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REDUCTION OF HELICOPTER NOISE BY USE OF A QUIET TAIL ROTOR

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Abstract

Helicopter noise is a complex combination of a number of sources and although tail rotor noise has been known to have a marked effect on the noise levels on approach, the importance of this source has often been underrated. Research conducted using the Lynx has shown that it does not only control the noise at distance, but can also dominate the noise as the helicopter flies overhead. This latter effect, for which to date there is no adequate theory, is similar to the noise heard on approach in that it is a result of main rotor wake/tail rotor interaction. Investigations at Westland Helicopters Limited over a number of years conducted under MOD and Company funding have confirmed the presence of two interaction sources and indicated the method by which they can be controlled.

The outcome of the research studies lead to the design and manufacture of a Quiet Tail Rotor (Q.T/R) which was subsequently flight tested on a Lynx. As a result reductions of up to 15 dB on approach and 5 dB(A) at overhead have been obtained. This successful concept has been incorporated in the Westland WG30 and, in comparison with an early prototype fitted with a standard tail rotor, significant reductions obtained.

The concepts behind the Q.T/R are described in this paper, together with the research work conducted to highlight the sources and their dependency on operating parameters.

1. INTRODUCTION

With the increasing use of helicopters particular attention has been focused on the likely noise impact on the community. The main area of interest is the noise experienced on the ground under the flight path. In the case of a helicopter, unlike aircraft where the main problem is associated with the high peak or maximum noise level, it is the noise heard on the approach at distance which appears to give rise to the main concern, while the noise as the helicopter flies overhead is of secondary importance. As a helicopter approaches the noise can be dominated by blade slap, impulsive (banging) main rotor noise, and/or tail rotor noise both of which have subjectively unpleasant characteristics. Tail rotor interaction noise can also be important at the overflight point and can have a major influence on the 'peak' or maximum noise generated by the helicopter. Blade slap can be controlled by choice of main rotor parameters and reductions of tail rotor noise and tail rotor interaction noise can be achieved by use of Quiet Tail Rotor (Q.T/R) as discussed in this paper.

2. TAIL ROTOR NOISE

The importance of tail rotor noise to the overall helicopter noise is often underrated yet it is fairly clear that, in addition to often controlling the level and/or subjective character of the noise on approach, it can have a marked effect on the 'peak' or maximum noise level generated during overflight. This lack of appreciation of the contribution of tail rotor noise has arisen partly as a result of the deficiencies in predicting tail rotor noise and partly since it is difficult to measure and isolate the tail rotor noise sources. The position is further complicated by the fact that in addition to the basic tail rotor noise, "interaction noise" resulting from the interaction of the main rotor wake by the tail rotor blades is often the dominant source. It was established during a research programme on the Lynx during the period 1974-75 that the noise on the approach on this helicopter was characterised by 'burble noise'. This work was reported in reference 1 together with the preliminary results of an experiment which confirmed that considerable noise reductions could be obtained by modifying the operating parameters of the tail rotor.

The outcome of these research studies lead to the design and subsequent manufacture of a Quiet Tail Rotor (Q.T/R) which in due course was flight tested on a Lynx. In parallel with this activity further investigations into the noise generated by a helicopter in flight were conducted, which lead to the detection of another interaction noise source which manifested itself during overflight. This source has again been attributed to an interaction between the tail rotor and the tip vortices shed by the main rotor, but unlike 'burble' which is a function of the direction of rotation of the tail rotor, this source is essentially dependent on the speed of the tail rotor only. The Q.T/R on the Lynx was configured to reduce this source as well as that associated with 'burble'. The concept has also been applied to the tail rotor for the Westland WG.30.

3. TAIL ROTOR NOISE - BASIC CHARACTERISTICS

Tail rotor noise is impulsive in character with the impulses occurring at the blade passing interval which is typically in the range 60Hz to 130Hz. Due to this relative high repetition rate and the short duration of the individual pulses, it is classified subjectively as a 'whine' very much akin to propeller noise. A narrow band analysis of such a signal contains 'discrete frequencies' at the blade passing frequency and its harmonics and since it is impulsive it will be rich in higher harmonics.

When interaction with the wake shed by the main rotor occurs the pressure amplitude-time history is further complicated since the tip vortices are "spaced" at a period corresponding to the main rotor interval which typically corresponds to a frequency in the range 15 to 20Hz. As a consequence a complex impulsive character (waveform) which contains both components of main rotor and tail rotor is generated. The resulting narrowband analysis therefore contains both tail rotor harmonics and 'side bands' of these with frequencies corresponding to combination frequencies of the main and tail rotors (1).

Due to its impulsive character tail rotor noise, like other impulsive type signals, is underestimated by conventional rating methods based on dB(A) or EPNL analysis. Detailed studies at Westland Helicopters Limited have suggested that subjective corrections in the order of 5dB(A) are required (2) and recently some studies have suggested even higher corrections (3). It is important, therefore, that this aspect is taken into account when evaluating helicopter noise, particularly when it is remembered that tail rotor noise often dominates the helicopter noise heard on approach. In the studies relating to selecting parameters for the Q.T/R a 5dB(A) allowance was assumed.

4. INTERACTION NOISE SOURCES

The two interaction noise sources of main interest are illustrated diagramatically in Figure 1, which shows the effect of change in direction of tail rotor rotation. As shown the sources are associated with the intersection of the tail rotor blades with tip vortices shed by the main rotor. The figure shows 'burble noise' which is radiated in the direction of flight and hence heard on approach and 'overhead interaction' noise which is "beamed" in a vertical plane. These two sources give rise to a time history plot of the type indicated in Figure 2 where the 'dashed line' represents the time history resulting from a flyover of a helicopter where these two sources have been reduced or eliminated.

The mechanism associated with these two sources can be understood by reference to Figure 3 which shows the main rotor tip vortex trajectories during hover and flight on the Lynx.

In the case of 'burble' the tip vortices shed at the rear of the main rotor 'clip' the top of the tail rotor and lead to a pulse chain of the form indicated in Figure 4. Here the individual pulses are "spaced" approximately 1/4T apart (where 1/4T is the tail rotor blade passing interval for the 4 bladed tail rotor) with the 'groups' spaced at 1/4R (where 1/4R is the main rotor blade passing interval and hence the 'distance' between successive tip vortices shed by the 4 bladed main rotor). This is discussed in detail in references 1, 4 and 5. As can be seen from Figure 1 the interaction velocity is approximately $V_T \pm V_F$ (where V_T is the blade tip speed and V_F the flight speed) and hence the magnitude of interaction is dependent on the direction of rotation of the tail rotor as well as flight speed.

