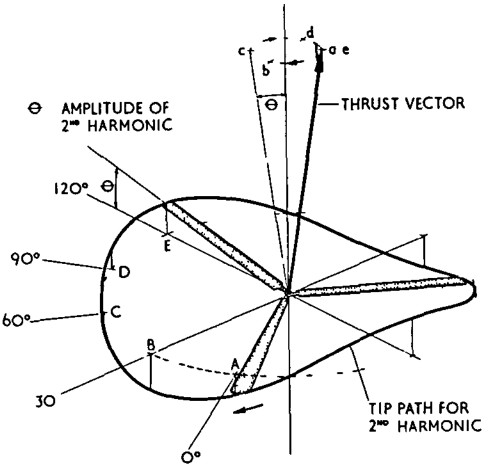

Fig 16—Diagram of three-bladed rotor with 2nd harmonic flapping

By analogy with the previous case, if we add a second set of three blades to make a six-bladed rotor, the thrust vectors from the two sets of three blades will always be inclined in opposite directions so that a helicopter fitted with a six-bladed rotor will suffer no vibration due to the second harmonic of flapping Vibration due to the second harmonic is thus always cancelled out in rotors having an even number of blades other than two

When a helicopter with a three-bladed rotor is flown, as in Ref 3, in conditions in which retreating blade stall is predicted, it is natural to assume that the resulting vibration is entirely due to the discontinuities in blade lift and drag associated with the stall It was a conviction that a large part of this vibration was due simply to the inherent motion of a three-bladed rotor in the presence of the second harmonic of flapping, which led to the argument underlying the trials of the four-bladed Dragonfly

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4 3 *Number of blades and the harmonics of flapping*

Each harmonic of flapping has physical reality in the path travelled by a point on the blade typically located at 70% of the radius In second harmonic flapping each blade rises above its mean path on the sides of the rotor, and falls below in the fore and aft positions, so that it travels a path containing two bumps and two valleys In third harmonic flapping the blade travels a path containing three bumps, in fourth harmonic flapping a path containing four bumps, and so on As shown by Stewart[4] the amplitude of each harmonic is generally only a small fraction of the amplitude of the preceding one — i e the size of the bumps is rapidly reduced as the number of bumps increases

An unlimited number of harmonics may be excited simultaneously but their effects are directly additive and each may be considered separately as a source of vibration In rotors having three or more blades, vibration due to flapping results only from the two types of motion previously described in connection with the second harmonic, namely vertical vibration caused by simultaneous coning of all the blades together, or rolling and pitching vibration caused by conical wobbling of the rotor thrust vector

If we consider a rotor having N blades rotating in a clockwise direction, inspection of a simple model shows that the rotor experiences vertical vibration from the Nth harmonic, a clockwise wobble from the N—1th harmonic, and a much smaller anti-clockwise wobble from the N+1th harmonic, all at N times rotor frequency

The rotor will also experience vertical vibration from the 2Nth harmonic, a clockwise wobble from the 2N—1th harmonic and an anti-clockwise wobble from the 2N+1th harmonic, all at 2N times rotor frequency In rotors having four or more blades vibrations at 2N times rotor frequency or higher are generally completely negligible, but in the three-bladed Dragonfly the six times rotor frequency vibration is a frequent source of annoyance since it causes a tingling sensation in the pilot's feet and resonance of some instrument panels

This vibration is unlikely to arise from the 7th harmonic which is undoubtedly extremely small, nor from the 6th which would give a vertical excitation, involving the whole weight of the aircraft and thus very small amplitudes unless there were a resonant response of the airframe The cause is most likely the wobble due to the 5th harmonic, which is surprisingly large in the four-bladed Dragonfly A disproportionately large 5th harmonic of flapping in three-bladed and four-bladed versions of the same aircraft would be an interesting subject for further investigation

