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THE NOISE PROTECTION AREA AS A CRITERION FOR THE PROBLEM OF AIRCRAFT NOISE DURING THE TAKE-OFF OF VTOL AIRCRAFT

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1. Introduction

Noise requirements more and more influence the performance of take-off and landing of commercial airplanes. As a measure for the acoustic situation in the vicinity of airports, noise regions can be determined, which are enclosed by a curve of constant noise annoyance. The German aircraft noise law of 1971[1] uses the mean annoyance level, which is called the noise index $\bar{Q}$, and which can be obtained by taking the integral mean value of the instantaneous noise levels of all flights during a long time, and defines as the noise protection area that area, in which the noise Index $\bar{Q}$ is greater than 67 dBA. Herein the spectral content and the long time effects of the noises are considered, but more important characteristic parameters are missing, e.g. the maximum perceived noise level [2].

In the following, the noise protection area corresponding to the German law against aircraft noise is computed for the take-off of VTOL-aircraft. Moreover, the noise protection areas are computed taking into consideration the maximum perceived noise level; the noise protection area is now defined as that area, in which either the noise index $\bar{Q}$ is greater than 67 dBA or the maximum perceived noise level Q_{max} is greater than 95 dBN or both is the case. Besides, the effect of different flight path profiles (height of the vertical ascent, transition flight path angle) on the noise protection area is investigated with the aim to determine noise optimal VTOL-flight paths. An important effect is the engine noise characteristic. Therefore it is investigated how far the noise optimal flight trajectories are effected by a more or less simplification of the engine noise characteristics.

2. Calculation of the take-off flight profile

In this study, calculations are performed for a typical VTOL-aircraft with seperate lift and cruise engines. The take-off weight is W=550 000 N and the thrust/weight ratio is $T_{max}/W=1.1$. Since the emphasis is on performance the pitching degree of freedom is disregarded. The longitudinal motion can then be discribed by the following equations:

$$m\dot{V}=-C_D(\alpha,\eta)\,\frac{\varrho}{2}SV^2-W\sin\gamma+\sum_{e=1}^{E}[T(V,h)\cos(\sigma+\alpha)-N(V,h)\sin(\sigma+\alpha)]_e \quad (1)$$

$$mV\dot{\gamma}=-C_L(\alpha,\eta)\frac{\varrho}{2}SV^2-W\cos\gamma-\sum_{e=1}^{E}[T(V,h)\sin(\sigma+\alpha)+N(V,h)\cos(\sigma+\alpha)]_e \quad (2)$$

The drag and lift coefficient C_D and C_L are prescribed dependent on the angle of attack α and the flap angle η. The thrust T of the engines is the net thrust, which decreases with increasing forward speed V because of the increasing ram drag, and which decreases proportional to air density with increasing height. That component of the ram drag which is perpendicular to the engine axis acts as an external force on the aircraft. E denotes the number of engines and σ is the angle of rotation of the thrust vector. The motion of the aircraft is controllable by the variables T, σ, α and η.

In the following three equations, representing the integral VTOL flight performances, the tangential acceleration $\dot{V}$ is the essential variable:

duration of flight $t = \int_0^{V_T} \frac{dV}{\dot{V}(V)}$

distance $x = \int_0^{V_T} \frac{VdV}{\dot{V}(V)}$ (3)

fuel consumption $m_f = \int_0^{V_T} \frac{\dot{m}_f(V)dV}{\dot{V}(V)}$

Therefore the VTOL take-off is considered then optimal, when the control variables of the aircraft mentioned above, at any time or at any rate of speed are chosen so that the tangential acceleration is a maximum. The control variables as well as their first derivative with respect to time are restricted, because of constructional reasons and passenger comfort. The integrals are to be taken for the total VTOL section of the take-off, beginning at V=0 and ending with the speed V_T at the end of the transition.

To simplify the problem, the trajectories are seperated into two parts: the vertical ascent to a certain height h_V and the transition on a flight path with constant angle γ_T (see figure 2). The demand for maximum acceleration means, that the vertical ascent has to be flown with maximum thrust. The acceleration during this ascent decreases because of the decreasing thrust with increasing height and because of the increasing ram drag. This ram drag acts as a damping factor which increases with decreasing jetvelocity. To calculate the optimal acceleration during the transition flight, the control variables in discrete straight flight path segments of constant time duration are combined so, that the equations (1) and (2) are satisfied and the demanded acceleration is at its maximum value. The climbing flight following the end of the transition is flown on the steepest possible flight path with regard to flight performance with maximum continous thrust of the cruise engines and with the lift engines off.

For each of the take-off flight trajectories, which are prescribed by the parameters h_V and γ_T now exist optimal states of the control variables with regard to flight performance, and resulting forward speed and acceleration throughout the trajectory. From the manifold of this flight trajectories, that trajectory is selected, which gives the minimum value for the noise protection area. To compute the noise protection areas, a VTOL airport is assumed, which has an annual transport capacity of 4.5 Mill. passengers and 30.000 t of freight, half of which is transported by the departing aircraft, each of which can carry maximal 100 passengers or 10 t of freight. The load factor is assumed to be 80 %. To calculate the effective number of flights per time unit, it is considered that the annoyance of flight movements during daytime hours, from 0600 to 2200 hours, is weighted with the factor 1 and for flight movements during the nighttime hours the annoyance is weighted with the factor 5. Moreover it is assumed, that the frequency of the flight movements during the nighttime hours is reduced inversely proportional to the weighting factor.

3. The acoustic assumptions

The aircraft used in the study is propelled by 12 lift engines with a bypass ratio of 10, and 2 cruise engines with a bypass ratio of 6.5. For each of the two types of engines a different noise characteristic is used which are computed by procedures described in Ref. [3]. Figure 3 shows the noise characteristic of one lift engine. For a cruise engine a corresponding noise characteristic is valid with the difference, that the low frequent jet noise is little more emphasized compared with the fan noise because of the lower bypass ratio. The essential features of jet noise and fan noise referring to spectral characteristics, directivity charcteristics and thrust reduction can be seen in figure 3. To study the effect of a more or less simplified engine noise characteristic, the following cases are defined:

Case 1: This is the case, which includes the complete noise characteristic shown in figure 3, that is directivity characteristic in relation to the engine axis, different spectral characteristics in different directions, and the effect of thrust reduction on the spectral characteristics.

Case 2a: The directivity characteristic is taken into account, that is, each engine produces in different directions different overall sound pressure levels. The spectral characteristic however is disregarded. The atmospheric absorption rate δ is assumed to be 0.001 dB/m corresponding to the frequency of the maximal jet noise emission. This case is lateron called "with directivity, without spectral characteristics, jet noise".

Case 2b: Like in case 2a, however is the atmospheric absorption rate δ assumed to be δ = 0.016 dB/m, which corresponds to the fundamental fan blade passage frequency. This case is lateron called "with directivity, without spectral characteristics, fan noise".

Case 3a: The directivity characteristic is disregarded but the spectral characteristic is taken into account, i.e. each engine produces in any direction noise with the same spectral content. The characteristic frequency spectrum of the engine is assumed to be that of the direction of maximum jet noise. This case is called "without directivity, with spectral characteristics, jet noise".

Case 3b: Like in case 3a, however is the characteristic frequency spectrum of each engine assumed to be that of the direction of maximum fan noise emission. This case is called "without directivity, with spectral characteristics, fan noise".

Case 4a: Directivity and spectral characteristics are disregarded. Each lift engine (cruise engine) produces an overall sound pressure level of 113 dB (118 dB) in a distance of 45.7 m, which corresponds to the overall sound pressure level of the maximum jet noise. The atmospheric absorption rate δ is that of case 1a. This case 4a is called "without directivity, without spectral characteristic, jet noise".

Case 4b: Like in case 4a, however the overall sound pressure levels of the engines are these of the maximum fan noise; for the lift engine 103.9 dB and for the cruise engine 105.1 dB in a distance of 45.7 m. The atmospheric absorption rate δ is that of case 1b. Case 4b is called "without directivity, without spectral characteristics, fan noise".

The energy and intensity of the noise decrease with increasing distance r from the noise source because of the spherical spreading and the atmospheric absorption. The atmospheric absorption rate δ depends on the noise frequency and the atmosperic conditions. In this study a relative humidity of the air of 75 % and an air temperatur of 30°C on the ground as well as a gradient of the humidity of -10 % and a temperatur gradient of -4.5°C per km of increasing height is assumed. The sound pressure level of one frequency band j in one direction i in the distance r is:

$$Q_{ij}=Q_{ref_{ij}}+k_{ij}\ \log(T/T_{ref})-20\log(r/r_{ref})-\delta_{ij}(r-r_{ref}) \qquad (4)$$

In this, $Q_{ref_{ij}}$ is the noise level of the j-th frequency band in the i-th direction at the reference distance r_{ref} for reference thrust T_{ref}. The factor k_{ij} describes the noise attenuation due to thrust reduction, which has different values depending on direction and frequency. By summing up n frequency bands on an energy basis (in this study n=8 octave bands are used), one can compute the overall sound pressure level in many points in the surroundings of the airport.

To include the time behaviour of the noise in the calculation of the aircraft noise annoyance, and with this the duration and the number of the noise events during a reference time the mean annoyance level is used in Germany called the noise index $\bar{Q}$ [4], [5]. This noise index $\bar{Q}$ is generally defined as follows:

$$\bar{Q} = 13.3\log\left\{\frac{1}{t_0}\int_0^{t_0} 10^{\,Q(t)/13.3}\, dt\right\} \qquad (5)$$

In this, Q(t) is the time dependend overall noise level in dBA (or dBN) and t_o is the total time of observation. The factor 13.3 means, that the noise index $\bar{Q}$ is increased by 4 dB per dubling of the noise duration. Because the flight trajectories are given in time discrete segments (m segments of Δt_k duration), the noise index $\bar{Q}$ was discretized with reference to the flight path and computed piecewise:

$$\bar{Q} = 13.3\log\left\{\frac{N}{t_0}\sum_{k=1}^{m}\int_0^{\Delta t_k}\left[\sum_{j=1}^{n} 10^{0.1\ Q_{ij}(t)}\right]^{10/13.3} dt\right\} \quad (6)$$

In this, N denotes the number of take-offs during the reference time t_O. $Q_{ij}(t)$ is the momentary overall noise level corresponding to equation (4), which includes the levels of all engines of the aircraft.