The 'overhead interaction' noise is associated with the intersection of the trailing main rotor tip vortices passing (approximately) horizontally through the central region of the tail rotor disc. As can be seen from Figure 3 the relevant tip vortices are those shed at the front of the main rotor disc. However since these vortices pass near the main rotor hub en route to the tail rotor they could be considerably disturbed. An alternative explanation is that the vortices come from the root of the blade at the rear of the main rotor. These could travel undisturbed into the tail rotor, but these are unlikely to be of sufficient strength to be acoustically important. The former assumption is therefore preferred, particularly when it is remembered that the tail rotor is offset by about 1.5 ft. to one side of the helicopter. Irrespective of the source of the tip vortices, the resulting pulse sequence takes the form illustrated in Figure 5 where the sequence of pulses are separated by approximately 6/4T due to the ratio on the Lynx between the main and tail rotor. This is very near to 1/4R and hence the major pulses occur approximately at the main rotor passing frequency even though the source is generated at the tail rotor. In practice overlapping between the various groups of pulses occurs and as a result a very complex waveform results. With this model the interaction magnitude is dependent essentially on the tip speed of the tail rotor and, assuming the tip vortices can pass undisturbed across the tail rotor disc, independent of the direction of rotation. It follows that this source can only be reduced by reductions in the tip speed of the tail rotor. Since the impulses occur at approximately the time interval associated with the main rotor, it is also clear why in many instances this source, which is dependent on the tail rotor, has been associated with the main rotor and confused with main rotor noise.

5. Q.T/R DESIGN CONSIDERATION

5.1 Acoustics

Following the investigations reported in reference 1 and detailed theoretical studies (4, 5) a Quiet Tail Rotor was designed which would effectively eliminate 'burble' and reduce the level of the basic tail rotor noise. As explained previously the former is dependent on the tip speed and direction of rotation, while the latter is essentially a function of tip speed only.

Theoretical studies (5) and flight tests (1) had indicated that the 'burble noise' on approach would be reduced by 10 to 13 dB by reversing, relative to the standard Lynx, the direction of rotation. In the subsequent calculations the least favourable value of 10 dB was assumed as illustrated in Figure 6. It was decided that the aim should be to reduce the level of the tail rotor noise so that it was 3 dB below the level of the main rotor noise, so that it would have negligible effect on the approach noise. Before the precise reduction required could be established an allowance for the relative subjective impression and rating of main rotor and tail rotor noise had to be established. For this use was made of the standard 'equal loudness contours' and the results of 'ad hoc' tests conducted within Westland Helicopters Limited. This suggested the need for a further 8 dB reduction as indicated on Figure 6. It had been shown during high speed flight that the tail rotor noise levels on approach (in terms of the absolute pressure peak and rms harmonic noise levels) were dependant on the blade thickness and could be readily predicted by the theory developed by Hawkings and Lowson (6). The calculated SPL/tip relationship showed that a tip speed of 650 ft./s was required to obtain the necessary 8 dB reduction.

At the time of the initial design of the Q.T/R the overhead interaction noise had not been identified in detail and hence this aspect was not taken into consideration.

5.2 Aerodynamics/Dynamics

The design and final selection of operating parameters was, of course, an iterative process and hence somewhat difficult to summarise. An estimation of the minimum tip speed for a tail rotor with an 'advanced technology' aerofoil to give a yaw performance compatible with the standard Lynx indicates that tip speeds as low as 625 ft./s would be possible. Since, however, from the acoustic study the minimum tip speed required was 650 ft./s this was selected for the Q.T/R.

In the practical design the loss in thrust due to the tip speed reduction could be offset by changing the geometry of the tail rotor (radius, chord, number of blades) or by use of an improved aerofoil or by a combination of all these aspects. The design finally selected was based on a 'cropped' version of a composite 'cambered blade' being developed for another application, this had an advance aerofoil section, a slightly larger chord and since the study also showed that a larger radius could be tolerated this was increased by $1\frac{3}{4}$ inches. The initial evaluation of the dynamic characteristics revealed unfavourable characteristics, but it was soon shown that a simple re-arrangement of the hub geometry combined with an addition of a 'tip weight' resulted in an acceptable design.

5.3 Other Changes

The Q.T/R required, of course, a new tail gearbox to reverse the direction of rotation (relative to the standard Lynx) and to lower the rotational speed. This was designed and built. A number of minor changes to the control linkages etc. were also required. These changes resulted in an overall increase in weight of 10 lbs. which was considered acceptable. The gearbox was designed so that it could be directly mounted on the existing Lynx tail pylon.

5.4 Performance

There were no performance implications of the Q.T/R since in all aspects it was designed to be the same or better than the current Lynx tail rotor. There was, however, a 10 lb increase in weight associated with the new gearbox, which would mean a slight loss in payload. The heavier gearbox would also have some minor influence on CG, but it was shown that "weight" in the nose could be rearranged to offset any adverse effects.

6. EXPERIMENTAL VERIFICATION

6.1 Test Configurations

In the early Reversed Tail Rotor Experiment reported in references 1 and 7, a simply reversing gearbox was incorporated on the Lynx in order to reverse the direction of rotation. The rotor had, of course, the same tip speed as that on the standard Lynx (717.5 ft/s).

The composite Q.T/R based on a cambered aerofoil discussed in section 5 was never built, since it was shown that considerable reductions in cost (and time scale) could be achieved by testing with an "interim solution Q.T/R" based on available Sea King tail rotor blades. The diameter, chord and tip speed were the same as that selected for the Q.T/R and it was shown that it did not have any adverse dynamic characteristics, although the hub had to be slightly reconfigured. Such a rotor was manufactured and used for the Q.T/R flight test programme. This rotor, of course, had poor aerodynamic characteristics as compared to the existing Lynx tail rotor, but was adequate for the noise tests. From the acoustic point of view the rotor was of course identical to the initial design since it had a tip speed of 650 ft./s and, relative to the standard Lynx, a different direction of rotation and as a consequence the results obtained using the Lynx fitted with this rotor are in this report designed as for the Q.T/R.

6.2 Test Format

Experimental verification of the theoretical 'burble' model and that subsequently developed for 'overhead interaction noise' was obtained using a Lynx helicopter. This was initially tested with a standard tail rotor (datum condition) and then with the (interim solution) Q.T/R fitted. Tests were conducted with microphones mounted at the certification height of 1.2m and using ground level microphones. A tail mounted microphone as discussed in reference 1 was also used. Flights were in the main conducted at 500 ft. (150m) altitude, which corresponds to the 'minimum' height allowed for normal overflight of communities and the height quoted in the proposed noise certification standards. A range of flight speeds were flown (70 knots to 150 knots), but in this paper the results quoted refer in general to 130 knots with emphasis on the data collected under the flight path.

In addition to the two sets of Lynx data with the standard tail rotor and Q.T/R obtained on the same helicopter, data recorded previously during the simple 'Reversed Tail Rotor' experiment (7) has been analysed to highlight the relative importance of direction of rotation and tip speed. (The tip speed of the Reversed Tail Rotor was 717.5 ft./s as on the standard Lynx.) This data was obtained in a similar manner to that of the main programme.

6.3 Tail Mounted Microphone

Results obtained on the tail boom mounted microphone, which was positioned approximately 1.5 rotor diameters from the centre of the tail rotor (1) are reproduced in Figure 7 for the Standard, Reversed and Q.T/R tail rotor configurations. The upper trace for the standard tail rotor shows clearly the tail rotor noise harmonics plus the numerous sidebards associated with the 'burble'. Reversing the tail rotor eliminates the 'burble', but leaves high levels of tail rotor harmonics and it is necessary to reduce the tip speed as on the Q.T/R to reduce these levels. (On the traces the 'broadband' base noise is the wind noise.) The results obtained on the tail boom microphone are not directly related to the noise heard on approach due to the directivity associated with the source and the fact that the microphone is close to the tail rotor. Also because of the position of the microphone, relative to the rotor disc - it is approximately on a horizontal plane through the disc - it does not measure the 'overhead interaction' noise which is radiated in a vertical plane (see Figure 1).