4 4 *Flapping vibration of rotors with three or more blades*

Figure 17 records the relative amplitudes of the flapping harmonics measured on the four-bladed Dragonfly, and indicates the excitations to be expected in rotors having three, four, five and six blades

Increase in the number of blades is obviously an important step in reducing vibration of the helicopter,but this simple rule deserves some ampli-

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fication There is a whole order of difference between the amplitude of vibration experienced by a three-bladed rotor and that experienced by a four-bladed rotor, since four blades are the minimum required to isolate the rotor from excitation by the very large second harmonic of flapping The less marked difference in the vibration experienced by four and five blade rotors is also important since five blades is the minimum required to isolate the rotor from the third harmonic which is the next largest source of excitation

I must confess that until preparation of this paper was in hand, I was very suspicious of the five bladed rotor because of a fancied excitation by the second and third harmonics of flapping It is only recently that I have been able, with the aid of a model, to see that vibration in a five-bladed rotor is excited only by the fourth, fifth and sixth harmonics

Whether a six-bladed rotor is better than a five-bladed rotor is clearly dependent on whether the amplitude of the fifth harmonic of flapping is always disproportionately large as measured in the four-bladed Dragonfly If this proves to be an inherent characteristic of rotors generally, then the five bladed rotor is obviously exceptionally good in that it experiences vibration due to the fifth harmonic as a vertical excitation involving the whole weight of the helicopter so that the resulting amplitude of movement will be extremely small In a six-bladed rotor the fifth harmonic of flapping will excite a 6R wobble, of the same magnitude experienced in a three-bladed rotor, and possibly requiring suppression to avoid a tingling sensation felt by occupants seated far from the C G of the helicopter

To suppress the vibration excited by the fifth harmonic of flapping in a six-bladed rotor or by the fourth harmonic in a five-bladed rotor, should be a very simple matter In rotor systems which provide access from the bottom of the main gear box direct to the top of the rotor head through a hollow main rotor shaft, this can be effected by a central quill shaft driven at N times rotor r p m and carrying a small offset counterweight at the top For the high frequencies and small amplitudes of wobble involved in these two cases, the weight penalty involved in such an installation would be quite negligible

To suppress the vibration excited by the third and fifth harmonics of flapping in a four-bladed rotor, concentric counterweights rotating in opposite directions could suppress all significant vibration for a very small weight penalty

Mechanical suppression is probably unnecessary in helicopters having rotors with four or more blades since their natural level of vibration is generally well below Constant's threshold of discomfort Even the excitation due to the fifth harmonic of flapping in the Dragonfly is not noticeable with well matched blades and should not attract attention in a passenger cabin upholstered to normal aircraft standards Nevertheless, because the flapping motions of the blades are the main source of those vibrations which are peculiar to the helicopter, the possibility that all significant vibration due to these excitations could be suppressed by simple means is a guarantee that comfortable vibration-free travel can be provided in helicopters intended for passenger transport

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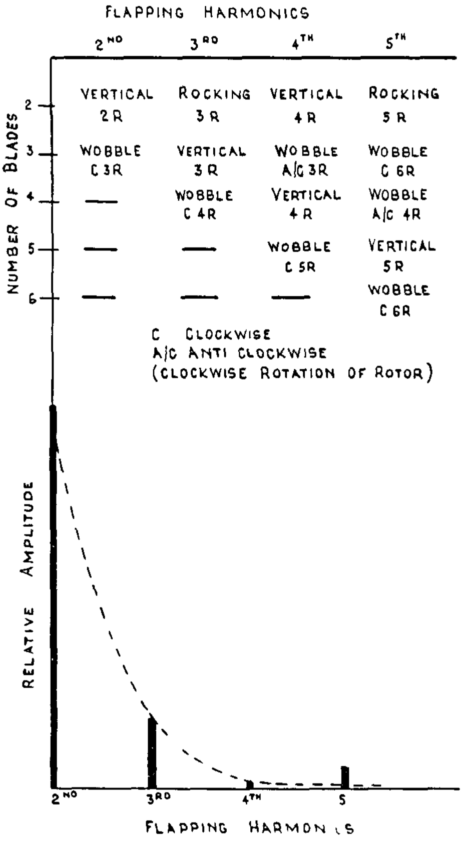
From Fig 17 it can be seen that three-bladed rotors are suitable only for operation in conditions where the tip speed ratio is low and where stalling of the retreating blade cannot occur even in turbulent air conditions Where they are operated outside these limits the resulting severe vibration cannot be suppressed by a simple counterweight installation Such an installation would have to deal with a sizeable 3R vertical excitation due to the third harmonic of flapping as well as 3R wobbles due to the second and fourth harmonics, and possibly a 6R wobble due to the fifth harmonic The resultant complication and weight penalty would be unacceptable



