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STATISTICAL EPNL ANALYSIS OF HELICOPTERS (S.E.A.H.) AS NOISE PREDICTION TOOL

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STATISTICAL EPNL ANALYSIS OF HELICOPTERS (S.E.A.H.) AS NOISE PREDICTION TOOL

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Abstract

A method for the EPNL calculation in the three certification conditions take-off, approach and flyover as prescribed in ICAO Annex 16 and other noise certification rules is presented. The method is based on the statistical analysis of the existing helicopter caracteristics and the noise certification EPNL data base. Finally, a correlation between EPNL and other metrics such as SEL and dBA is provided.

Notation

adv	$\left(\frac{0.9V_H}{\Omega R}\right)$
B	Number of blades
BRC	Best rate of climb, m/s
c	Chord, m
C_T	Thrust coefficient
C_W	Loading coefficient
dB(A)	A-weighted sound level
EPNL	Effective Perceived Noise Level (EPNdB)
R	Rotor radius, m
S	Blade area, m^2
SEL	Sound Exposure Level (dB)
SHP	Shaft Horse Power
V_H	Maximum speed in flyover at power not exceeding maximum Continuous power, m/s
V_T	Tip speed, m/s
Vy	Speed for best rate of climb, m/s
W	Helicopter gross weight, N

σ	rotor solidity
Ω	angular velocity of rotor, (rad/s)
$(EPNL)_{FLYOVER}$	EPNL for flyover condition

Subscripts

m	main rotor
t	tail rotor

1. Introduction

Actually, sophisticated prediction codes utilizing the Lighthill acoustic analogy as expressed by the Ffowcs Williams-Hawkings equation or Goldstein's version and the Kirchhoff approach are available. But from the formulation through the computational procedures to the final prediction of the EPNL values of a new or derived helicopter many problems have to be solved. First of all at the beginning of a new project not all the information that a complicated tool needs is available and when it is available an aerodynamic calculation needs to be performed which involves a lot of time as a big amount of data must be created as input for the aeroacoustic code. The code must be a comprehensive tool for the prediction of total helicopter system noise which means that it has to take into account the rotational and impulsive noise but also the broadband noise, and flight simulation has to be performed for all the certification conditions. For the above reasons sometimes very simple formulations may be necessary useful as preliminary design tools. The term "simple" in this case must be interpreted in terms of number and type of parameters which normally are known at the beginning of a project. The data base used is composed of ICAO Data Base I (1977) and Data Base II (1985), the Rainbow report (1986) [2] and other data which have been collected from relevant acoustics literature . The data consist of the EPNL values for the three certification conditions, flyover, approach and take-off, the main features of both rotors as blade diameter, chord, tip speed, number of blades and other more general characteristics of the aircraft like the gross weight, test speeds, the best rate of climb (BRC) and shaft horsepower (SHP). These data then have been correlated in a suitable way and statistically processed, giving as final result, three equations one for each certification condition. Sometimes commonly used alternative scales for the noise levels are SEL (Sound Exposure Level) and dB(A). Again statistically, the correlation between EPNL/SEL and SEL/dB(A) have been determined.

2. Certification rules

The noise certification standards for helicopters were introduced in 1981 at the sixth meeting of the Committee on Aircraft Noise (CAN/6) and are described in Chapter 8 and Appendix 4 of [1] . For the conditions described in Chapter 8, the standard establish that the maximum allowable noise levels are a function of the aircraft weight and require that the noise evaluation measure be the EPNL (Effective Perceived Noise Level). EPNL was chosen in order to respond more closely to the sensitivity of the human ear to aircraft noise.The reference noise measurement points on the ground are: one along the flight path and two other points disposed at 150 meters symmetrically to the first on both sides of the flight path. Three are also the test procedures which the helicopter must be certificated: flyover (Figure 1), take-off (Figure 2) and landing (Figure 3).

