together and the final positions which they will occupy are marked The pockets are then removed and the spar and pocket surfaces to be bonded are given the appropriate coatings of cement When the cement is ready for bonding the pockets are sprung over the spar into their previously marked positions and the jig is clamped up for an initial period of air curing of the cement

After removal from the assembly jig the blade is placed in a low temperature oven, heated by the steam pipes The blade is cured in this oven for approximately 16 hours at a moderately low temperature

We could use Redux for all bonding operations on the blade including the pocket assemblies but the rubber cements, although not as strong as Redux, have given results well above the desired minimum The rubber cement is easy to apply and also has the very useful property of air curing, so that should a trailing edge pocket be damaged in the field it can be removed and a new pocket cemented in its place, provided reasonable cleanliness precautions are taken, and thereafter left to air cure The desired minimum strength is in such cases reached after approximately 10 days in normal storage although the bond does not reach its full strength for 3 weeks

The trailing edge of the pockets forms a natural kind of tab which is useful in the final matching of the blades, carried out with special instrumentation either on a helicopter or on a test tower The blade tip assembly incorporates a weight which is movable chordwise, the position of this weight also being finally determined as a result of whirl tests During these tests a temporary tip cover is used, but when they are completed the production tip cover is riveted and cemented in place When the blade has been finally checked out it will, when we have fully developed our matching technique, be interchangeable with any other blade so that it can be supplied individually as a spare

Fig 3 shows the first set of metal helicopter rotor blades built at Yeovil and the photograph was taken during the course of the Type Test These blades have completed some 60 hours ground running and over 60 hours of flying, all of which has been concluded without incident This is the first set of all metal rotor blades to be built and flown in this country and the first to have successfully concluded a Type Test outside the United States

I hope that this short description has indicated the scale of the production which we are undertaking on metal rotor blades and the care in manufacture and inspection which is being devoted to this effort Although the blades appear superficially to be simple to build, in fact a great deal of painstaking work is necessary to obtain the high standard required In the course of our efforts we have received invaluable assistance from Messrs Sikorsky, but even so have met a number of interesting and sometimes difficult problems mainly concerned with the methods and facilities available to us The experience gained with the first few sets of blades has removed a great many of our earlier worries so that we are in a position to undertake with confidence the quantity production which is now commencing

The metal blades have proved very smooth in flight and almost immune from the random variations in day-to-day behaviour which have been a typical feature of many previous types of helicopter rotor blades All our helicopter production will from now on be based on these blades and from our experience with both American and British sets we know that when they come into service they will be recognised as a very considerable advance in helicopter construction technique

For the facilities which I have been given in preparing this talk I am indebted to the Management of Westland Aircraft Limited, and to Mr Worsdale of the Birmetals Company who kindly lent the first two slides

Mr Fitzwilliams talk was illustrated by 19 slides

(FIFTH PAPER)

The **Chairman** Our next speaker is Mr K W **Turner**, who joined the Bristol Aeroplane Company in 1937 During the War Mr Turner served for a time with the Airborne Forces Experimental Establishment, and later in India as Chief Technical Officer at the Airborne Forces Research Centre At present he is Deputy Flight Research Engineer at the Bristol Company

Tuning the Rotor

By K W TURNER, M A, A F R Ae S

(Paper read before the Helicopter Association of G B on 6th October, 1951)

In some ways I am an intruder into this discussion on the Design and Construction of Rotor Blades, because my paper deals with what happens to rotors long after they have been designed and constructed , when, that is to say, they are passing through the hands of the test pilot, the operating pilot and the maintenance engineer I shall try to confine myself to those parts of the rotor's career which have repercussions on design and construction

Tuning, whether of an engine or a musical instrument, consists of adjusting all the variables available in a systematic manner calculated to make the device as a whole work in the best way possible If the device is a piano, this may mean doing what the piano tuner does on his three-monthly visit , but it may perhaps involve a bit of what happened when the earlier types of piano were developed into what J S Bach called his " well-tempered clavier " The former kind of tuning in the case of the helicopter includes the process of " tracking " and I think most of us are familiar with this, or with the lack of it, in various forms that the latter or creative kind of tuning may also be possible in a small way with the helicopter will be one of the conclusions reached in this paper dealing with experiences in this field during the development of one family of British helicopters I should like here to thank the Bristol Aeroplane Company for permitting me to give this paper and to state that, while I must take personal responsibility for any opinions expressed, as regards many of the facts presented I am merely the honoured mouthpiece of a team which for a number of years now has been working under the leadership of Mr Raoul Hafner on the problems of rotating wing flight

