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MAIN ROTOR WAKE/TAIL ROTOR INTERACTION

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1. INTRODUCTION

During the early stages of the flight programme on the Lynx it was noticed that the Lynx generated a distinctive noise which can be best described as a deep throated 'burbling' noise. The burble noise could be heard over and above normal helicopter noise from the main rotor, engines, tail rotor, etc. and was considered to be subjectively annoying. Comparisons of the Lynx external noise levels with those of other helicopters showed that the Lynx was no noisier than helicopters of comparable size and it was decided, therefore, to conduct a detailed investigation into the apparently unusual noise characteristics of this helicopter.

From listening tests made during the early flying it was found that the burble noise was not present during the hover condition, but was very noticeable during the approach of a flyover, especially at relatively large distances from the observer. After passing by the observer this noise was no longer distinguishable. It was not certain if the origin of the burble noise was actually on the helicopter or if it was due to an interaction some distance away from the helicopter of individual helicopter noise sources. Also it was not clear if the noise was associated with the rotors or with the gearbox and at one stage credibility was given to the latter possibility since the main noise source was prominent around 1kHz and the gearbox meshing frequencies occurred in this region. In addition to gearbox noise excitations, other possible generating mechanisms were the interaction of the rotor noise signals with themselves or with the gearbox noise giving rise to a modulation effect. In order to clarify the situation, therefore, it was decided to measure the external noise of the Lynx in flight both on the ground and at positions on the helicopter structure.

This paper describes the theoretical and experimental studies that were carried out to determine the nature of the burble noise (1). Much of the work was experimental but since some of the analysis techniques were not fully understood, it was necessary to assist the comparison by considering the theoretical approach and developing a computer program for the Fourier analysis of periodic signals.

Based on the findings of this work a further theoretical study (2) was undertaken to assess the effect of reversing the direction of rotation of the tail rotor and recently the opportunity was taken to repeat the noise measurements during flight trials on a Lynx helicopter fitted with a reversed tail rotor (3).

2. STANDARD TAIL ROTOR - EXPERIMENTAL STUDY

The experimental flight programme consisted of hovers and level flight flyovers over a ground array of microphones with three microphones mounted externally on the helicopter structure; these were on the transmission decking around the gearbox, on the undercarriage skid and on the tail cone corresponding to approx. $1\frac{1}{2}$ diameters from the centre of the tail rotor (see Figure 1).

The preliminary analysis of the noise recordings at the ground positions showed that the Lynx external noise levels compared quite favourably with those of other aircraft in that the Lynx does not exhibit unusually high noise levels.

The burble noise was most noticeable on the tail mounted microphone and the ground microphone positions during the flyover conditions but not the hover conditions. The burble noise could be heard as a rise and fall in level versus time and comparisons of the frequency analyses for the parts of the recording with and without burble noise showed that the former analysis was richer in harmonics of the tail rotor blade passing frequency 4T (4 = no. of tail rotor blades and T = tail rotor speed in cycles/sec) and contained a large number of unidentifiable discrete frequency peaks in the 500 - 1500Hz frequency region. Further analyses on a Spectral Dynamics SD 301C Real Time Analyser showed that the frequency spectrum of the tail microphone recording was dominated by the tail rotor harmonics 12T, 16T, 20T, 24T, etc. together with a large number of prominent peaks occurring at intervals of 4R (main rotor blade passing frequency) after each harmonic. The latter appeared to be given only by the frequencies $n4T + m4R$ where $m = 1$ to 5, but there may have been more peaks at $n4T - m4R$ frequencies buried beneath the general noise level. Similar results were obtained for the ground microphone when analysing those parts of the recording for which burble noise could be heard. The 4R discretes were not present when the burble noise was no longer audible on tape.

The ground microphone recordings were subject to a Doppler shift in frequency dependent on the forward flight speed of the helicopter and the relative angle between the flight path and the line joining the observer to the source. This had to be taken into account when comparing the results of the ground microphone recordings with those of the tail microphone.

It appeared from the results that the noise signal around 1000Hz (and to a lesser extent 2000Hz) was being modulated by other signals and it was decided to identify these modulation frequencies by filtering out the signal below 800Hz and above 1kHz (i.e. removing that part of the signal which is outside the 800-1000Hz frequency range), full wave rectifying and then re-analysing. Although the process of rectification introduces additional frequency peaks, it does, however, enhance the amplitudes of the modulation signals and, therefore, makes the modulation frequencies easier to detect.

