THE ULTRALIGHT AEROPLANE - A "PAIN IN THE AIR" OR AN ENVIRONMENTALLY ACCEPTABLE FLIGHT VEHICLE?

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Executive Summary

Stringent noise limits have been imposed on ultralight aeroplanes in the Federal Republic of Germany. Some countries have less severe noise rules, while others prohibit the operation of ultralight aeroplanes altogether. The 'Committee on Aviation Environmental Protection' (CAEP) of the 'International Civil Aviation Organization' (ICAO) intends to formulate internationally binding noise regulations for ultralight aeroplanes, as a separate Chapter in the 'ANNEX 16' |Ref. 1|.

In view of these developments an experimental and theoretical research program was initiated to investigate specifically the noise sources and noise characteristics of ultralight aeroplanes. The objective of this study was to evaluate the technical feasibility of meeting existing or proposed noise limits - especially in comparison with the noise limits for "light propeller-driven aeroplanes" (Annex 16/Chapter 6) and to further establish the minimum noise radiation from various types of ultralight aeroplanes within operational limitations. For this purpose, flyover and ground static noise measurements on tractor- and pusher-propeller driven ultralight aeroplanes and wind tunnel noise measurements on isolated full-scale ultralight-aeroplane propellers were conducted. Engine noise was studied separately providing information on the relationship of engine rotational speed and exhaust noise. The experiments served to identify the important propeller and engine related acoustic source mechanisms and to understand their dependences on relevant operational, geometric and aerodynamic parameters.

The experiments have established propeller blade tip-speed and thrust as the important parameters, rather than flight speed or number of propeller blades. Also, at the relatively low operational helical blade tip Mach numbers, propeller broadband noise, rather than propeller harmonic noise, determines ultralight aeroplane propeller noise. Engine noise - even if well muffled - was frequently found to equal propeller noise in magnitude. Pusher propeller driven ultralight aeroplanes were 5 to 15 dB noisier than those equipped with tractor propellers and totally unable to comply with the present German noise limits. Semi-empirical formulations were developed for tractor propellers concerning the dependence of propeller harmonic noise on helical blade tip Mach number, thrust, blade number and distance, and of propeller broadband noise on helical blade tip Mach number, thrust and distance; broadband noise was found to be insensitive of blade number at the prevailing blade tip Mach numbers.

In an overall sense the study showed that only tractor propeller driven ultralight aeroplanes have a chance to comply with the current stringent (German) noise limits; they must be of clean aerodynamic design (to minimize drag for low thrust requirements), be equipped with thoroughly muffled engines and their operational propeller blade tip Mach number must be limited to values well below 0.5.

List of Symbols

BLN	-	number of blades
c_T	-	thrust coefficient
D	m	propeller diameter
f	Hz	frequency
f_g	Hz	fundamental frequency of rotational noise
h	m	flyover height (above microphone)
L	dB	sound pressure level
L_A	dB	A-weighted sound pressure level
L_{Amax}	dB	maximum L_A (meter time-constant "slow")
$L_{A,HM}$	dB	A-weighted sound pressure level of engine rotational noise
$L_{A,HP}$	dB	A-weighted sound pressure level of propeller rotational noise
$L_{A,BP}$	dB	A-weighted sound pressure level of propeller broadband noise
$L_{A,P}$	dB	A-weighted sound pressure level of total propeller noise

MH	-	helical blade tip Mach number
N_M	1/min	engine rotational speed
N_P	1/min	propeller rotational speed
r	m	source/receiver distance
R	m	propeller-hub/receiver distance
t	s	flyover instant in time
T	N	propeller thrust
u	m/s	blade tip speed
u_p	-	90% confidence limit
v	m/s	true air speed
v_∞	m/s	(wind tunnel) flow speed
v_G	m/s	ground speed
v/u	-	advance ratio

greek

β	degree	blade pitch angle at 75% radius
θ	degree	radiation direction in the vertical plane
ϕ	degree	radiation direction in the horizontal plane
ρ	kg/m^3	air densitiy

indices

o	-	reference value
max	-	maximum
min	-	minimum

note:

sound pressure levels re p_o = 20 µPa

1. INTRODUCTION

In the past decade a new type of a technically simple and affordable aeroplane for leisure aviation has appeared: the "ultralight" or "microlight" aeroplane. The possibility of powered flight "for everybody", initially unrestricted by complicated pilot training and government regulations has caused a rapid growth in the number and variety of such aeroplanes. Ultralight aeroplanes are - by definition - light in weight, ranging from 100 kg (single seat) to 150 kg (twin seat) empty. They are driven by propellers, utilize high-rotational-speed 2-stroke or 4-stroke piston-engines, and attain flight speeds in the order of 50 to 100 km/h. On account of such low flying speeds and many pilots' preference to fly close to the permitted minimum safe flight height of 150 m (perhaps to enhance the subjective feeling of speed) the noise from an ultralight aeroplane is considered a nuisance, although such an aircraft by itself is not necessarily a very powerful noise source.

The current sensitivity to aircraft noise caused several countries to issue noise legislation. In the Federal Republic of Germany, for example, ultralight aeroplanes are required to pass a noise test where the aircraft must execute a horizontal flyover at a height of 150 m above ground at maximum continuous engine power. The maximum flyover-noise is measured with a microphone 1.2 m above ground; the noise level must not exceed a value of 60 dB(A) for those ultralight aeroplanes, which had obtained an airworthiness certificate before the end of 1985. After that date, a 55 dB(A) limit was set.

The noise limit of 55 dB(A) must be considered very stringent, indeed, especially when compared with the noise limit of 68 dB(A) for General Aviation type propeller-driven aeroplanes not exceeding a take-off mass of 600 kg and tested according to ANNEX 16/Chapter 6. In this latter case the certification test flight height is 300 m, rather than only 150 m. Thus, this regulation requires an ultralight aeroplane to radiate 19 (!) dB less noise, than a Chapter-6 aeroplane.

Although such noise regulations for ultralight aeroplanes exist, they are not strictly enforced. This might be due to the fact that little experience exists in measuring the noise specifically from ultralight aeroplanes. This situation is considered not very satisfactory, and many unresolved problems still remain:

For example, should a (certification-type) flight test be required or would perhaps a ground static noise tests suffice. If a flight test was indeed called for, should it be conducted along the lines of ANNEX 16/Chapter 6 with substantial cost (of 5 to 10% of the buying price of an ultralight aeroplane). How accurately could flight conditions be maintained or reproduced by an aeroplane which, after all, is very light and hence sensitive to even slight wind gusts. Is the A-weighted overall maximum flyover noise level an appropriate measure or would a time-duration weighted flyover level, such as the 'Sound Exposure Level' provide a better measure of annoyance, since ultralight aeroplanes are slow and have a low ground speed. And how critical is the microphone position of 1.2 m above ground as currently used in all ANNEX 16 type certification measurements as far as ground reflecton effects are concerned, considering the harmonic content of the typical ultralight aeroplane flyover noise spectrum.

Beyond the rather fundamental problem of the most suitable noise measure (≙ noise metric), the question remains whether existing and proposed noise limits can be technically achieved at all. Are there differences in the minimum attainable noise level due to different types of ultralight aeroplanes (e.g. those equipped with tractor- or with pusher-propellers). Is there hope to reduce noise by "conventional" means, such as increasing the number of blades or reducing the flight speed and/or propeller-rotational speed. How would such measures affect the performance of ultralight aeroplanes. Will a clean aerodynamic design have any positive effect at all, considering the extremely low flight speeds involved. How should a sensible noise certification procedure look; is it really necessary to conduct flight tests or can these be avoided and a certification noise level be determined "on paper" from "first principles". Does any lowest noise limit exist for ultralight aeroplanes, commensurate with operational requirements. After all, ultralight aeroplanes should merge well within a comfortable ambient noise if they are to be considered environmentally acceptable rather than a "pain in the air"!