6.4 Overhead Interaction Noise

This can be easily seen by studying pressure amplitude-time histories for the under flight path microphone reproduced in Figure 8 - this gives results for the Standard and Q.T/R tail rotor helicopters. (The corresponding result for the Reversed Tail Rotor is not available.) It will be observed that the Standard Tail Rotor generates high levels of impulsive noise at approximately 1/4R intervals, whilst in the case of Q.T/R the signal is much lower in level and at first glance more random in nature. It is worth noting, however, that the signal for the Q.T/R helicopter is in fact still impulsive with what appears 'pulses' approximately 1/4T apart, with several "sequences" or groups superimposed. The importance of tail rotor component is confirmed by studying the corresponding narrowband analysis results even though to date the details cannot be fully explained.

The impact on the dB(A) analysis for a 150 knots flyover over concrete can be seen from Figure 9 where the reduction in the maximum level is in the order of 5dB(A). Corresponding data for the Reversed Tail Rotor helicopter is not available, but as reported in reference 1 this gave the same maximum level as the Standard Lynx during overflight.

6.5 'Burble Noise'

The 'burble' noise detected on approach is similarly reduced by the Q.T/R, this can be seen in terms of dB(A) on Figure 9 where at distance the reduction is up to 15dB(A). This reduction, combined with the subjective change in the character of the noise, explains why the Q.T/R Lynx could not be heard whilst at the same distance the standard Lynx was very audible.

The corresponding results for the Reversed Tail Rotor helicopter show a similar reduction at distance to the Q.T/R due to the elimination of 'burble', although the basic level of the tail rotor noise is higher due to higher tail rotor tip speed (1).

The reduction in the level of the tail rotor noise, and the 'burble', can be readily seen from Figure 10 which shows for a 130 Knot flyover the narrowband analysis for the two helicopters together with the corresponding pressure amplitude time history. It will be observed that the 'burble' noise has been eliminated and the level of the basic tail rotor noise reduced well below that of the main rotor, which although subjectively less important, now dominates the unweighted signal.

6.6 Variation in Level with Distance

The variation of the magnitude of tail rotor noise and tail rotor interaction noise, as measured on the ground, with distance is summarised is Figure 11. This shows the 'peak' levels associated with the individual impulses - also indicated on the figure for reference is the level of the main rotor 'peaks'. The 'overhead interaction noise' clearly dominates the signal at the overhead position and an 8 dB reduction is obtained by use of the Q.T/R. It will also be noted that there is a 'dip' in the level of the tail rotor noise 'peaks' at 500 ft. before overhead - this is a genuine effect due to "change" in the magnitude of individual sources and is often reflected in the dB(A) history. This is not very clear on Figure 9 although it can be just detected (an arrow indicates the approximate region). It can also be seen from Figure 11 that the tail rotor noise is reduced, as predicted, by 8 dB at distance - this result is also reflected in the analysis based on the sum of tail rotor noise harmonics.

7. WG.30 TAIL ROTOR

The Q.T/R concept has also been incorporated in the Westland WG.30 and as a result this helicopter is very quiet on approach during high speed flight. The tip speed chosen for the tail rotor was 690 ft./s with the value being somewhat higher than on the Q.T/R for the Lynx due to relative differences between the levels of main rotor noise on the two helicopters. Prior to the installation of the 'quiet tail rotor', some preliminary flight tests were conducted on the WG.30 fitted with a standard Lynx tail rotor (tip speed 717.5 ft./s). Noise measurements were performed in both configurations and the results obtained were for all practical purposes identical to those for the experimental Q.T/R Lynx. A typical dB(A) time history is reproduced in Figure 12 and as can be seen reductions at overhead and on approach of 5 dB and 10 to 15 dB respectively have been obtained.

8. DISCUSSION OF RESULTS

The values quoted for the Q.T/R show that reductions on approach of 10 dB(A) or more are possible and this is of major importance when considering community response to helicopter noise. Overhead the reduction is typically in the order of 5dB(A) and since the signal is still influenced by tail rotor noise, some further reductions may be possible. It is thought, however, that this source is associated with rotor wake interaction rather than, say thickness noise associated with the tail rotor, and hence possibly can be only reduced by further reduction in tail rotor tip speed or removing the tail rotor from the influence of the main rotor wake. The former may be possible but in terms of performance the limit of tip speed reductions is being approached, while the latter approach is difficult to envisage.

It is worth noting however, that if a Q.T/R is used the level of tail rotor noise, except directly under the helicopter during overflight, is well below that of the main rotor and other sources. Thus the overall impact of additional tail rotor noise reductions, unless combined with reductions in main rotor noise which are difficult without major performance penalties, will be small. On the Q.T/R Lynx and the WG.30 for example, although when the helicopter is overhead tail rotor noise can be detected, it is for all practical purposes non-existent at distances up to within 500 ft. (150 m) of this point.

In terms of EPNL, which will be used for certification, the reductions are less marked than indicated by dB(A) measurements since this unit does not fully reflect the importance of tail rotor noise or take into account the level on approach at distance. At 130 Knots on the Lynx and at 122 Knots on the WG.30 the reductions are only 2.8 EPNdB and 2.3 EPNdB respectively, yet clearly the noise heard on the ground is much less.

The models for the 'burble' and overhead interaction noise explain the majority of the observed features and the simple theoretical methods developed for 'burble' noise (4, 5) are adequate. As explained previously there is, however, no theory available for predicting overhead interaction noise and even with the proposed model there are a number of aspects which as yet cannot be explained. The most important of these is the clear increase in the noise (pulse amplitude) with flight speed, while according to the simple model this should only influence the amplitude structure within each group of pulses. Part of this concern can be overcome by postulating that the tip vortex track passes some distance from the rotor hub, so that the intersection speed includes a resolved component of the flight speed. This cannot, however, at this time be used fully to explain the observed trends or define the precise aeroacoustic interaction mechanism: work in this area is therefore continuing.

9. CONCLUDING REMARKS

It has been shown that marked reductions in noise on approach (up to 15 dB(A)) and significant reductions in overhead noise (by typically 5 dB(A)) can be obtained by use of a tail rotor whose operating parameters are chosen to minimise noise. It has also been shown that much of the noise initially considered to be associated with the main rotor during overflight is due to main rotor wake/tail rotor interaction. With the use of Q.T/R the noise level on approach is very low and providing no other impulsive source, such as blade slap, is present the helicopter would be acceptable from the community point of view. This, however, does not automatically imply it would meet the proposed noise certification since this is concentrated mainly on the level of noise as the helicopter flies directly overhead at 500 ft. (150 m) altitude.

The design and manufacture of Quiet Tail Rotor does not appear to present any major problem with the advanced aerofoil sections available and weight penalties are negligible. There is no erosion of performance and hence in the future tail rotor noise should become of secondary importance from the point of view of helicopter noise.