Having computed the noise annoyance in many points around the airport by using the noise index $\bar{Q}$ or the maximum perceived noise level Q_{max}, one can get by interpolation a curve of constant noise annoyance, which is the boundary of the noise protection area.

4. The noise protection areas

As mentioned above, two different definitions of the noise protection area are used in this study. On the one hand, the noise index $\bar{Q}$ is the boundary of the noise protection area, which corresponds to the German law against aircraft noise. This noise protection area is called the simple noise protection area. On the other hand, the noise protection area is that area, in which either the noise index $\bar{Q}$ or the maximum perceived noise level Q_{max} exceed given values. That noise protection area is called the extended noise protection area. The value for the maximum perceived noise level is Q_{max} = 95 dBN and for the noise index $\bar{Q}$ = 67 dBA. All areas are shown as relative areas, i.e. in each case the respective areas are referred to that areas, which result from the flight

trajectory with $h_V = 0$ m and $\gamma_T = 0^o$ for the simple noise protection area ($\bar{Q} = 67$ dBA).

Figure 4 shows the results of the systematic computations for the relative noise protection areas in dependence of the vertical ascent h_V and the transition flight path angle γ_T for the different, in chapter 3 described simplifications of the engine noise characteristics.

In case 1, that is the case which considers all the noise features of figure 3, it can be seen, that increasing vertical ascent h_V results in almost linearly increasing of the simple noise protection area. This at first astonishing fact has the following reasons: The formation of the simple noise protection area is essentially affected by the low frequent jet noise. Since the atmospheric absorption rate is very small for low frequencies, an increasing distance from the noise source to the ground with increasing height h_V gives a small decreasing of the noise level - however mainly along the ground track of the climbout path -, on the other hand, the duration of the noise integration increases. The integral mean value of the noise level, which is the noise index $\bar{Q}$, contains a strong effect of the vertical ascent h_V. Within the considered values of h_V, this effect increases with increasing h_V. This is valid for the transition flight path angle $\gamma_T = 0^o$ as well as for $\gamma_T = 12^o$. The noise protection areas for $\gamma_T = 12^o$ are about 70 % larger than for $\gamma_T = 0^o$, because of the increasing horizontal distance until reaching the end of transition, i.e. until the lift engines are turned off.

When the maximum perceived noise level is taken into account to obtain the extended noise protection area described above, this maximum perceived noise level is the defining criterion for the noise protection area, when the vertical ascent h_V is small, because the curve of constant maximum perceived noise level $Q_{max} = 95$ dBN lies completely outside the curve of constant noise index $\bar{Q} = 67$ dBA. With increasing vertical ascent h_V the extended noise protection area decreases until reaching a minimum for a height of about $h_V = 80$ m. Further increasing the vertical ascent h_V results in increasing of the extended noise protection area, because now the noise index $\bar{Q}$ is the defining criterion for the boundaries of the extended noise protection area. Increasing the transition flight path angle γ_T results in an increasing of the extended noise protection area, again as an effect of the increasing horizontal distance to the end of the transition, but the minimum value is now at a height $h_V = 0$. From the case 1 in figure 4 it can be concluded, that a vertical ascent to a height $h_V = 80$ m and a subsequent transition flight on a flight path angle of $\gamma_T = 0^o$ is noise optimal with respect to the extended noise protection area, if the complete noise characteristics of figure 3 are used.

Case 2, which is also represented in figure 4, shows the effect of neglected spectral characteristics of the engine noise. If the noise energy is concentrated in one frequency band, corresponding to the frequency band of maximum jet noise, the duration of the noise increases because of the very low atmospheric absorption rate. This means, that the effect of the duration is overestimated against the effect of the distance from the noise source to the ground when computing the noise index $\bar{Q}$. Therefore the size of the simple noise protection area is increasing stronger with increasing vertical ascent h_V than in case 1. That stronger increase results in shifting the

height h_v of minimal extended noise protection area to $h_v = 0$. An increase of the transition flight path angle γ_T again results in increasing the noise protection areas, because of the increasing horizontal distance until the lift engines are turned off. For case 2a it can be concluded, that a vertical ascent of $h_v = 0$ and a subsequent transition on a flight path angle $\gamma_T = 0$ is the noise optimal take-off trajectory.

In case 2b, the noise energy is concentrated in one frequency band corresponding to the frequency band of maximum fan noise emission. Now the duration effect is underestimated against the distance effect, because of the rather high atmospheric absorption rate. Therefore, in case 2b, a vertical ascent h_v = 300 m and a subsequent transition with $\gamma_T = 0$ is the noise optimal take-off trajectory with respect to the extended noise protection area.

Case 3 shows the effect of neglected directivity characteristics compared with case 1. If the jet noise is assumed to be the characteristic noise for all directions, (case 3a), this means, that the acoustic power of the engine is overestimated, because in all directions exept one, the noise level is actually lower. This results in too large computed absolute noise protection areas (see A_O in figure 4, case 3a). Since the distance from the flight path to the boundary of the noise protection area is now very great, the duration of the noise increases to a large extend while the aircraft flies along its flight path, so that the curve of constant noise index $\bar{Q}$ = 67 dBA on the ground lies completely outside the curve of constant maximum perceived noise level Q_{max} = 95 dBN. This is valid for all heights h_v. Therefore, in case 3a, the extended noise protection area is identical to the simple noise protection area. Because of the low frequent noise in this case 3a, the noise protection area increases with increasing vertical ascent h_v due to the increasing noise duration. In this case, a take-off trajectory with $h_v = 0$ and $\gamma_T = 0$ is the noise optimal trajectory.

If the high frequent fan noise is the characteristic spectrum - case 3b -, the effect of increasing distance with increasing vertical ascent h_v is overestimated, especially for the maximum perceived noise level Q_{max} = 95 dBN and $\gamma_T = 12^o$, so that the noise optimal take-off trajectory is a vertical ascent to h_v = 300 m and a subsequent transition flight on a flight path angle of $\gamma_T = 12^o$.

Finally, in case 4 the directivity as well as the spectral characteristics are neglected. Looking on figure 4, it is obvious, that the results for case 4 almost agree with the results of case 3. The reason for this is, that for the low frequent jet noise as well as for the high frequent fan noise one respectively frequency band is dominant in the prescribed engine noise characteristics. Therefore the omission of all other frequency bands has no great effect.

5. Conclusions

The aim of the present study was to compute noise optimal VTOL take-off trajectories with respect to the noise protection area, and how far a simplification of the used engine noise characteristics has an effect on the optimal take-off trajectory. The investigation shows, that the "simple noise protection area", this is the noise protection area which corresponds to the German law against aircraft noise

with the noise index $\bar{Q}$ = 67 dBA as the boundary, has a minimum value, when the height of the vertical ascent h_v = 0 m, and the flight path angle γ_T of the subsequent transition is $\gamma_T = 0^o$. This is independend of each of the simplifications made in this study.

However, far outside of the simple noise protection area, maximum perceived noise levels of more than 95 dBN can occur. Therefore the definition of the noise protection area is extended by the maximum perceived noise level in the described manner. If now this "extended noise protection area" is computed, using a complete engine noise characteristic, the take-off trajectory is noise optimal when the aircraft ascend vertically to a height of about h_v = 80 m and fly the subsequent transition on a flight path angle $\gamma_T = 0^o$. However, it has to be emphasized, that a change in the number of flights per time unit results in changing the optimal vertical ascent; that is increasing the frequency of the flight movements decreases the noise optimal vertical ascent h_v.

When the engine noise characteristic is simplified by neglecting particular peculiarities, it is shown, that take-off trajectories with different flight path parameters h_v and γ_T are determined as noise optimal, such as: h_v = 0m and $\gamma_T = 0^o$; h_v = 300 m and $\gamma_T = 0^o$; h_v = 350 m and $\gamma_T = 12^o$. Hereby statements concerning noise-optimal VTOL take-off trajectories can be adulterated heavily. To get safe statements, it is necessary to take into account complete engine noise characteristics.