Figure 2 shows an instantaneous spectrum (0-500Hz frequency range) for the tail mounted microphone signal filtered at the 1kHz octave band and full wave rectified. The levels of the discretes at the modulation frequencies have been increased by the rectification process and the frequencies are accurately given by $n4T \pm m4R$ where $m = 0, 1, 2, 3, 4$ or 5 and n determines the harmonic of 4T. The positions of the discretes and the shape of the spectra are consistent with the Fourier analysis of impulsive signals and not modulated sinusoidal signals.

Time history analyses were obtained on a standard frequency analyser and level recorder and Figure 3 shows the dBA and filtered 1kHz octave band time histories for the flyover condition recorded on the tail microphone. It can be seen from the results (especially the filtered 1kHz octave band trace) that the signal is being modulated by another signal of period $\frac{1}{4R}$ and to a lesser extent by a signal of period $\frac{5}{4R}$. The period of $\frac{5}{4R}$ corresponds to the time when one blade of the tail rotor coincides with any blade of the main rotor.

In order to examine the burble noise signal in more detail, pressure amplitude 'peak-to-peak' time histories were obtained with a U-V recorder and Figure 4 shows a dBA time history for the ground microphone. This is not a true dBA weighted analysis since it was necessary to play back the recorded signal at $\frac{1}{4}$ of its recorded speed in order to provide a suitable time scale. It is clear that the signal consists of a number of impulses which form fairly well defined and repeatable groups of 3, 4 or 5 impulses. Also although the number of positive and negative peaks in the individual impulses varies from 2 to 5 there is a predominance of 3 peak impulses. The impulses follow closely a sinusoidal form and their duration corresponds to a frequency of about 1000Hz, thus accounting for the fact that burble noise is subjectively most noticeable around this frequency.

Narrowband filtered U-V time histories, however, were subject to limitations since the pulse signal was always affected to some extent by the filtering process being used. The filter 'rise time' must be short compared to the typical impulse duration and since the impulse frequency was about 1kHz this meant ideally a filter bandwidth greater than 4kHz. Such a filter, however, would not be able to detect the impulses buried in the normal broadband helicopter noise. Thus analyses obtained with a 100Hz hetrodyne crystal filter were affected by the filter rise time as shown in Figure 5 and closely resemble the filter shape characteristics. The $\frac{1}{3}$ octave R-C type filter results, on the other hand, (Figure 5) were not affected so much by the filter shape but they do have a 'spiky' appearance which is due to a 'ringing' (oscillating) effect caused by the impulses.

It is still possible to obtain information on durations from such traces, however. By measuring the time intervals between each impulse and between each group of impulses, it was found that the repetition frequency of an impulse was on average 140Hz and the repetition frequency of a group of impulses was in the order of 21Hz. Although these frequencies are only approximate they appear to correspond to 4T + 4R and 4R respectively.

3. SUBJECTIVE EFFECT OF BURBLE NOISE

The main frequencies associated with the burble noise are the impulse frequency, the impulse repetition frequency and the group repetition frequency. During forward flight at about 115 knots with the tail rotor operating in the normal direction, these frequencies are approximately 1000 to 1200Hz, 140Hz and 21Hz respectively. The maximum repetition rate at which individual impulses can be detected subjectively is in the order of 25 per second and thus the individual impulses (of repetition frequency 140Hz) are not heard by the observer. The 21Hz or 4R repetition rate is just below the audible detectability limit and hence will be heard. Thus the combined effect from a subjective point of view is a deep throated burbling sound which consists of a carrier signal around 1kHz (impulse frequency) being modulated at a frequency of about 21Hz. It is this modulation effect which is thought to account for the burble noise being so distinctive and subjectively annoying.