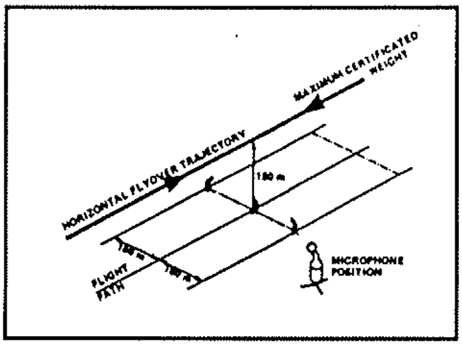


Figure 1 Flyover trajectory

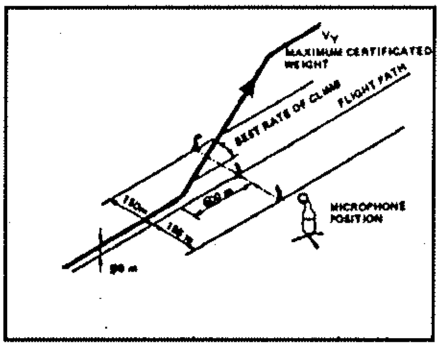


Figure 2 Take-off trajectory

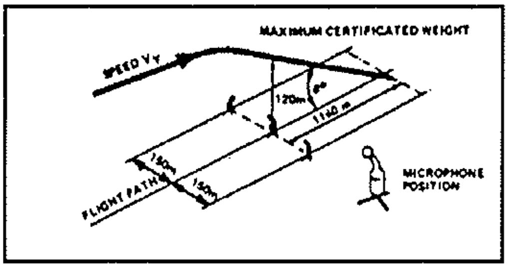


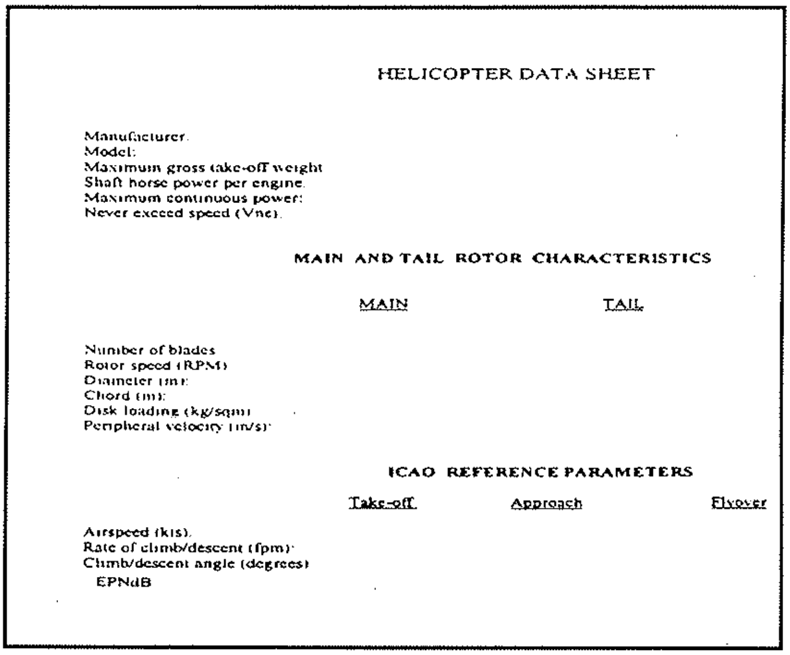
Figure 3 Landing trajectory

The as measured noise levels are successively analyzed and corrected for deviations from the reference flight path as shown in figure 1 to 3, and from the reference meteorological conditions temperature (25ºC), humidity (70%), atmospheric pressure (1013.25 mb) and zero wind. Other corrections are related to the reference ground speed and the tip Mach number the so called source noise correction for the flyover.

Three numbers, one for each flight condition, are the EPNL values certificated. These adjusted final results of noise levels are submitted to the certification authority to demonstrate the compliance with the noise rule.

3. Data statistical analysis

A considerable amount of work is to fill up a form as in figure 4, one for each type or version of helicopter, with all the data which is the basis of the statistical analysis work. The criterion used in the statistical analysis is based on previous experience of the effect of those parameters that are more significant on helicopter noise.