6. References

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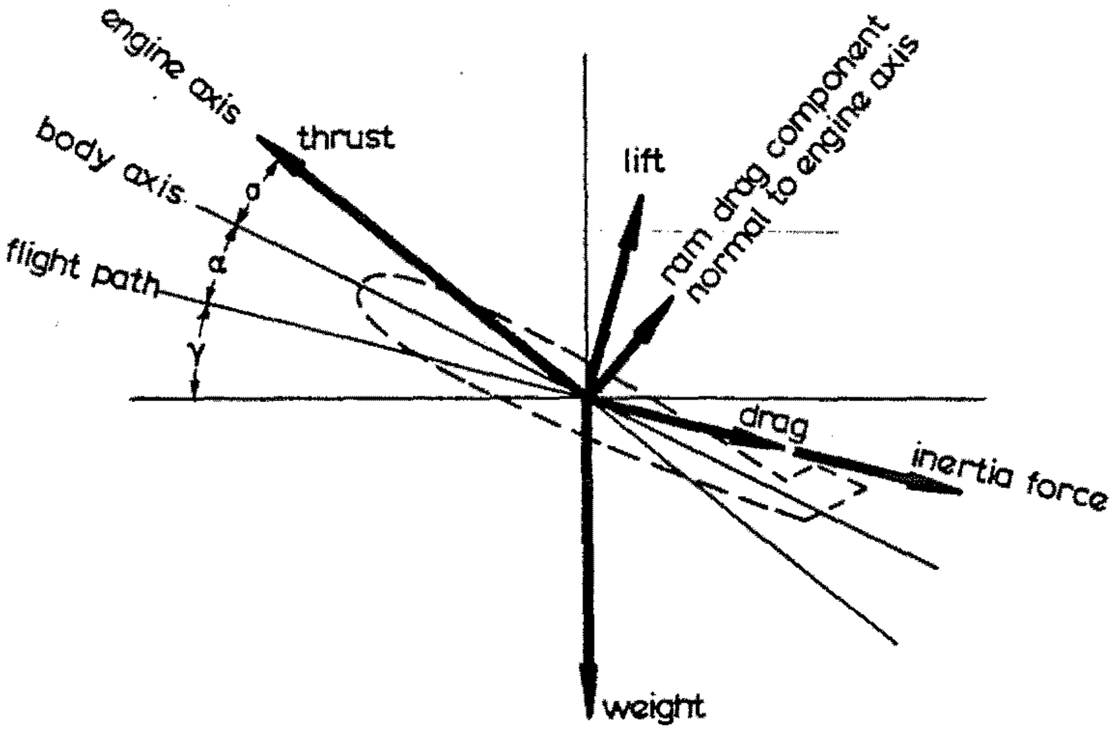


Figure 1 Forces acting on the aircraft.

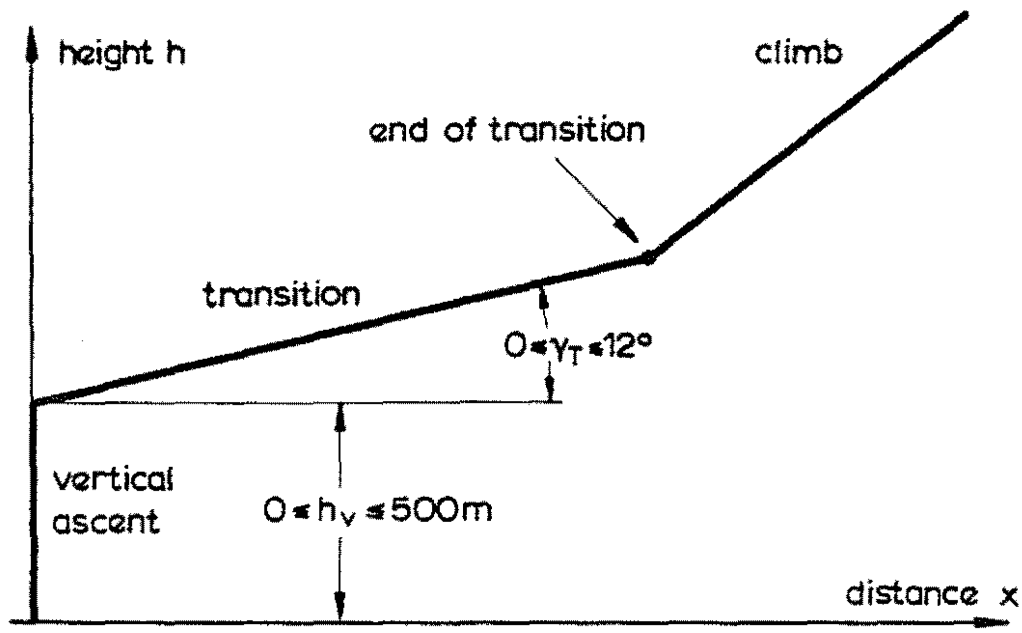


Figure 2 Take-off flight path shape

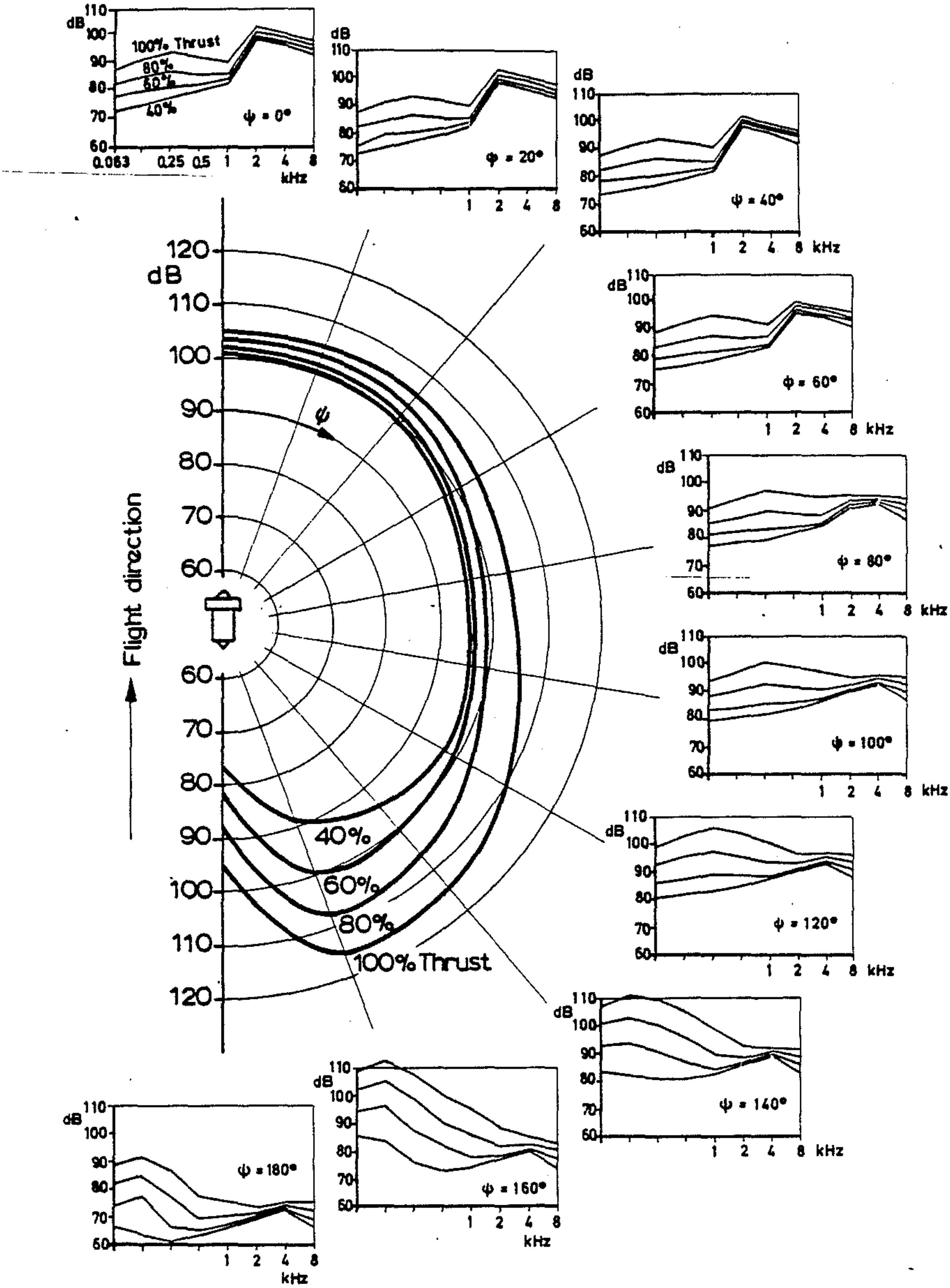
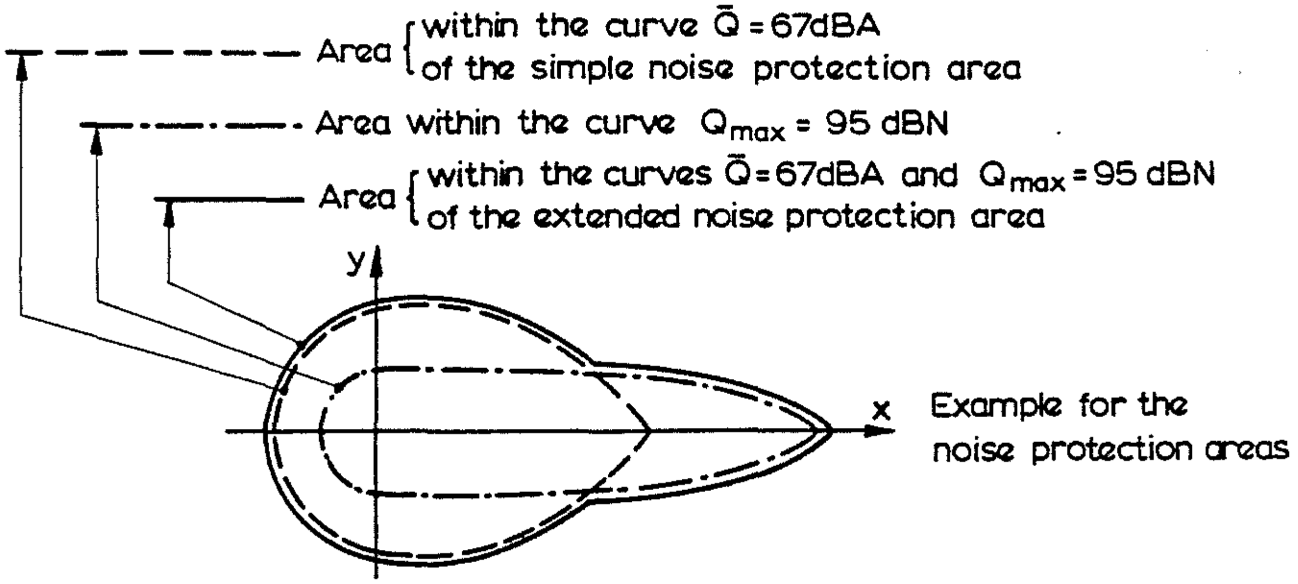
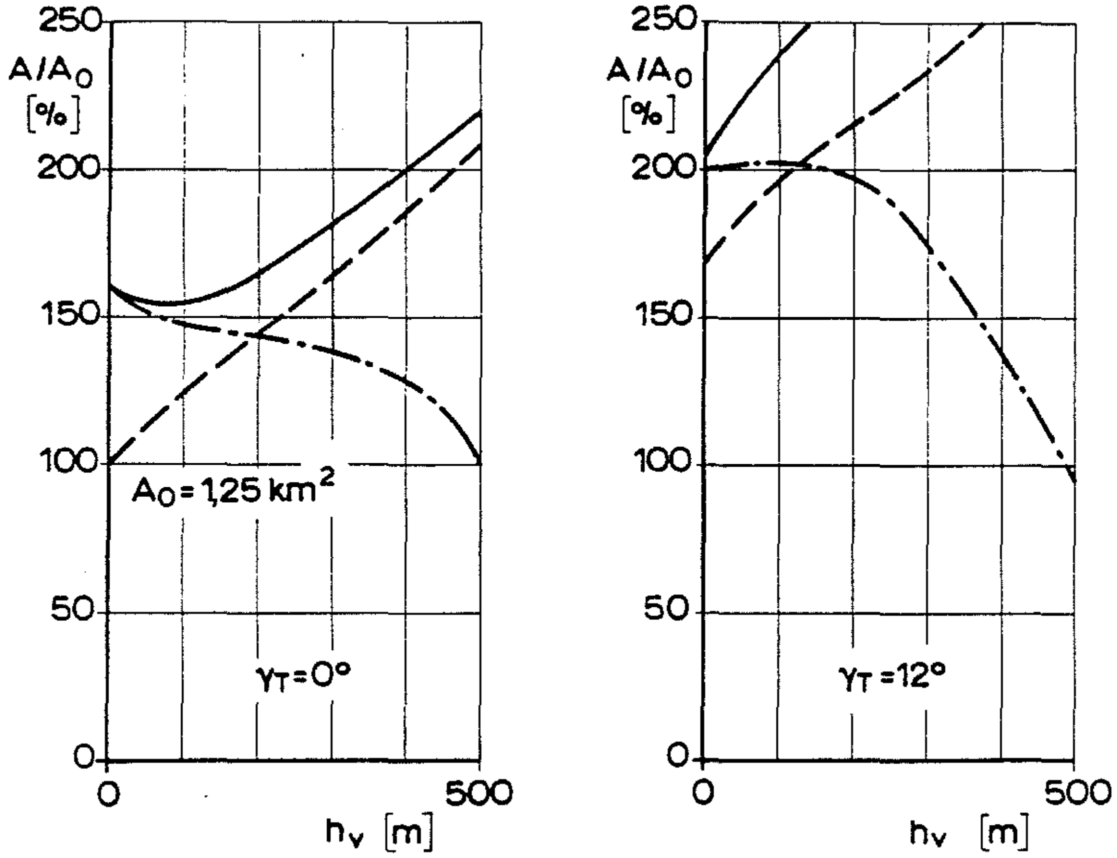