Our work leads us to believe that a helicopter rotor can be adequately tuned if three forms of adjustment per blade are provided, and we have found the most convenient variables to be a trimmable portion of the trailing edge near the tip, a similar portion further inboard and an incidence adjustment These variables grew upon us in an empirical, perhaps I should say Darwinian, manner during the first two years of our flight development work, and I think the most convenient way of explaining their purpose is briefly to survey this period of evolution

When in May, 1947, the prototype helicopter was first run with a rotor the only adjustments available to us were those altering the incidences of the blades and these were used in orthodox fashion for tracking, that is to say for making all three blades develop the same lift and consequently travel round along the same path Very soon it became evident that not only the lift but also the pitching moment of the blades required attention This manifested itself at first in an excessive operating force being required to increase collective pitch A two-fold attack on this problem was undertaken by providing a trimming tab on the trailing edge, whereby the aerodynamic pitching moment might be changed, and also a small moving weight near the leading edge, whereby the chordwise centre of gravity might be shifted The latter method was soon discarded as a means of rotor tuning the manufacturing process of blades now includes a procedure of adjusting the mass axis of the blades to that position, near the quarter chord axis, deemed necessary for avoidance of flutter After tests on the Rotor Tower to confirm this particular, the mass distribution of the blade is settled and thereafter considered inviolate

For using the trim tab it became necessary to know the pitching moment experienced by each blade, and this was for a time measured by electronic means, using a pick-up on a member of the control system whose strain depended on the blade moments This proved inconvenient and not accurate enough and eventually this method was replaced by an ingenious and much simpler mechanical one We were able however to adjust the sum of the three blade pitching moments to the value required to give the pilot a light collective pitch operating force But greater refinement was soon needed in differential adjustment, that is to say in making the pitching moments of all three blades equal to avoid a shake of once-rotor frequency passing down through the azimuth control to the pilot's hand Recourse was had to the Test Tower which also was fitted with electronic torque measuring means, but although the aircraft and its controls were made reasonably smooth in hovering flight we were still unable to avoid roughness creeping in at modest forward speed Believing this might be due to fickleness, either structural or aerodynamic, of the trimming tab, we tried as an alternative building up the trailing edge with thin strips of perspex and later plywood These showed no better results and we soon found that what was needed was a simple and more accurate means of torque measurement

In September, 1947, we first experimented with a small platform mounted on top of the control column whose offending vibrations we were attempting to cure The platform carried a piece of paper and in contact with this a pencil was held fixed relative to the aircraft structure A number of superimposed ellipses would be drawn, and by studying their size and the inclination of their axes we hoped to be able to calculate the rotor's out-of-balance vector We found ourselves defeated by the unknown phase displacement, which was likely to vary with rotor speed, caused by the mass of the control column itself and the other moving members of the circuit This problem was overcome by the following artifice, which after four years we have improved upon in nothing but detail

A weight of about a pound is mounted on each of the three arms of the control spider in turn, thus adding to the rotor three out-of-balance vectors equal in magnitude but separated 120° in direction, and in each condition a record is made of stick shake amplitude Each of these represents, to an unknown scale and with an unknown phase displacement, the applied vector plus the rotor's unknown vector, and the ratios of the three amplitudes provide sufficient information for the latter to be determined The calculation is at present made graphically and can be done in about a quarter of an hour, as follows

Having recorded the shakes with the weight on Green Red and White spider arms, draw an equilateral triangle GRW and its centre O Divide GR both internally and externally in the ratio of Green trace amplitude to Red, and make a circle with these two points as diameter Make corresponding circles on the other two sides of the triangle The circles should intersect at a point P Then PO represents the rotor's out-of-balance vector, and the components of OP resolved along whichever pair of the lines OG, OR, OW it lies between, represent the corrective moments required on the two blades indicated The linear scale is that OG represents the eccentric moment applied by the weight