4. STANDARD TAIL ROTOR - THEORETICAL STUDY

It was clear from the experimental results that the burble noise was not directly associated with normal helicopter noise sources and in order to determine if the burble noise consisted of impulsive noise signals arising from an interaction effect between the main rotor wake and the tail rotor, it was decided to examine the wake patterns produced by the Lynx main rotor. On the Lynx helicopter the tail rotor rotates in an anticlockwise direction and in forward flight the tail rotor blades cut through the wake produced by the main rotor as shown in Figure 6. During hover, however, the main rotor wake is shed away from the tail rotor. In forward flight each vortex from a main rotor blade enters the tail rotor disc and, depending on the relative positions of the vortex and the tail rotor blades, it will intersect with several blades before leaving the disc. Since there are 4 tail rotor blades, it is usual for there to be 4 intersections per vortex, although 3 or 5 intersections are also possible. After the first vortex has passed through the disc there will be a certain time delay, dependent on $\frac{1}{4R}$ before the second vortex reaches the disc. Thus every time a vortex passes through the tail rotor there will be a group of 4 or 5 intersections followed by a time delay before the next group. Figure 7 shows on a time scale the calculated intervals between each intersection (represented by a straight line) and between each group of intersections assuming that at time t = 0 a vortex intersects with a blade just at the point of entry to the tail rotor disc. After applying a time delay correction to account for the relative positions of the microphones and the tail rotor, it was found that the intersection frequency or impulse repetition frequency was about 140Hz and the group frequency was about 21Hz. These figures agree well with the measured data. As a vortex passes through the tail rotor disc it will intersect with each blade at different parts of the blade depending on the blade azimuth position. An intersection at a blade tip will produce a greater impulse than one further down the blade (owing to relative velocities of blade and vortex) and thus it is possible to assess each impulse on an amplitude scale. Figure 7 shows how the amplitudes vary with time with an approximate period of $\frac{5}{4R}$. These results can only be taken as a general guide, however.

As a blade cuts a tip vortex it is subjected to an impulsive blade loading having positive and negative characteristics and this generates a bang or impulsive pressure wave. The width of the impulse and its characteristic frequency are dependent mainly on the velocity profile of the tip vortex, as seen by the blade, and the relative dimensions of the blade chord and tip vortex. In order to determine the shape of the resulting acoustic impulse it is necessary to know the loading on the tail rotor blade which in turn is dependent on the velocity profile of the tip vortex. The blade loading was calculated to a fair approximation by adapting a method developed for main rotor blade/main rotor tip vortex interaction or blade slap (4). The blade was considered to intersect the vortex with the span of the blade at right angles to the tip vortex and not parallel to the vortex as for the blade slap case. The vortex velocity profile was taken from measurements on a Wessex rotor as Lynx data was not available and this information was fed into a computer program developed at Southampton University together with the forward speed of the helicopter, the tail rotor tip speed and the relative distances and angles between the tail microphone and the interaction path. The acoustic pressure amplitude time plot obtained from the blade loading is shown in Figure 8. The characteristic 3 peak impulse response was predicted and when this was Fourier analysed it gave a spectrum peaking around 1200Hz.

The amplitude of the third peak (Figure 8) is, however, significantly lower than indicated by the U-V time histories and, although there is no real explanation for this, it is thought to be associated with the blade loading, since increasing the loading decay rate enhances the peaky nature of the acoustic impulse (see dotted line on Figure 8).

In order to link the experimental and theoretical results and to understand the processes of rectification and modulation, a computer program was developed for the Fourier analysis of signals. Unfortunately there were several limitations in the programme owing to the fact that it was difficult to simulate the burble noise signal. It was possible, however, to confirm the narrowband frequency analysis results in that rectification displaces the modulating frequency from the rest of the spectrum and makes it easier to detect. Also it confirmed that amplitude modulation of an impulse signal by a sine wave gives a lobe shape spectrum with sidebands about the individual discretes in each lobe.

5. THEORETICAL EFFECT OF REVERSING TAIL ROTOR

Since the burble noise characteristics are dependent on the direction of rotation of the tail rotor, reversing the tail rotor should significantly reduce the magnitudes of the impulses and the subjective effect of the interaction noise. Using the theoretical model discussed previously, calculations were made for different forward speeds ranging from 60 knots to 200 knots with the tail rotor rotating in both clockwise and anticlockwise directions. For the standard tail rotor direction the impulse repetition frequency increased with increasing forward speed but when the tail rotor was reversed the frequency decreased with increasing forward speed. Similarly, as shown in Figure 9, the impulse amplitude increased with increasing forward speed for the standard tail rotor, while a fairly rapid decrease in noise level occurred when the tail rotor was reversed. At 130 knots forward speed the estimated reduction in impulse peak sound pressure level was about 13dB (see Figure 9) and since the impulse peaks are about 15/20dB above the general helicopter noise in the normal configuration, reversing the tail rotor would mean that the burble noise should be effectively masked by the noise from the main rotor, engines, etc. particularly at high forward speeds. Thus the burble noise should no longer be distinguishable from a subjective point of view.