To answer these questions, a comprehensive research program was initiated by the German Aerospace Research Establishment (DFVLR) Braunschweig Research Center |Ref. 2| involving three basic test phases:

- Flyover noise measurements
- Ground static noise measurements
- Wind tunnel noise measurements

2. FLYOVER AND GROUND STATIC EXPERIMENTS

2.1 Test Aeroplanes

For the flight and ground static tests eight different ultralight aeroplanes were used. One of these could be equipped with either a 2-blade, a 3-blade or a 4-blade propeller, such that a total of 10 different aeroplane configurations were available. Of these, 5 had pusher-, and 5 tractor-propellers. Figs. 1 and 2 show two of the test aeroplanes. All test aeroplanes were powered by two-stroke piston- engines with 1 to 4 cylinders. The following ultralight aeroplanes (manufacturer/type) were tested:

Pusher propeller configurations:

Scheibe/Uli I (2-blade prop)
Scheibe/Uli I (3-blade prop)
Scheibe/Uli I (4-blade prop)
Pohl/Mitchell-Wing (2-blade prop)
HFL/Stratos (2-blade prop)

Tractor propeller configurations:

Pioneer/Flightstar (2-blade prop)
Eipper/Quicksilver (3-blade prop)
Möller/Me 13 (2-blade prop)
Icarus/Sherpa (2-cyl. engine, 2-blade prop)
Icarus/Sherpa (4-cyl. engine, 3-blade prop)

The following propeller-propulsion related parameter ranges were covered:

Propeller rotational speed	1600 - 2500 min^{-1}
Engine rotational speed	3400 - 6000 min^{-1}
Propeller diameter	1.3 - 1.5 m
Number of propeller blades	2 - 4

2.2 Data Acquisition

2.2.1 Acoustic Data

B&K-1/2-inch condenser microphones (type 4131) were used for all acoustic measurements. For the **flyover noise measurements** the microphones were arranged as follows: One microphone each was positioned 1.2 m above a concrete surface, and above a grass-covered surface; one was positioned off-center in an inverted manner 7 mm above a 40-cm-diameter metal plate on grass (ICAO Annex 16/Chapter 10 recommended microphone arrangement), and one was laid flat on a concrete surface. All microphones were

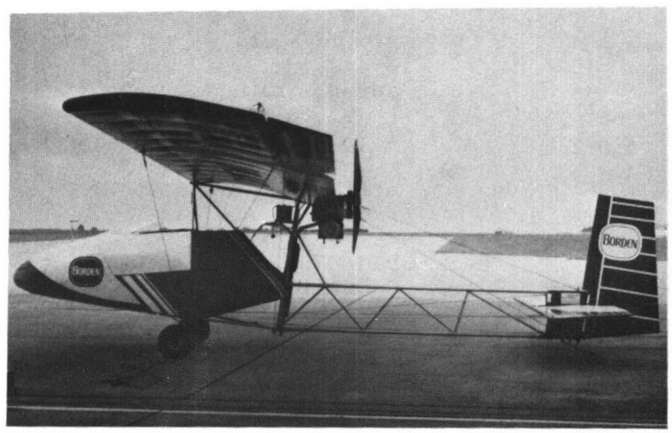

Fig. 1 Scheibe/Uli I 2-blade pusher propeller ultralight aeroplane

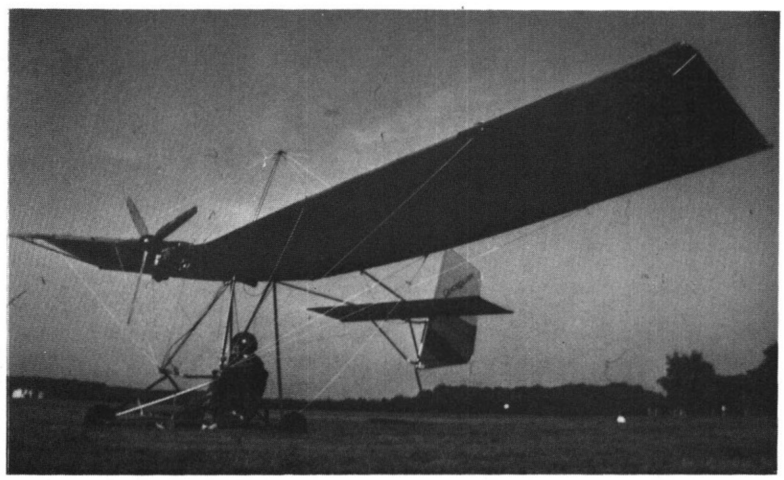

Fig. 2 Eipper/Quicksilver 3-blade tractor propeller ultralight aeroplane

located within a few meters of each other. These arrangements were intended to provide quantitative information on the influences of ground reflection from grass and concrete surfaces. All microphone signals were simultaneously recorded on a multi-channel tape recorder.

For the **ground static noise measurements** microphones were arranged on one half circle of radius 20 m to one side of the test aeroplanes. Data were subsequently taken on both sides. These measurements were exclusively made on a concrete surface, and all microphones were laid on the ground. Fig. 3 shows the arrangement.

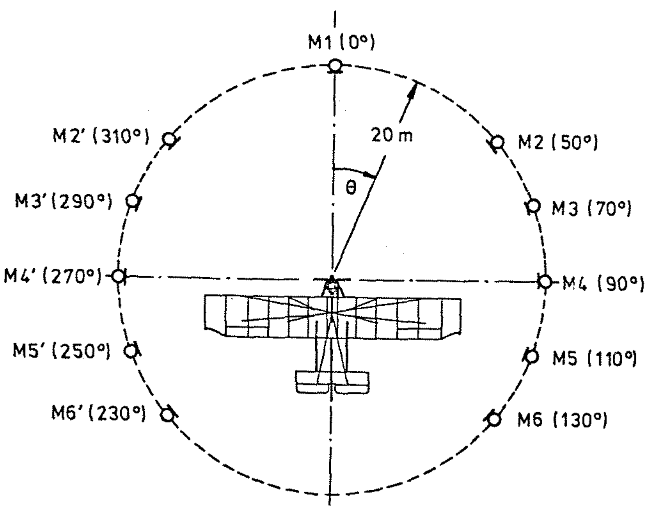

Fig. 3 Microphone arrangement for ground static noise measurements

2.2.2 Flight Height and True Airspeed

Flight height and ground speed were determined by means of two vertically oriented instant-picture cameras. The cameras were positioned under the flight path approximately 50 m before and after the point of vertical flyover above the microphones. Ground speed and true air-speed will not necessarily agree, especially for a light-weight aeroplane. Flyovers were therefore conducted in two opposing directions; the mean of the two ensuing ground speeds provided a sufficiently accurate indication of the mean true airspeed. This speed must be known to determine the helical propeller blade tip Mach number.

2.2.3 Meteorological Data

Air temperature, relative humidity and wind speed were measured and monitored through instruments 2 m above ground. Due to the relatively low test-flight heights of typically 50 to 100 m air temperature aloft was assumed to agree with that measured on the ground.

2.3 Data Analysis

2.3.1 Determination of Propeller Rotational Speed

It was not possible to directly monitor the rotational speed of the propellers on board the aircraft. Instead the flyover noise signature of the propeller rotational fundamental frequency was determined from narrowband analyses and plotted for a sufficiently long time span of flyover. A typical example of the Doppler-effect induced change in the propeller harmonic frequency is shown in Fig. 4. From such plots the actual propeller rotational speed can be derived. This speed must be known to determine the helical blade tip Mach number.

