SECOND EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 17

A REVALUATION OF HELICOPTER MAIN ROTOR NOISE

J.W. Leverton, B.J. Southwood
A.C. Pike and M.A. Woodward

Westland Helicopters Limited

Yeovil, Somerset

England

September 20 - 22, 1976

Bückeburg, Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.V.
Postfach 510645, D-5000 Köln, Germany

A REVALUATION OF HELICOPTER MAIN ROTOR NOISE

J.W. Leverton, B.J. Southwood,
A.C. Pike and M.C. Woodward
Westland Helicopters Limited
Yeovil, Somerset.

1. INTRODUCTION

Following an extensive series of tests using a full size (56ft./17.07m diameter) rotor run in an inverted (up-side-down) mode, detailed analysis was performed which enabled the rotational, broadband and overall noise characteristics to be assessed (1, 2). Although there are a number of theoretical and semi-empirical models and formulae available, the data did not appear to follow the trends suggested. This was particularly true in the case of the high speed results which were for all practical purposes independent of the rotor thrust (T) and hence very different from the commonly accepted T^2 dependency. At this time correlation was limited, due to the lack of a suitable model, to simply studying the variation in level with tip speed (V) and thrust (T). This was far from satisfactory since the data could not be collapsed in a meaningful manner. It did, however, appear that although the trends observed could not be explained, a mechanism based on 'profile drag' (which at constant speed is practically independent of the blade angle) or blade thickness could be used to account for the results obtained. It was also found from a brief review of the data published by previous investigators that, in the majority of cases, the measured noise levels followed a similar pattern to those found during this particular study, and that the T^2 relationship proposed resulted simply from the method used to correlate the data. It has also been assumed prior to this study that the rotational noise characteristics were very different from those associated with broadband noise. This was found to be true to some extent when making comparisons with the fundamental and low harmonics of the rotational noise, but the high harmonics and the broadband noise exhibited, as intuitively expected, very similar characteristics. For both the rotational noise and broadband noise the variations in level with operating condition appear to be well defined and repeatable and, although the spread of results over the complete test range was well over 20dB, it was considered that it should be possible to establish a relatively simple relationship to account for the trends observed. This paper discusses the procedures adopted and the empirical relationship obtained. These are equally applicable to the 1, 2 and 4 blade rotors tested, although the data illustrated in this paper has been mainly limited to that derived from a 2 blade S55 rotor, the general characteristics of which are summarised in Table 1.

2. ROTOR NOISE CHARACTERISTICS

The broadband noise and the rotational noise levels as a function of thrust (at constant tip speed) and tip speed (at constant thrust) are illustrated in figures 1 to 4. The broadband noise levels refer to the maximum level (measured with a 20Hz constant bandwidth analyser) in the region below 2kHz and to distinguish from the broadband noise which exists at higher frequencies it is denoted as "low frequency broadband noise". The value quoted has been termed the "Flat SPL" since the hump or peak of broadband energy has a relative "flat" appearance (2). The data shown refers to a microphone (F7 broadband noise/F13 rotational noise) positioned 11.5° above the inverted test rotor, which in conventional notation, is

"11.5° below the rotor disc". There are variations with angle to the rotor disc plane, but the general trends illustrated still apply (1, 2). Similarly, as can be seen in figure 1 for the broadband noise, the characteristics illustrated are equally applicable to the 1, 2 and 4 bladed rotors tested.

It will be observed that the rotational and broadband sources both show, except in the case of the fundamental rotational noise component, very similar trends. At constant speed (figures 1 and 3) the levels tend, as thrust is initially increased, to decrease slightly in level until a point is reached where the levels rise according to T^2. This change over point between the two characteristics is dependent on the actual tip speed and as can be seen from a examination of the thrust/velocity parameters appears to occur at a constant C_{L_T} value*. The velocity dependencies (at constant thrust-figures 2 and 4) are less well defined and clearly a function of the actual thrust level. It will also be noted that the 'best fit' to the data on the log velocity plots shown is a curve indicating that the power of the velocity law is not constant over the test range. It is also obvious from this data that the V^2T^2 relationships often associated with broadband noise and rotational noise are not applicable.