6. REVERSED TAIL ROTOR TESTS

Flight tests have recently been completed on a Lynx helicopter fitted with a reversed direction tail rotor and a reversing gearbox. Noise measurements were taken with microphones mounted on the ground and on the tail boom at the same positions as for the standard tail rotor. Although there were a few unexplained differences between the ground microphone and tail mounted microphone results, the general conclusions confirmed the theoretical findings.

On the reversed tail rotor, U-V analysis showed that tail rotor blade passing noise pulses and not burble noise pulses dominate the dBA time histories of the tail mounted microphone. There was some indication of pulse grouping effects on the 1kHz octave band time histories at the lower forward speeds which could be attributed to burble noise. The amplitude levels of the impulses were well below those of the tail rotor noise in the 2kHz octave band, however, and it appeared that the tail rotor noise was most noticeable in the 2kHz band. Figure 10 shows the 1kHz and 2kHz octave band time histories for the 115 knot flyover on the reversed tail rotor and the tail rotor blade passing pulses are clearly seen on the 2kHz octave band analysis. A main rotor noise prediction method based on blade thickness effects (5) is currently being developed at W.H.L. and if this is applied to tail rotors, then the tail rotor noise levels measured by the tail microphone should be 6dB higher on the reversed tail rotor than on the standard tail rotor. This is because the maximum noise will be radiated by the advancing blade which is at different positions for the two configurations. The test results for the 1kHz octave band analysis supported the 6dB difference, although it was difficult to distinguish the tail rotor pulses from the burble noise pulses on the conventional tail rotor.

On the ground microphone there was no indication of the grouping effect of burble noise but tail rotor blade passing pulses occurred at regular intervals especially in the far field. Although the maximum noise levels (dBA and dBLIN) for the flyovers were similar for both configurations, the reversed tail rotor exhibited lower noise levels on approach in the far field. As can be seen from Figure 11 the reversed tail rotor at 130 knots is quieter at 2000ft by 10dBA and the difference appears to increase even further with distance. Just prior to the flyover peak, however, the reversed tail rotor exhibits higher noise levels. The tail microphone results suggest that the tail rotor noise levels in the far field should be similar and thus it is considered that the large differences measured by the ground microphone are due to changes in the directivity and source strength of the tail rotor noise. Narrowband frequency analysis of both microphone positions confirmed the absence of burble noise frequencies on the reversed tail rotor tests.

7. CONCLUDING REMARKS

The subjectively distinctive noise characteristics of the Lynx helicopter during the approach flight condition are generated by the intersection of the tail rotor with tip vortices shed by the main rotor. During forward flight the relative positions of the vortices and the tail rotor blades are such that the main rotor tip vortex is intersected by 4 or 5 tail rotor blades giving rise to groups of impulses as each vortex passes through the tail rotor disc. Owing to this grouping effect and the variation in amplitude which results, the chain of impulses is effectively modulated and the interaction noise is heard as a deep throated burbling sound.

Reversing the tail rotor has eliminated the burble noise, as predicted and significantly reduced the tail rotor blade passing noise in the far field. Prediction methods based on blade thickness effects have calculated the tail rotor noise at the tail microphone to within 2 or 3dB but owing to problems of directivity etc. accurate predictions for the ground microphones have not been possible. On a dBA basis the far field noise has decreased by 15-20dBA at distances of about 3000 ft. and thus the noise detectability of the helicopter has effectively been doubled by reversing the tail rotor.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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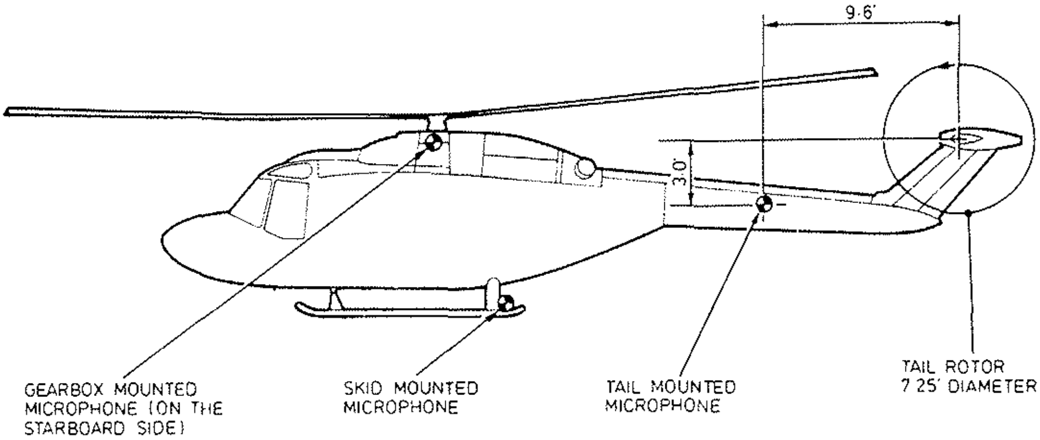