Figure 3 Directivity and spectral characteristics of one lift engine at a distance of 45.7m

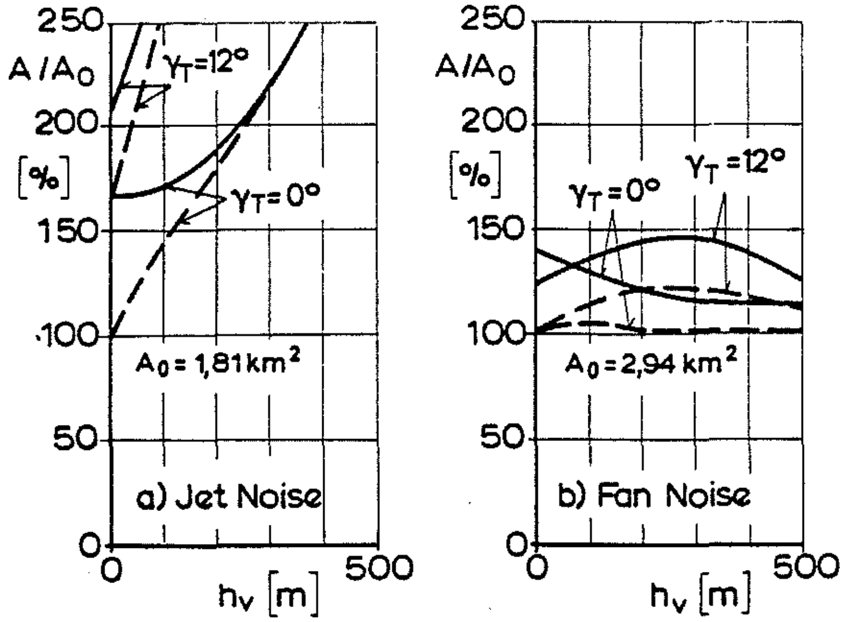


For each case A_0 is the noise protection area for $\bar{Q} = 67$dBA and $h_v = 0, \gamma_T = 0$



<u>Case 1</u> with engine noise directivity characteristics
with engine noise spetral characteristics

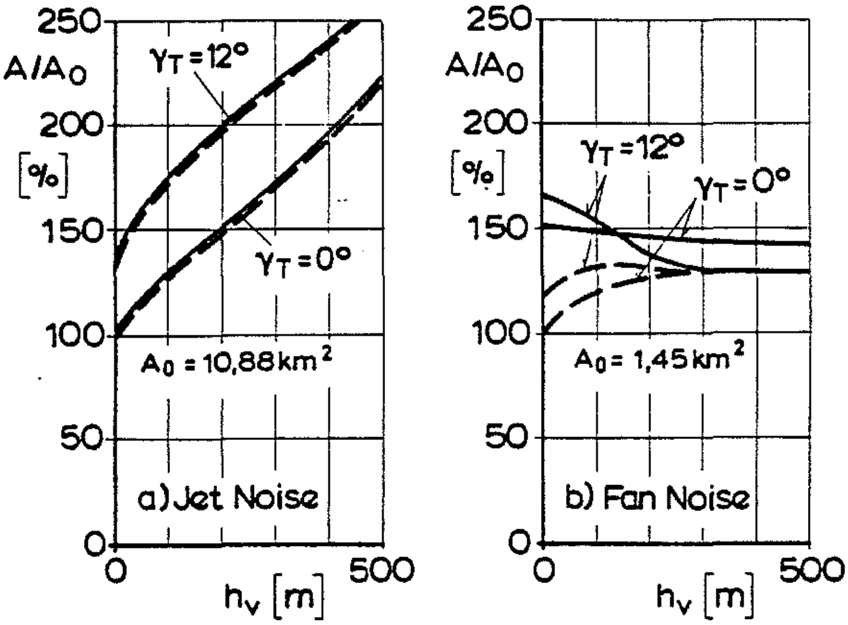
<u>Figure 4</u> Relative noise protection areas as a function of the height of the vertical ascent h_v for two transition flight path angles γ_T



Case 2

with directivity characteristics

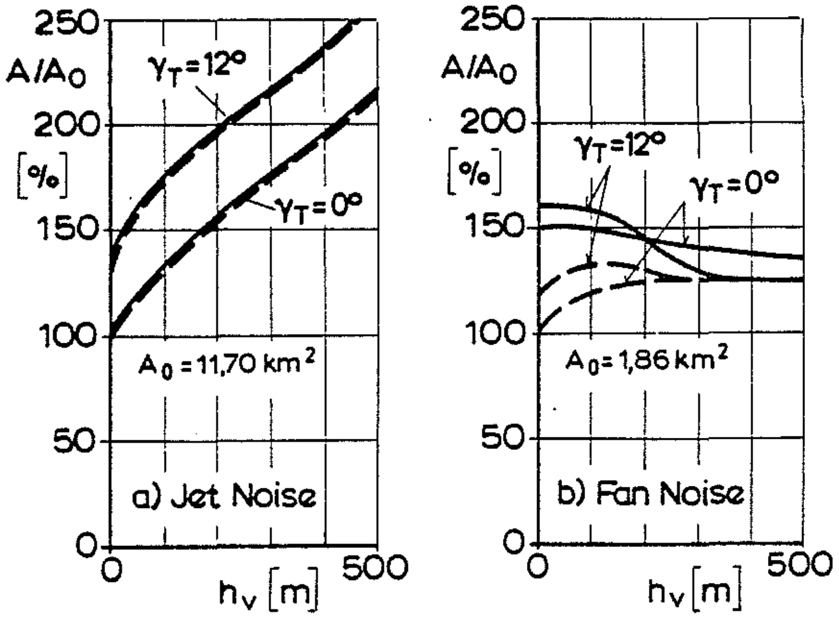
without spectral characteristics



Case 3

without directivity characteristics

with spectral characteristics



Case 4

without directivity characteristics

without spectral characteristics

Figure 4 Continued

characteristic of one lift engine. For a cruise engine a corresponding noise characteristic is valid with the difference, that the low frequent jet noise is little more emphasized compared with the fan noise because of the lower bypass ratio. The essential features of jet noise and fan noise referring to spectral characteristics, directivity charcteristics and thrust reduction can be seen in figure 3. To study the effect of a more or less simplified engine noise characteristic, the following cases are defined:

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In this, N denotes the number of take-offs during the reference time t_0. $Q_{ij}(t)$ is the momentary overall noise level corresponding to equation (4), which includes the levels of all engines of the aircraft.

Having computed the noise annoyance in many points around the airport by using the noise index $\bar{Q}$ or the maximum perceived noise level Q_{max}, one can get by interpolation a curve of constant noise annoyance, which is the boundary of the noise protection area.