3. CORRELATION OF TEST DATA

The initial correlation, which took the form of establishing the generalised velocity and thrust dependencies illustrated in figures 1 to 4, did not appear to offer a method of collapsing the test data or explaining the trends observed. The constant velocity data (figure 1 and 3) suggested, as mentioned previously, that a C_{L_T} type relationship controlled the change over point on the "dips". Apart from this, the dependence on the value of C_{L_T} appeared to be small. A re-examination of the data was therefore made. This showed that in addition to the "dip" being a function of C_{L_T}, it correlated to some extent to the case where the local pitch angle at the blade tip was zero. A brief review of the data indicated that the blade pitch, or more likely the projected blade thickness-t_p-could explain the S.P.L. relationships obtained. It soon became clear that the latter was more appropriate and the test data was correlated on this basis. This gave a fair collapse of the data, as illustrated for the broadband noise in figure 5, and suggested a t_p^4 relationship. Relative to the general trend, however, the "zero lift" results tended to be 2/4dB low as can be seen on figure 5. Projected thickness (t_p) values were re-calculated for the blade section at 0.95R and 0.9R. Use of the latter improved the overall correlation but the 'zero lift' results were still relatively low.

In practice the "effective thickness", or projected thickness relative to the inflow, would be dependent on the angle of incidence (angle of attack), α, at the section of interest and not soley on the

---

* $C_{L_T} = \frac{C_T}{S} = \frac{T}{\frac{1}{2}V_T^2 \rho \, NcR}$ where C_T = thrust coefficient,
S = rotor solidity,
T = total thrust,
ρ = density,
V_T = tip speed, c = blade chord,
R = rotor radius

pitch angle. It appeared logical, therefore, to correlate the data with a t_p value based on α. This required a knowledge of the angle of attack α in the tip region and presented difficulties since the available momentum theories are unable to predict α accurately for the low thrust values because the tip region goes into negative pitch and the inflow at the outer portion of the disc reverses. Values of α (as a function of cuff pitch) were, however, calculated and in the negative α region the values were adjusted empirically. A typical case is shown in figure 6 for 0.9R. The results from the momentum theory, which over-estimates the value of α in the negative flow region since it assumes uniform inflow, are given by the continuous line and the "adjusted values" used in the calculations by the dashed line. Use of such an approach, combined with the assumption that the noise was dependent on t_p^4, gave a considerable improvement in the correlation and brought the zero and low lift results in line with the other values.

The variation of t_p^4 ($40\log t_p$) is shown in figure 7 as a function of rotor thrust for three rotor speeds. It will be observed that the t_p^4 term exhibits the same characteristics as the broadband noise and rotational noise results presented in figures 1 and 3 respectively. It can also be seen that the "change over point" or dip is a function of the rotor operating parameters and that at the higher thrust values, particularly at the low tip speeds, t_p^4 approximates to T^2.

4. BROADBAND NOISE

Assuming that a t_p^4 relationship applied, the velocity dependency was determined by plotting the "FLAT SPL - 40 log t_p" as a function of tip speed. A typical result is shown in figure 8 and as can be seen the noise followed, as anticipated, a V^6 relationship. Similar results were obtained for two other sets of data; but in one other case a better correlation appeared to be obtained if a V^8 law was considered. A careful examination of this data revealed that the broadband levels were being influenced at the high velocity conditions by rotational noise, which as discussed later, appears to be dependent on V^8 at the higher tip speeds.

Assuming a $V^6 t_p^4$ relationship, the test data was collapsed in the form illustrated in figure 9. In this case the standard deviation is 2dB which is considered extremely good when taking into account the type of experiment and that the test results refer to a thrust range of 0 to 5000lb and a tip speed range of 408ft/sec. to 758ft/sec. (140RPM to 260RPM).

Based on the above a formula for rotor noise of the form:-

$$S.P.L. = 60\log V + 40\log t_p + K$$

has been developed. K obviously contains such parameters as number of blades, rotor radius, blade chord etc but to date there is insufficient data to enable the determination of these parameters. The influence of blade number has been examined to a limited extent and although no precise dependency can be proposed, it is clear that it is significantly greater than the 10logB usually assumed.

5. ROTATIONAL NOISE

The rotational noise components have been examined in a similar manner to the broadband noise. Again the t_p model correlates well with the test data, but the variation or scatter is relatively large. This is, to some extent, expected when studying rotational noise components because of the large variation in level associated with individual harmonics and the known sensitivity of the higher harmonics to minor changes in operating condition/inflow characteristics. The large spread of the test results and the general trends are, however, predicted fairly accurately by the approach adopted.

