A Brief Survey of Characteristic Vibration Sources in Helicopters

By J SHAPIRO, A F R Ae S (*Founder Member*)

Rotor Unbalance Rotor unbalance is a once per rev impulse This is a case of clear separation of impulse and response Unbalance is a rotating force Its origin can be mass unbalance of blades or geometric dissymmetry in their distribution which can be caused by (*a*) unequal pitch, (*b*) errors in the geometry of articulation, (*c*) unequal damper settings Unequal pitch can occur in spite of equal pitch setting if the elastic twists are unequal due to unequal pitching moments In practice these are mainly aerodynamic moments which can be corrected with tabs or avoided by superprecision in blade making

Response depends on rotor mountings Rotor r p m must be removed from the natural frequency of the hub on its mountings Subcritical and supercritical mountings are practical Supercritical mountings due to the isolation of the rotor system are mostly introduced for other reasons (discussed below)

In considering natural frequency it must be borne in mind that a hub with rotating blades is a system with several degrees of freedom If a second degree of freedom is added to a system with one only, the effect is that of introducing a second natural frequency , the lower of the two is less than the lowest individual natural frequency The sum total of the effect of rotating articulated blades is that of a further degree of freedom and the natural frequency of the system is lower than with equivalent masses representing the blades The natural frequency can be computed if the dynamic and elastic characteristics of the hub mountings are known The N F of the combined system is about 80% of that of the stationary system

Vibration due to dissymmetry in forward flight In the maze of interrelations required for a full description, a useful approximation can be employed with some profit The blade is replaced by its centrifugal force imagined acting along the blade axis This mental picture renders a few useful rules

In a 3 *bladed rotor* (*a*) The first harmonic of flapping produces no fluctuating forces and moments

(*b*) With flapping hinge offsets, the second harmonic of flapping produces no fluctuating force but third harmonic fluctuating moment

(*c*) The third harmonic of flapping produces third harmonic force and no moment

The effect of forward flight dissymmetry is therefore almost invariably a third harmonic We recall the approximate rules which apply to flapping motion namely that the first harmonic is proportional to tip speed ratio and therefore speed, the second harmonic of flapping is proportional to the square of the tip speed ratio, and the third harmonic is proportional to its fourth power The higher orders of vibration therefore mount quickly with forward speed In fact there is another source of third harmonic in a 3 bladed rotor, which is interference Generally, second and third harmonics are reduced by high blade inertia

To reduce impulses arising from forward speed it is therefore advisable to have a low order of flapping hinge offset, and a fast rotor with high inertia

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In practice such conclusions can be no more than warnings It is generally found that 1st and 3rd harmonics are in evidence

Another isolated corner of this vast field on which a few general remarks can be made is the elastic vibration of the blade in flapping Hinge motion is due to flapping forces of the same frequency and these forces result in a bending moment which induces elastic oscillation It is usually the third harmonic which causes an unexpectedly high order of elastic oscillation because in most blades it is the nearest order to a natural frequency of the rotating blade In blades of more or less current design it is sufficient to investigate the first three elastic modes but in highly unconventional blades any modes giving frequencies up to the 5th or 6th order should be examined In this isolated sense prediction is well established Judgement of elastic blade oscillation by comparing the frequencies of harmonic impulses with the natural frequency of a blade rotating in symmetrical flow are not precise but satisfactory

Blade motions about the drag hinge are of vital concern in several vibrating systems We are here dealing with forced oscillations due to impulses arising directly and indirectly from airflow dissymmetry in forward flight Direct effects are drag variations which cause movements about the hinge, indirect effects are Coriolis forces which arise when flapping takes place in the presence of coning (fundamentally due to the radial component of flapping motion) 1st order flapping produces among others a 2nd order Coriolis acceleration and hence motion

In motion about the drag hinge it is also useful to employ a substitute picture of the blade replaced by centrifugal force acting along the blade axis Combinations of 3 blades give the following results No fluctuating forces or moments arise from 1st harmonic motions 3rd harmonic motion produces no forces but a 6th harmonic moment which becomes a torque oscillation 2nd harmonic motion produces no moment but a 3rd harmonic force on the hub

Many claims have been advanced for the rotor with rigidly mounted blades and a floating hub In the light of the above there is substance in such claims Whether it is important enough in practice and outweighs the disadvantages we cannot discuss

A near relative is the two bladed " semi-rigid " rotor which has no higher order flapping, no free coning and no drag freedom It is blessed with mechanical simplicity but afflicted with the peculiar vices of 2 bladed rotors One of these is a 2nd harmonic vibration due to drag fluctuations, particularly at selected forward speeds On the whole this form of rotor has probably the most difficult set of residual forced vibrations Yet among the machines in which this system is applied there are some with an excellent reputation for smoothness

This has been achieved by adjusting the suspension of the rotor to take care of the residual impulse and to isolate the rotor from the machine In fact the success of this procedure has led to a general rule that rigid blades require flexible rotor mountings and rigid rotor mountings can only be used with articulated and/or very flexible blades

Forced vibrations due to abnormal aerodynamic states ' Tip stalling,' due to the occurence of high incidences on the tip of the retreating blade, can give rise to critical increase in magnitude of an impulse obviously equal in