FLAPPING HARMONICS

NUMBER OF BLADES	2ND	3RD	4TH	5TH
2	VERTICAL 2R	ROCKING 3R	VERTICAL 4R	ROCKING 5R
3	WOBBLE C 3R	VERTICAL 3R	WOBBLE A/C 3R	WOBBLE C 6R
4	—	WOBBLE C 4R	VERTICAL 4R	WOBBLE A/C 4R
5	—	—	WOBBLE C 5R	VERTICAL 5R
6	—	—	—	WOBBLE C 6R

C CLOCKWISE
A/C ANTI CLOCKWISE
(CLOCKWISE ROTATION OF ROTOR)

Fig 17—Excitation due to flapping

4 5 *Flapping vibration of two-bladed rotors*

With two-bladed rotors, as with three-bladed rotors, vibration is excited by every harmonic of flapping Where the two-bladed rotor is provided with flapping hinges, the blades will "cone" up and down in an obvious manner in the presence of every even harmonic of flapping Where flapping hinges are not provided, this motion is replaced partly by a vertical displacement

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of the rotor as a whole, and partly by bending of the blades, the extent of each depending on the rigidity of the rotor

Where the rotor is provided with flapping hinges only, or with a simple see-saw hinge, the rotor will react to each odd harmonic of flapping with an obvious rocking motion such that when the tip of one blade is at the top of a bump the tip of the opposite blade will be at the bottom of the corresponding valley If we imagine a vertical pointer to be erected at the hub, it is clear that the combined rotational and rocking motion of the pointer would cause its tip to describe a typical pantograph pattern for each odd harmonic of flapping

In the case of gimbal mounted see-saw rotors the motion of a similar pointer is indeterminate For example, as an alternative to the pantograph pattern described above, the tip of the pointer could equally well describe a circle, as is the case for a pair of blades forming part of a four or six-bladed rotor Thus the movements of the hub of a gimbal mounted see-saw rotor are dependent on the type of restraint applied to the hub in respect of movements about the blade pitch change axis The behaviour of a model rotor of this type in the presence of odd harmonics of flapping suggests that powerful "snatching" motions of the hub are possible about the pitch change axis This (or compressibility effects) might account for the curious behaviour of the control systems of some small helicopters using this type of rotor in turbulent air conditions

For small helicopters with light disc loadings the gimbal mounted see-saw rotor is very attractive but satisfactory behaviour can only be expected in conditions in which the distribution of lift over the rotor disc is substantially uniform

5 *IN-PLANE VIBRATION*

Vibration due to excitation in the plane of the rotor is not generally a cause of serious concern Such vibration has existed to a serious extent in certain two-bladed experimental rotors but it affects current two-bladed designs only to a minor extent so long as they are operated within their natural limitations To a much lesser extent it also affects articulated rotors having drag hinge dampers

5 1 *Blade drag fluctuations*

The effect of fluctuations in the in-plane component of the air forces acting on a blade can most easily be seen if we consider a two-bladed rotor When the blades are in the fore and aft positions the air forces acting on each blade, and their distribution along its length, are substantially identical for both blades When the blades are in the athwartships position the rearward drag of the advancing blade may not be equal to the forwardly directed drag of the retreating blade Any difference will impart a force to the hub in a fore and aft direction, and this force will reach its maximum value every time the blades are in the athwartships position — i e twice per revolution With three or more blades the summation of these vibratory forces gives only a steady force