A typical set of results for the fundamental (1st harmonic), 10th harmonic and 50th harmonic are plotted against the projected thickness (based on α at 0.9R) in figure 10. It can be seen that the 50th and 10th harmonics increase according to $t_p{}^4$. In the case of the fundamental however, the correlation with tip breaks down completely. This is not surprising since the fundamental is essentially controlled by the steady forces on the blade whereas the 10th harmonic (and above) are controlled by fluctuating forces. The corresponding velocity dependency, assuming that $t_p{}^4$ applies, is illustrated in figure 11. These results suggest that the velocity relationship is not a simple "power law" and that the rate of increase with tip speed tends to increase with the actual tip speed. As illustrated on the figures, the departure over the test range from a single power law relationship was, however, small with the mean slope being in the region of V^8. This applied at all angles to the rotor (although the actual laws differed) except in the rotor disc plane where the departure from a single relationship is larger.

6. OVERALL NOISE

The dB.LIN (OASPL) and dBA levels for the rotor follow similar trends to the broadband noise and higher harmonics of the rotational noise. A typical result for the dBA measurements is shown in figure 12. Superimposed on this figure are the results of a prediction method derived from the low frequency broadband noise characteristics and assuming a $V^6 t_p{}^4$ relationship. This method obviously needs further refinement, but it is clear that the generally accepted methods which, with a few exceptions, all have a T^2 term, would not predict the measured variations in noise.

7. DISCUSSION OF RESULTS

The results and in particular the suggestion that the low frequency broadband noise and the higher harmonics of the rotational noise are dependent on $t_p{}^4$ may at first glance appear unrealistic. As already pointed out data published by many other investigators can be re-interpreted in a form similar to that found during this study. It is also of interest to note that Wright in a paper in 1973 (3) suggested that broadband rotor 'self noise' was directly dependent on 1.5α (where α is the angle of attack). After further correlation Wright subsequently modified this term to 2α (4). Wright's method cannot be used for blade pitch angles of zero degrees, but if typical operating conditions are considered it can be shown that 2α is approximately the same as $40\log t_p$. More recently correlation of "in flight" propeller data (5) has shown a dependency on tip thickness and although the dBA data presented cannot be compared directly with t_p^4 relationships, the variations with blade thickness appear to be of a similar order.

8. CONCLUDING REMARKS

The dependence of broadband noise and higher harmonic rotational noise on t_p^4 has been clearly established from the results of this study. This conclusion was reached despite theoretical evidence - particularly in the case of rotational noise - which indicates that the "thickness" term is unimportant.

Broadband noise appears to correlate well with $V^6 t_p^4$ and an empirical method based on such a model gives good agreement with overall rotor noise. At low thrusts t_p^4 varies as V^{+1}, while at high thrust it is approximately $V^{-2.5}$. Thus the velocity dependency (at constant thrust) can vary between V^7 and $V^{3.5}$ depending on the actual thrust value. At intermediate thrust values the relationship can change from V^{-2} to V^{+1} as the tip speed is increased and hence the velocity law (at constant thrust) can vary from V^4 to V^7 as tip speed is increased. This could explain the poor agreement often obtained when correlating data on a velocity basis. These values, of course, refer specifically to the rotor examined, although the general trends are applicable to all twisted helicopter rotors.

The higher harmonic rotational noise levels follow approximately a $V^8 t_p^4$ relationship, but in this case it would appear that the velocity power increases - as suggested by many previous investigations - with increasing tip speed. This obviously needs further investigation, although the relationship established can be used to predict the trends associated with rotational noise on conventional helicopter rotors.

The approach outlined in this paper has been based soley on calculations referred to 0.9R. It could be argued that, rather than use a single point, the assessment should have been made by integrating along the blade according to, in case of broadband noise, $V^6 t_p^4$. Although ideally desirable this is, at this stage, impracticable because of the difficulty of calculating α . Also because the velocity term implies that the major noise is generated near the tip it is most likely that only the outer 10/20% of the blade would have to be considered.

9. ACKNOWLEDGEMENTS

The authors wish to thank colleagues in the Applied Acoustics Department for their help in the preparation of this paper. The investigation was carried out under a Ministry of Defence contract. The views expressed in this paper are, however, those of the authors and do not necessarily represent those of Westland Helicopters Limited.