4. The noise protection areas

As mentioned above, two different definitions of the noise protection area are used in this study. On the one hand, the noise index $\bar{Q}$ is the boundary of the noise protection area, which corresponds to the German law against aircraft noise. This noise protection area is called the simple noise protection area. On the other hand, the noise protection area is that area, in which either the noise index $\bar{Q}$ or the maximum perceived noise level Q_{max} exceed given values. That noise protection area is called the extended noise protection area. The value for the maximum perceived noise level is Q_{max} = 95 dBN and for the noise index $\bar{Q}$ = 67 dBA. All areas are shown as relative areas, i.e. in each case the respective areas are referred to that areas, which result from the flight

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Figure 4 shows the results of the systematic computations for the relative noise protection areas in dependence of the vertical ascent h_V and the transition flight path angle γ_T for the different, in chapter 3 described simplifications of the engine noise characteristics.

In case 1, that is the case which considers all the noise features of figure 3, it can be seen, that increasing vertical ascent h_V results in almost linearly increasing of the simple noise protection area. This at first astonishing fact has the following reasons: The formation of the simple noise protection area is essentially affected by the low frequent jet noise. Since the atmospheric absorption rate is very small for low frequencies, an increasing distance from the noise source to the ground with increasing height h_V gives a small decreasing of the noise level - however mainly along the ground track of the climbout path -, on the other hand, the duration of the noise integration increases. The integral mean value of the noise level, which is the noise index $\bar{Q}$, contains a strong effect of the vertical ascent h_V. Within the considered values of h_V, this effect increases with increasing h_V. This is valid for the transition flight path angle $\gamma_T = 0^o$ as well as for $\gamma_T = 12^o$. The noise protection areas for $\gamma_T = 12^o$ are about 70 % larger than for $\gamma_T = 0^o$, because of the increasing horizontal distance until reaching the end of transition, i.e. until the lift engines are turned off.

When the maximum perceived noise level is taken into account to obtain the extended noise protection area described above, this maximum perceived noise level is the defining criterion for the noise protection area, when the vertical ascent h_V is small, because the curve of constant maximum perceived noise level $Q_{max} = 95$ dBN lies completely outside the curve of constant noise index $\bar{Q} = 67$ dBA. With increasing vertical ascent h_V the extended noise protection area decreases until reaching a minimum for a height of about $h_V = 80$ m. Further increasing the vertical ascent h_V results in increasing of the extended noise protection area, because now the noise index $\bar{Q}$ is the defining criterion for the boundaries of the extended noise protection area. Increasing the transition flight path angle γ_T results in an increasing of the extended noise protection area, again as an effect of the increasing horizontal distance to the end of the transition, but the minimum value is now at a height $h_V = 0$. From the case 1 in figure 4 it can be concluded, that a vertical ascent to a height $h_V =$ 80 m and a subsequent transition flight on a flight path angle of $\gamma_T = 0^o$ is noise optimal with respect to the extended noise protection area, if the complete noise characteristics of figure 3 are used.

Case 2, which is also represented in figure 4, shows the effect of neglected spectral characteristics of the engine noise. If the noise energy is concentrated in one frequency band, corresponding to the frequency band of maximum jet noise, the duration of the noise increases because of the very low atmospheric absorption rate. This means, that the effect of the duration is overestimated against the effect of the distance from the noise source to the ground when computing the noise index $\bar{Q}$. Therefore the size of the simple noise protection area is increasing stronger with increasing vertical ascent h_V than in case 1. That stronger increase results in shifting the

height h_V of minimal extended noise protection area to $h_V = 0$. An increase of the transition flight path angle γ_T again results in increasing the noise protection areas, because of the increasing horizontal distance until the lift engines are turned off. For case 2a it can be concluded, that a vertical ascent of $h_V = 0$ and a subsequent transition on a flight path angle $\gamma_T = 0$ is the noise optimal take-off trajectory.

In case 2b, the noise energy is concentrated in one frequency band corresponding to the frequency band of maximum fan noise emission. Now the duration effect is underestimated against the distance effect, because of the rather high atmospheric absorption rate. Therefore, in case 2b, a vertical ascent $h_V = 300$ m and a subsequent transition with $\gamma_T = 0$ is the noise optimal take-off trajectory with respect to the extended noise protection area.

Case 3 shows the effect of neglected directivity characteristics compared with case 1. If the jet noise is assumed to be the characteristic noise for all directions, (case 3a), this means, that the acoustic power of the engine is overestimated, because in all directions exept one, the noise level is actually lower. This results in too large computed absolute noise protection areas (see A_O in figure 4, case 3a). Since the distance from the flight path to the boundary of the noise protection area is now very great, the duration of the noise increases to a large extend while the aircraft flies along its flight path, so that the curve of constant noise index $\bar{Q} = 67$ dBA on the ground lies completely outside the curve of constant maximum perceived noise level $Q_{max} = 95$ dBN. This is valid for all heights h_V. Therefore, in case 3a, the extended noise protection area is identical to the simple noise protection area. Because of the low frequent noise in this case 3a, the noise protection area increases with increasing vertical ascent h_V due to the increasing noise duration. In this case, a take-off trajectory with $h_V = 0$ and $\gamma_T = 0$ is the noise optimal trajectory.

If the high frequent fan noise is the characteristic spectrum - case 3b -, the effect of increasing distance with increasing vertical ascent h_V is overestimated, especially for the maximum perceived noise level $Q_{max} = 95$ dBN and $\gamma_T = 12^o$, so that the noise optimal take-off trajectory is a vertical ascent to $h_V = 300$ m and a subsequent transition flight on a flight path angle of $\gamma_T = 12^o$.

Finally, in case 4 the directivity as well as the spectral characteristics are neglected. Looking on figure 4, it is obvious, that the results for case 4 almost agree with the results of case 3. The reason for this is, that for the low frequent jet noise as well as for the high frequent fan noise one respectively frequency band is dominant in the prescribed engine noise characteristics. Therefore the omission of all other frequency bands has no great effect.

5. Conclusions

The aim of the present study was to compute noise optimal VTOL take-off trajectories with respect to the noise protection area, and how far a simplification of the used engine noise characteristics has an effect on the optimal take-off trajectory. The investigation shows, that the "simple noise protection area", this is the noise protection area which corresponds to the German law against aircraft noise

with the noise index $\bar{Q}$ = 67 dBA as the boundary, has a minimum value, when the height of the vertical ascent h_V = 0 m, and the flight path angle γ_T of the subsequent transition is $\gamma_T = 0^o$. This is independend of each of the simplifications made in this study.

However, far outside of the simple noise protection area, maximum perceived noise levels of more than 95 dBN can occur. Therefore the definition of the noise protection area is extended by the maximum perceived noise level in the described manner. If now this "extended noise protection area" is computed, using a complete engine noise characteristic, the take-off trajectory is noise optimal when the aircraft ascend vertically to a height of about h_V = 80 m and fly the subsequent transition on a flight path angle $\gamma_T = 0^o$. However, it has to be emphasized, that a change in the number of flights per time unit results in changing the optimal vertical ascent; that is increasing the frequency of the flight movements decreases the noise optimal vertical ascent h_V.

When the engine noise characteristic is simplified by neglecting particular peculiarities, it is shown, that take-off trajectories with different flight path parameters h_V and γ_T are determined as noise optimal, such as: h_V = 0m and $\gamma_T = 0^o$; h_V = 300 m and $\gamma_T = 0^o$; h_V = 350 m and $\gamma_T = 12^o$. Hereby statements concerning noise-optimal VTOL take-off trajectories can be adulterated heavily. To get safe statements, it is necessary to take into account complete engine noise characteristics.

6. References

1. Anon., Gesetz zum Schutz gegen den Fluglärm. Bundesgesetzblatt Nr. 28(1971), Teil I, S. 282-286.
2. W.Bürck, Zur Entstehung des Fluglärms, über seine meßtechnische Erfassung und die akustischen Kenn- und Meßgrößen, die Wirkung auf den Menschen und Minderungs- oder Schutzmaßnahmen. Vortrag auf dem DGLR-Symposium Flugtechnik und Umweltforschung.
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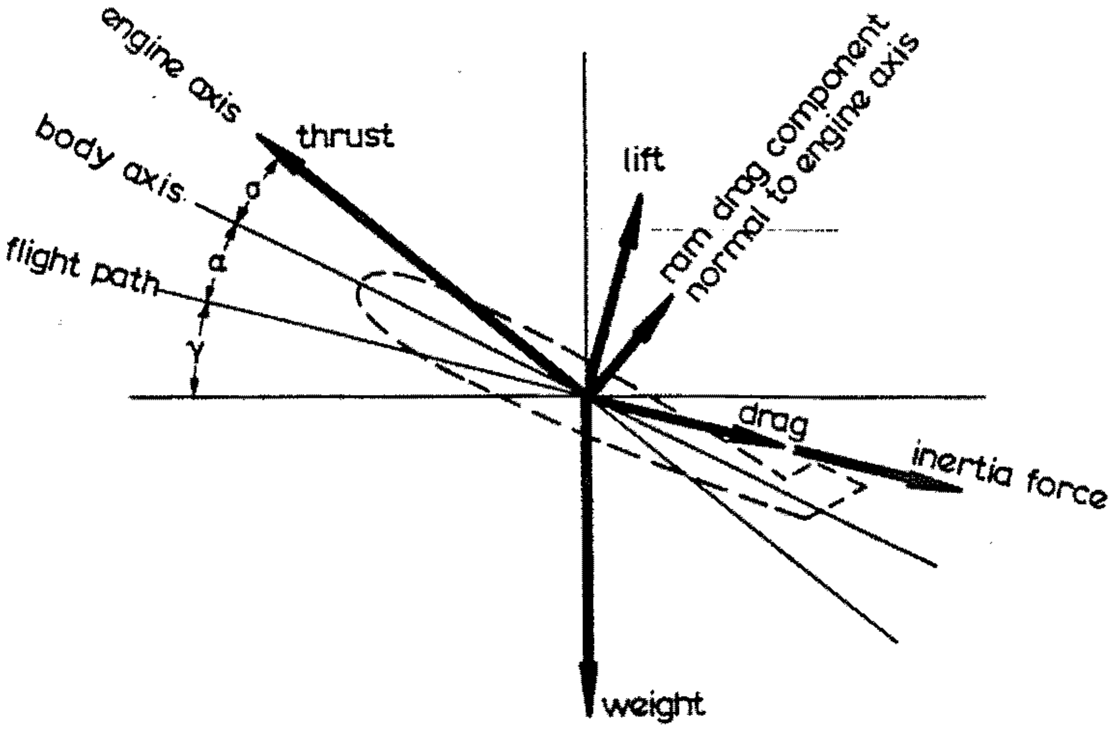


Figure 1 Forces acting on the aircraft.