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frequency to r p m multiplied by the number of blades Tests carried out in the United States appear to show that the onset of tip stall is predictable In a machine with an otherwise acceptable general vibration level, excessive vibration is experienced when the analytically determined aerodynamic incidence at the tip of the retreating blade reaches 4 degrees above the stall of the profile It is visualised that, in view of the non-stationary nature of the stall, its effect is delayed Tip stall can be made to occur at higher forward speeds otherwise by blade twist, the use of cambered profiles, and high tip speed

Steep descent in conditions in which the rotor continuously works in disturbed air (sometimes known as the ‘ vortex ring state ’) gives rise to oscillatory impulses of high magnitude There is some evidence to suggest that a once per rev impulse is possible, but this matter is largely unexplored

Forced vibrations due to engine torque impulses Torsional vibrations Peculiar to helicopters is the articulated rotor Its dynamic equivalent is an inertia which depends on frequency Similar elements in transmission systems are centrifugal pendulum dampers Formulae for dealing with such systems have been derived by several investigators and are easily used in the customary computational procedures, wherein the rotor, like other parts of the transmission, is represented by effective inertias

There appears to be no reason why the operating range of r p m cannot be kept totally clear of resonant frequencies except for some very high engine orders, for which the inherent damping in the system appears to be invariably adequate So far as the regular excitation from normally working piston engines is concerned, even a 4 cylinder engine is not a difficult proposition There appears to be no call for special devices or artificial dampers Low frequencies due to articulations are unimportant Even the usual blade dampers are unnecessary in so far as torsional vibration is concerned

However, a transmission has to withstand transient impulses and faulty conditions Transient impulses are encountered in starting-clutch engagement, collective pitch manipulation, and engine cuts Faulty conditions are misfires, ignition faults, and the like The result of transient impulses is to set up free vibrations at all the natural frequencies of the system In practice it is mainly the lowest frequency unless the associated shape of vibration has a node where the transient force is applied The application of a sudden force can produce a transient stress up to twice that corresponding to the same force applied gradually This fact has to be borne in mind in designing transmissions Transient torques can be very much higher than any steady maximum which the engine will produce When, for example, the inertia of the engine is suddenly released into a transmission system by abrupt clutch application, very large torque oscillations can be set up It is against such occurrences that special devices have to be used, such as slipping clutches, flexible couplings, and others, and the difficulties of prediction make measurement highly desirable

Vibrations set up by large transient torques are the main danger to the transmission and determine its design and strength approval, but unless such impulses are recurring, their duration is too short to be of importance for comfort

Engine Unbalance The conventional way of dealing with this source of vibration is isolation through flexible mountings Engines are usually

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suspended on rubber fittings for supercritical isolation from 1st and 2nd orders In helicopters there are two main systems of suspension One which closely follows fixed-wing practice consists of elastic suspension of the whole power system, transmission system and rotor system This suspension is designed mainly with rotor frequencies in view Isolation of the engine by itself is more common with helicopters but requires a universally jointed transmission shaft from the flexibly mounted engine

Vibrations in Control Systems Blades have been made of sufficiently uniform and durable shape to make tabs and tab adjustment superfluous On the other hand blades can be adjusted to a master blade on a simple dynamic rig I believe that tab adjustment as a field method will not be acceptable in operation and one of the above solutions will be adopted, though it is too early to tell yet which will be chosen by practical engineers

Coupled Drag Oscillations Of the self excited vibrations the so called ground oscillations are by far the most general and important They have been observed and recognised as a danger to rotary wing aircraft on the ground ever since Autogiro days and indeed probably constituted the most important cause of accidents to Autogiros These ground oscillations earlier known as " ground resonance," a thoroughly misleading designation, have always been associated with drag articulated blades The oscillations involve many degrees of freedom and a large number of factors but the most fruitful advance in understanding and mastering the danger of ground oscillations was made when it was discovered that the main features of ground oscillations could be derived from the study of a much simpler mechanical model, namely a " hub " of a certain mass mounted with lateral elastic constraint in both directions The hub carries 3 thin heavy rods articulated to the hub through vertical pins and is driven at constant angular velocity

Such a mechanical model has 5 degrees of freedom in all, but when the geometrically obvious displacements are grouped into dynamically significant ones it is trivial that one of the latter, namely the displacement of all 3 blades by equal amounts about the drag pin is isolated from the rest and of importance only in relation to the torsional oscillations of the drive shaft The remaining 4 degrees render 4 natural frequencies which depend on the rotational scheme In a certain region of r p m there is a gap In this gap there are complex solutions to the frequency equations and analysis shows that these solutions have a self exciting character

The main task facing the designer is to avoid an unstable gap falling even in part within the operating r p m range Furthermore it is not permissible to operate at a point where the natural frequency of the mechanical system coincides with the rotational frequency, since there are always once per rev impulses To fulfil these two conditions the analysis derived from the mechanical model is entirely adequate One of the practically significant results of analysis is that drag hinge offset is the most powerful means to increase the r p m corresponding to the lower limit of the instability gap The theory also includes consideration of elastic constraints in blade displacement about the drag hinge and such constraints have the not unexpected effect of raising the r p m of instability but the amount required for effective correction is such that considerable fluctuating bending moments

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

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

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

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

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

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

DISCUSSION

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

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

Turning to Mr Shapiro’s paper on the sources of vibration I have one general comment to make I would like to have seen much more information on the relative importance of the various vibration phenomena It seems to me that helicopter vibrations can be divided into two groups Firstly, there are those due to lack of symmetry in parts, errors in manufacture or

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