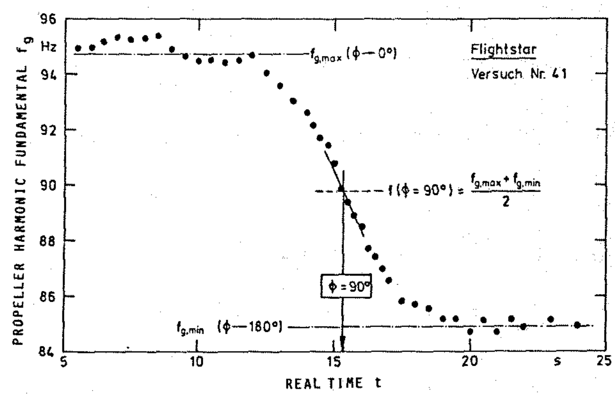

Fig. 4 Doppler-effect-induced change in the fundamental propeller frequency during flyover

2.3.2 Separation of Noise Components

To interprete the flyover and ground static test data it is important to separate the various noise contributors, foremost the propeller and the engine-exhaust. It is also necessary to distinguish between harmonic propeller and exhaust sound and broadband noise. To this end, the following procedure was employed:

Narrowband spectra in the frequency range from 0 Hz to 1600 Hz were obtained at 0.5-second intervals during the flyover time span of interest. A typical example is shown in Fig. 5.

The transmission (gear) ratio between engine and propeller rotational speeds was non-integer in all cases, but one. Thus, the engine and the propeller harmonics can be readily distinguished as shown in Fig. 5. This information allows to separately determine the A-weighted "propeller-flyover harmonic noise" and the "engine flyover harmonic noise" levels, simply by A-weighting and summing the respective discrete frequency components (in terms of squared sound pressure). Both together - with added broadband noise components - should constitute the combined overall A-weighted flyover noise time history. Fig. 6 presents such time histories, where the engine harmonic sound contribution is much less than the propeller harmonic sound contribution (other than at the instant of vertical flyover). The sum of the engine and the propeller contributions does, however, not yield the total overall flyover noise level time history as obtained by direct analysis. The obvious difference must be attributed to broadband components from the propeller or from the aircraft itself ("airframe noise"). It will be shown that broadband noise is indeed a significant noise source of an ultralight aeroplane. In case of a ground static test, separation of engine and propeller contributions is straightforward since sound signatures are essentially steady state and no Doppler-effect occurs.

2.4 Test Results - Flyover Noise Measurements

The discussed data analysis procedures are essential to derive guidelines for the design of low-noise ultralight aeroplanes. Noise certification procedures require, however, only the maximum overall A-weighted noise level during flyover. Such "certification noise levels" were therefore determined for all test aeroplanes in order to check, among other things, whether compliance with the current German ultralight aeroplane noise regulations is possible at all.

A listing of the important operational and acoustical test data for one representative pusher-propeller type ultralight aeroplane is provided in TABLE 1. Here, for an operational condition of maximum continuous power and two opposite flight directions (09 ≙ east, and 27 ≙ west) the values of flight height and ground speed are presented, together with the acoustic data as measured through the 4 microphone arrangements. The block of the 4 right-most columns presents the acoustic data corrected for the reference flight-height of 150 m. The mean noise level for the (certification relevant)

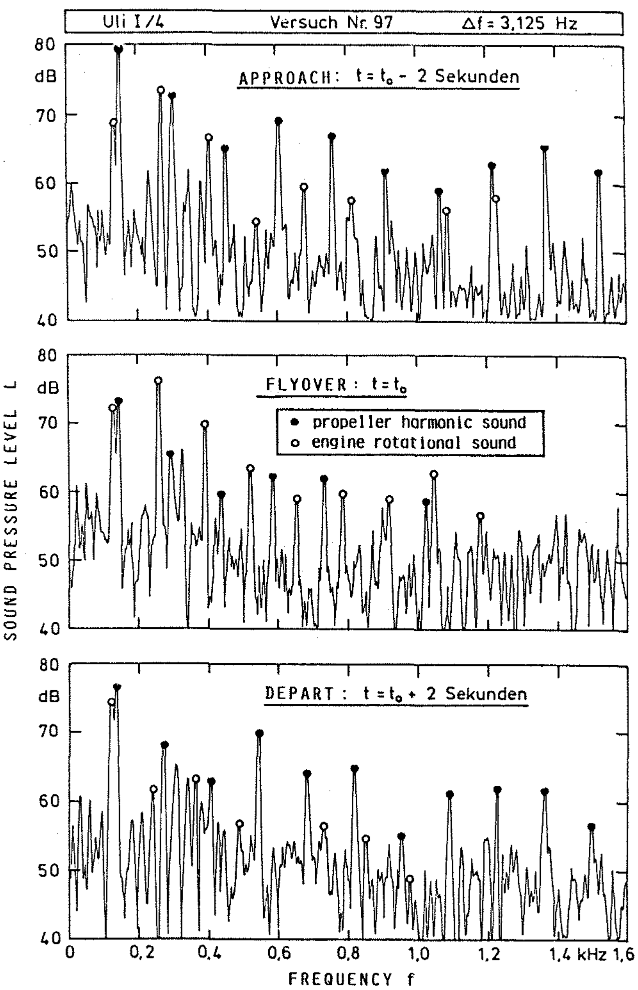

Fig. 5 Narrowband analyses of flyover noise signature 2 s before, at instant of, and 2 s past flyover, respectively

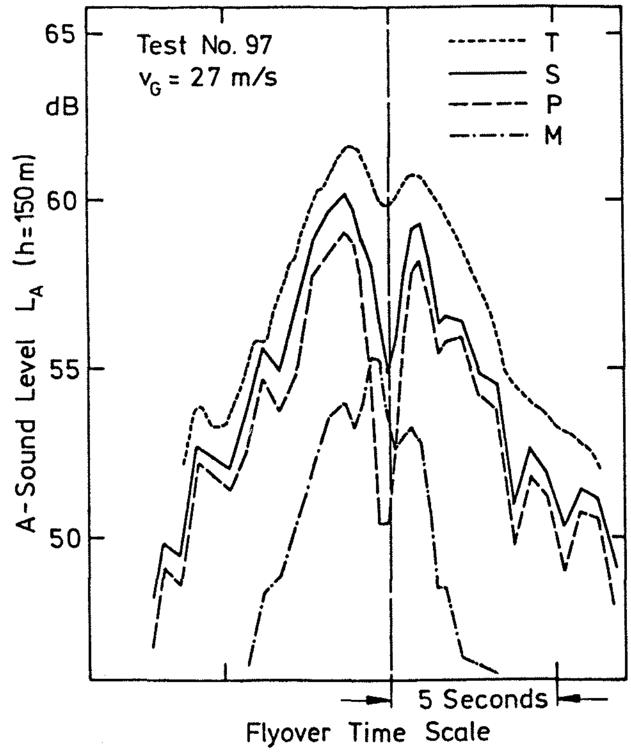

Fig. 6 A-weighted flyover noise time histories for a typical pusher-propeller ultralight aeroplane, separated into the contributions from propeller rotational (P), engine rotational (M), sum of 'P' and 'M' (S), and measured total (T)

microphone 1.2 m above grass in the case shown is 62.9 dB (u_p = +/-0.4 dB). This aeroplane would therefore not meet the 60 dB noise limit and much less so the 55 dB noise limit. It is of interest to note that none of the pusher-propeller ultralight aeroplanes passed the 60 dB limit; only one of the tractor propeller aeroplanes just barely met the 55 dB limit.

The difference in test results for the various microphone positions is shown in Fig. 7, encompassing data from all test aeroplanes. Here the upper representation uses the "1.2-m-above-grass microphone position" as the reference, the lower representation the "0-m-above-concrete position". It is of interest to note that the microphone positions "laid on the hard surface" and "1.2 m above grass" yield a statistically significant mean level difference and confidence limit at 95% probability, respectively, of 4.0 dB and +/- 0.1 dB, rather than the ideally expected 3.0 dB. Comparing the positions "on grass" and "1.2 m above grass" still yields a difference of 3.5 dB +/- 0.1 dB.