Acknowledgements

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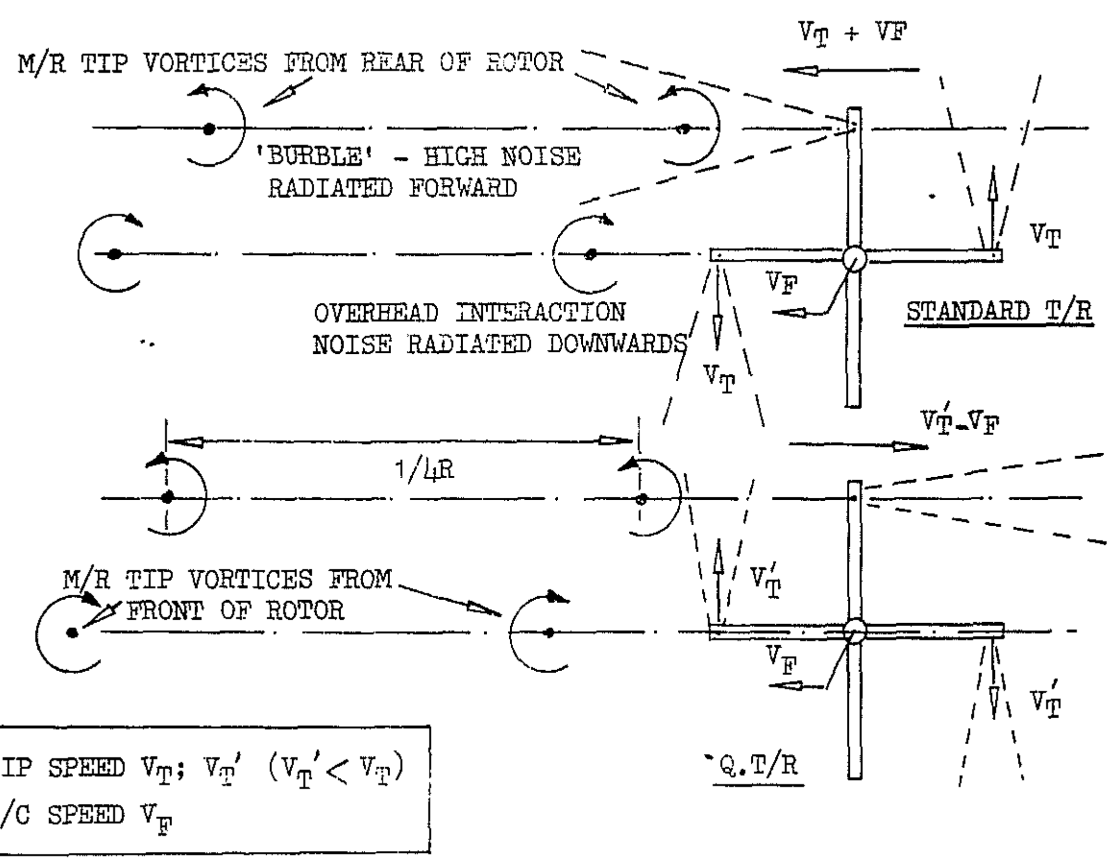