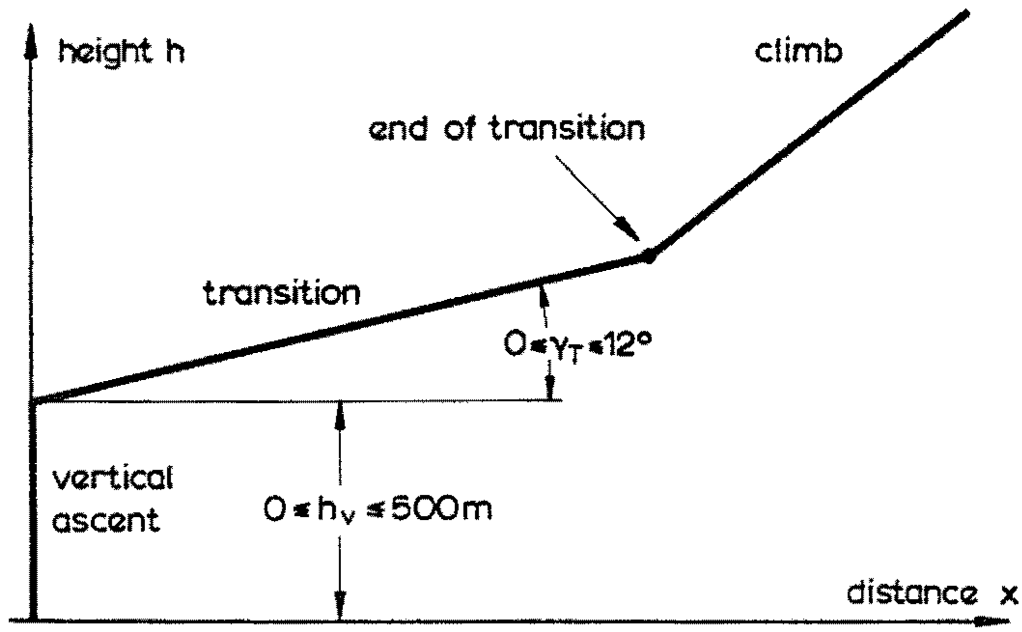


Figure 2 Take-off flight path shape

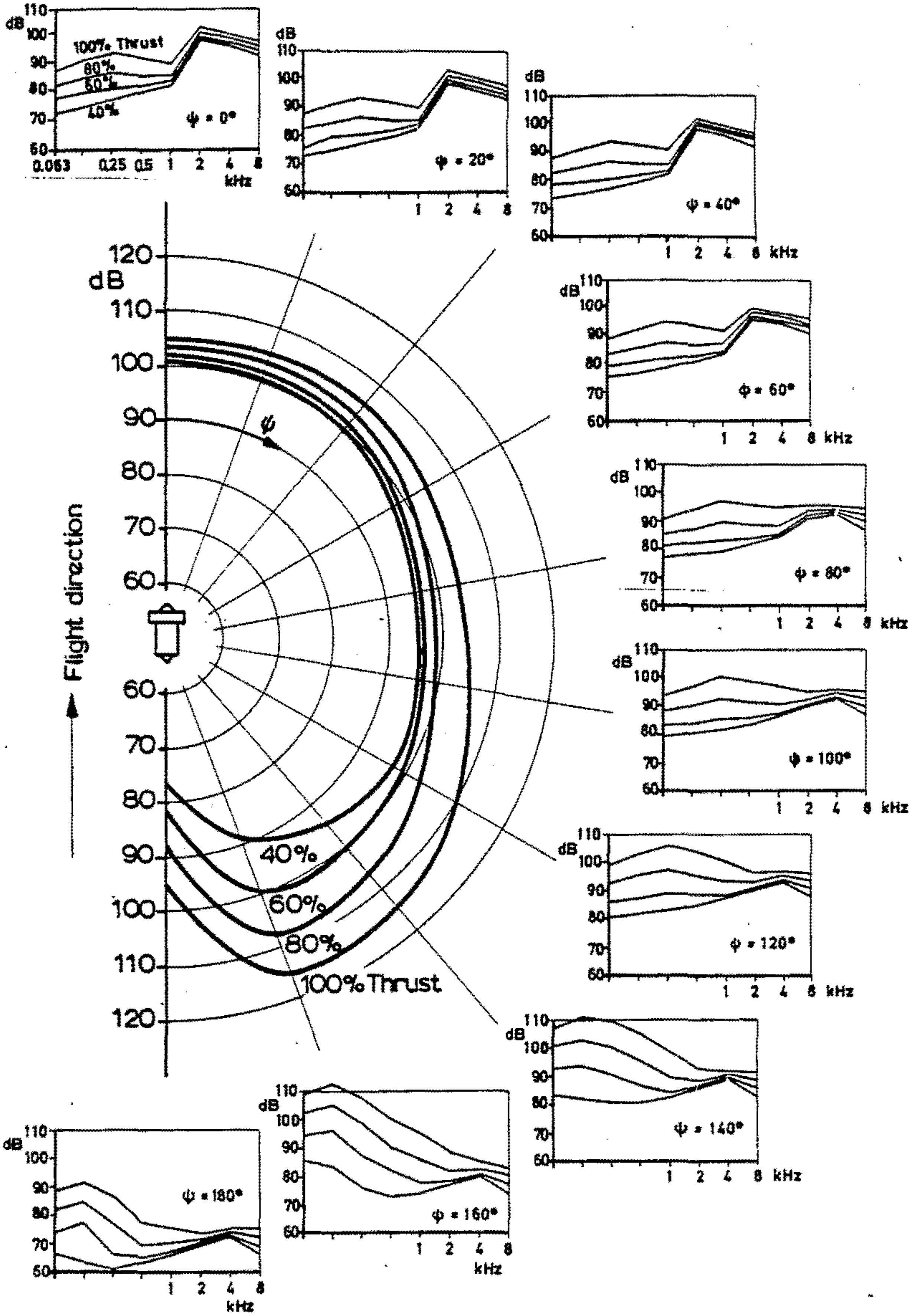
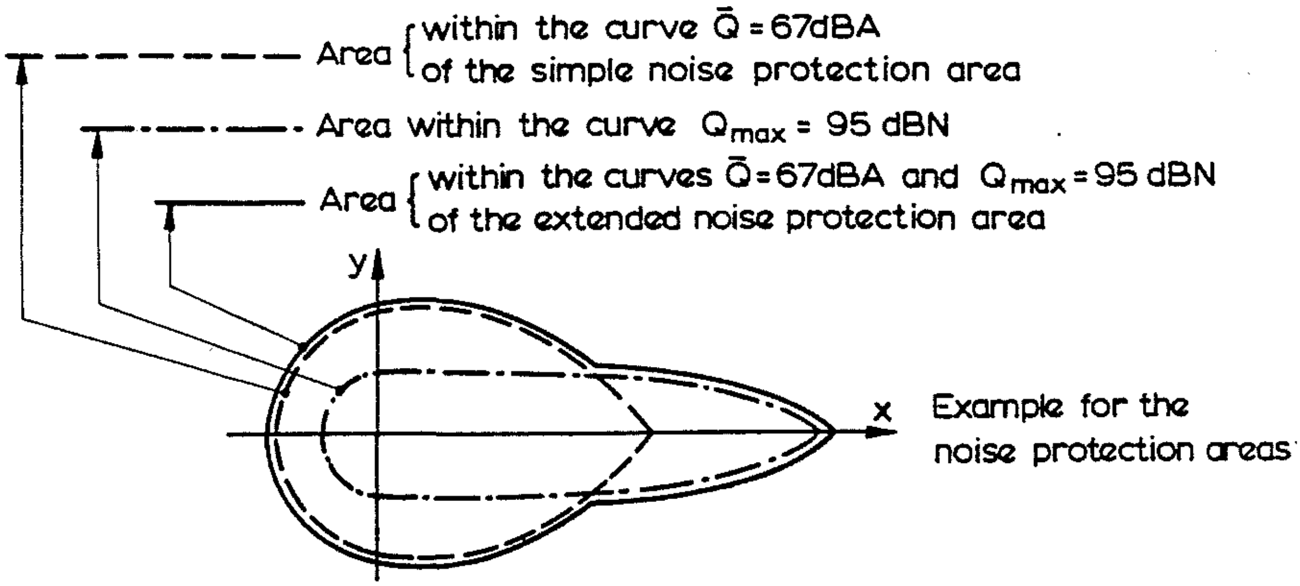
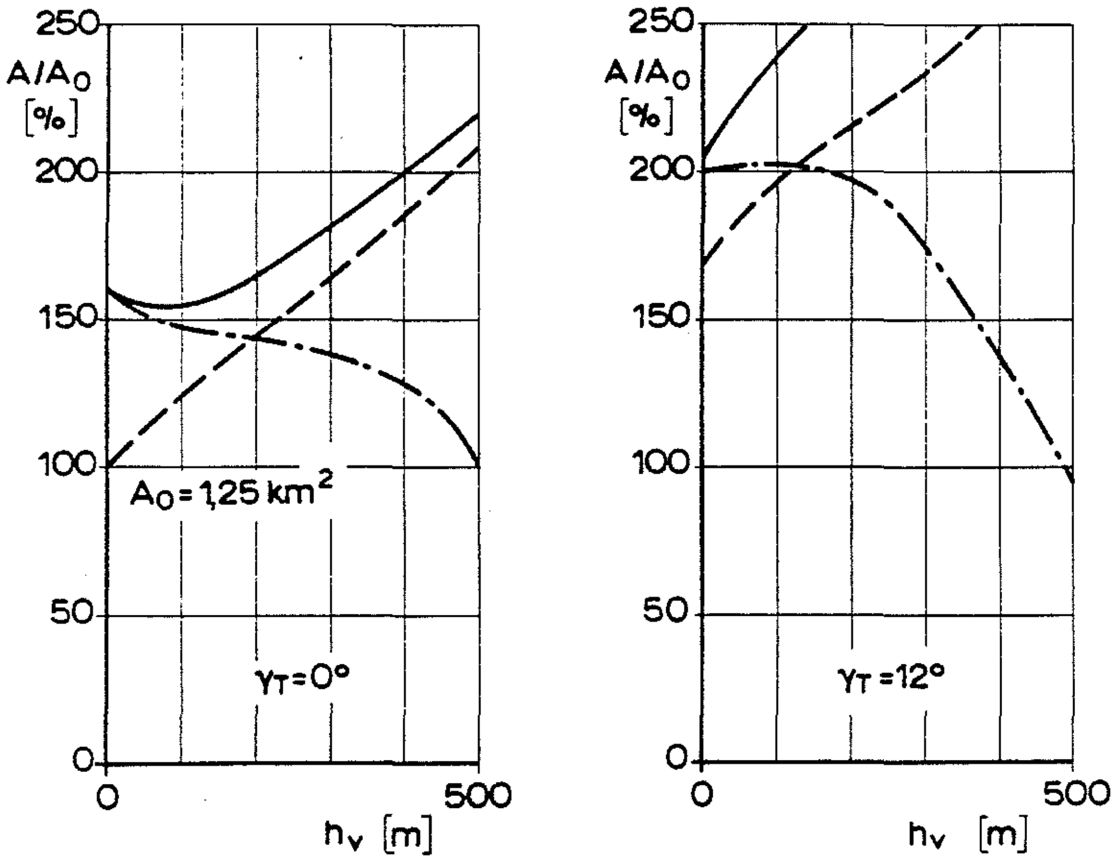