FIG. 1. MICROPHONE POSITIONS ON AIRCRAFT

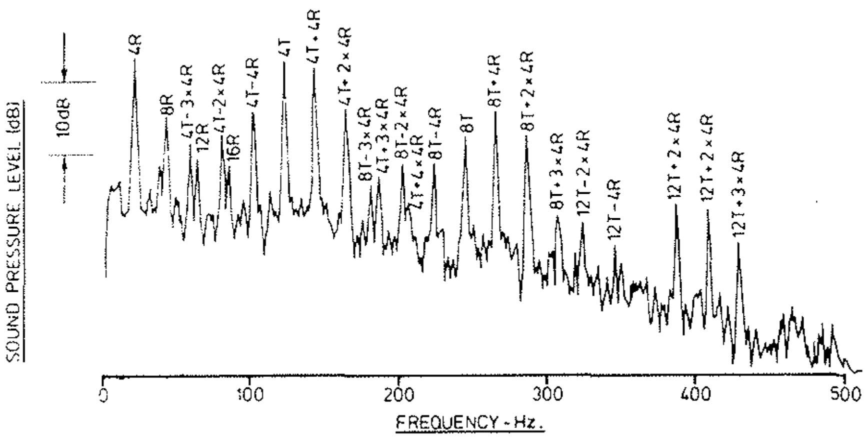

FIG. 2. NARROWBAND ANALYSIS ON REAL TIME ANALYSER – SIGNAL FILTERED AT 1000 HZ ⅓ OCTAVE BAND AND FULL WAVE RECTIFIED.

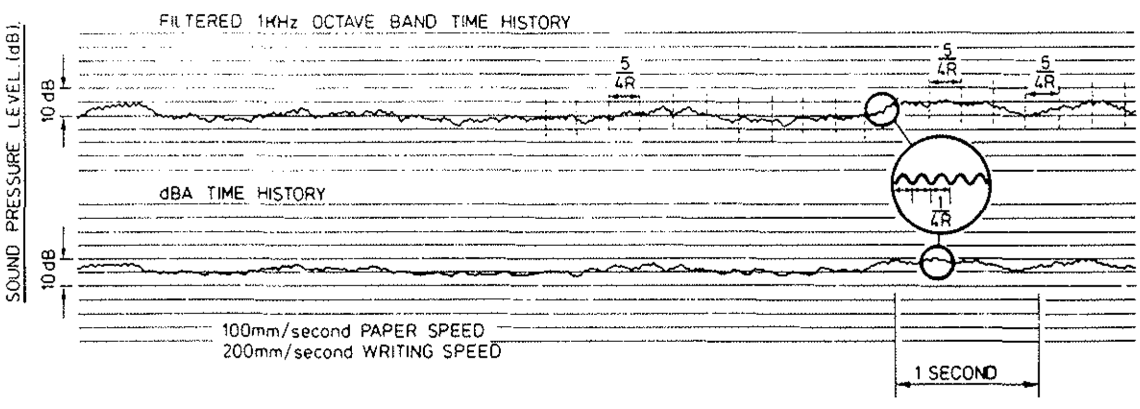

FIG. 3. RMS TIME HISTORIES FOR TAIL MOUNTED MICROPHONE

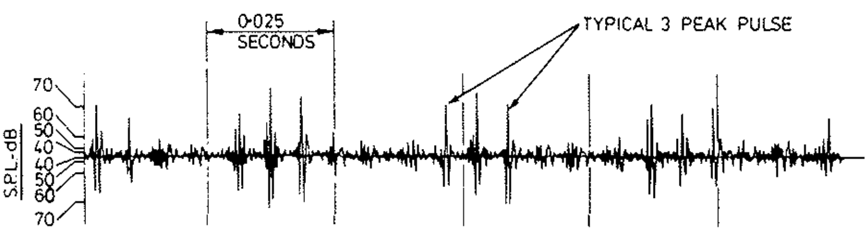

FIG. 4. dBA TIME HISTORY FOR GROUND MOUNTED MICROPHONE (TAPE SPEED REDUCED BY A FACTOR OF 4).