FIGURE 1 INTERACTION NOISE MODEL

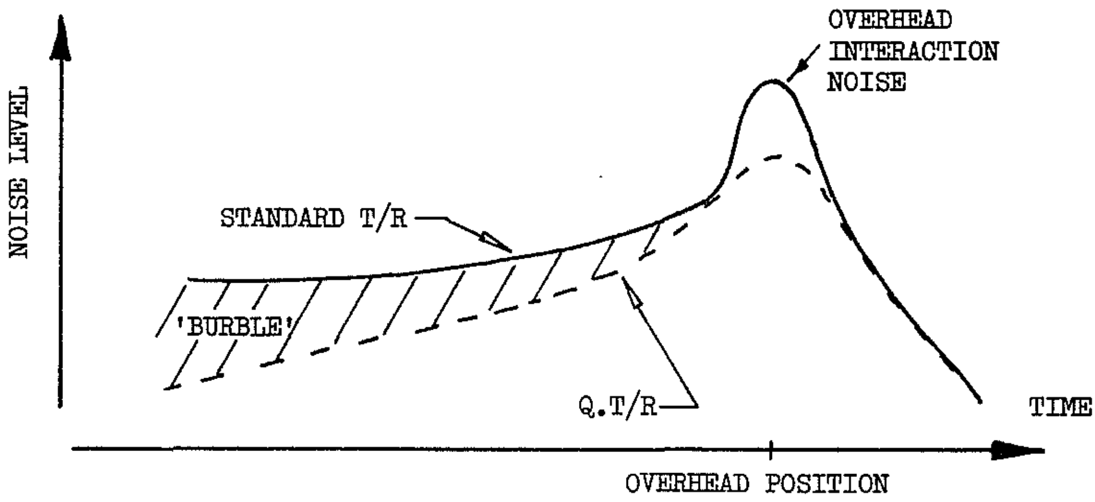

FIGURE 2 GENERALISED NOISE TIME HISTORY

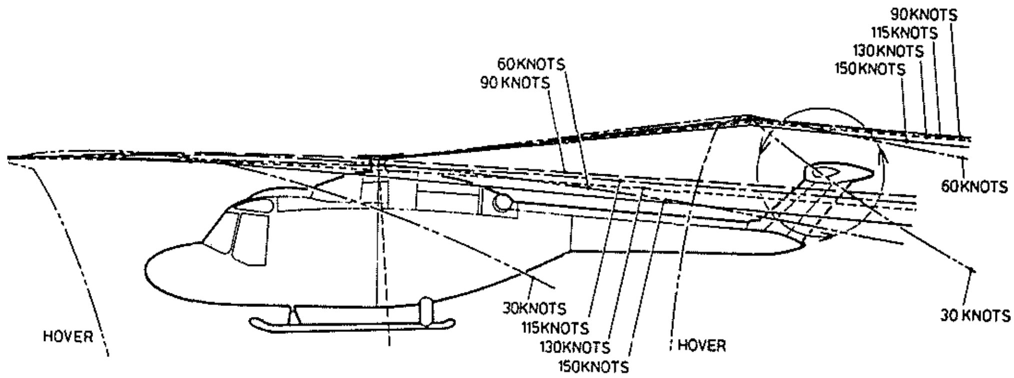

FIGURE 3 MAIN ROTOR TIP VORTEX TRAJECTORIES

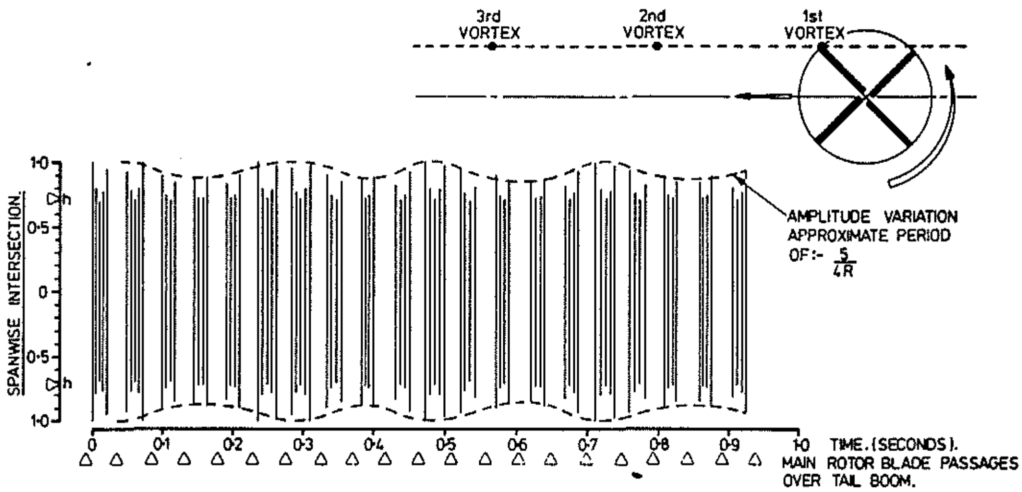

FIGURE 4 BURBLE PULSE CHARACTERISTICS

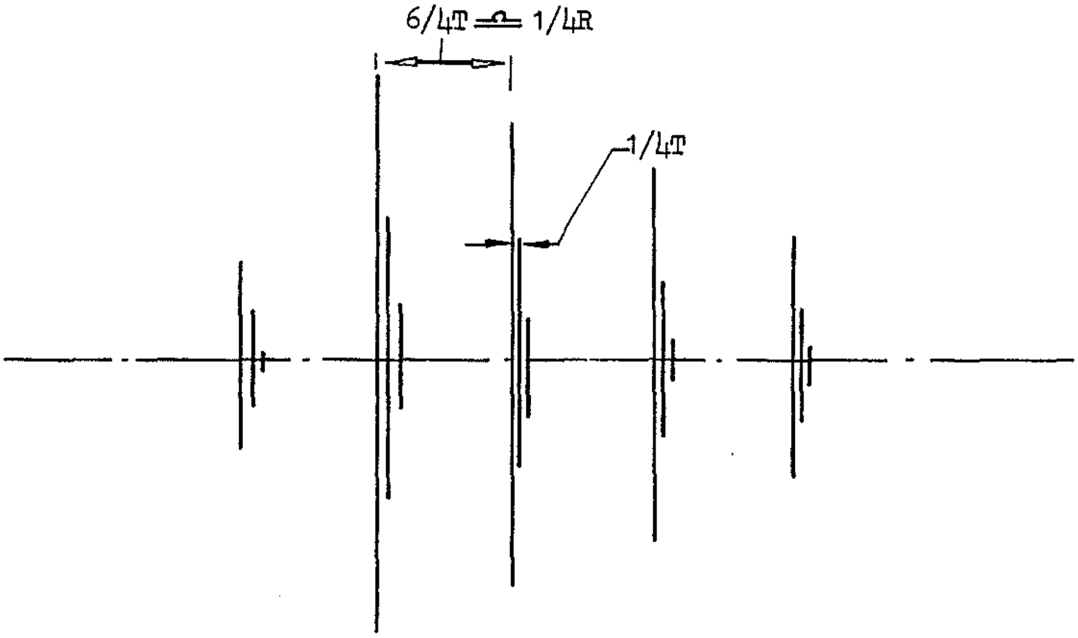