Simplified methods using generalised graphs, tables or a mechanical computor, can and probably will be devised The current geometrical method has, however, been taught to about a dozen ground engineers engaged in maintenance or manufacture of Bristol helicopters and appears to be giving them little trouble

Having by these means discovered the pitching moment being fed in by each blade, it remains to adjust all these to equality At first this was done by using the eccentric weight itself as a means of correction as well as of measurement The weight is devisable into small plates of 2 oz each, and the required numbers of these were bolted on to two spider arms

This scheme produced excellent, almost magical, results, and within two days of using it we were able to fly at speeds exceeding 100 m p h for the first time with relative freedom from vibration

It will be appreciated that these offset weights, although supplying precisely the moments required to remove vibration from the control circuit, would impart a small shake to the aircraft as a whole Although this was noticeable only in bad cases where large weights had to be used, it served to prompt us toward the more elegant solution of removing the pitching moments at their source, namely somewhere out along the blade, rather than merely applying this antidote Moderate success was achieved by applying tip tab adjustments instead of weights, but we were reluctant to pursue this means of correction to its bitter end, because we had by now appreciated and indeed measured the effect that these tip tabs had on the rotor's tracking Incidence adjustments can achieve perfect tracking at one particular rotor speed, but it does not then follow that the tracking will remain perfect when this speed is changed This is because moments on the outer portion of the blade cause elastic twisting which alters the blade's lift, and unfortunately this effect is dependent upon the square of the speed at which the blade passes through the air To reduce this effect to zero, that is to say to make tracking independent of rotor speed, we had by now adopted the practice of using tip tab adjustments, and consequently we were not free to adjust the tabs to the other criterion of torque balance This is just another way of saying that the offending pitching moment in a blade may not always be near the tip but may sometimes be further inboard Consequently we decided to provide ourselves with a further variable in the form of an inboard trimming tab

The area of this was chosen as a matter of convenience to produce, in spite of its lower airspeed, the same pitching moment per thousandth of an inch adjustment as the outer tab The location of the two tabs now adopted as standard is shown in Fig 1 It should be emphasised that the tabs are not widely overhanging surfaces liable to distortion by any passing bird or spectator's umbrella, but merely portions of the trailing edge which happen to be made of duralumin instead of wood Fig 2 shows the means of adjusting incidence this and the two tabs provide the three variables per blade which we believe are required for properly tuning a helicopter rotor

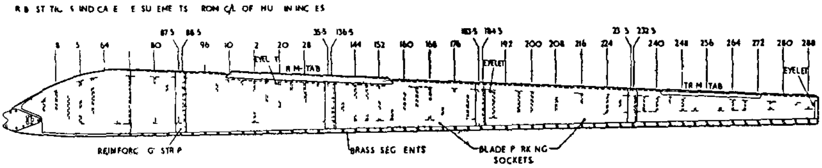

Fig 1 Sycamore rotor blade, showing location of trim tabs

Here, perhaps, I should say something about the various techniques we have used in the practical work of tuning This began simply, and has now I think become reasonably simple again after passing in development through a period of rather provocative complication This has caused some observers of our work to conclude that a Bristol helicopter cannot be properly tuned without an assortment of calculating machines, systems of mirrors, Bostick and Bowden cables operated, as a previous speaker before this Association has alleged, " by six men and a boy " Those days are happily over, and regarding the last point I should like to say that I have myself on occasion tuned a rotor without the aid of any of the six men For tracking measurements we have tried most of the obvious expedients At first we used the canvas flag held up at the edge of the rotor disc so that the blade tips, which were chalked in three different colours, inscribed marks showing their relative heights Owing to the high tip speed of modern rotors and to the high density of the blades, we found this became too expensive in flags, and therefore made the convenient hypothesis that what mattered was not the blade tip but the angle at which the axial loads were fed into the hub We therefore held up paint brushes until they just touched the steel tubular portions of the blade roots This method, irrespective of the truth of the