HELICOPTER DATA SHEET

Manufacturer:
Model:
Maximum gross take-off weight
Shaft horse power per engine
Maximum continuous power:
Never exceed speed (Vne)

MAIN AND TAIL ROTOR CHARACTERISTICS

	MAIN	TAIL
Number of blades		
Rotor speed (RPM)		
Diameter (m):		
Chord (m):		
Disk loading (kg/sqm)		
Peripheral velocity (m/s):		

ICAO REFERENCE PARAMETERS

	Take-off	Approach	Flyover
Airspeed (kts)			
Rate of climb/descent (fpm):			
Climb/descent angle (degrees)			
EPNdB			

Figure 4 Helicopter data sheet

The outcome of this analysis is a "loading term" $\left(\dfrac{W}{BcRV_T^2}\right)$ a parameter related to $\left(\dfrac{C_T}{\sigma}\right)$ assuming that $C_T = C_W$, the blade area S=(Rc) and the broadband contribution is included in the parameter $(V_T^6 S)$ for both main and tail rotors.Other parameters are taken from experience; it is infact, reasonable that the engine power (SHP) has for certain, an influence on the noise level during a take-off more than during a flyover.

4. S.E.A.H. equations

Using an interactive statistics code for microcomputers which permits performing unweighted least squares linear regressions given the coefficients of an equation to link the EPNL parameter to the helicopter parameters, with the calculated coefficients, the mean square error and standard deviation. The resulting equations for the three conditions are shown below.

Take-off

$$\mathrm{EPNL} = 7.9\log\left(\frac{W}{BcRV_T^2}\right) + 2.8\log\left(V_T^6 S\right)_m - 5.4\log\left(V_T^6 S\right)_t - 3.4\log(SHP) + 10.8\log(S)_m + 3.8\log(S)_t + 50.5\log(V_T)_t - 1.4\log(BRC) + 17.5 \tag{1a}$$

$$\mathrm{EPNL} = 8.3\log\left(\frac{W}{BcRV_T^2}\right) + 2.8\log\left(V_T^6 S\right)_m - 5.7\log\left(V_T^6 S\right)_t + 11.0\log(S)_m + 4.1\log(S)_t + 52.3\log(V_T)_t - 3.7\log(SHP) + 16.5 \tag{1b}$$

Approach

$$\mathrm{EPNL} = 8.1\log\left(\frac{W}{BcRV_T^2}\right) + 9.7\log\left(V_T^6 S\right)_m + \log\left(V_T^6\right)_t - 0.2\log(S)_t - 58.7 \tag{2}$$

Flyover

$$\mathrm{EPNL} = 13.4\log\left(\frac{W}{BcRV_T^2}\right) + 6.9\log\left(V_T^6 S\right)_m + 0.6\log\left(V_T^6 S\right)_t + 6.4\log(S)_m - 5.4\log(S)_t + 5.2\log(adv) - 11.8 \tag{3a}$$

$$\mathrm{EPNL} = 13.6\log\left(\frac{W}{BcRV_T^2}\right) + 5.7\log\left(V_T^6 S\right)_m + 0.4\log\left(V_T^6 S\right)_t + 8.2\log(S)_m - 5.2\log(S)_t + 4.9 \tag{3b}$$

In two flight conditions, take-off and flyover, one more equation is presented (1b) and (3b) which permit to calculate the EPNL without a parameter but guaranted that the obtained result is about ± 1dB the (1a) or (3a) EPNL value.

5. S.E.A.H. other metrics

The final results required by ICAO Annex 16 or other national rules must be expressed in EPNL but often it is necessary to have the noise level in other metrics for instance those used in environmental rules dB(A) and SEL. A relationship between EPNL and SEL/dB(A) has been developed using statistical analysis. Again, some relations have been derived between the three metrics.
Analyzing the first data was noticed that the difference between dB(A) or SEL and EPNL is not constant but it increases as the weight or/and the test speed of the helicopter. This leads to correlate the metrics by means of the parameters in order to obtain a better regression. Thus, using these parameters a better regression is obtained leading to a better correlation between the metrics involved. Again, in order to have the possibility to correlate two metrics when only one parameter is known two equations are given as seen previously.

Take-off

$$SEL = 1.15 EPNL - 5.0 \log(W) + 16.5 \log(V_y) - 19 \qquad (4a)$$

$$SEL = 1.06 EPNL - 2.3 \log(W) + 1.8 \qquad (4b)$$

Approach

$$SEL = 1.04 EPNL - 2.9 \log(W) + 4.9 \log(V_y) - 1.8 \qquad (5a)$$

$$SEL = 1.01 EPNL - 2.15 \log(W) + 3.4 \qquad (5b)$$

Flyover

$$SEL = 0.88EPNL - 2.1\log(W) + 25.7\log(0.9V_H) - 30.1 \quad (6a)$$

$$SEL = 0.91EPNL - 1.4\log(W) + 11.3 \quad (6b)$$

Instead of correlating the dB(A) unit straight with the EPNdB, since the best regression which is possible to obtain between the two metrics is established through SEL and then using the equations 4 to 6, it is possible to obtain the relationship required.