FIGURE 5 OVERHEAD INTERACTION NOISE - PULSE CHARACTERISTICS

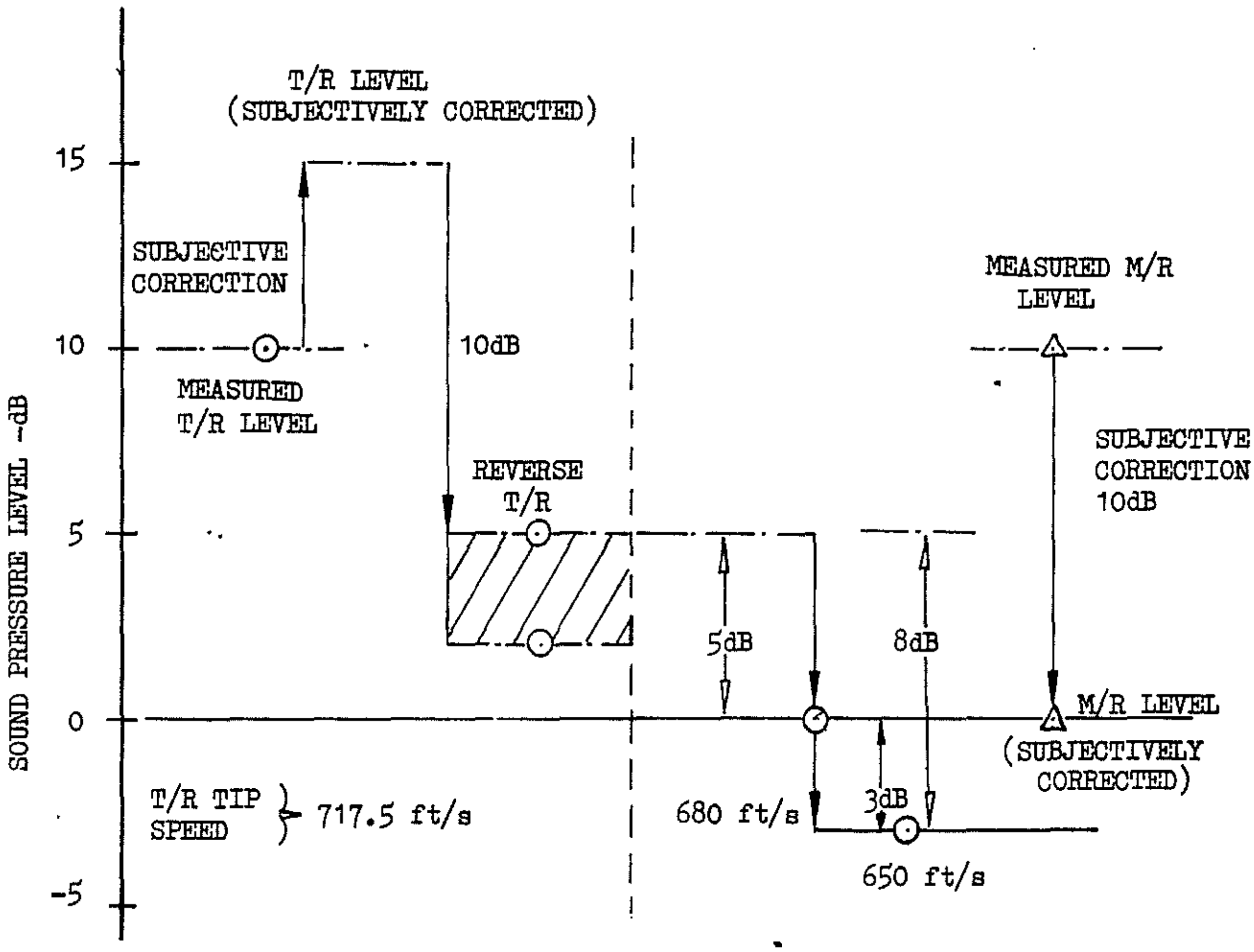

FIGURE 6 DIAGRAMMATIC REPRESENTATION OF NOISE REDUCTION ON APPROACH

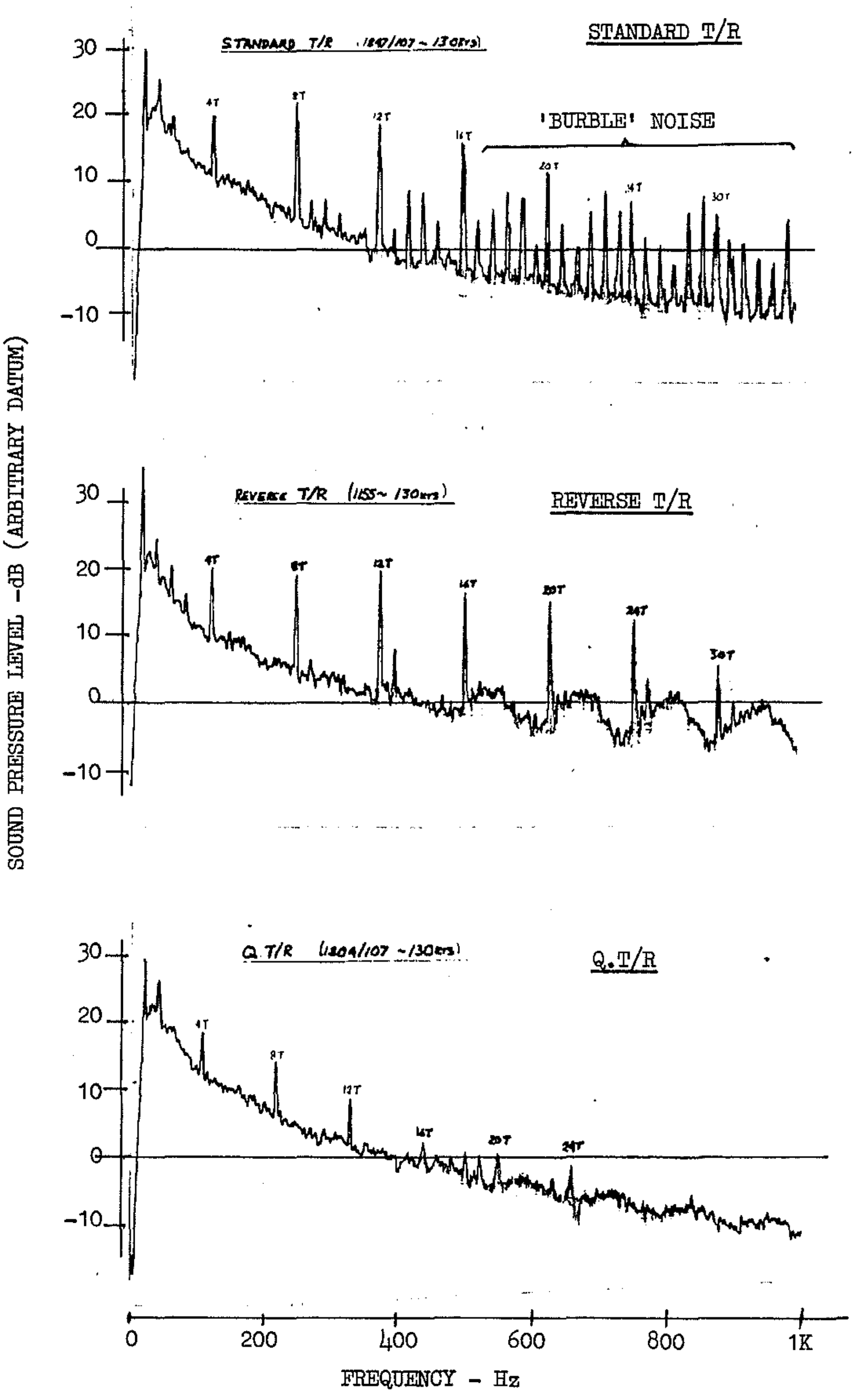

FIGURE 7 NARROWBAND ANALYSIS - TAIL MOUNTED MICROPHONE (FLIGHT SPEED 130 KNOTS)