2.5 Test Results - Ground-static Measurements

Ground static measurements were conducted to determine the noise emission of the aircraft while simultaneously measuring the static thrust

TABLE 1 Typical flyover acoustic test results for a 4-blade pusher-propeller ultralight aeroplane where M1 ≙ microphone 1.2 m above concrete surface; M2 ≙ microphone laid directly on concrete surface; M3 ≙ microphone 1.2 m above grass; M4 ≙ inverted microphone above circular plate on grass

Test-nbr	Flight-direct.	Flight-height (m)	Ground-speed (m/s)	L_{Amax} as measured (dB)				L_{Amax} re 150 m height (dB)			
				M1	M2	M3	M4	M1	M2	M3	M4
88	09	75,6	19,7	70,9	73,8	69,3	72,5	64,8	67,9	63,2	66,5
89	27	77,2	24,6	70,5	73,9	68,4	71,8	64,6	68,1	62,5	66,0
90	09	73,9	20,8	70,8	74,2	69,8	72,5	64,5	68,1	63,5	66,4
91	27	88,0	22,5	68,4	71,1	67,0	70,4	63,6	66,4	62,3	65,8
93	27	92,7	25,8	68,7	71,9	66,7	69,9	64,4	67,7	62,4	65,7
94	09	92,3	18,7	69,1	72,7	67,5	70,3	64,8	68,5	63,2	66,1
95	27	39,6	25,7	76,1	79,1	75,4	78,4	64,2	67,5	63,6	66,8
97	27	42,3	27,0	75,2	78,6	74,8	77,0	63,9	67,6	63,5	66,0
98	09	35,1	22,1	76,6	80,0	75,1	79,5	63,6	67,3	62,2	66,9

of the propeller. Propeller thrust does change under conditions of forward flight; the influence on noise generation, however, is small compared with that of propeller rotational speed. For data interpretation this ground-static-determined thrust was considered to be a measure for the one occurring at flight.

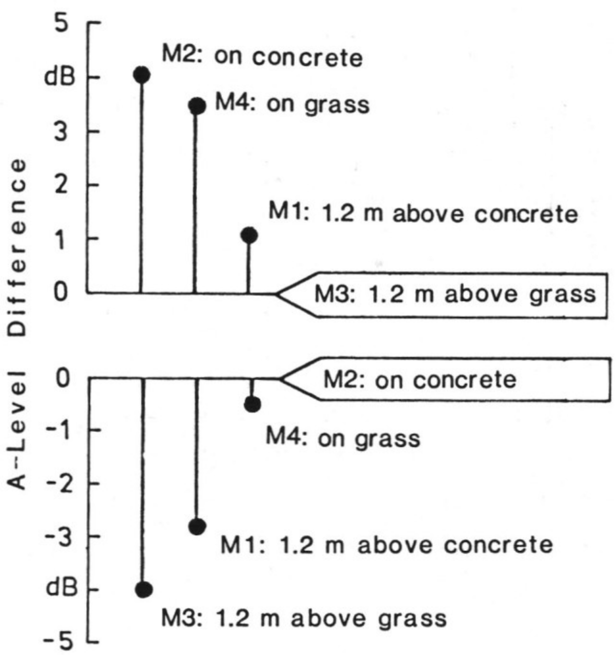

Fig. 7 Mean difference in measured A-weighted flyover noise levels for 4 microphone arrangements

Fig. 8 shows the test set up with the thrust balance in the foreground. For the measurement the engine operated at full power while the aeroplane was connected to the thrust balance with a pulley.

Expectedly, no firm relationship can be established between the noise data from a ground static test and those from a flyover test. A pusher propeller inherently operates in the highly disturbed wake from upstream aeroplane components and from the pilot. A tractor propeller operates under undisturbed inflow conditions. In both cases, though, there is a forward flight component not present in a ground static test. For pusher-propellers in particular, the effect of forward flight on the ensuing noise is substantial.

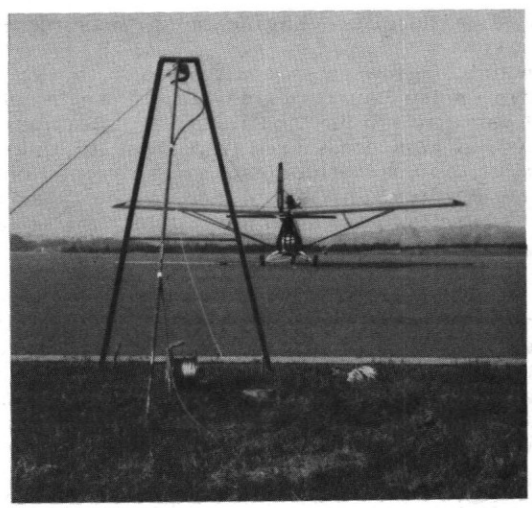

Fig. 8 Test set up for ground stationary thrust and noise measurements

Ever present wind, however light, has a considerable effect on the measured propeller noise from an ultralight aeroplane on ground. This is exemplified in Fig. 9, where acoustic data, as obtained "to the left" and "to the right" are compared. In actuality, the aeroplane was turned by 180° such that the microphones arranged in a semicircle to one side would now measure the respectively other side. For a steady wind condition this meant that in one case inflow was fairly undisturbed, while in the other case inflow was disturbed ("backwind condition") under otherwise identical operational conditions. Clearly, the noise levels "right" and "left" differ substantially. Ground static noise measurements can not be used therefore to obtain a flyover noise certificate.

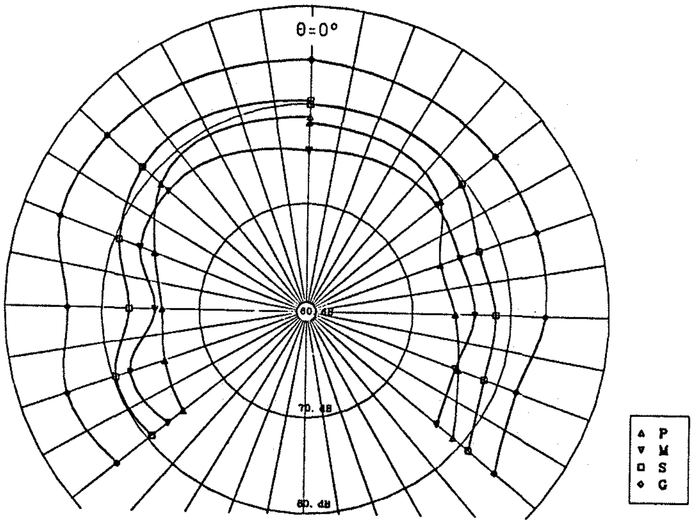

Fig. 9 "left" and "right" noise signature for an ultralight aeroplane under ground static test conditions: P ≙ propeller harmonic; M ≙ engine harmonic; S ≙ sum of propeller and engine harmonic; G ≙ total

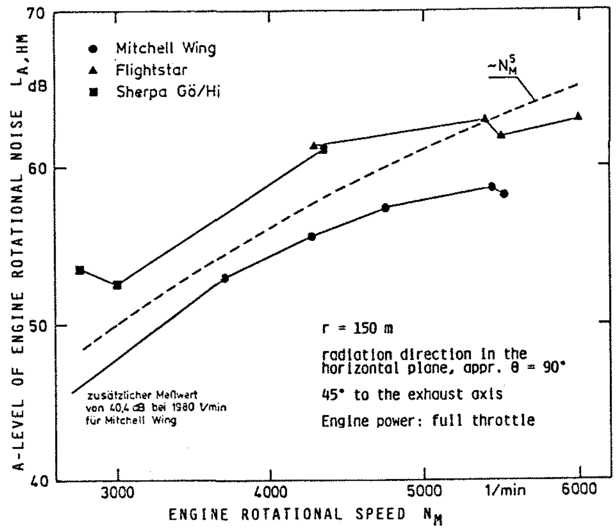

Fig. 10 Engine rotational speed dependence of A-weighted overall sound pressure level for 3 engines from ground static measurements