Take-off

$$dB(A) = 1.2SEL - 0.88\log(W) + 15.3\log(V_y) - 45.2 \quad (7a)$$

$$dB(A) = 1.16SEL + 1.3\log(W) - 28.0 \quad (7b)$$

Approach

$$dB(A) = 1.27SEL - 3.02\log(W) + 24.4\log(V_y) - 57.1 \quad (8a)$$

$$dB(A) = 1.22SEL + 0.45\log(W) - 31.1 \quad (8b)$$

Flyover

$$dB(A) = 0.92SEL - 0.5\log(W) + 23.8\log(0.9V_H) - 42.4 \quad (9a)$$

$$dB(A) = 0.97SEL + 0.1\log(W) - 5.9 \quad (9b)$$

The difference between equations (a) and (b) has been evaluated in ± 1.5dB or ± 1dB(A).

6. Flyover vs Take-off and Approach

Sometimes it is useful to start from a flyover EPNL value, predicted or experimental, to evaluate the EPNL values in the other two ICAO conditions take-off and approach. Infact, it is easy and less expensive to perform a flyover test compared with the other two conditions.

Take-off

$$EPNL = 0.44(EPNL)_{FLYOVER} + 3.3\log(V_T^6 S)_m + 3.3\log(SHP) - 0.3\log(S)_t - 7.5 \quad (10a)$$

$$EPNL = 0.52(EPNL)_{FLYOVER} + 5.6\log(V_T^6 S)_m - 39.4 \quad (10b)$$

$$EPNL = 1.1(EPNL)_{FLYOVER} + 1.11\log\left(\frac{W}{BcRV_T^2}\right) - 5.8 \quad (10c)$$

$$EPNL = 1.05(EPNL)_{FLYOVER} - 3.5 \quad (10d)$$

Approach

$$EPNL = 0.6(EPNL)_{FLYOVER} + 3.0\log(V_T^6 S)_m + 4.0\log(SHP) - 4.0\log(S)_m + 1.6\log(S)_t - 14.1 \quad (11a)$$

$$EPNL = 0.66(EPNL)_{FLYOVER} + 4.76\log(V_T^6 S)_m - 37.2 \quad (11b)$$

$$EPNL = 1.1(EPNL)_{FLYOVER} + 3.2\log\left(\frac{W}{BcRV_T^2}\right) - 0.3 \quad (11c)$$

$$EPNL = 1.1(EPNL)_{FLYOVER} - 6.7 \quad (11d)$$

The error should be ± 2EPNdB for equations (a) which are given by the best regression of data analysis while the (d) equations, having a worst regression, could be ± 4EPNdB worse.

7. Comparisons

Even if the S.E.A.H. equations 1 to 9 have a good regression , it is evident that those values are referred to the helicopters included in the data base. So, in order to have a true evaluation of the equation's "goodness" it must to predict the noise levels of a new or a new version of a helicopter not included in the used data base. Using the equations described above it is possible with a pocket calculator to evaluate the noise level of a helicopter. It is also possible to perform with a Personal Computer and a short program to introduce the single helicopter parameters and then the program itself performs all the calculations giving a hard copy of inputs and relative output.The two examples shown here are the A109 C [3] Table 1 and A109 K2 [4] version of A109 family Table 2 .

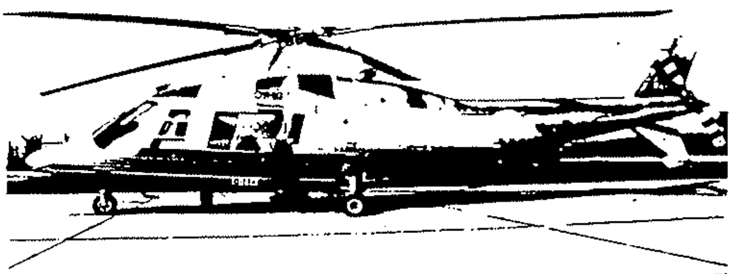


Figure 5 Agusta 109C

Tables 1 and 2 show the predicted results obtained from the S.E.A.H. equations. It is also possible to start from a measured EPNL value to calculate the SEL and/or dB(A) values.