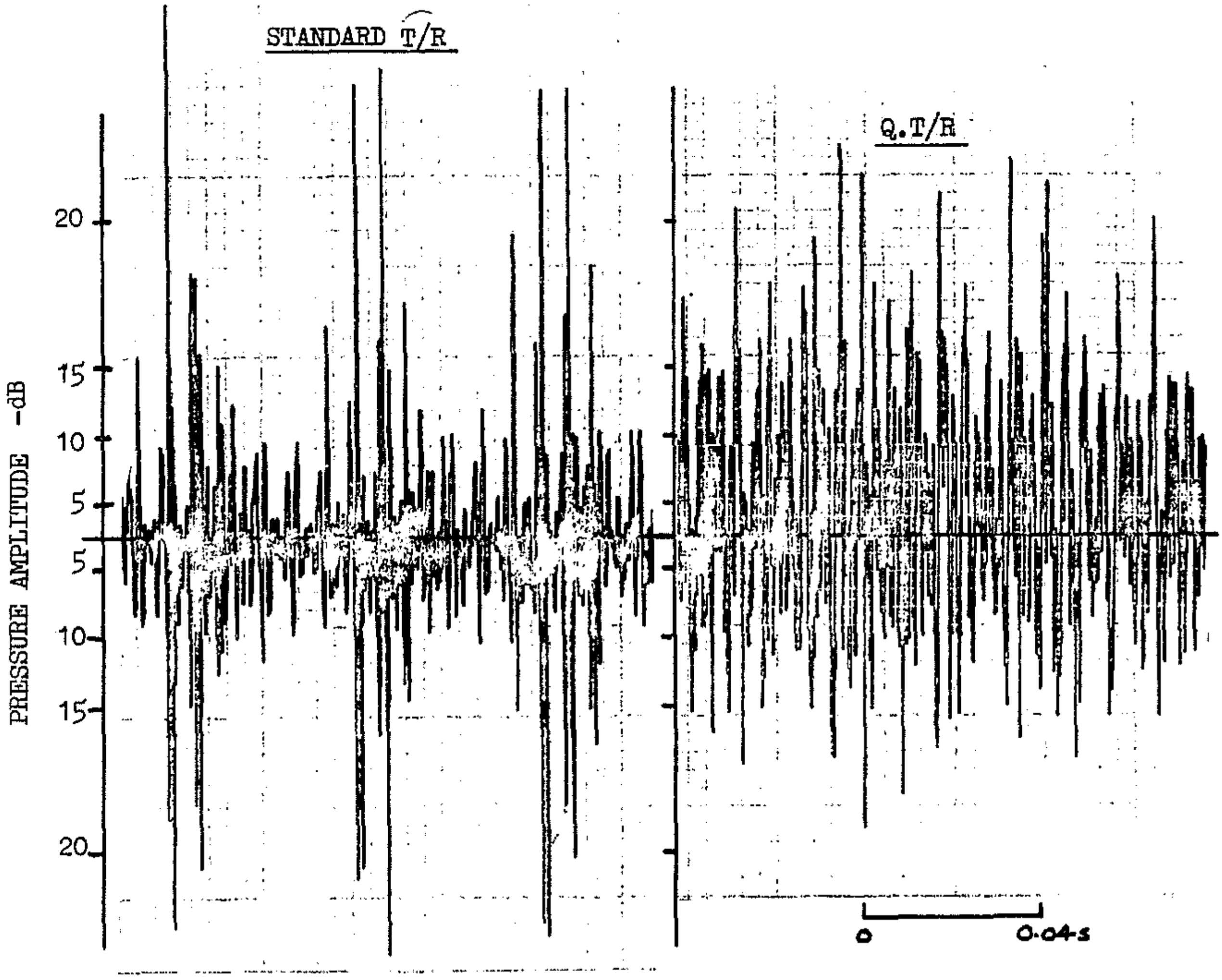

FIGURE 8 OVERHEAD INTERACTION NOISE - PRESSURE/TIME PLOTS

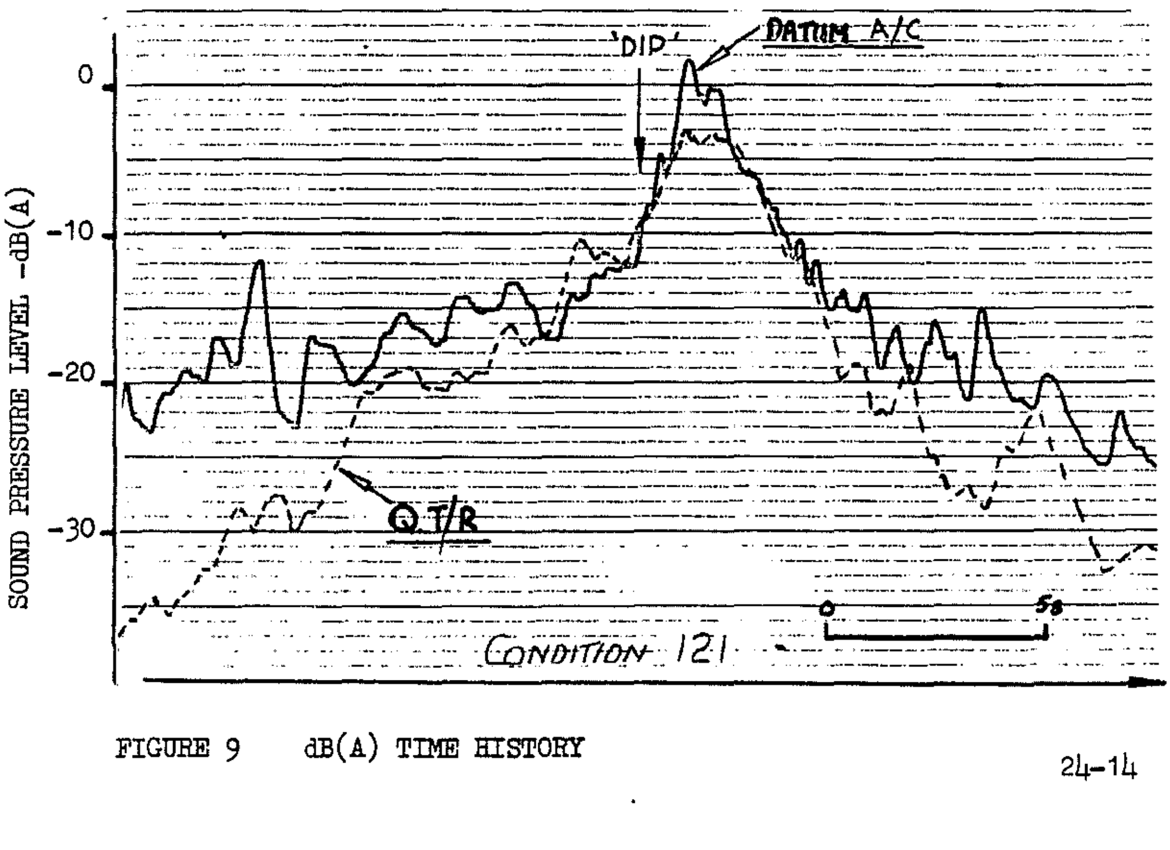

FIGURE 9 dB(A) TIME HISTORY

DATA: 4500 .. ~ 20s BEFORE OVERHEAD: 130 KNOTS

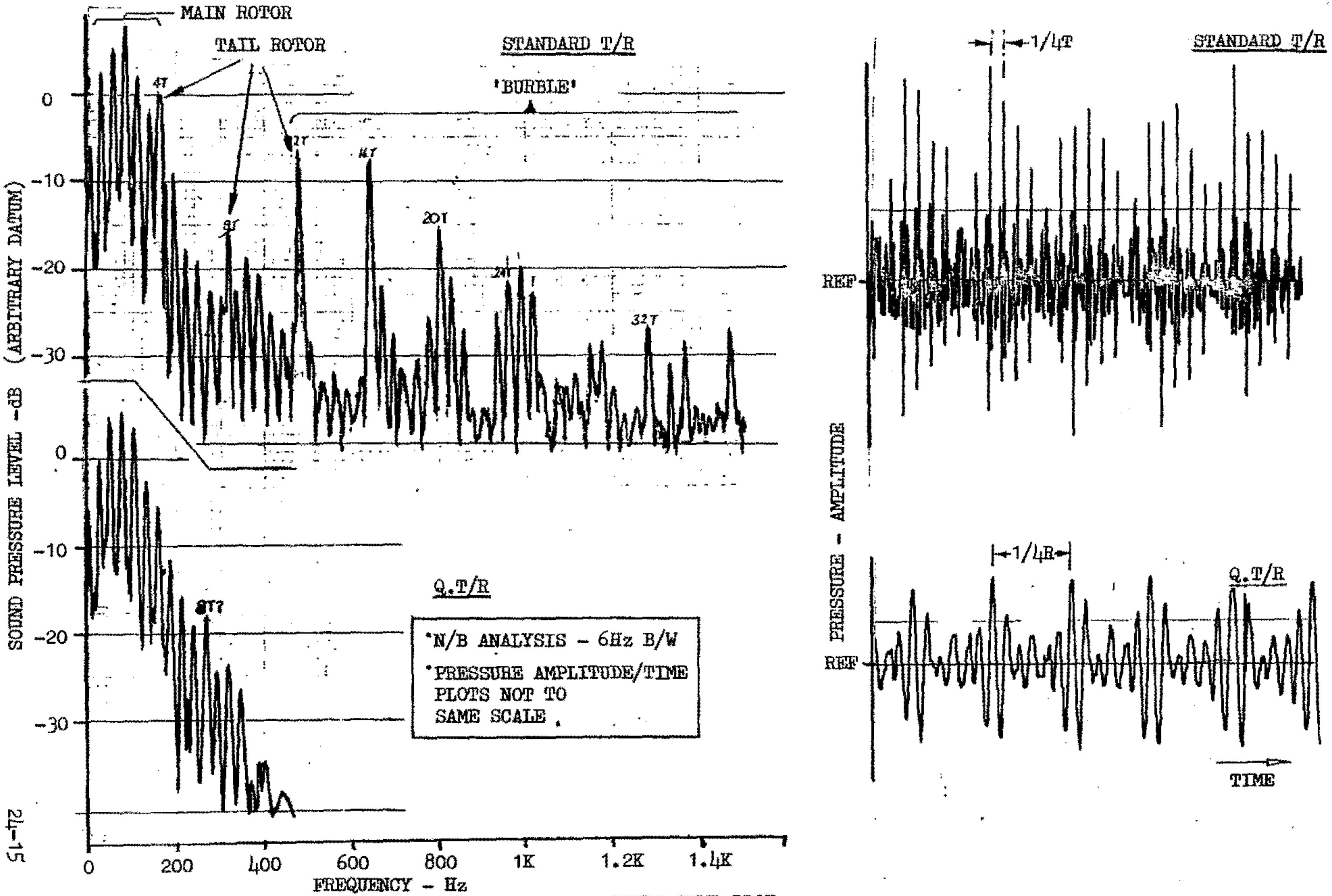

