Discussion

Mr K Reed (*Member—Test Pilot, Saunders-Roe Ltd*), in opening the discussion, said it might be wondered why he was participating in the discussion in view of the technical nature of the paper He had been physically attacked by the phenomenon, which resulted in injury, and the prescribed repair action included the wearing of a steel jacket to restrict movement Ironically enough, similar action had been applied to the aircraft, involving restricting or damping movement of the undercarriage and alterations to the drag hinge friction dampers Such experiences must allow the individual to express his opinion

It was not sufficient to be just a driver of a machine accepting all that one was told as fact, or to be brow-beaten by mathematics "The acid test" could only be that which was shown by the flying machine No dynamic model or any other model could be a substitute with any common sense degree of accuracy The elements, including human, and environment could be proportioned and applied

As an example, we were told that provision of a viscous damper for the drag hinges proved a very difficult problem, and, after some abortive attempts to make hydraulic viscous dampers, it was decided to make multi-plate stepped friction dampers Was it, or was it not, reasonable to assume that had more effort been put into the making of hydraulic viscous dampers the observations and recordings might have been different from those of the friction dampers ?

He had no doubt that from a technician's point of view the paper was first-rate, and if he understood it he would be the first to offer his congratulations However, he felt that the paper had not dealt with the subject broadly or clearly enough for it to be understood by people other than technicians, who formed the core of the Association The thirst for knowledge of others on the subject could not have been quenched, and in a few cases the paper had not permitted confidence in technicians to be regained

With regard to the Deutsch suggestion for checking an aircraft on the ground —run the rotors with cables attached to the rotor mounting to be pulled taut to arrest any instability that set in—that was considered dangerous and inconclusive, and yet a very prominent and successful helicopter manufacturer used and recommended the practice, and added that if resonance was encountered as rotor r p m were increased, the cables were pulled tight and the vibrations were damped out owing to an instantaneous change in the natural frequency of the helicopter on the ground, as well as restricting the rotor unbalanced force amplitude No doubt that practice might be used for the want of a better, for apparently a better had not yet been found

As to the question concerning the effect of a slow puncture or burst tyre, which might lead to high lateral stiffness and cause ground resonance to set in, surely if there was the least chance of avoiding resonance the appropriate steps should be taken In that case, why have pneumatic tyres at all ? Why not solid or some other alternative ?

No one doubted that theoreticians were essential, for they held the key to all mysteries, but some problems could not be solved efficiently if theories and laws applied were allowed to pass without the application of common sense in the form of practical knowledge, coupled with other people's experience

There were far too many cases of the stable door being closed after the horse had left The modifying of a rotor system or undercarriage after resonance had occurred presented a case of theory not fully applied and without due consideration being given to practical knowledge and experience during initial design

Was it possible, when designing a new project, to determine the basic moment of inertia of the helicopter, thus enabling a fuselage to be designed with a much lower or much higher natural frequency which would be outside any resonant frequencies of the rotor system ? That appeared to be the fundamental problem

What advantages had any form of friction damper over the hydraulic ? They had heard about the vital part that dampers played in the rotor system in respect of improving resonance characteristics Autogiros, with friction dampers fitted, were said to be far from resonance-free, and cars, particularly of the racing type, were not efficient with that type of shock absorber fitted owing to settings varying with atmospheric conditions and thus continual checking and adjusting being essential

Incidentally, a technical publication referred to changes to the rotor system being about four times more effective than changes to the undercarriage in tackling the resonance problem What are the views towards this ?