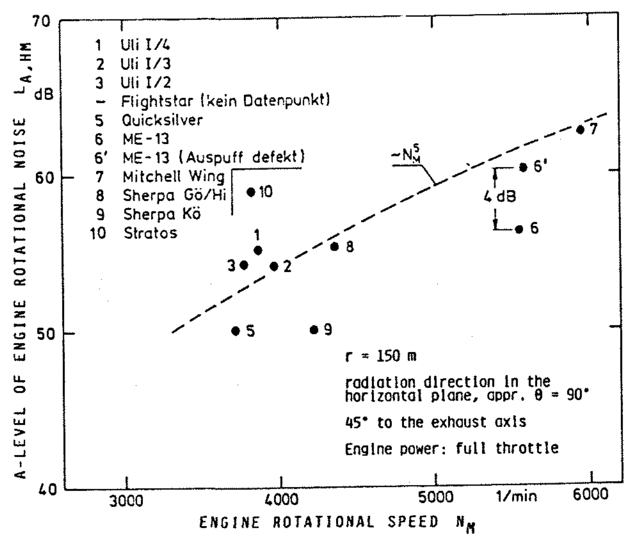

Fig. 11 Engine rotational speed dependence of A-weighted overall sound pressure level for 10 aeroplane/engine configurations from flyover noise measurements

2.6 Test Results - Engine Noise Measurements

Although engine noise contributions to the total flyover noise can be extracted by means of the analysis technique outlined in Section 2.3 above, it was considered important to make separate ground static noise measurements on engines of ultralight aeroplanes in the absence of the propeller to determine their noise-level-vs.-RPM behavior.

For this purpose, the propeller was removed from the aeroplane and replaced by a disk-brake. The brake could be adjusted to simulate different loads on the engine. In this way, the relationship of noise and engine rotational speed under conditions of maximum engine throttle was established.

A typical result from 3 ultralight aeroplane engines is shown in Fig. 10; here the A-weighted noise level at a lateral distance of 150 m from the engine exhaust orifice is plotted vs. engine rotational speed. The data suggest a N^5-dependence for each engine (as equipped with its own muffler).

A similar result is obtained from the flyover noise data. Fig. 11 shows the engine rotational speed dependence of the A-weighted sound pressure level for the engine noise contribution only. Data are plotted for all 10 ultralight aeroplane configurations tested under condition of full engine power.

All engine noise data from both flyover and ground static tests together are shown in Fig. 12. This presentation illustrates the current state of technology with respect to ultralight aeroplane engine noise and engine noise muffling. The obvious spread in the levels is a consequence of engine and muffler differences. Accordingly, a potential for a 10 dB engine noise reduction for some engines seems to exist.

3. WIND TUNNEL EXPERIMENTS

To obtain more detailed information than is possible from flyover noise tests a comprehensive wind tunnel test program was carried out using full-scale ultralight aeroplane propellers. Primary parameters of interest were number of blades, thrust, power, propeller rotational speed, flow-speed ("flight-speed") as well as helical blade tip speed and tip Mach number, respectively.

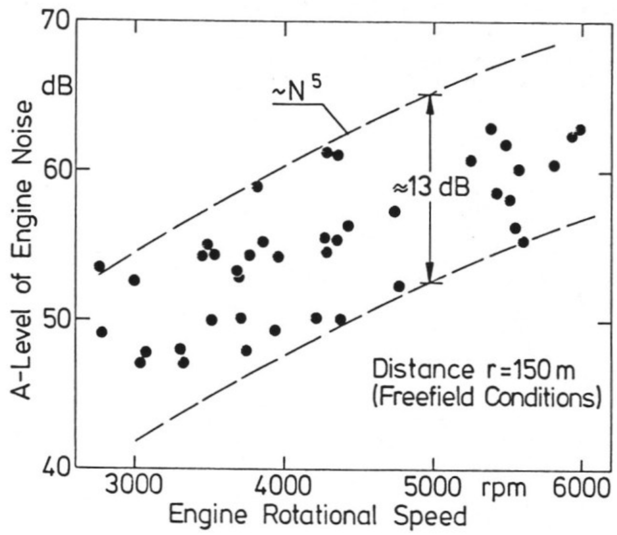

Fig. 12 Engine rotational speed dependence of A-weighted overall sound pressure level for all ultralight aeroplanes from flyover and ground static measurements corrected to a reference distance of 150 m

3.1 Test Set-up

Tests were conducted in the DFVLR Göttingen Low Speed 3-meter Wind Tunnel. This tunnel has an open test section, surrounded by a partially anechoically treated test hall. Fig. 13 shows the 50 kW propeller test stand in the open test section.

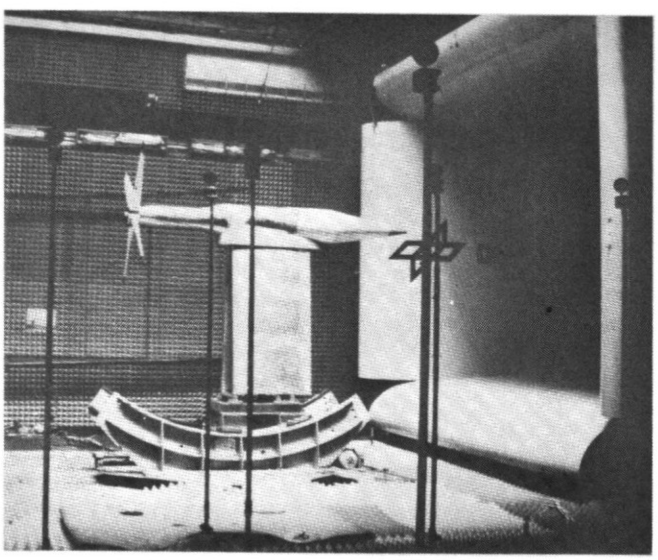

Fig. 13 Ultralight aeroplane propeller test stand in the DFVLR-Göttingen 3-meter Low Speed Wind Tunnel

Wooden Clark-Y-profile propellers (manufactured by the Mühlbauer MT-Propeller Company, Rosenheim, FRG) of 1.4 m diameter (square tip) with 2, 3, and 6 blades, and of 1.6 m diameter (round tip) with 2, 3, and 4 blades were tested. Blade pitch angles could be adjusted for different thrust and power settings. Tunnel flow speeds ranged from 10 m/s to 30 m/s, corresponding to the typical flight speed range of ultralight aeroplanes.

3.2 Data Acquisition

Microphones were positioned in the plane of rotation (≙ 90°), 105° and 120° in the aft-section, and 75° in the forward section at various distances from the propeller hub.

Data from 6 microphones were recorded simultaneously on one multichannel tape recorder. For each data point, thrust, torque, rotational speed and tunnel flow speed were independently recorded.

3.3 Data Analysis

Propeller-noise contains both periodic and random components. The unaveraged frequency spectrum shows a substantial noise floor. To increase the signal-to-noise ratio, the measured time histories were routinely triggered once per revolution and averaged over many revolutions. This procedure essentially eliminates all random components, as well as the stochastic amplitude fluctuations of the periodic components, resulting in a "clean" rotational harmonic time history and frequency spectrum (Fig. 14). The spectral harmonics can now be used - after A-weighting and logarithmic summation - to determine the overall A-weighted noise level at the particular microphone position.

3.4 Test Results - Undistorted Inflow

For a typical lateral microphone location in the propeller plane Fig. 15 exemplifies the helical blade tip Mach number (MH) dependence of the overall A-weighted harmonic noise level for tunnel flow speeds from 15 m/s to 30 m/s. There is, expectedly, very little influence of flow speed, as the relative contribution of the flow speed to MH is small, compared with the blade tip speeds; in this case blade-loading does not change significantly within the operational regime of flight speeds.