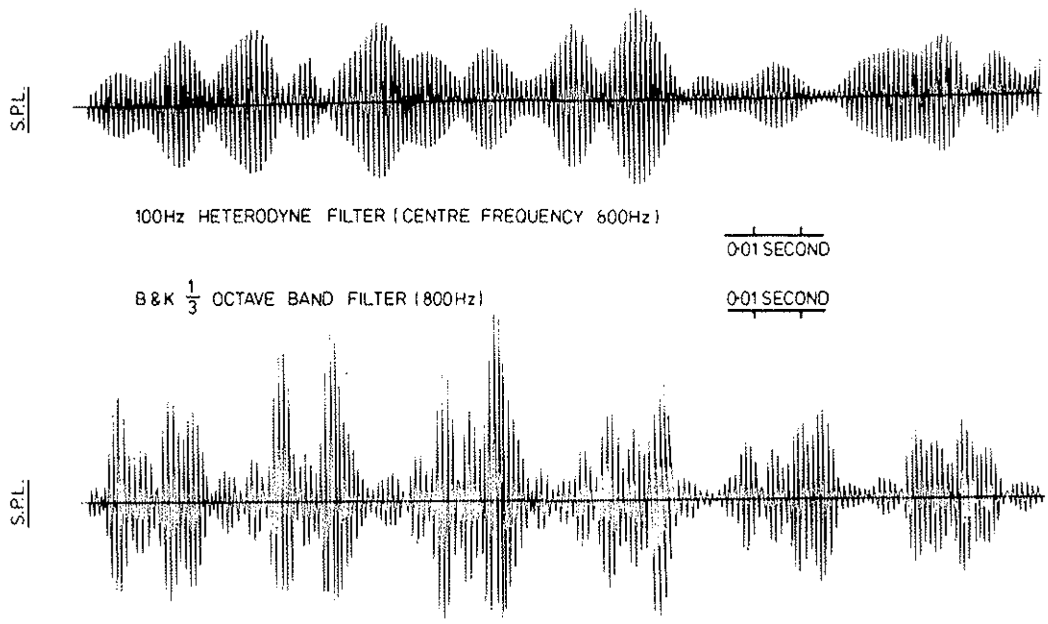

FIG. 5. COMPARISON OF U-V TIME HISTORIES

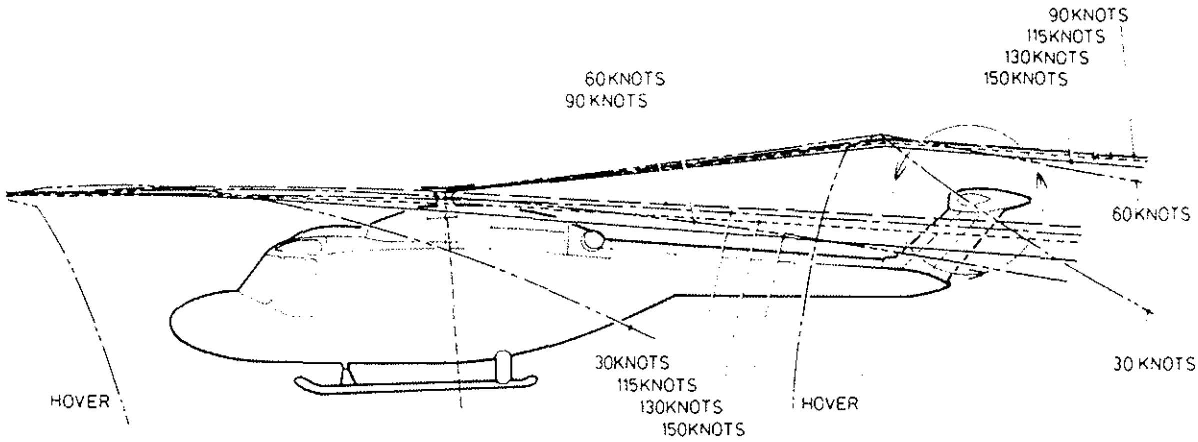

FIG. 6. MAIN ROTOR TIP VORTEX TRAJECTORIES DURING HOVER AND FORWARD FLIGHT

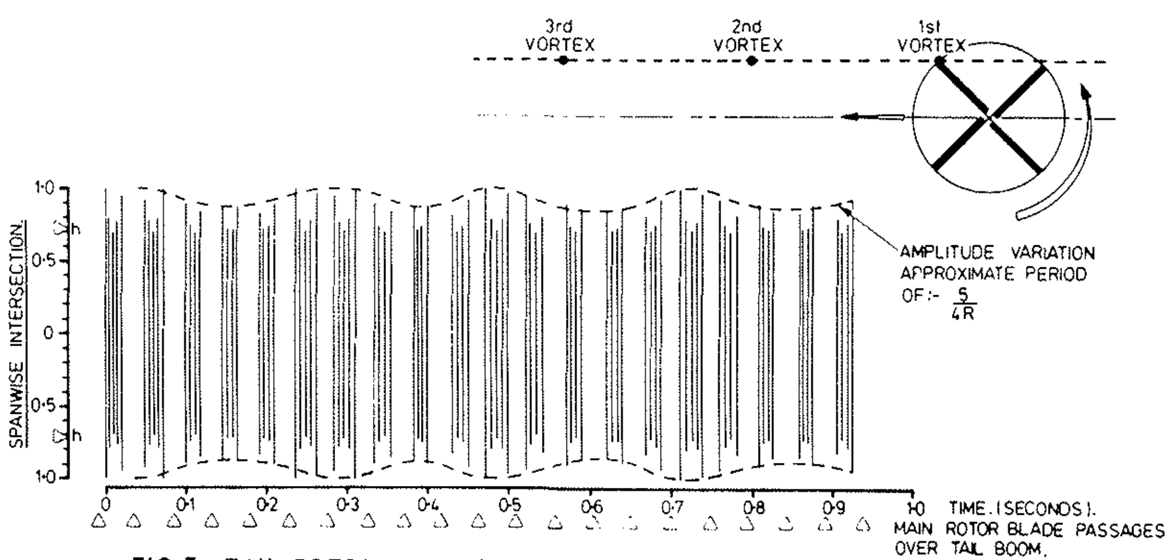