Figure 3 Directivity and spectral characteristics of one lift engine at a distance of 45.7m

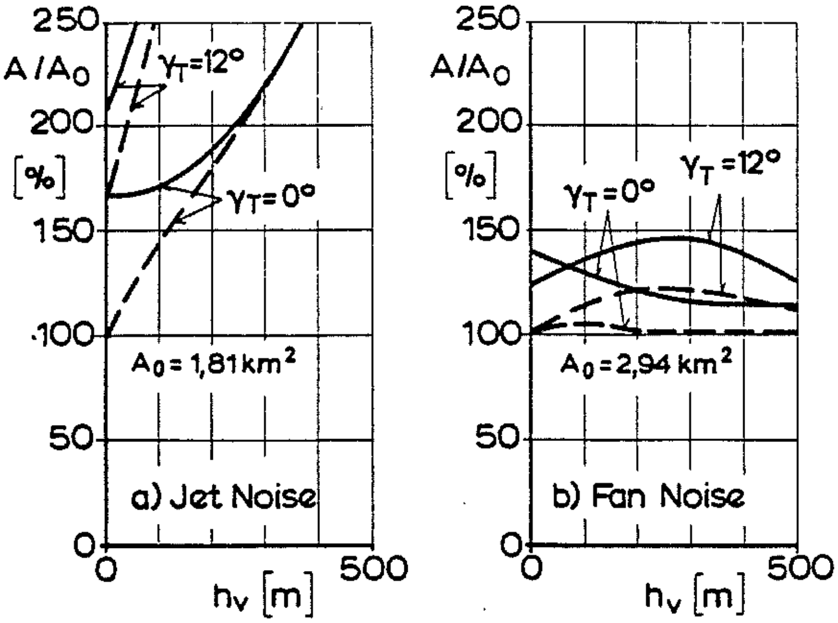


For each case A_0 is the noise protection area for $\bar{Q} = 67$dBA and $h_v = 0, \gamma_T = 0$



<u>Case 1</u> with engine noise directivity characteristics
with engine noise spetral characteristics

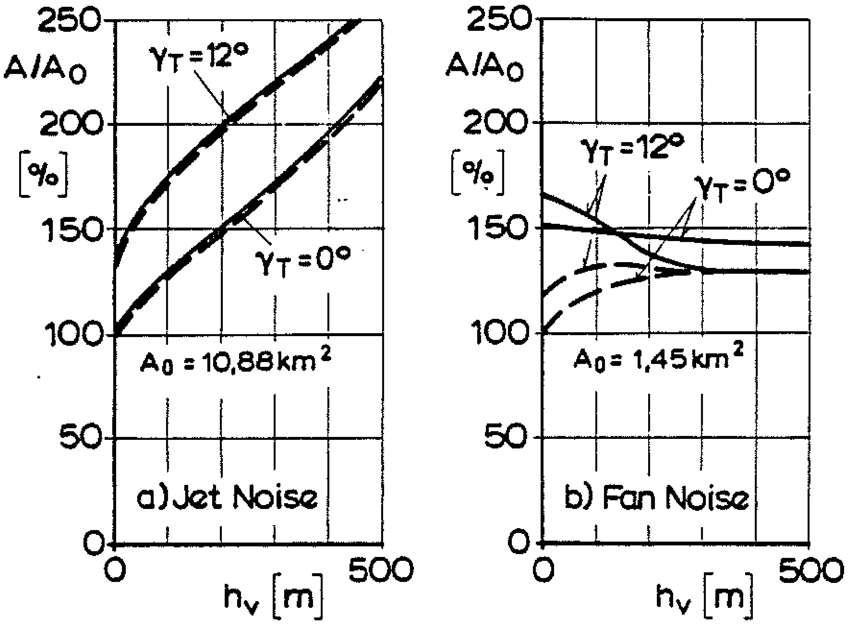
<u>Figure 4</u> Relative noise protection areas as a function of the height of the vertical ascent h_v for two transition flight path angles γ_T



Case 2

with directivity characteristics

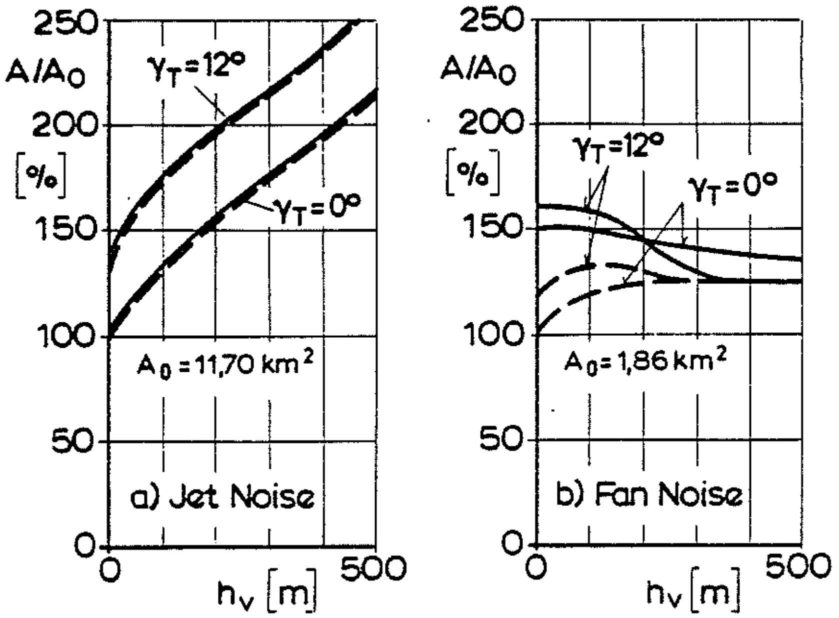
without spectral characteristics



Case 3

without directivity characteristics

with spectral characteristics



Case 4

without directivity characteristics

without spectral characteristics

Figure 4 Continued

trajectory with $h_v = 0$ m and $\gamma_T = 0^o$ for the simple noise protection area ($\bar{Q} = 67$ dBA).

Figure 4 shows the results of the systematic computations for the relative noise protection areas in dependence of the vertical ascent h_v and the transition flight path angle γ_T for the different, in chapter 3 described simplifications of the engine noise characteristics.

In case 1, that is the case which considers all the noise features of figure 3, it can be seen, that increasing vertical ascent h_v results in almost linearly increasing of the simple noise protection area. This at first astonishing fact has the following reasons: The formation of the simple noise protection area is essentially affected by the low frequent jet noise. Since the atmospheric absorption rate is very small for low frequencies, an increasing distance from the noise source to the ground with increasing height h_v gives a small decreasing of the noise level - however mainly along the ground track of the climbout path -, on the other hand, the duration of the noise integration increases. The integral mean value of the noise level, which is the noise index $\bar{Q}$, contains a strong effect of the vertical ascent h_v. Within the considered values of h_v, this effect increases with increasing h_v. This is valid for the transition flight path angle $\gamma_T = 0^o$ as well as for $\gamma_T = 12^o$. The noise protection areas for $\gamma_T = 12^o$ are about 70 % larger than for $\gamma_T = 0^o$, because of the increasing horizontal distance until reaching the end of transition, i.e. until the lift engines are turned off.