The dependence of the overall A-weighted harmonic noise level on propeller thrust is shown in Fig. 16; here MH and blade-pitch were varied. The same dependence is shown in Fig. 17, where, however, MH and blade number were varied. These two representations (for otherwise constant geometric and operational conditions as in the figure legends) indicate that a required thrust may be obtained in a number of ways, yielding different (harmonic!) levels in the course: for example, a two-blade propeller at some constant "flight"-speed provides a thrust of 600 N at a MH of 0.4 and a blade pitch angle of 25°, causing little noise; alternatively substantial noise is generated with a MH of 0.65 and a blade pitch angle of 10°, for the identical thrust. Likewise, at a given thrust a 6-blade propeller generates much less (harmonic!) noise than a 2-blade propeller.

It should be cautioned, however, that below a certain critical MH it is not the propeller harmonic components which determine the overall level but rather the broadband components. This critical Mach number lies somewhere between 0.50 and 0.55. Moreover, on an ultralight aeroplane there are additional engine noise contributions, which are of course absent in a tunnel test.

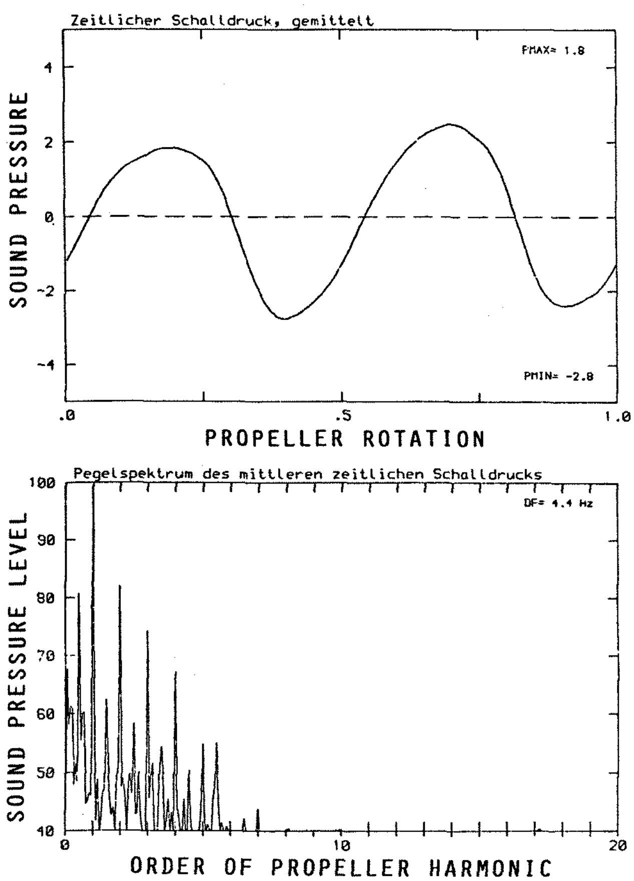

Fig. 14 (a) time history and (b) corresponding narrowband spectrum of once-per-revolution triggered and averaged propeller acoustic pressure

3.5 Test Results - Distorted Inflow

Ultralight aeroplanes equipped with pusher propellers are inherently noisier, than those with tractor propellers. To obtain at least some order of magnitude information on the effect of a substantial inflow distortion, such as caused by the pilot upstream of a pusher propeller on the ensuing noise, the set up in the tunnel was changed to accomodate a (dummy) pilot. The dummy was oriented horizontally to allow measurements "under" the ultralight aeroplane's propeller (Fig. 18).

A *comparison* of a typical averaged time history and the corresponding harmonic spectrum for the undisturbed and the disturbed inflow cases is shown in Fig. 19. Clearly, level increases from *10 to 20 dB - especially at the higher*

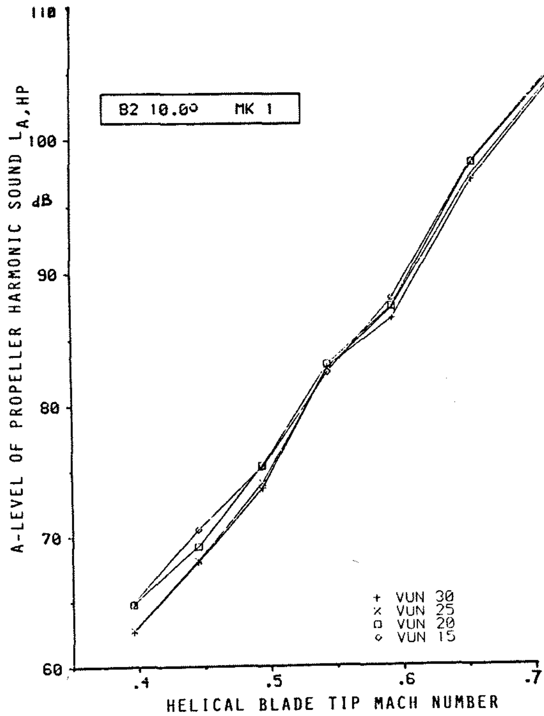

Fig. 15 A-weighted harmonic propeller sound level dependence on helical blade tip Mach number

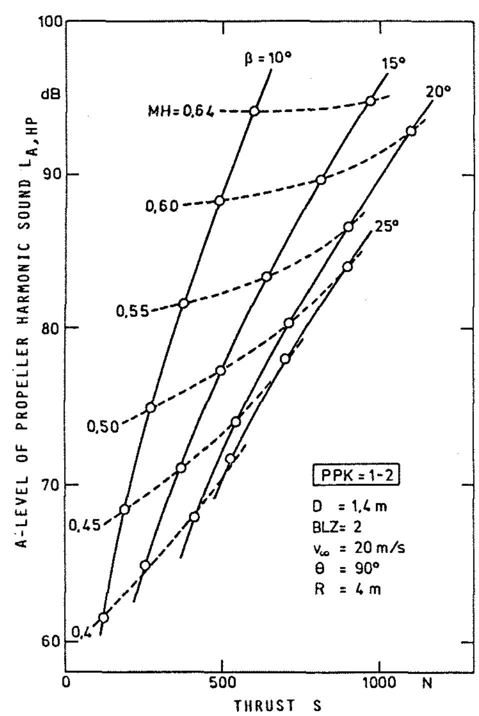

Fig. 16 A-weighted harmonic propeller sound level dependence on thrust with parameters helical blade tip Mach number (MH) and blade-pitch angle

harmonics - result from the grossly disturbed inflow; this emphasizes the potentially severe noise problem caused by pusher-propeller ultralight aeroplanes.

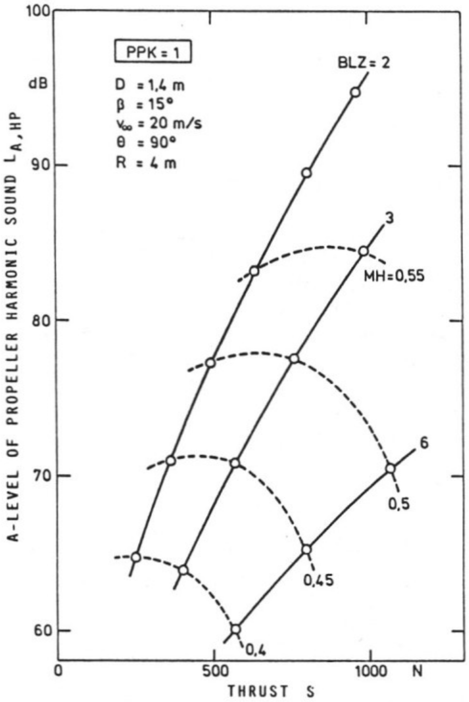

Fig. 17 A-weighted harmonic propeller sound level dependence on thrust with parameters helical blade tip Mach number (MH) and number of blades (BLN)