10. REFERENCES

1. J.W. Leverton, Discrete Frequency Rotor Noise AIAA Paper 75-451 (March 1975)

2. J.W. Leverton, The Noise Characteristics of a Large "Clean" Rotor. AGARD "Aerodynamics of Rotary Wings" Proceedings - September 1972. Also 1973 Journal of Sound and Vibration 27, 357-376.

3. S.E. Wright, Spectral Trends in Rotor Noise Generation. AIAA Paper 73-1033 (October 1973).

4. S.E. Wright, The Acoustic Spectrum of Axial Flow Machines ISVR Technical Report No. 69, April 1975.

5. The Infleunce of Design and Operational Factors on Propeller Aircraft Noise - General Aviation Manufacturers Association Report - May 4th 1976.

TABLE 1

ROTOR BLADE PARAMETERS

Type	-	S55
Number of Blades	-	1, 2 and 4
Radius	-	28ft. - 8.54 metre
Section	-	NACA 0012
Chord	-	1.37 ft. - 0.417 metre
Thickness	-	0.164 ft. - 0.05 metre
Twist	-	8^{o}

TEST CONDITIONS

Tip Speed Range	408ft.sec. - 758 ft/sec.
Rotor RPM Range	140rpm - 260 rpm
Mach Number Range	0.37 - 0.68
Thrust	0lbs - 5000lbs
Microphone distance	250ft. (5 rotor diameters)

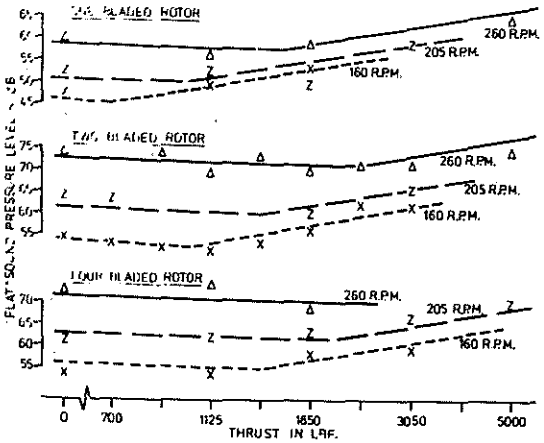

FIG. 1: LOW FREQUENCY BROADBAND NOISE
"Flat" S.P.L. v/s Thrust

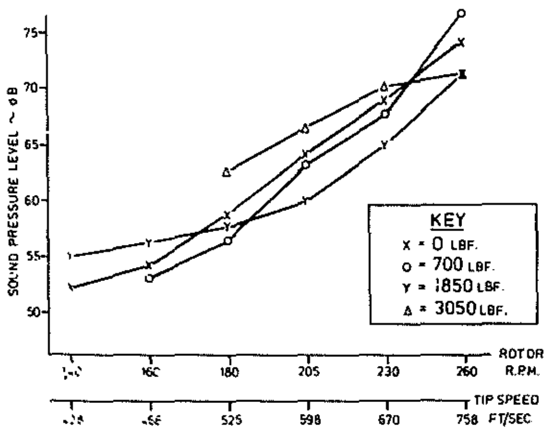

FIG. 2: LOW FREQUENCY BROADBAND NOISE
"Flat" S.P.L. v/s Rotor R.P.M.