Condition	EPNL		SEL		dB(A)	
	P	M	P	M	P	M
Take-off	91.6	92.4	88.8	88.6	80.3	80.0
Approach	91.1	90.1	87.4	88.4	76.9	77.4
Flyover	89.3	88.8	86.5	87.5	78.7	77.4

Table 1 A109 C predicted (P) vs measured (M) EPNL values

The previous EPNL have been obtained using the (a) equations. If the (b) equations are used:

Take-off (1b) 90.8

Flyover (3b) 89.3

In this case the (b) equations still give good results and, in this particular case, for flyover the EPNL is equal to that obtained with the equation (3a).

Another example as regard to equations 10 and 11 to predict the EPNL value in the take-off and approach conditions when the predicted or measured flyover EPNL is known.

From equation (10a) take-off EPNL=90.5 (-1.9 under pred.)

From equation (11a) approach EPNL=91.6 (+1.5 over pred.)

The next example is referred to the Agusta 109K2 a high performance multi-purpose helicopter which have the same main and tail rotors of A109 C but the following operational parameters have been changed:

- Weight +5%
- Engine power +14%
- Vy +8%
- BRC +23%
- V_H -3%

The reduced cruise speed of A109K2 is due to higher drag due to the fixed landing gear.

Condition	EPNL		SEL		dB(A)	
	P	M	P	M	P	M
Take-off	90.5	91.7	88.0	87.5	79.8	80.4
Approach	90.8	91.1	87.2	87.7	77.4	78.9
Flyover	89.3	89.1	85.7	86.6	77.3	78.4

Table 2 A109 K2 predicted (P) vs measured (M) EPNL values

From equation (10a) take-off EPNL=90.9 (-0.8 under pred.)

From equation (11a) approach EPNL=92.7 (+1.6 over pred.)

8. Tail rotor configurations

The previous equations have been obtained from a data base of helicopters with a conventional tail rotor. The tail rotor in certain flight conditions contribute largely to the overall noise level generated by a helicopter as demonstrated by experimental works done in the early 1970's. In the case of a different type of tail rotor such as fenestron/fan-in-fin tail rotor or Notar the equations could not be still valid because of the different mechanisms of the tail rotor noise. Actually, it is not possible with just one or restricted number of "non conventional tail rotor", to perform a statistical analysis.

Fenestron

The Fenestron rotor consist of a fan housed in a shroud which have the dimensions of the same order of the acoustic wave lenght emitted and act as difraction obstruction reducing the noise radiated in the far field [5].

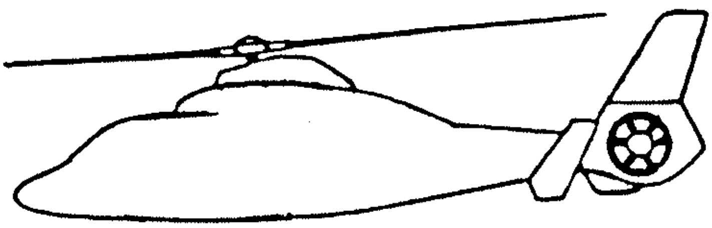


Figure 6 Helicopter using a fenestron fan-in-fin tail rotor

The sound generation of a Fenestron rotor is similar to that of a stage of axial-flow machine and Huebner suggested that is a dipole the important source of fan sound. Chanaud has shown, by his measurements, that unenclosed impellers generate fundamentally dipole sound but the fan case can alter the sound radiation from V^6 to V^5 [6]. During a flyover the most of totality of the anti-couple force in a helicopter equipped of this tail rotor system, is given by the large vertical fin and the noise generated by the fenestron is mainly due to the perturbed aerodynamic environment which generates a broadband noise. For the fenestron rotor the equations are still valid but for the flyover condition the predicted value are close to the measured if the "broadband" term $\left(V^5S\right)_t$ is used instead of $\left(V^6S\right)_t$. Two evaluations have been done on two different Aerospatiale helicopters respectively SA365N Dauphin 2 and SA341G.

The results are shown on tables 3 and 4.