When the maximum perceived noise level is taken into account to obtain the extended noise protection area described above, this maximum perceived noise level is the defining criterion for the noise protection area, when the vertical ascent h_v is small, because the curve of constant maximum perceived noise level $Q_{max} = 95$ dBN lies completely outside the curve of constant noise index $\bar{Q} = 67$ dBA. With increasing vertical ascent h_v the extended noise protection area decreases until reaching a minimum for a height of about $h_v = 80$ m. Further increasing the vertical ascent h_v results in increasing of the extended noise protection area, because now the noise index $\bar{Q}$ is the defining criterion for the boundaries of the extended noise protection area. Increasing the transition flight path angle γ_T results in an increasing of the extended noise protection area, again as an effect of the increasing horizontal distance to the end of the transition, but the minimum value is now at a height $h_v = 0$. From the case 1 in figure 4 it can be concluded, that a vertical ascent to a height $h_v =$ 80 m and a subsequent transition flight on a flight path angle of $\gamma_T = 0^o$ is noise optimal with respect to the extended noise protection area, if the complete noise characteristics of figure 3 are used.

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6. References

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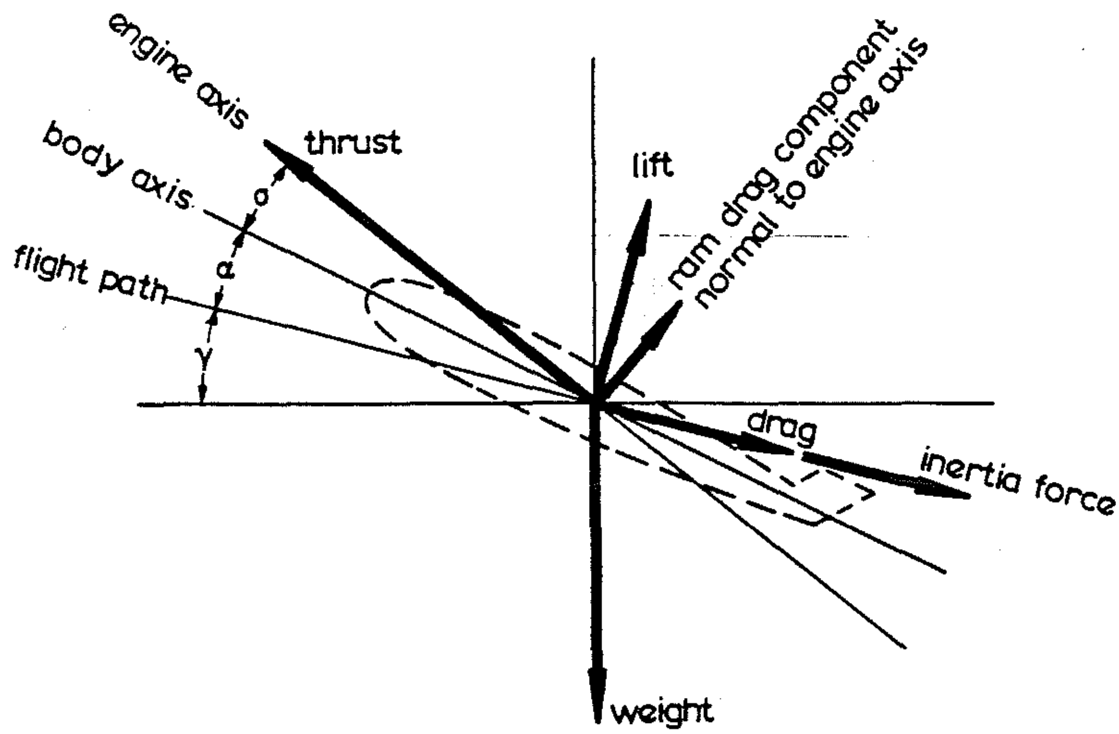

Figure 1   Forces acting on the aircraft.

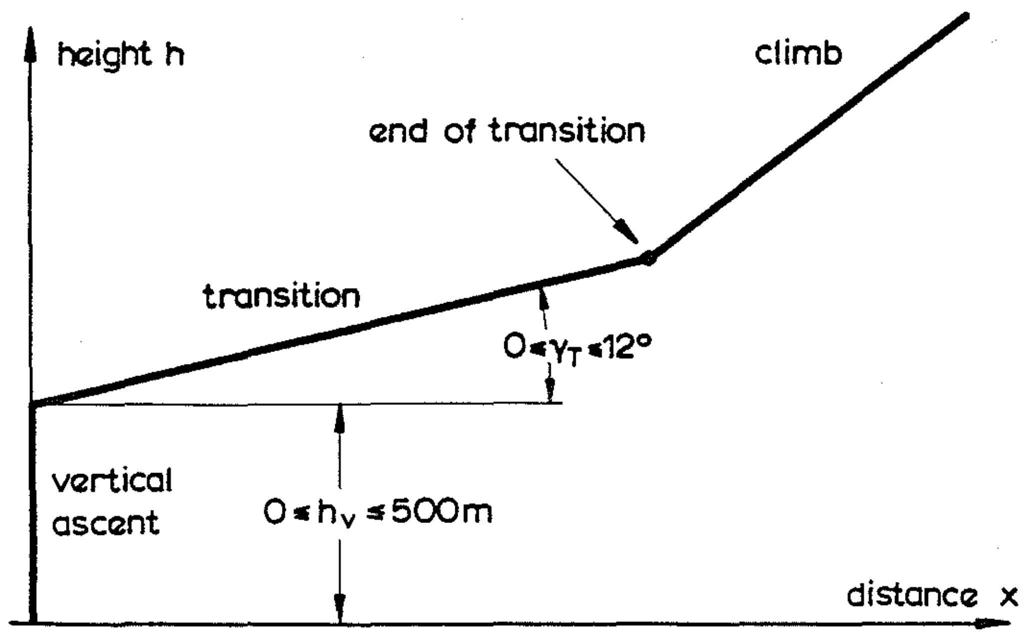

Figure 2   Take-off flight path shape

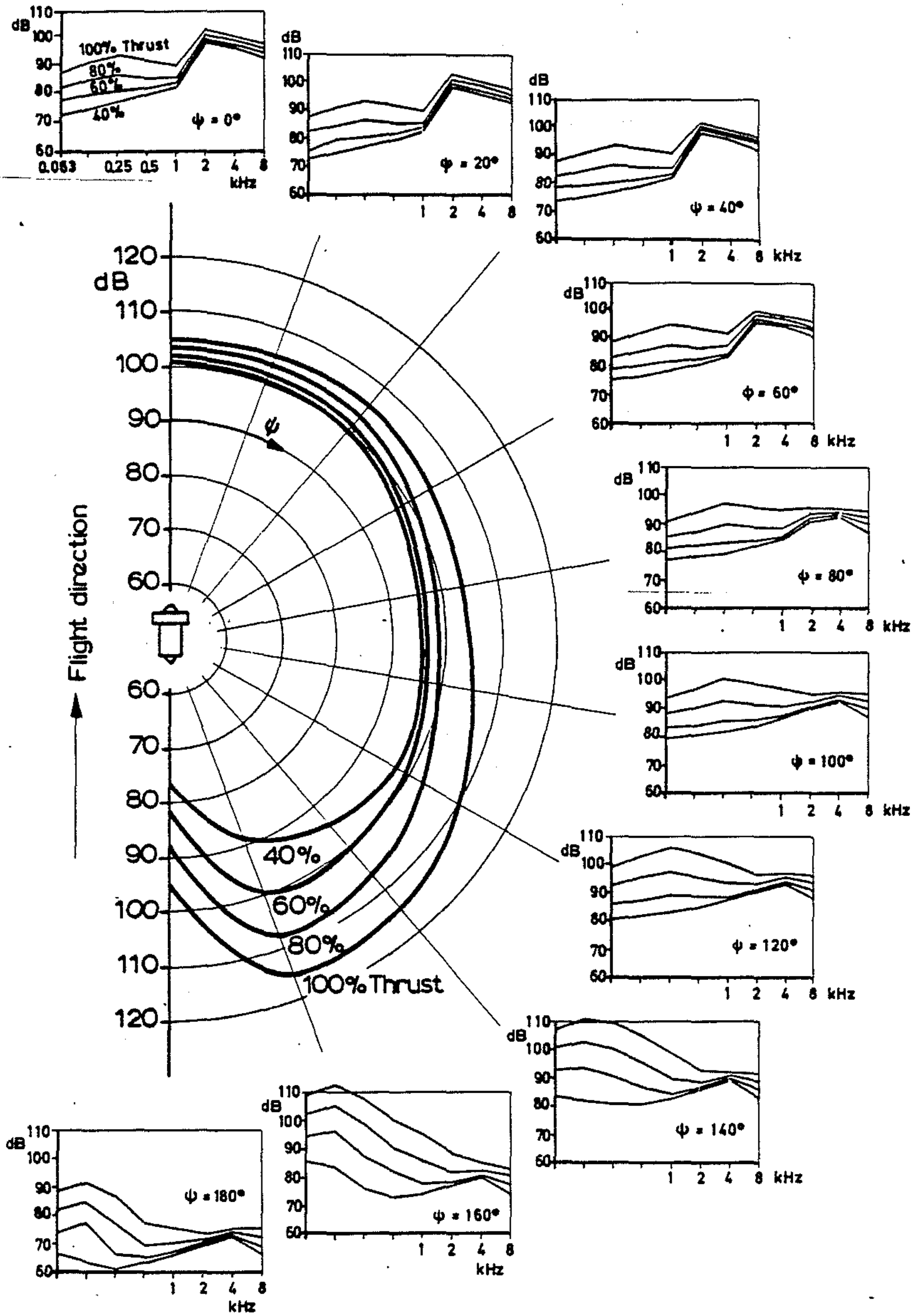

Figure 3 Directivity and spectral characteristics of one lift engine at a distance of 45.7m