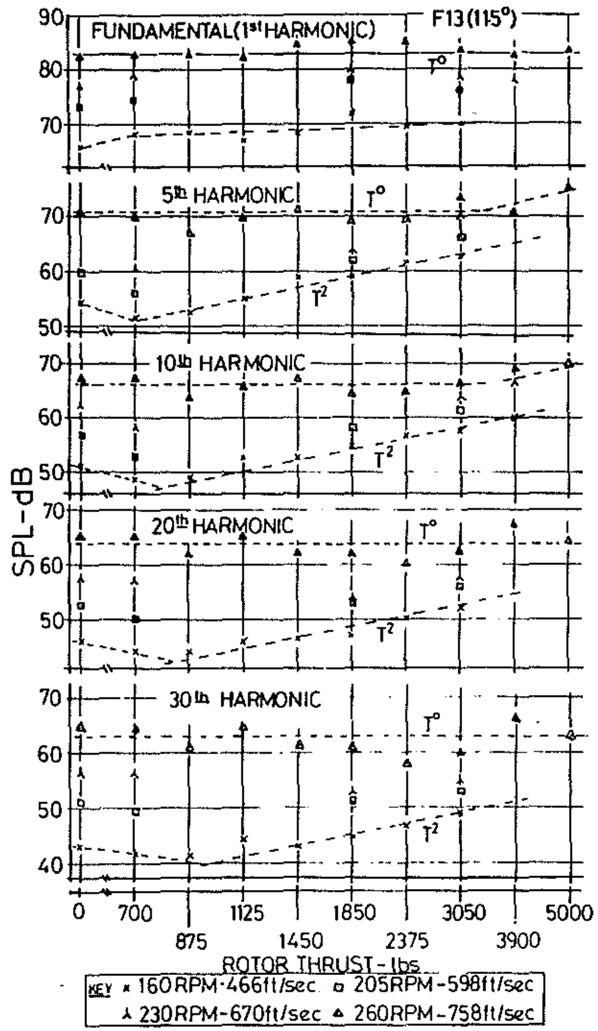

FIG. 3: ROTATIONAL NOISE STUDY
S.P.L. v/s Thrust

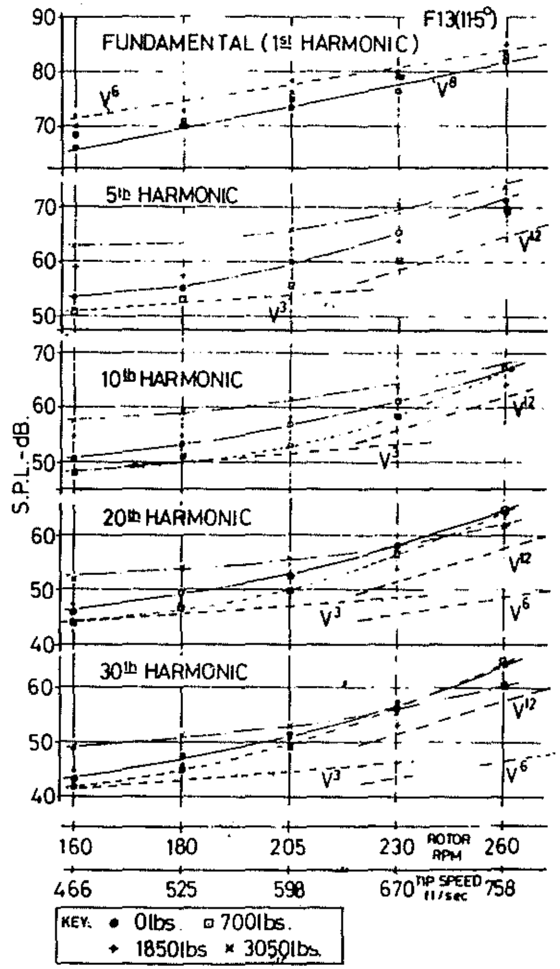

FIG. 4: ROTATIONAL NOISE STUDY
S.P.L. v/s Rotor R.P.M.

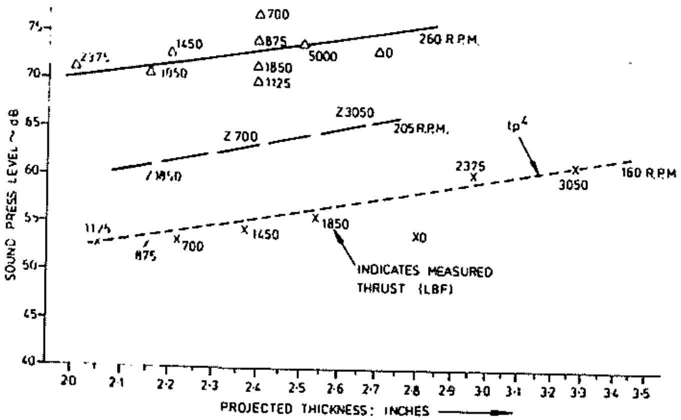

FIG. 5: LOW FREQUENCY BROADBAND NOISE "Flat" S.P.L. v/s Tip Thickness (t_p) based on θ