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5 2 *Coning and flapping*

The effect of combined coning and flapping can also be most easily seen by considering a two-bladed rotor, in which the blades are attached by drag and flapping hinges to a hub mounted rigidly on the rotor shaft When the blades are coned upward, and flapping so that the disc is tilted rearwardly with respect to the shaft, if the rotor is viewed in a direction normal to the disc it will be seen that when the blades are in the athwartships position both blades are inclined rearwardly about their drag hinges, so that they impart to the hub a rearward force which will reach its maximum value every time the blades are in the athwartships position As before, with three or more blades the summation of these vibratory forces gives only a steady force

Where a two-bladed rotor is provided with flapping hinges only, or with a simple see-saw hinge, movement of the blades about the drag hinge is replaced partly by fore and aft movement of the rotor as a whole and partly by bending of the blades, the extent of each depending on the rigidity of the rotor

Two-bladed rotors of the kinds described above are unsuitable for general application because of their vibration in conditions of combined coning and flapping Where either or both of these can be suppressed such rotors can operate satisfactorily—as for example the two-bladed metal tail rotor of the S 55 which is of very rigid construction with zero coning angle, and the main rotor of the Jet Gyrodyne in which both coning and flapping angles are very small

For successful general application the two-bladed rotor requires an additional degree of freedom allowing movement about the pitch change axis, as provided in the gimbal mounted see-saw rotors which have achieved a wide popularity

5 3 *Vibration due to dampers*

The articulated two-bladed rotor is again a convenient model for examining the excitation produced by drag hinge dampers To begin with, consider each blade restrained by a single-plate, or constant-force, friction damper and for simplicity let the drag hinges and dampers be concentric with the rotor shaft As before, let the blades be coned upwards, and flapping so that the rotor disc is tilted rearwardly with respect to the shaft Then, when the blades are in the athwartships position, both blades will be inclined rearwardly about their drag hinges

It will be clear from Fig 18 that when blade A moves from the advancing side toward the retreating side it must move anti-clockwise about its drag hinge Similarly blade B, in moving from the retreating to the advancing side, must move clockwise about its drag hinge

The forces overcoming the resistance of the damper are aerodynamic and inertia forces, acting at or near the centre of percussion of the blade, which are transmitted to the hub by the drag hinge pin, where they can be represented as a vector Consequently the forces acting on the hub due to the dampers can be represented by the vectors A′ and B′, which combine to give the single force vector P

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The action of this vector is unusual When the blades are incrementally past the athwartships position the vector P points forward From this position it swings anti-clockwise with the rotor so as to point aft when the blades are again in the athwartships position It then disappears, and instantaneously reappears pointing forward, to repeat the cycle indefinitely It will be seen that this gives rise to a non-sinusoidal excitation at twice rotor frequency, of magnitude $\pm P$ in the fore and aft direction and $\pm P/2$ laterally to port If the rotor disc were tilted forward instead of rearward with respect to the shaft, the magnitude of the fore and aft excitation would remain the same but the lateral excitation would be to starboard

In a four-bladed rotor each pair of blades produces a similar force vector but, assuming the total weight of the blades remains the same and that the damper pull-off torque is proportional to the individual blade weight, each of the two vectors would be only half as large Moreover, the resultant vector of magnitude $P/\sqrt{2}$ would sweep through only 90°, producing a fore and aft excitation of $\pm P/2$ and a lateral excitation of $\frac{1}{2}\,(P/\sqrt{2}-P/2)$, or approximately $\pm P/10$ From similar vector addition the excitations due to single-plate dampers are found to be as shown to scale in Fig 18, for various numbers of blades