Condition	EPNL	
	P	M
Take-off	93.0	92.7
Approach	93.0	94.7
Flyover	91.1	91.0

Table3 SA365N Dauphin 2

Condition	EPNL	
	P	M
Take-off	89.8	89.5
Approach	88.1	89.1
Flyover	86.8	86.1

Table 4 SA341G

It is interesting to notice that in the flyover condition, the application of equations (3a) or (3b) over estimates the EPNL value and only applying the term $\left(V^5S\right)_t$ as predicted by the theory, the result is close to the measured EPNL value.

No Tail Rotor (NOTAR)

The MD 500N it is actually the only helicopter equipped with a Notar anti-torque system and obviously it is not possible to perform a statistical analysis but thinking to the anti-torque system some consideration can be done. The most important noise source of the Notar system is the fan with a variable pitch, mounted inside the helicopter which provides air to the circulation control tail boom and the direct jet thruster.

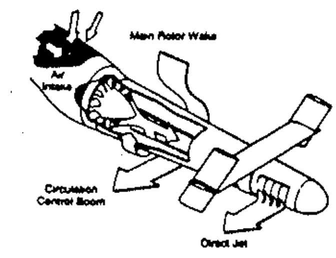


Figure 7 NOTAR antitorque system (from reference[7])

Three consequences on the noise attenuation are: first of all the higher frequencies of fan harmonics have the advantage of an increase of the atmospheric attenuation;

second, this anti-torque system eliminates the noise generated by the main/tail rotor interactions. Reduction of stochastic and rotational noise could be effected also by boundary layer removal from the wall of the duct. Sharland concluded in [8] that in axial flow fans the noise is dominantly of broadband-dipole type and that originates from lift fluctuations on the blades. But when a rotor generates sound in a duct the sound radiated depends on the coupling of the rotating dipole modes and the acoustic modes of the duct and this effect which is very complicated to predict, can be powerful.

For air duct elements Bullock [9] found that the overall sound pressure level generated by air flow depends on the total cross-sectional area of jet efflux and of a parameter G function of the duct end shape and the air flow speed $V^{2.4}$ in this duct section. Considering that at fast forward speeds the vertical fins provides a significant portion of the anti-torque force needed while, during a translation flight at low speeds the direct jet supplies the major portion of the anti-torque force, the considerations written before modify the "broadband tail term" $\left(V^6 S\right)_t$ to $\left(V^{2.5} S\right)_t$ again for only the flyover condition where the jet efflux is not predominant,and the MD500N shows a significant noise reduction. The result is shown in Table 5 compared to the certification EPNL values [10].

Condition	EPNL	
	P	M
Take-off	86.3	85.4
Approach	86.6	87.9
Flyover	80.4	80.2

Table 5 MD500N

Another interesting example of the use of S.E.A.H. equations is a comparison between two rotorcraft Hughes 500 D/E and MD 500ER which are similar except the tail rotor. The number of blades decrease from 4 to 2, the blade area decreases but the tip speed increases. The (1a) gives the indication that the take-off EPNL increases of 2.8 EPNdB while the measured value increase of 3.5 EPNdB.

A complete regression using the term $\left(V^5 S\right)_t$ for fenestron or $\left(V^{2.5} S\right)_t$ for NOTAR has been done but generally, no good results have been obtained as the equations here described.

9. Design parameters

The effect of two design parameters when the S.E.A.H. equations are used, can be shown graphically in order to see the trend of each parameter and its influence on the three flight conditions.

Taken as a reference tip speed 200 m/s, the result in figure 8 shown that the main rotor tip speed have more influence in the approach than the take-off or flyover condition. Examining the equation (2) which is the best regression of approach data , it is clear that the EPNL is determined by the term $(V_T^6 S)$ which is related to the main and tail rotors broadband noise and certainly BVI is a very important noise source in this flight condition.