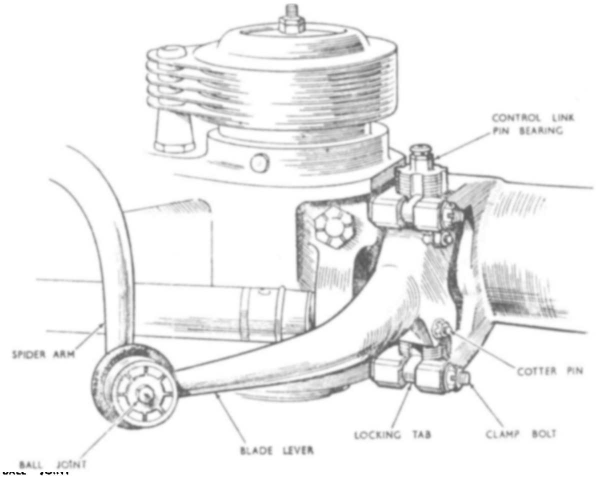

Fig 2
Method of adjusting blade incidence

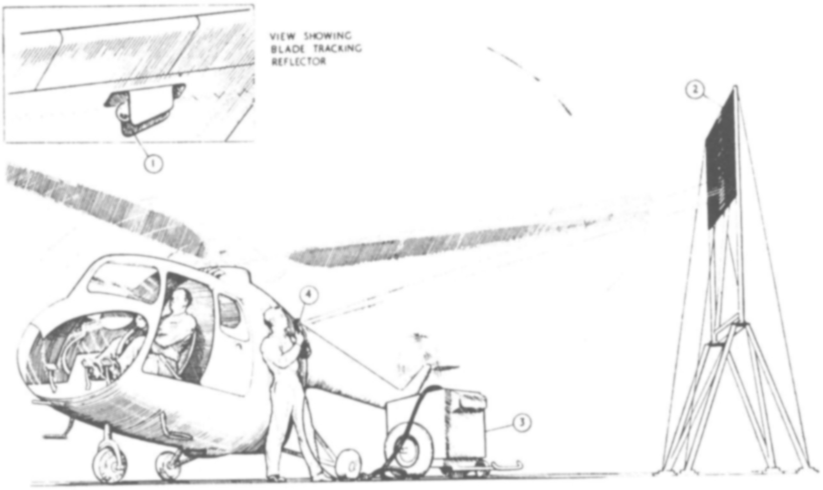

Fig 3 Tracking in progress
(1) cat's-eye reflector,
(2) blackboard,
(3) battery,
(4) lamp

hypothesis, proved insufficiently accurate and we were forced to return to the tip This time we made a great cylindrical drum of canvas which was advanced slowly toward the disc until contact occurred, the theory being that contact when it did occur would be tangential and thus would not tear the canvas This hope was only partially realised and in addition the device was rather hazardous to use in a wind After experimenting with stroboscopic methods at night, the final and now fairly orthodox method was adopted of mounting small mirrors of different colours on the tips, and observing the light reflected by them from an Aldis or similar lamp held by