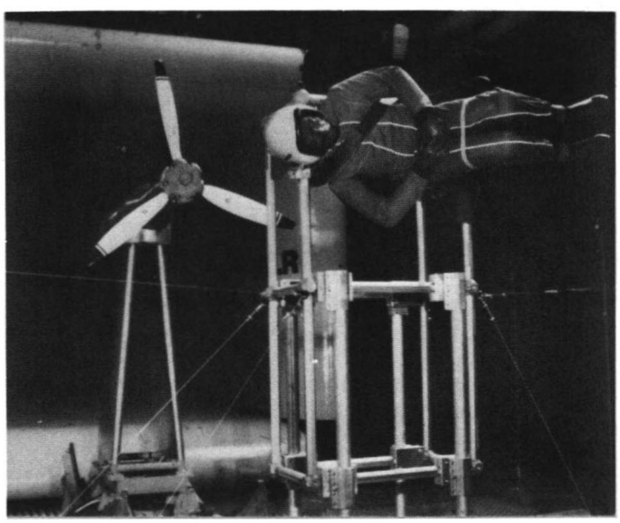

Fig. 18 Dummy pilot upstream of propeller in tunnel open test section

4. DATA INTERPRETATION AND DISCUSSION

The experimental results obtained from the flight, the ground static, and the wind tunnel tests can now be used to derive certain characteristics of the noise from ultralight-aeroplane propellers.

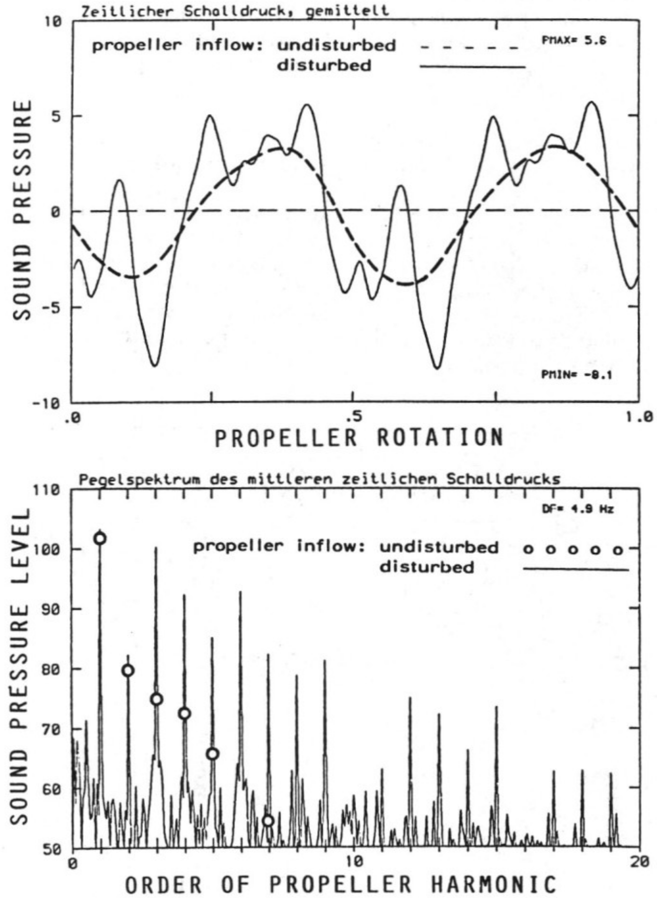

Fig. 19 Effect of an upstream disturbance (full-size dummy pilot) on the ensuing harmonic pressure time history and spectrum

Due to the different source mechanisms that govern discrete and broadband propeller noise and rotational engine noise radiation, influences of operational and geometrical parameters are discussed separately.

In the context of this study, essential propeller noise parameters are helical blade tip Mach number (MH), blade-loading, number of blades (BLN) and propeller diameter (D). Since ultralight aeroplane propellers typically operate at Mach numbers well below 0.6, rotational thickness noise can be neglected. Data interpretation is to yield the dependencies of noise levels on Mach number, empirically normalized with specified blade-loading and propeller geometry.

Ultralight aeroplane propellers operate at extremely low advance ratios v/u. Thus, it is likely that thrust-loading governs the total loading noise radiation. Normalization of noise data with respect to blade-loading can therefore be based on the propeller's thrust coefficient

(1) $c_T = T / \rho \, (N/60)^2 \, D^4$

However the effects of blade diameter and number on the A-weighted levels of rotational propeller noise are manifold and cannot be short-cut by means of a simple physical parametric relationship.

4.1 Propeller Rotational Noise

Employing basic principles, an empirical analysis was performed using the wind tunnel test results for different propeller configurations. By correlating appropriate findings with the rotational propeller noise levels from flyovers, good agreement with wind tunnel data is obtained for tractor propellers (Fig. 20).

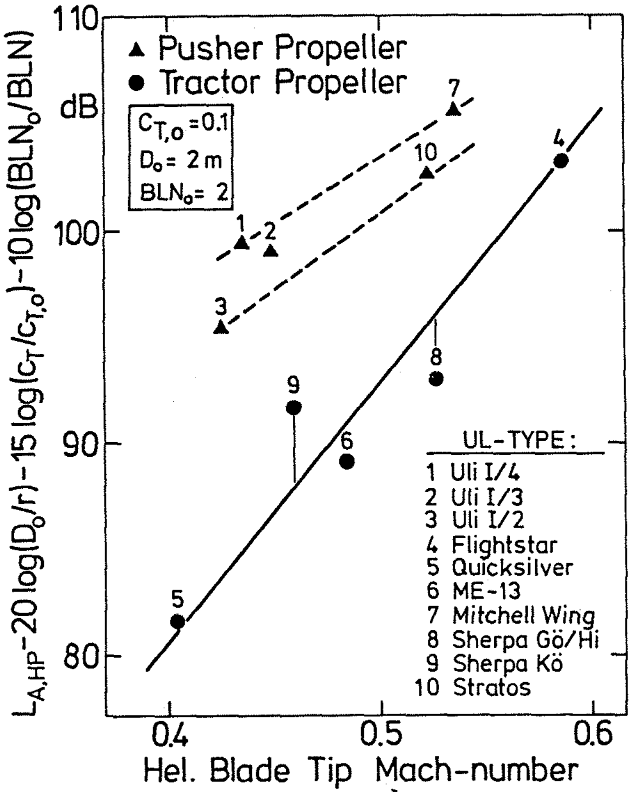

Fig. 20 Normalized A-weighted level maxima of propeller rotational noise vs. helical blade tip Mach number from flyover noise measurements

If corresponding data-points are approximated by a linear dependency, an empirical equation can be derived for the maximum A-weighted level of rotational propeller noise at distance r:

(2) $$L_{A,HP,max} = 31.9 + 122\,(MH) + 20\log(D_o/r) + 15\log(c_T/c_{T,o}) + 10\log(BLN_o/BLN);$$

where $D_o = 2$ m; $BLN_o = 2$; $c_{T,o} = 0.1$;

This equation is valid for parameter regimes:

propeller diameter	$1.4\text{ m} \leq D \leq 2.0\text{ m}$
blade number	$2 \leq BLN \leq 6$
tip Mach number	$0.3 \leq MH \leq 0.6$
thrust coefficient	$0.02 \leq c_T$

Compared with this result rotational noise levels from pusher-propellers are as much as 10 dB higher as a consequence of the disturbed inflow.