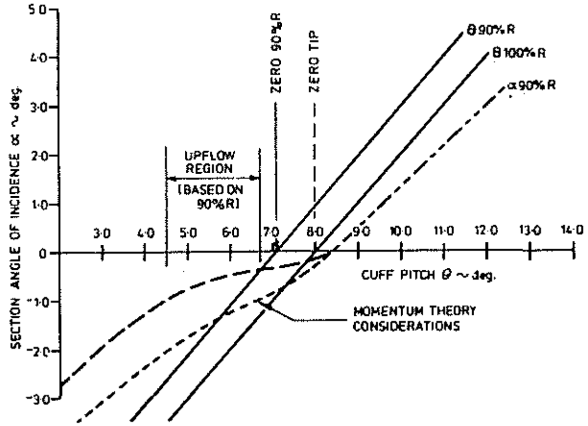

FIG. 6: Angle of Incidence (α) v/s Pitch (θ)

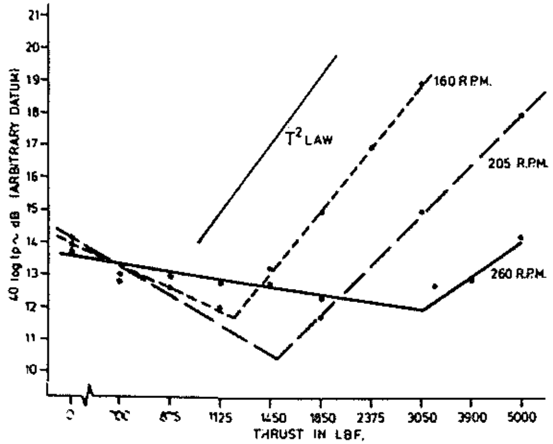

FIG. 7: Variation of $40\log t_p$ with Thrust (t_p based on α at 90%R)

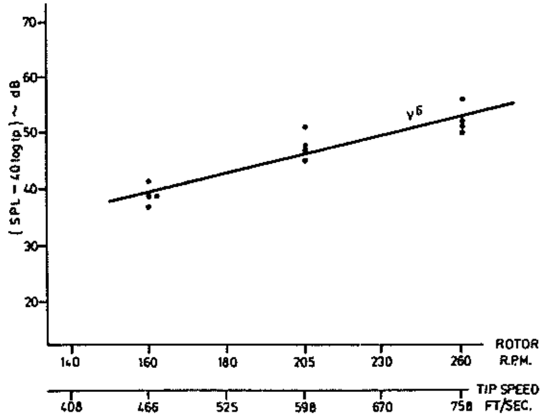

FIG. 8: LOW FREQUENCY BROADBAND NOISE ("Flat" S.P.L. – $40\log t_p$) v/s Rotor R.P.M.

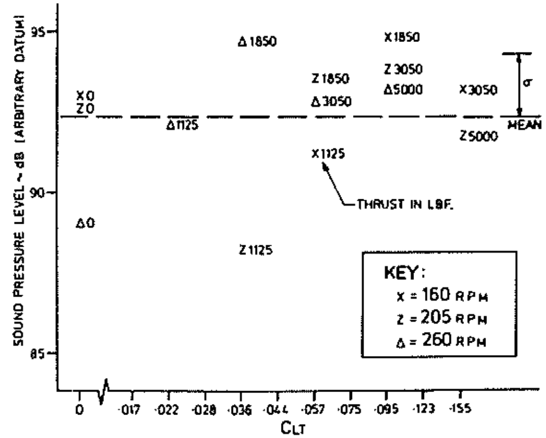

FIG. 9: LOW FREQUENCY BROADBAND NOISE "Flat" S.P.L. – ($60\log V + 40\log t_p$) v/s C_{L_T}