It was the manufacturers' liability to prove conclusively by thorough full-scale tests that resonance was virtually non-existent within the operating range An approving body should make mandatory requirements, tabulating tests required before considering the acceptance of a helicopter Resonance was, perhaps, the biggest headache to technicians , the problem was spreading rapidly like a disease, and unless it was arrested by common agreement on ground and flight tests procedure, there was the threat that it would become a hazard with a completely wrong sense of proportion

He suggested the following tests (1) Determine the highest taxying speed coupled with manoeuvres and also combined with rapid directional control applications or rapid application of wheel brakes , (2) Ascertain wheel padding characteristics when carrying out light tounh-on landings , (3) Carry out extended period in a partial airborne condition and ascertain wheel padding characteristics , (4) Landings to be made on rugged terrain, particularly soft or marshy ground Observe tendencies for resonance build-up , (5) Take-offs and landings using various high revolutions and low collective pitch settings—note wheel padding, etc Tests to include gusty wind conditions The tests would include various combinations of rotor speeds, collective pitch and intentional rapid displacement of the flying controls The test pilot must always consider an average pilot and judge aircraft characteristics accordingly

No flying with a prototype should be carried out without comprehensive ground tests, with particular reference to resonance, incorporating all applicable theories " Suck it and see " methods, from sheer cost and prestige alone, should not be tolerated

He stated that the views expressed were entirely his own and any reference to Companies or individuals was for his part unavoidable, and it was far from his intention to imply anything derogatory towards individuals or Companies

Those who had experienced a beating with their hands tied behind their backs would have a little idea of the conditions during severe resonance for a pilot The experience and consequent thoughts provided the fuel for his contribution to the discussion

Mr Howarth (in reply), said that by the time the helicopter was built and the pilot was in it on the runway, it was far too late to do much about ground resonance Thought must be given to the problem in the early design of the machine, and at that stage ground testing was impossible One must start with a theory and must check the theory—that was what the model rotor was for—and, having checked the theory, one then built the aircraft, and one was then justified in calling for ground tests

The stepped hinge dampers have been found to be quite satisfactory and more reliable than viscous dampers In treating the friction damper as if it were a viscous one, one must, of course, provide substantially greater damping that is theoretically necessary for neutral stability

The theme of Mr REED's remarks was that he wanted not something which was good enough but something which was perfect If they could have perfection, let them have it, but if they could not—well, they had to have helicopters, and they must do the best they could with existing knowledge

Mr A E Cowle (*Fairey Aviation Co*) asked how far representation of the ground resonance problem was Coleman's theory, and suggested that representation of the rotor by two masses was crude If the rotor was completely rigid, it might be possible to treat it with two masses, but if it was flexible and had natural frequency near running conditions, that would influence the question of ground resonance anyway

Another crudity related to impedance at the hub, the force which would act upon the rotor owing to a given displacement of the rotor in time to produce a force consistent with that motion being represented by a spring and a damper One wondered to what extent one could predict stable and unstable ranges on such primitive grounds Impedance of the rotor was easily worked out, but due to the symmetry of the rotor system, but the impedance of the rest of the aircraft was complicated, and that was not given the same treatment as the rotor

Mr Howarth (in reply) said he agreed very sweeping assumptions were made in Coleman's theory, notably that the phenomenon is confined to motion in the plane of rotation However, in the case of the Bristol blade at least, it was certainly realistic to consider rigid blade motion only This did not involve significant errors The use of impedance at the hub of the helicopter was precise and unassailable It could be calculated given the shock absorber and tyre characteristics Despite criticism using the formula $u = 2$

Mr C H Jones said that the theory presented applied to three blades or more , the two bladed rotor was a special case

Mr D J Mead (*Southampton University*) urged the use of electronic simulation in the ground resonance problem Because of computational difficulties in aircraft flutter calculations, an electronic flutter simulator had been built at Farnborough and more recently elsewhere This could certainly be applied to ground resonance, and would reduce enormously the laborious work involved in taking into account further degrees of freedom (*e g* , pitching, fore-aft motion, elastic freedoms, etc) and in determining the effect of varying certain coefficients whose actual value may be doubtful It would be the only practicable way of solving the equations if non-linearities were introduced, *e g* , undercarriage damping and stiffness coefficients varying with amplitude and frequency Work along these lines is proceeding at Southampton University He wondered whether any work had been done incorporating non-linearities in ground resonance equations In one simple case investigated at the University, when a non-linear damping was considered, the damping required to prevent instability was considerably greater than that required by a linear damping