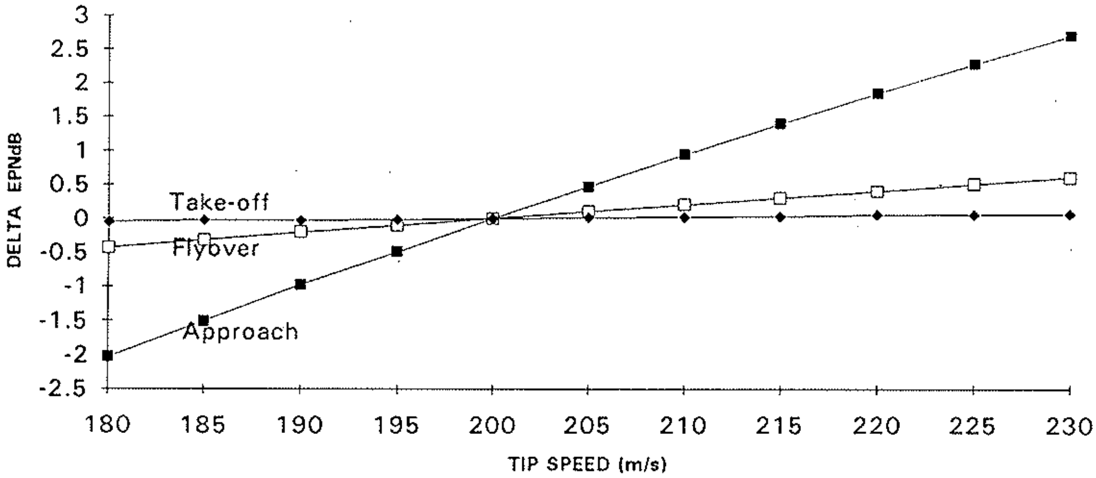


Figure 8 Effect of tip speed using S.E.A.H.

Figure 9 shows the EPNL sensitivity to the helicopter weight and where the flyover condition is the most sensitive to this design parameter.

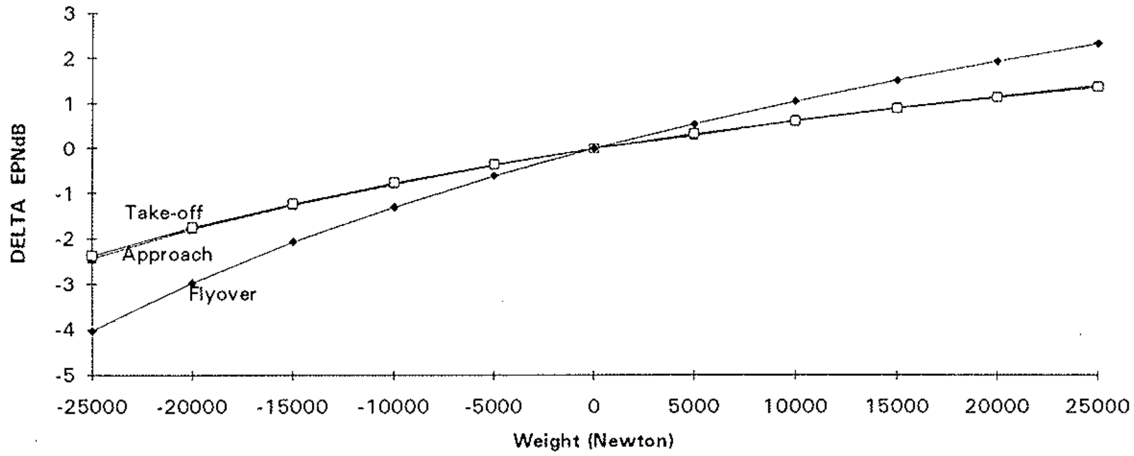


Figure 9 Effect of helicopter weight using S.E.A.H.

10. Conclusions

The theories to predict noise are complicated if all the effects are included and normally gross simplifications are necessary to obtain solutions.

The purpose of this paper is to provide equations which are helpful in a preliminary design study and there is a need of a rapid evaluation of the final EPNL value . The equations are valid only to predict the EPNL values for the certification conditions take-off, flyover and landing with 6º slope as prescribed by the actual certification rules. If the helicopter is certificated using for the flyover certification speed (0.45VH+65 kt) this speed must be used in the previous equations instead of (0.9VH). When the tip shape of the blade is not rectangular, the average chord lenght between 0.9R and R should be used for a better agreement of the prediction. The precision of the equations (a) is estimated in ±2dB for take-off and flyover condition and ±3dB for approach (±4dB for the worst (d)) which is at the same level of complicated codes but, obviously, they are not and would be not an alternative of these but only one more tool for the engineer wanting to reduce and predict noise from an helicopter at the beginning of the project.

11. Acknowledgments

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