FIG. 7. TAIL ROTOR BLADE/MAIN ROTOR VORTEX INTERSECTION POINTS

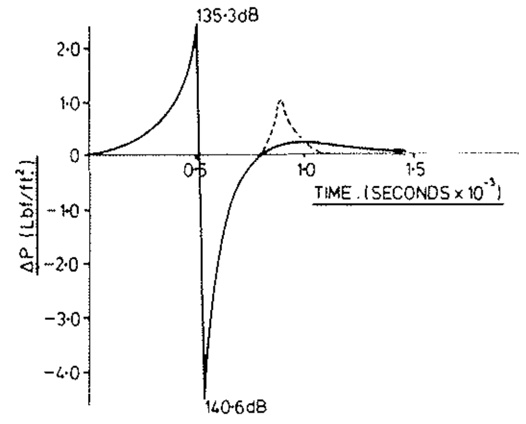

FIG. 8. ACOUSTIC PRESSURE-AMPLITUDE TIME PLOT

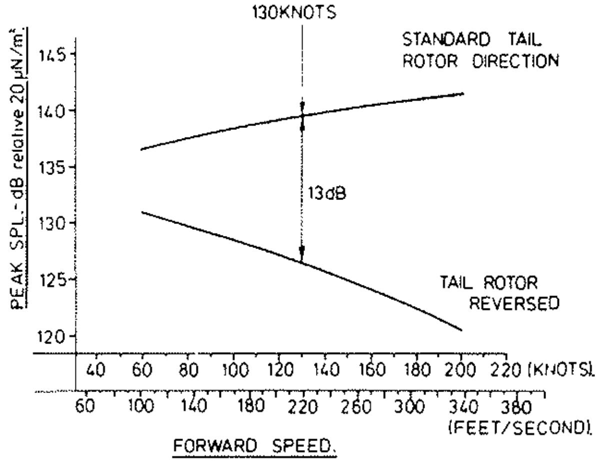

FIG. 9. VARIATION OF IMPULSE PEAK SOUND PRESSURE LEVEL WITH FORWARD SPEED

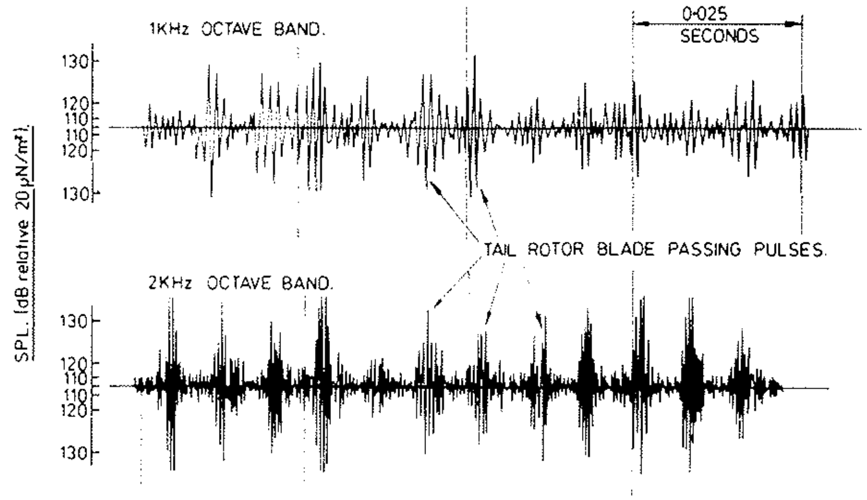