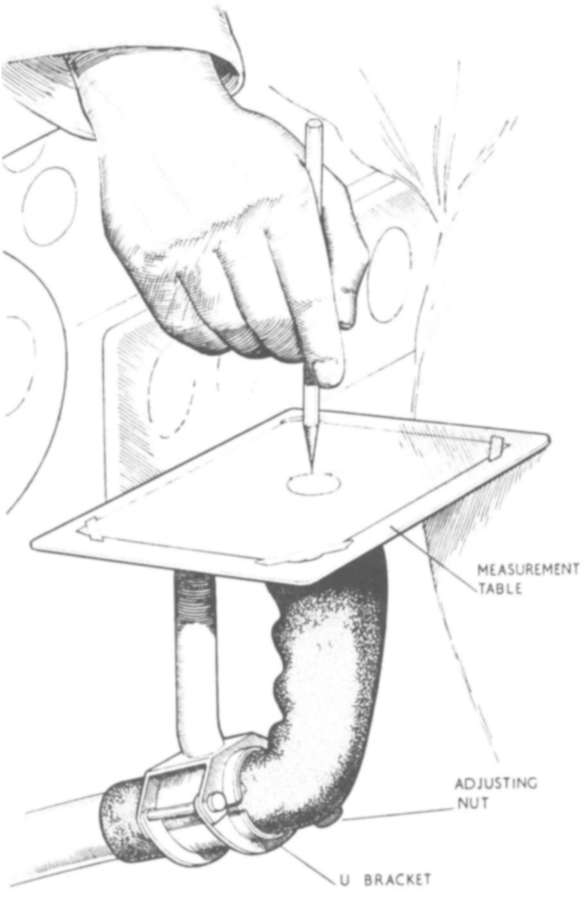

Fig 4 Measurement of control column shake

the observer Chromium plated and lacquered metal mirrors were tried for some time but so far nothing has been found to beat the cat's-eye reflectors of the type used to mark the centre line of main roads These are made by the Franco-British Glass Company Limited, but other sources of supply in small quantities are available These reflectors have the valuable property of returning a beam of light very closely in the direction whence it came, thus eliminating the need for the accurate and tiresome adjustments found necessary with the metal reflectors A helpful luxury is a blackboard with a vertical scale of inches in white placed just outside the rotor disc for the observer to take his readings against Fig 3 shows this method of tracking in progress

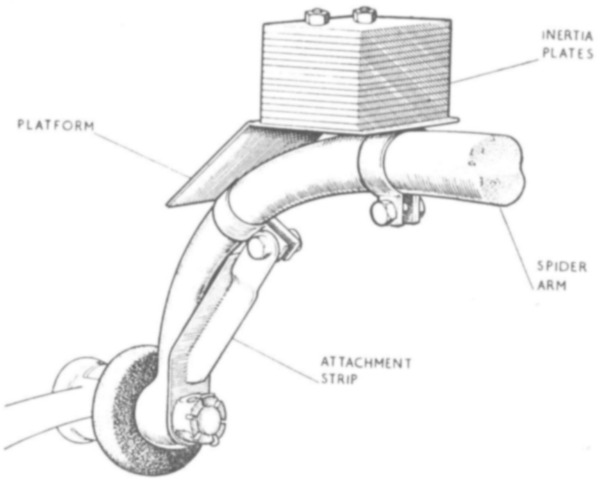

Fig 5 Eccentric weight mounted on spider

The measurement of control shake by the platform-on-stick method is shown in Fig 4, while Fig 5 shows the eccentric weight attached to one of the spider arms It is evident that for tuning rotors by trailing edge adjustments an accurate but easy method of standardising and measuring the tab setting is required Fig 6 shows the device we have developed for this purpose It consists of a clock gauge mounted on a frame with pick-up points, such that when the device is offered up to the trailing portion of a blade it rests in a standard and repeatable position Our practice is to apply this measurer at each of the few stations of the tab defined by a blade rib, and to average the readings In this way it is practicable to set tabs to within one thousandth of an inch of a desired mean position, which is the order of accuracy normally useful in rotor tuning

Having arrived at nine variables with which to tune a three-blade rotor it is desirable to have a systematic routine for manipulating these to produce required rotor characteristics Like the procedures of measurement, this analytical part of the problem went through some unhappy development stages, the worst of which involved solving a nine-fold simultaneous equation The final scheme is simpler and is based upon the following philosophy

The mass distribution of a rotor is settled by flutter-safety and alterations of shape only remain These may be such as to alter the blades lift (twist or incidence change), or its pitching moment (camber or tab adjustment) Moment changes may be substantially outboard, in which case they will twist the blade elastically and so alter the lift , or they may be substantially inboard, in which case this effect is small or absent There are thus two forms of lift change the first varies, like centrifugal force, with the square of the rotor speed, but the second varies with the fourth power These effects on a blade change as it passes round the cycle, being greater while the blade is advancing and lesser while it is retreating The moments consequently feed into the azimuth control a longitudinal force which varies with the helicopter's forward speed Furthermore the outboard moments, by virtue of their effect on lift and thus on the rotor disc inclination, necessitate a displacement of the azimuth control longitudinally which varies again with forward speed Each form of adjustment may thus have a number of consequencs on the behaviour of the helicopter