Mr Howarth (in reply) said that a simulator would be first-rate for the task and he hoped Southampton University would be able to provide one No work had been done on the introduction of non-linear parameters, but he would like to know what was being done at Southampton

Mr J S Shapiro (*Founder Member—Consulting Engineer*) said that for those who appreciated its mathematical background the paper was extremely lucid and it was a restatement of Colman's theory in a novel, interesting and useful manner This theory he considered an outstanding example of an engineering analysis because it chose the right blend of simplification and universality

Like every useful engineering theory it left the engineer with the task of applying it In the present case the main problem facing the application of the theory was the study of the helicopter (without the rotor) as a vibrating system This study together with the Colman theory could produce a guide to action, particularly at the design stage

The problem of theoretical and experimental study of the helicopter without the rotor and that of marrying the results of this study with the Colman theory was mathematically within the bounds of normal methods and would produce more fruitful results than the attempt to introduce more refined mathematical methods which were likely to be useful mainly in analysing existing systems rather than finding remedies for their faults or better subsitutes In this sense the emphasis on simulator to other novel computational techniques made by some speakers was misguided

It was preferable to pursue a much wider sweep of design variables than had been given in the paper, even is such a broader view were accompanied by a total neglect of damping In fact damping was necessary and useful to get over the low r p m region of instability in running up To rely on damping for the prevention of instability in the operational range of r p m was unwise and in fact dangerous because of the erratic nature of intentional, and particularly unintentional, damping

Mr Howarth (in reply) said he agreed with most of what Mr Shapiro had said The main trouble with the theory was the labour involved in its application There is no doubt that an analogue for the frequency equation—not of the phenomena—would be very useful if not imperative

Mr T L Ciastula (*Member—Saunders-Roe Ltd*) said his firm used a full-scale helicopter instead of a model for final tests The sequences were determination of hub impedance , application of theory for known impedance , full-scale tests on the Skeeter External excitation was employed

For full-scale tests, hub and undercarriage damping could be adjusted over a widen range of values Manual snubbing was operated when oscillations of the aircraft showed a tendency to diverge Excitation was effected by large lateral displacements

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of the hub centre by single shakes and also operation of the azimuth stick with varying frequency, stick and machine frequencies and amplitudes being continuously recorded The whole range of rotor r p m and thrust up to 80 per cent a u w was covered

The tests began with large values of hub and undercarriage damping The undercarriage damping was gradually reduced until near critical value, when the condition of ground resonance was obtained the aircraft oscillations became slightly divergent The snubbing arrangement was satisfactory On one occasion when it was applied a little late the trailing edges of the blades and the snubbers were damaged Near critical damping at the hub was determined similarly

Critical values of damping were characterised by the fact that if undercarriage damping was at near critical value the aircraft response remained the same, although hub damping was appreciably varied Values of hub and undercarriage damping were determined for which, with excitation applied, ground resonance type oscillations were rapidly damped out

Model technique was an elegant approach to the problem and if it was fully representative it was a good calculating device to obtain large numbers of solutions quickly, but the fundamental question remained whether model tests were in themselves sufficient Ground resonance affected the safety of the crew and the aircraft The question arose whether it was safe to proceed with flight testing believing that impedance tests, theory and model tests had made the aircraft free from ground resonance, or whether model tests should be repeated full-scale with simulated disturbances likely to occur in operations

The next step would be to ask whether model technique could be dispensed with if efficient calculating means were available, and if it were agreed that full-scale tests were essential Stressing problem calculations were confirmed by tests to destruction because safety of aircraft was at stake Stability and control problems in fixed wing aircraft were carefully tested full-scale under all conditions affecting safety of the aircraft His firm was building an analogue computer for calculations, but he considered that full-scale testing was still essential

He presumed full-scale ground resonance tests were avoided because they were or could be dangerous and because they could result in destruction of a helicopter, which, in the case of large or very large helicopters, would mean large financial loss It appeared that danger to the pilot in full-scale ground resonance testing could be eliminated by dispensing with him While full-scale testing of a large helicopter would be complex and difficult, with the Skeeter, a small aircraft, it was easier