FIG. 10. U-V TIME HISTORIES FOR REVERSED TAIL ROTOR – TAIL MICROPHONE (115 KNOTS)

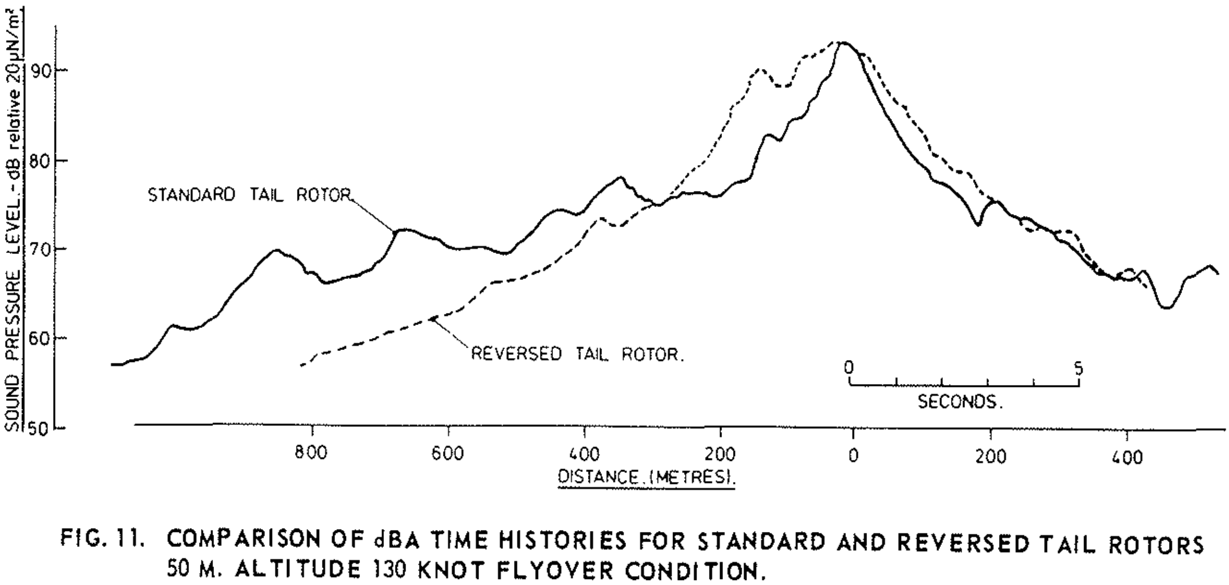

FIG. 11. COMPARISON OF dBA TIME HISTORIES FOR STANDARD AND REVERSED TAIL ROTORS 50 M. ALTITUDE 130 KNOT FLYOVER CONDITION.