Table 1 shows the various effects which the above argument would lead us to expect and which we have indeed found to occur in practice A study of this table

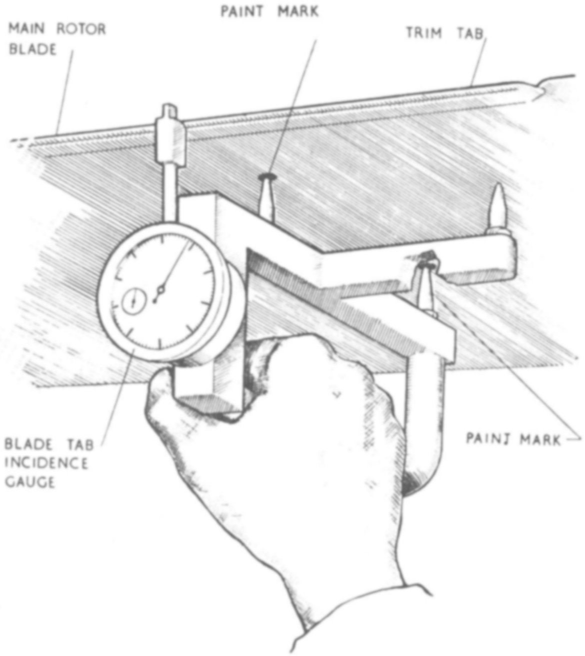

Fig 6
Tab measurer setting

TABLE 1

Adjustment	*Quantities Primarily Affected*
Incidence collectively	Max autorotation R P M Indicated pitch
Incidence differentially	Tracking Fuselage shake
Inner tabs collectively	Pitch operating force Stick-free stability
Inner tabs differentially	Control shake
Outer tabs collectively	Stick-fixed stability Stick-free stability Pitch operating force Max autorotation R P M Indicated pitch
Outer tabs differentially	Tracking variation with R P M Control shake Fuselage shake

suggests the possibility of the second or creative form of tuning which was mentioned at the beginning of the paper

It is clear that six only of the quantities listed can be independently manipulated the choice can suit the convenience of the tuning routine and the physical importance of the items for the aircraft's behaviour Our choice consists of the quantity shown at the top of each group We suppose it does not really matter which items are chosen, since if any six are adjusted to standard values the remainder will standardise themselves automatically

Partial derivatives expressing the effect of each form of adjustment on the various behaviour quantities have been obtained from flight and ground measurements As an example Fig 7 shows the effect of tab settings on the Sycamore's longitudinal stick-free stability The inner tabs, as our theory has suggested, do not have much effect but the slope of the outer tab line provides a powerful tool for the rotor tuner and enables him within limits to set the stability to the amount found best by the pilot For the Sycamore we have adopted the criterion that the stick displacement from steady hovering to steady cruising should be a forward one not exceeding 25% of the total range available It is now evident that the helicopter maintenance engineer has under his thumb—literally under his thumb if he cares to climb a trestle and lean on the rotor's trailing edge—a power which in fixed-wing aeroplanes is vested in the designer and exercised by altering the incidence of the tailplane This shows the importance of making rotor trailing edges, whether fixed or variable, as rigid as possible to be proof against unwanted alteration

In detail the sequence of tuning a newly manufactured helicopter rotor is as follows