The volume and complexity of ground resonance calculations were large and might be prohibitive for small design organisations The analogue computer might be the answer It was also hoped that the use of frequency response method would appreciably simplify ground resonance calculations, and his firm was working on that

Mr Howarth (in reply) said that every time a pilot took a machine into the air he did a full-scale ground resonance test, in fact, he did two tests per flight He appreciated what had been said, but one never did an ultimate tensile test on the actual material in an aircraft His firm believed that the theory gave the rotor behaviour with a good degree of accuracy The assumption was that when the theoretical rotor was married to the measured helicopter impedance, the combination would behave as the helicopter actually did In his experience, the result of such an analysis had erred, if anything, on the pessimistic side If one had no faith in such an approach, one must do full-scale testing

Mr A L Buchan (*Saunders-Roe Ltd*) said that, to date, theoretical research had not brought to light any new ways of eliminating the ground resonance phenomenon If anything, it had tended to emphasise the desirability of using the best engineering solutions even if they involved mechanical complications and sacrifices—in other aspects of the design

The following rules should not be lightly disregarded (1) Chassis natural frequencies should be low, (2) As much damping as possible should be used in the chassis to reduce blade damping requirements to a minimum, (3) The design should be such that the product of blade and chassis dampings (effective viscous damping values) increased with amplitude, so that if an oscillation began in a critical condition, such as might exist when the machine was nearly airborne, it would settle down to a steady oscillation instead of building up

The amount of computation involved in the theoretical treatment of the problem led to an early investigation of model techniques and electronic computers

A small dynamic model was made and a resonance testing method was tried with a view to devising a simple test technique, possibly applicable to full-scale machines, and to determining the usefulness of the model as a computing device The significant frequencies were of such small bandwidth that an unduly refined exciter control was needed, and in addition movement of the resonant frequencies due to friction as the amplitude changed were so great as to make the location of the resonances practically impossible, unless friction was reduced to an absolute minimum It was concluded that, though a very useful qualitative guide, such a model, had little value as a computer, if simple test methods were to be used , and that, in view of the difficulty which might be experienced in full-scale testing, other methods should be developed so that the need for comprehensive full-scale experiments might be reduced

An electronic simulator of the simple analogue circuit type was designed by specialists, but although it appeared promising to start with, it was soon found that the system could not be satisfactorily represented that way and that an orthodox analogue computer using integrating units would be required It was still felt that the electronic computer of the type now being designed at Saunders-Roe for general use in stability and flutter problems would allow rapid solution of the ground vibration problem in particular aircraft

On the theoretical side, attempts were made to adopt the frequency response method to the solution of the problem with a view to treating the chassis and blade systems separately until a late stage in the calculations and so avoid the use of numerous coefficients dependent on both blade and chassis parameters in final expressions Success in this approach led to the conclusion that profitable results might be obtained in estimating the behaviour of prototype machines if experimental results, reasonably easy to obtain for the chassis alone, were matched with blade characteristics estimated by purely theoretical means Such a method would be of considerable value in deciding whether new rotor systems fitted on existing chassis would be satisfactory

Recently on the Skeeter Coleman-type plots were derived satisfactorily, though care was needed to write the final expressions in a form giving the exact Coleman-type of plot A small unstable range was noted near 130 r p m , a rotor speed at which mild rocking was often noted as the machine was run up, and it was felt desirable that the degree of instability should be estimated

Since the chassis characteristics were only known in terms of amplitude and phase shift values taken from the tests, it at first appeared that a more careful analysis would be required so that the requisite polynomial expansion might be deduced