FIGURE 10 NARROWBAND ANALYSES & PRESSURE AMPLITUDE TIME PLOT

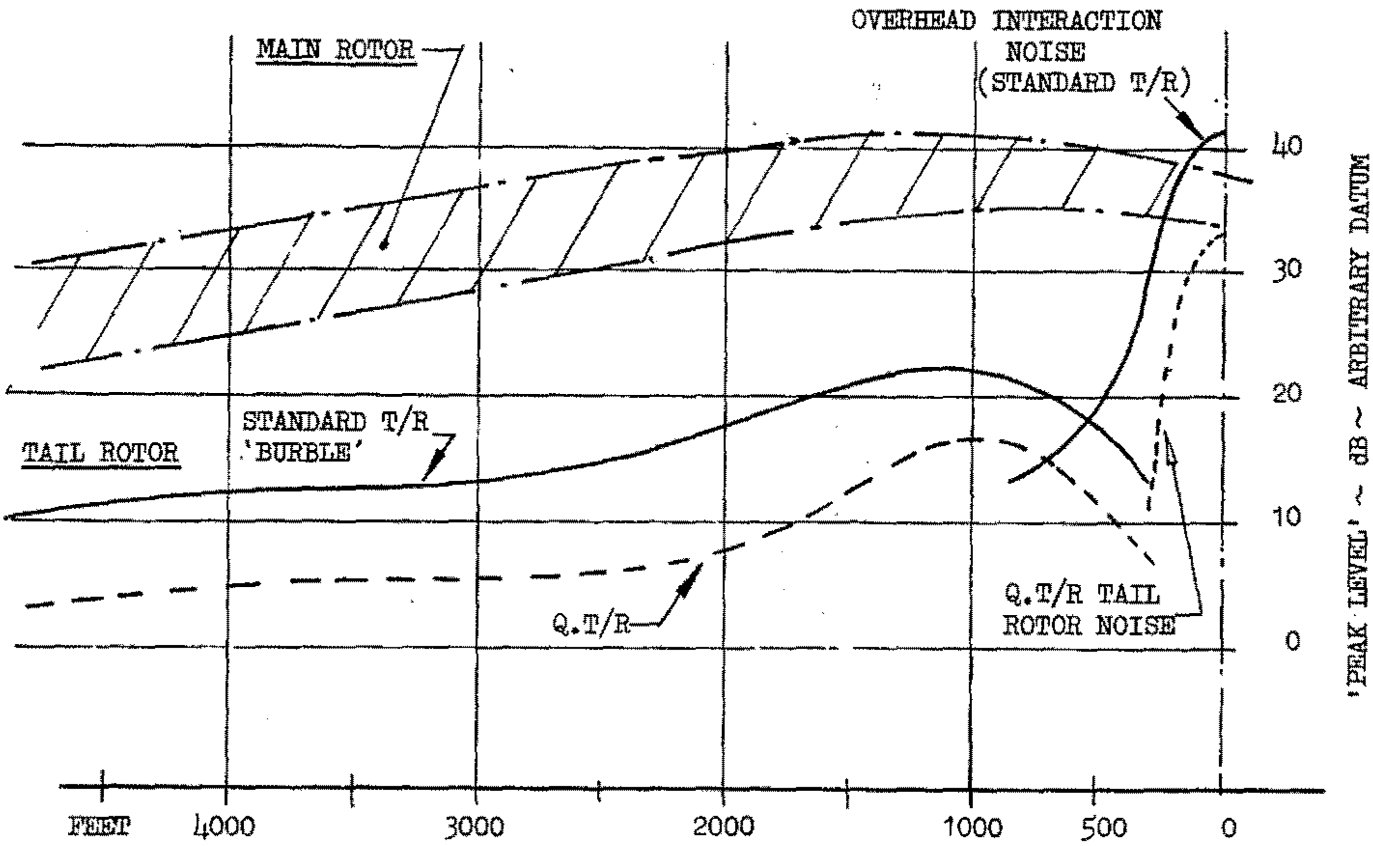

FIGURE 11 VARIATION IN 'PEAK' NOISE LEVELS WITH DISTANCE

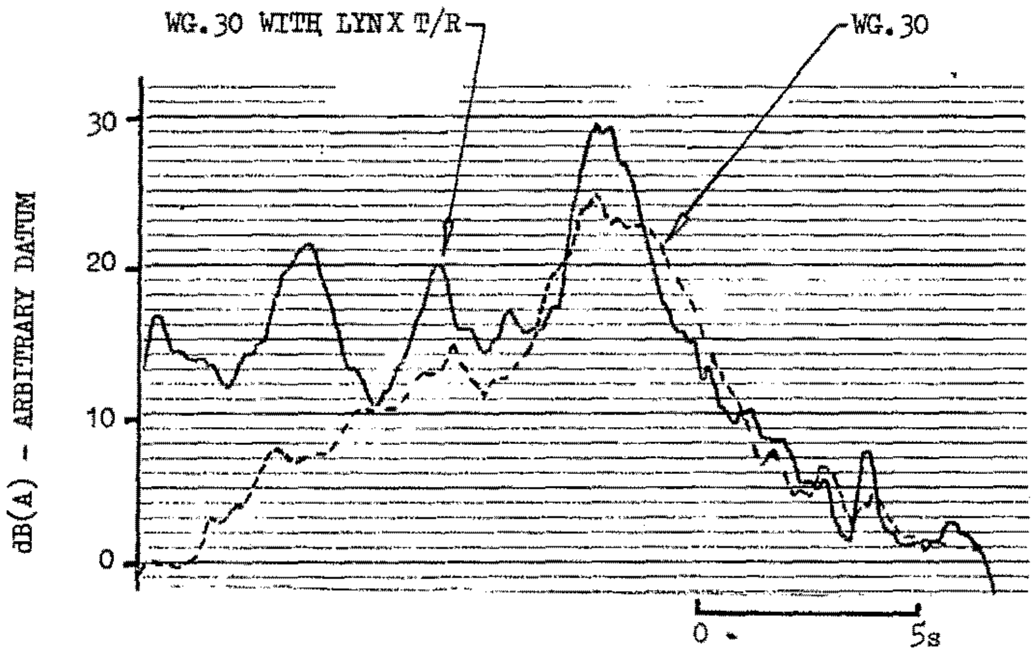

FIGURE 12 dB(A) TIME HISTORY - WG.30