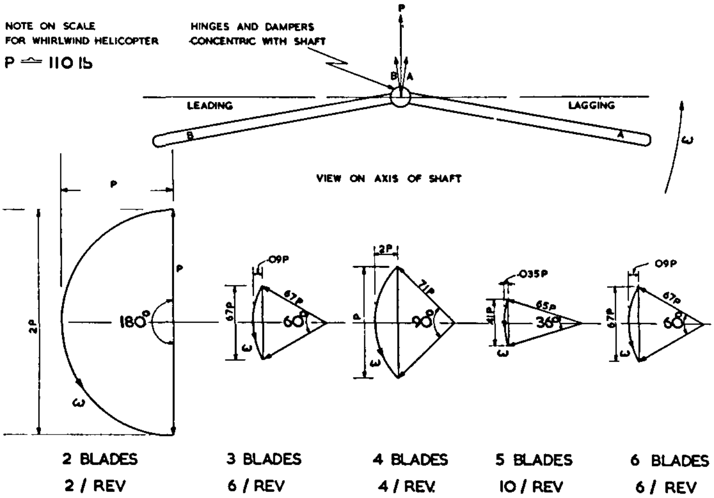

Fig 18—*In-plane excitation due to single-plate friction dampers for rotors with various numbers of blades*

For single-plate dampers the magnitude of the force vector is constant for all values of combined coning and flapping except zero, since all movements meet the same resistance For multi-plate progressive dampers the magnitude of the force vector can be made roughly proportional to the degree of combined coning and flapping Also the magnitude of the force vector would be least where the displacement is least In the example illustrated

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this would be when the blades are fore and aft, so the reduction would apply especially to lateral excitation, although this is in any case very small for rotors with three or more blades

For hydraulic dampers the resistance to movement is least where the velocity is least In the example given, the velocity of movement about the drag hinge is zero when the blades are in the athwartships position, and fore and aft excitation would be virtually eliminated If hydraulic dampers had purely viscous characteristics they might produce very high lateral forces, but in practice they are always fitted with relief valves giving constant damper force above a limiting velocity Thus, with hydraulic dampers, as the degree of combined coning and flapping increases, the lateral excitation will rise from zero to a maximum equal to the small values shown for single plate dampers in Fig 18

CONCLUSION

A moderate reduction of blade loading co-officients, the use of rotors with four or more blades, and the introduction of turbine engines—these are the main requirements for smooth operation at high forward speed, and they are characteristic of the next generation of helicopters which will shortly be in production

With these new helicopters we will have a suitable basis for closer examination of such secondary factors as the excitation due to blade bending and the extent of any need for second harmonic pitch control or mechanical suppression A suitable basis, in short, for finally eliminating vibration as a significant characteristic of the helicopter

ACKNOWLEDGMENT

My thanks are due to Westland Aircraft Limited, for the facilities placed at my disposal in preparing this paper, and to many colleagues for their invaluable assistance I am especially indebted to Mr Edgar Jackson and to the Pilots and Observers who were associated with him in tests of the four-bladed Dragonfly

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APPENDIX I

CALCULATION OF PERFORMANCE, BLADE FLAPPING AND RETREATING BLADE ANGLES

1 Performance

The rates of climb and descent of the aircraft were estimated on the basis of the standard momentum theory for a range of forward speeds and power settings, the coefficients used in the analysis being as follows —

(*a*) *Fuselage and other parasite drag*

$$D_{100} = 230 \text{ lb}$$

$$C_{D_f} = \frac{230}{11\ 89 \times 1882} = 0\ 01027$$

Parasite drag varies as V^2

(*b*) *Blade profile drag*

For the range of mean C_L represented by the calculations a value of blade profile drag coefficient giving reasonable accuracy is —

$$C_D = 0\ 009 + 0\ 17 \left(\frac{C_T}{S}\right)^2$$

where

$$C_T = \frac{2T}{\rho A(\Omega R)^2}$$

No additional increment in drag for the stalled areas of the disc was considered

(*c*) *Rotor profile torque in forward flight*

In forward flight, a factor of $(1 + 4\ 65\mu^2)$ was used for estimating the profile torque of the rotor, to correlate with measured performance data for the standard aircraft