However, it had been found that the damping or degree of instability could be estimated with sufficient accuracy by using only the numerical values of real and imaginary terms in an expression having exactly the same significance as Coleman's polynomial

$$(\text{Real}) + (\text{Imaginery})\, i = 0$$

$$\text{or} \quad E_R + E_I\, i = 0$$

Where $E_R = 0$ and $E_I = 0$ at any rotor speed and frequency indicates the presence of a steady oscillation, it was found that a damped or divergent oscillation of the form

$$q = e^{\lambda t} \sin \Omega t$$

can exist when

$$E_R + \lambda \frac{\delta E_I}{\delta \Omega} = 0$$

and

$$E_I - \lambda \frac{\delta E_R}{\delta \Omega} = 0$$

This method avoided the estimation of effective masses and stiffnesses and allowed direct use of the test result figures

In the case of the Skeeter result, where the lift was 85 per cent , the divergence only doubled amplitude in some 40 revolutions, and in view of the short time spent at that speed is was insignificant

Besides continual development of theoretical methods, there had been considerable success with full-scale testing The Skeeter had been shaken violently using both external excitation and stick shaking by pilot It was thought that, provided a motion so excited died rapidly, the machine might be considered acceptable, as fairly large amplitudes were induced and such resonaring could not be continued for any time except by artificial means

Mr Howarth (in reply) said dependence on damping was undesirable in the operating range One could largely dispense with it if one designed the double frequencies of the undercarriage low enough One was left to rely on damping to get one through the rotor r p m between starting and normal operation But he was conservative and liked to have a belt as well as braces He was interested to hear of the work being done at Saunders-Roe

Dr G S Hislop (*Member—Fairey Aviation Co Ltd*) asked Mr HOWARTH whether, on the basis of his calculations, model work and full-scale tests, he would feel confident that enough had been learned of the foundamentals of the problem that in any future Bristol design ground resonance would not be encountered Also whether if drag hinges were eliminated the ground resonance problem would automatically disappear Finally, whether it would be possible to choose cables of the correct elastic properties so that they would hold a helicopter securely to the ground without further damage should ground resonance occur during the testing process

Mr Howarth (in reply) said that, on the first point, he was confident that undercarriage-fuselage-rotor systems could be designed so that the stability margin was readily calculable He was not so certain if the machine was expected to operate off a platform which was rolling and pitching violently and moving up and down as well He did not know the answer to the second point, by Dr HISLOP was probably right On the third point, his reaction to cables was, " once bitten, twice shy " , it would be difficult to make them as adaptable as squads of men who operated in the case of landing vessels

Mr C T D Hosegood (*Founder Member—Bristol Aeroplane Company*) said that all Mr HOWARTH had promised in respect of the 173 had been completely justified, and he believed the machine was quite free from ground resonance Furthermore the machine would shortly be leaving the Bristol Stables and other Pilots, some of whom were present, would have a chance of confirming this He believed that whatever short-comings they might find in the machine ground resonance would not be one of them

Mr HOSEGOOD went on to say that if ground resonance did occur he believed that a set plan must be followed and that the aircraft must either be lifted into the air or set back firmly on the ground again, but which ever course was chosen it must be followed to the end as a change of mind after one of the two alternatives had been started was very ill advised Of the two alternatives, he believed that there was much to be said for staying on the ground, particularly with a prototype

Mr HOSEGOOD added that, though time was getting on, he would say that in the case of ground resonance the rotor brake can be used with much benefit if the pilot remains on the ground

Mr, J Wootton (*Member—Percival Aircraft Ltd*) said that some thought ought to be given to designing a head which did away with the Cardan joint effect He was interested in a truly constant velocity joint which did not suffer from the high rubbing characteristics of the one used on the Domain (?) Could the drag hinge beeliminated ?