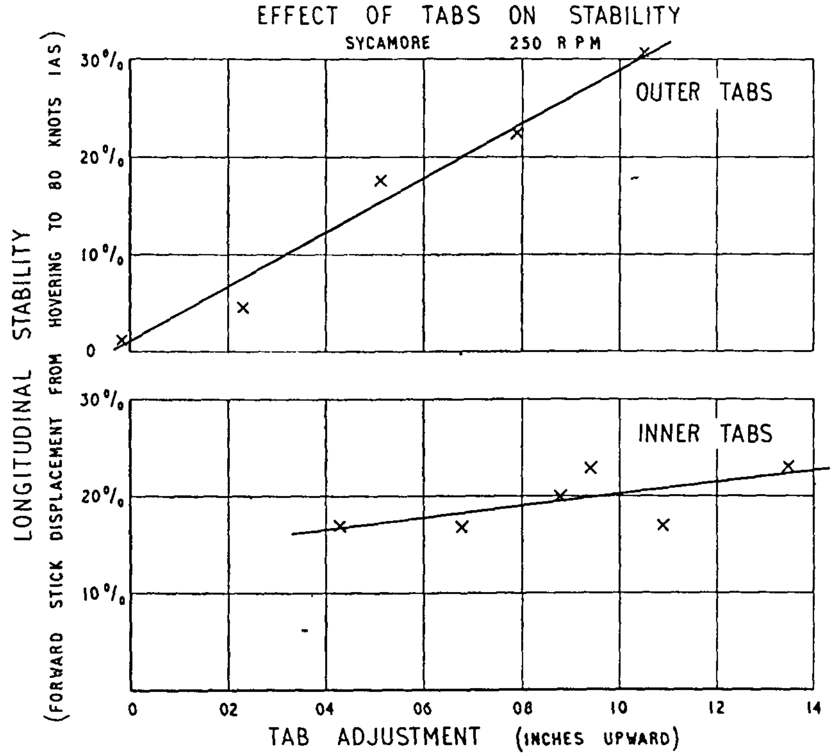

Fig 7

(1) Before being put on the aircraft the blades are mass balanced and run on the Tower, flutter-safety being demonstrated by an overspeed run with the chordwise centre of gravity moved artifically backwards

(2) During the aircraft's running-in on the ground, the outer tabs are differentially adjusted to make the tracking error independent of R P M
Also

(3) The blade incidences are differentially adjusted to make the tracking error zero at any one convenient R P M Also

(4) The inner tabs are differentially adjusted by the method already described to eliminate control shake

(5) From records obtained during the test flight, the outer tabs are collectively adjusted (if necessary) to obtain the desired relationship between stick position and forward speed Also

(6) The inner tabs are collectively adjusted to obtain roughly zero pitch-lever operating force (or strictly equal and opposite forces to raise and lower) Also

(7) The blade incidences are collectively adjusted to obtain the desired rotor R P M with the pitch lever fully down in autorotation

All this is part of the manufacturing process of the helicopter, and should not be confused with what an engineer in the field may be called upon to do for maintenance purposes This amounts to items 2, 3 and 4 only and, it may be noted, does not require flight or even, since ground running is done at zero pitch, the services of a pilot Two short instructional courses in this work have been given at Filton and a number of ground engineers trained

One naturally asks whether this tuning business is really necessary I would venture to suggest that for small helicopters it is optional, being a matter of how much vibration or changeability of flying qualities one cares to impose on the pilots and passengers, but that as helicopters become heavier and faster it will become increasingly important Of course the aim must be to manufacture blades which are already of the shape which subsequent tuning on the ground and in the air would mould them to However, all trailing edges, whether fixed or variable, are subject to damage or distortion and it is illuminating to consider for instance what is the consequence of all trailing edges of a helicopter distorting up or down by one thousandth of an inch Experiments show that this will cause a change in collective pitch operating load of about 03% of the helicopter's all-up weight, and scale considerations lead to the startling conclusion that this percentage will remain unchanged with increasing weight or altered configuration Power-operated controls or irreversibility will, of course, withhold this load from the pilot , but if the distortion is not equally distributed between the blades the vibration loads will continue to exist, being fed merely into the aircraft structure instead of the control system

It is true that the absolute magnitude of the vibration loads can be allowed to increase proportionately with the helicopter's weight without the vibration level imposed on pilots, passengers and structure being altered Against this it must be remembered that a manufacturing tolerance of ± 001″ becomes increasingly difficult to observe with increasing size of the object manufactured probably a percentage tolerance is more likely to be achieved This line of thought leads to the following conclusions

(1) The ability to be flown manually, even if not exploited, is a criterion of other good qualities in a rotor

(2) Control forces arising from random distortion will increase as the product of all-up weight and rotor blade size Consequently big helicopters will need power-operated, servo or some other form of indirect control, however well the rotors are tuned

(3) The vibration level produced by random distortion will be independent of all-up weight but will increase with blade size If blades are to grow in size, and not merely in number, there will be an equally growing need for tuning the rotor