(*d*) *Transmission efficiency*

After making allowances for transmission losses, engine cooling losses, and the power required for torque compensation, the percentage of engine power available at the main rotor is 83 5% above an advance ratio $\mu = 0\ 20$

2 2nd harmonic blade flapping

The analysis of blade flapping assumes constant induced velocity over the disc, with no corrections for reversed flow or stalled regions of the disc

The theory is based on the Fourier series for blade flapping motion —

$$\beta \doteq a_0 - a_1 \cos\psi - b_1 \sin\psi - a_2 \cos 2\psi - b_2 \sin 2\psi \text{ etc },$$

a_0 representing the constant coning angle

a_1, b_1 „ „ „ disc tilt

a_2, b_2 are the coefficients of 2nd harmonic flapping

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The analysis of the higher harmonics of rotor blade flapping has most recently been set down by Stewart[4] Using the same notation, the coefficients of 2nd harmonic flapping are estimated from the following two relationships

$$3a_2 - \frac{B^4}{4}\gamma b_2 = \frac{\gamma}{2}\left\{ -\frac{B^2\mu^2\theta_0}{4} + \frac{B^3\mu B_1}{3} \right\}$$

$$\frac{B^4}{4}\gamma a_2 + 3b_2 = \frac{\gamma}{2}\left\{ -\frac{B^2\mu^2 a_0}{4} - \frac{B^3\mu A_1}{3} \right\}$$

For the Dragonfly at low altitude, the rotor blade Inertia Number is —

$$\gamma = \frac{\rho a c R^4}{I_{flapping}} = 8\ 0 \textit{ approximately}$$

The magnitude of the a_2 coefficient is approximately three times greater than the value of $-b_2$ Consequently, the maximum amplitude of 2nd harmonic flapping is only slightly greater than the value a_2 and is phased about 8½°—9° from the true lateral and fore-and-aft blade positions in azimuth

3 Retreating blade angles

The estimation of retreating blade tip angles was based on simple strip theory and also assumed constant induced velocity over the disc with no corrections for reversed flow or stalled areas Account was taken of the 8° of geometric twist (wash-out towards the blade tip) of the Dragonfly rotor blade, and of the effect on blade pitch of 2nd harmonic blade flapping This latter effect is small and even in the most extreme cases does not amount to more than a 1° increase in blade angle

In the past, comparison of this simple analysis with flight test data at the onset of blade stall vibration has resulted in limiting angles of between 14½° and 16½° being used to denote the vibration limiting speed (V_{NE}) of the helicopter

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Discussion

The **Chairman** said that the Author had given a most interesting and instructive discourse They would all be grateful to him for the trouble he had taken in preparing his model and the two films he had shown, which helped one to have a physical grasp of the phenomena involved

Dr J A J Bennett (*College of Aeronautics, Cranfield*) (*Founder Member*), said that the vibration survey which the Author had presented was most valuable in helping them to revise their overall perspective of helicopter dynamics They were too apt to view the helicopter as an aero-elastic system with a whole spectrum of natural modes of oscillation on the one hand and another spectrum, of periodic excitation, on the other, and to conclude that it was impossible in practice to avoid having at least one of the exciting frequencies fairly close to the frequency of one of the natural modes, thereby resulting in troublesome vibration of one kind or another Perhaps the frequencies of the natural modes of oscillation of the blades could be included with advantage in Fig 4 Even if resonant vibrations were minimised by appropriate separation of frequencies between the two spectra, there was still a possibility of self-excited vibrations which were non-resonant in character and which had to be kept under control by adequate damping Thus, the Author s expectation of smoothness at high forward speed in the operation of the next generation of heli-

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