Mr Howarth (in reply) said that once a beautiful rotor system had been evolved there might be an even bigger problem than ground resonance round the cormer

Mr C H Jones (also in reply) said that in the case of rotors without drag hinges, the blades would still be flexible and have natural frequencies in the drag plane The danger would be the lower frequencies of the helicopter on its undercarriage or low hub to fuselage stiffness Stability was ensured the lowest natural frequency of the blade as a cantilever, when not rotating, was above that of maximum rotor angular velocity

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CONTRIBUTION TO THE DISCUSSION

Mr G H Tidbury (*Member—Saunders-Roe Ltd*) Speaking from one of the firms that have not been so " lucky ' as the lecturer s with ground resonance, and having witnessed two explosive resonances that have ended in destruction and many other cases that have started but have been successfully brought under control, it will be understood that I nearly got under the seat when the film of the 173 was being shown Seriously, the longer experience one has of this problem the more complicated it becomes and the authors are to be congratulated on the comprehensive nature of their paper The proposed undercarriage designs are perhaps the first published attempt to get the problem down in terms that designers can readily appreciate The mathematics in the paper are elegant, but the problem can be solved by more simple methods

Thinking, however, of the undercarriage of scheme 3, where it is not always possible to separate the mainly rolling and mainly lateral frequencies to a sufficient extent, we are faced with the problem of finding the impedance throughout the operating range and of putting the results in a theory which has to be more general than that given in the lecture in detail, but which is suggested in the section on the application to a Single Rotor Helicopter The hub effective masses, stiffnesses and damping are now variables with regard to frequency The problem has been solved but the method involves considerable computation and work is currently proceeding to find more elegant methods of using the experimental results, as Mr BUCHAN has indicated

We have adopted the method of shaking the machine in one direction at a time by a spring rather than the rotating inertia method given in the lecture, mainly for the reason given—to remove the limits to the frequency of excitation imposed by the engine speed range We find that for the Skeeter where there are two natural frequencies, one with lateral and rolling motions in phase, and one with these motions out of phase, that the test rig has to have a considerable range of exciting force and becomes quite elaborate To obtain greater accuracy in the measurement of the results, we are proposing to use lissajou figures photographed from a Cathode Ray Oscilloscope to measure the phase change between the ends of the exciting spring, in our case a torque rod We are also using the total blade mass attached to the hub rather than the root masses referred to in the paper

Attempts have also been made to induce ground resonance on a test machine with rotor running This machine was tethered with the minimum of restraint and fitted with manually operated snubbing ropes to try and limit any ground resonance that started The machine was run at various rotor r p m and at a collective pitch setting such that some 80% of the weight was taken by the rotor The control column was then rotated by the pilot at a frequency that corresponded to the apparent "ground resonance" frequency of the machine The control column was then centralised and the machine oscillations observed to see if they were increasing or decreasing The stick frequency and machine frequency were observed simultaneously on a pen recorder and the pilot could thus be guided into the correct frequency Starting with large values of damping we have reduced hub and undercarriage damping in turn until the oscillations were only slowly damped In one case, the amplitude appeared to be increasing and snubbing was applied

We have now determined the limits of hub and undercarriage damping such that the machine will rapidly damp-out any "ground resonance" type oscillation started in this manner and we cannot imagine any more severe method of initiating the phenomenon By the use of these parallel methods of investigation, first shaker tests and theory and second artificially inducing large fuselage amplitude, we hope to ensure that the Skeeter and future helicopters are as free from ground resonance as possible

Finally, a point on design, in spite of the confidence of the lecturer in wheeled undercarriages, one wonders if the fact that the conventional tyre represents a stiffness with very little damping means that pneumatic tyred wheels will eventually be replaced in helicopters by either a solid rim with damped spokes or by tracks

Mr Jones (in reply) said that at Bristol they had pinned their faith in separation of the natural frequencies of the fuselage on its undercarriage from those of rotor rotation In particular, if all rigid body frequencies of the fuselage were low, one could be sure that the instability could only occur at low rotor r p m One could take off and land without any possibility of trouble, without depending on damping and without complicated tests on the complete machine In such a system an impedance test was adequate for determination of the helicopter's stability If all the rigid body frequencies were sufficiently low there would be no trouble

Mr Howarth (in reply) said that one wanted to know whether the characteristics of a certain helicopter were right One did not deliberately do anything to alter the stiffness If one tethered a helicopter, one had to be careful that one did not affect its characteristics, or else one might be misled

A vote of thanks to the author, moved by Dr HISLOP, was carried unanimously, and the proceedings then terminated