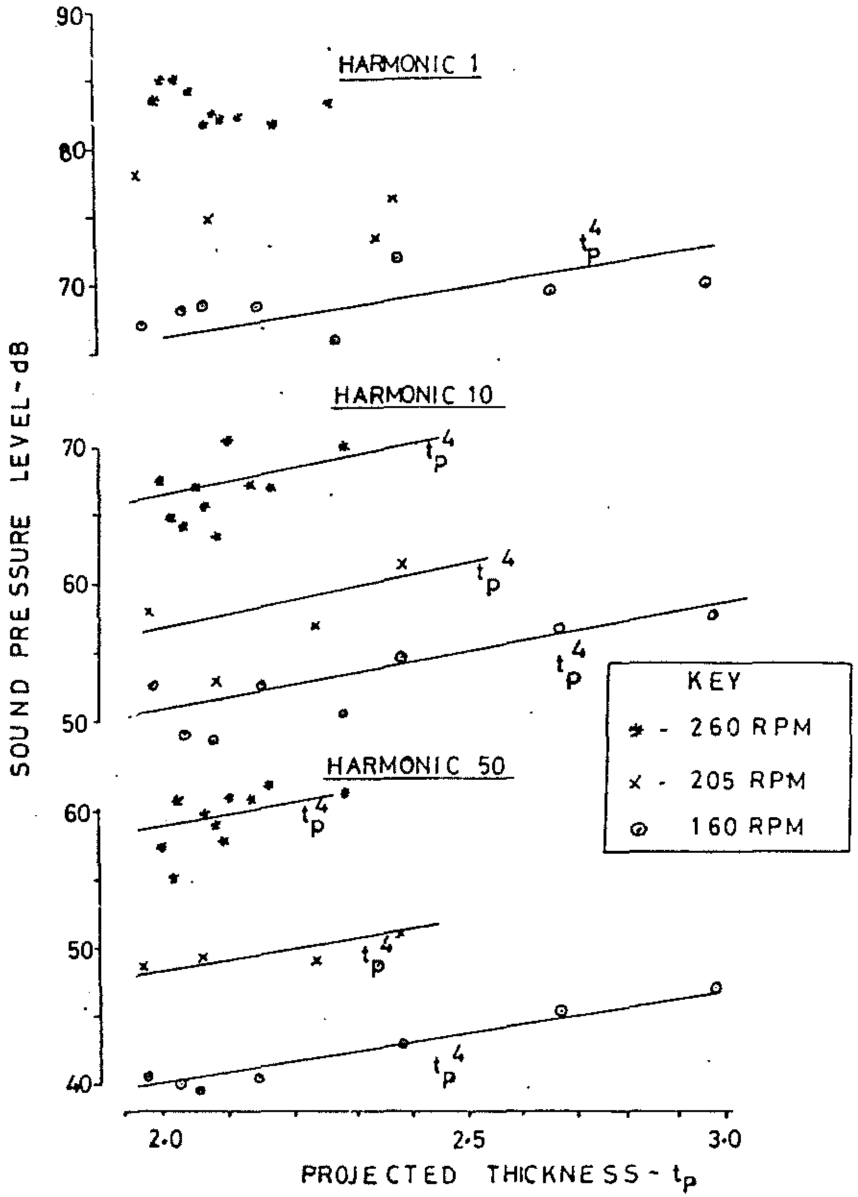

FIG. 10: ROTATIONAL NOISE STUDY
S.P.L. v/s Tip Thickness (t_p) based on
based on α at 90%R

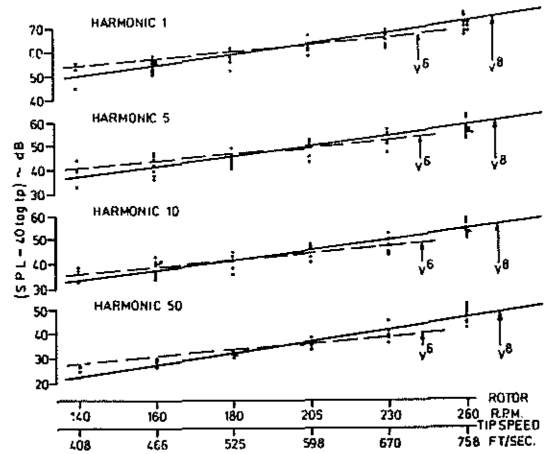

FIG. 11: ROTATIONAL NOISE STUDY
(S.P.L. – $40\log t_p$) v/s
Rotor R.P.M.

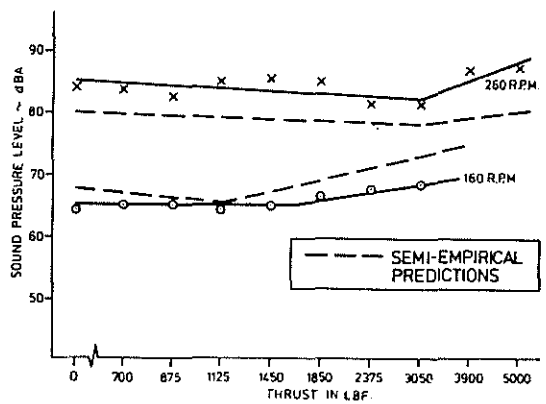

FIG. 12: OVERALL NOISE STUDY
Variation of dBA Level
with Thrust.