4.2 Propeller Broadband Noise

Parametric propeller broadband noise analysis was based on the mean squared sound pressure to increase with the 6th power of blade tip Mach number. Broadband noise data from flyover measurements confirm this assumption for tractor-propellers (Fig. 21). Approximating the corresponding data-points by a straight line yields an empirical equation to estimate propeller broadband noise levels:

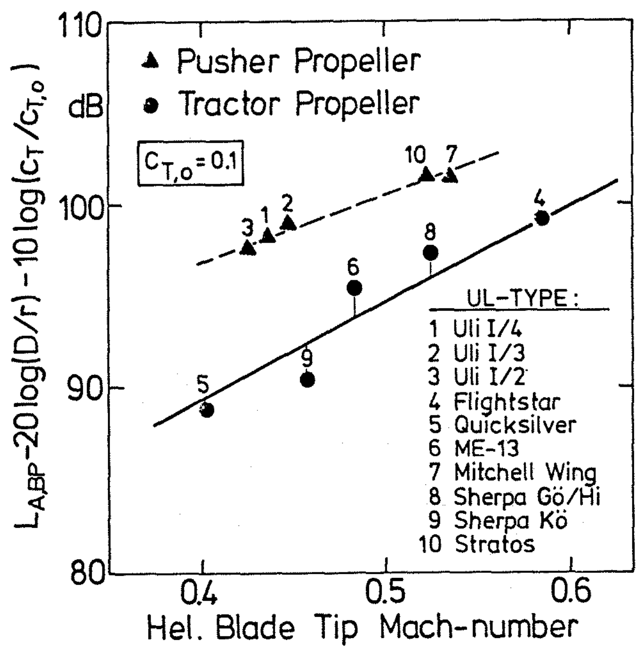

Fig. 21 Normalized A-weighted level maxima of propeller broadband noise vs. helical blade tip Mach number from flyover noise measurements

(3) $$L_{A,BP,max} = 68.3 + 52.5\,(MH) + 20\log(D/r) + 10\log(c_T/c_{T,o})$$

(parameter regimes same as for eq.(2)).

Using eqs.(2) and (3) the total noise radiation from tractor-propellers can be calculated. A corresponding result is presented in Fig. 22 based on a propeller diameter of 1.6 m. Manipulating eq.(3) by eq.(1) it is obvious that broadband noise radiation depends only on blade tip Mach number and thrust, while blade number and diameter seem to be of no importance in the low Mach number regime.

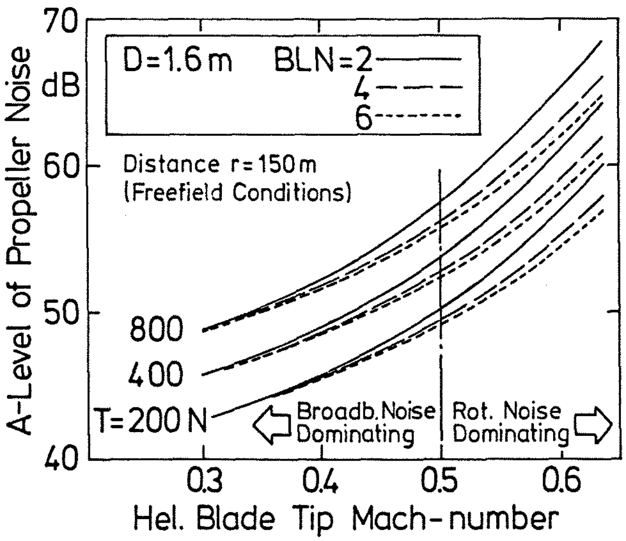

Fig. 22 Estimated A-weighted levels of total propeller noise vs. helical blade tip Mach number for various propeller thrusts and blade numbers

5. DESIGN CRITERIA FOR LOW NOISE ULTRALIGHT AEROPLANES

From the above discussion, certain general guidelines for the design of low noise ultralight aeroplanes can be derived. To-day, there are as many pusher as tractor propeller configurations. Although there are certain advantages of the pusher configuration (safety aspects, high-speed propeller-stream aft of the pilot etc), the acoustic experiments have clearly shown that the observed increase of 10 to 15 dB for a pusher propeller configuration against a tractor-propeller configuration cannot really be compensated by acoustical changes such as lower rotational speeds, for example. Compliance with stringent noise limits seems impossible for pusher-propeller ultralight aeroplanes. The following considerations for optimum combinations of geometric and operational propeller parameters to result in low noise ultralight aeroplanes are therefore restricted to tractor propeller configurations.

Propeller radiation may be conveniently expressed as the sum of the acoustic harmonic and broadband components, i.e.

(4) $$L_{A,P} = 10 \log \left(\left(10^{(L_{A,HP}/10)} + 10^{(L_{A,BP}/10}\right)\right).$$

Also, certain parameters have comparatively little influence and can be removed from further consideration; such parameters would be the air-density, the air-temperature, and the airspeed. In this case, the helical blade tip Mach number is solely a function of propeller rotational speed and propeller diameter. One can now express the thrust coefficient (see equ. 1) as function of the helical blade tip Mach number and propeller thrust only. The remaining free parameters of influence are then

- propeller diameter
- number of blades
- propeller thrust
- helical blade tip Mach number

Fig. 23 shows the dependence on the helical blade tip Mach number of the propeller A-weighted noise level (containing both harmonic and broadband components) for various propeller thrusts and blade numbers. Data are referenced to a flight height of 150 m, flight-speed is constant at 20 m/s and propeller diameter is 1.4 m. Fig. 24 provides the same information for a propeller diameter of 2.0 m. The noise level increase grows with Mach number. Also, propeller diameter and blade number become increasingly important. The effect of these two latter parameters vanishes, however, for helical blade tip Mach numbers below 0.4, such that below this Mach number it is the thrust remaining as the only parameter of importance. This statement is in agreement with the earlier finding that a decrease in Mach number causes broadband components to dominate the propeller noise, and vice versa.

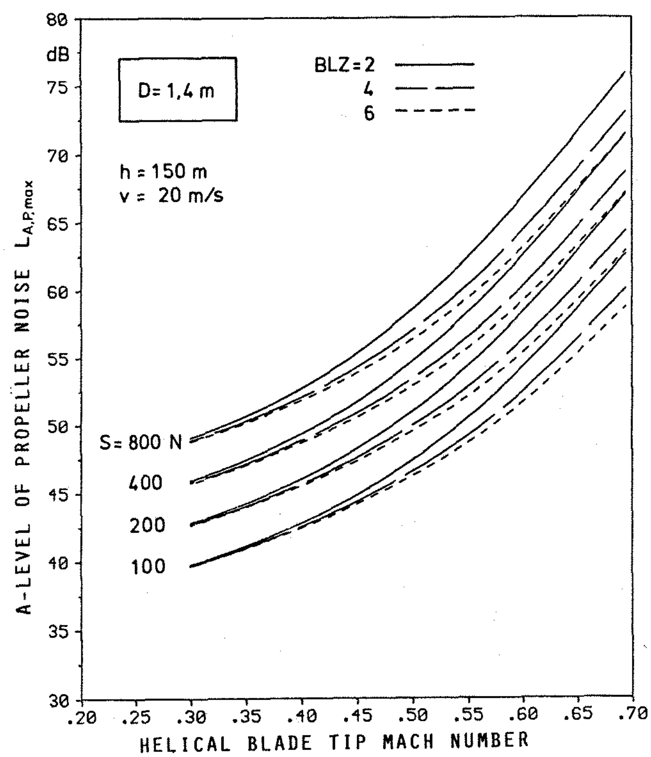

Fig. 23 Estimated A-weighted levels of total propeller noise vs. helical blade tip Mach number for a propeller diameter of 1.4 m and for various propeller thrusts and blade numbers

To achieve minimum propeller noise, it is thus generally advantageous to aim for minimum blade tip speeds for any required propeller thrust. Should such speeds still result in blade tip Mach numbers above 0.5, it would then be indicated to increase the propeller diameter and, if feasible, the number of blades. Without specifying certain blade profiles, one may state that sharp-contoured blade trailing edges and round blade tips tend to reduce the broadband noise generation. Since propeller thrust (at these low tip Mach numbers) is of such importance, it is now also strongly advisable to aim for a good aerodynamic design of the ultralight aeroplane itself.

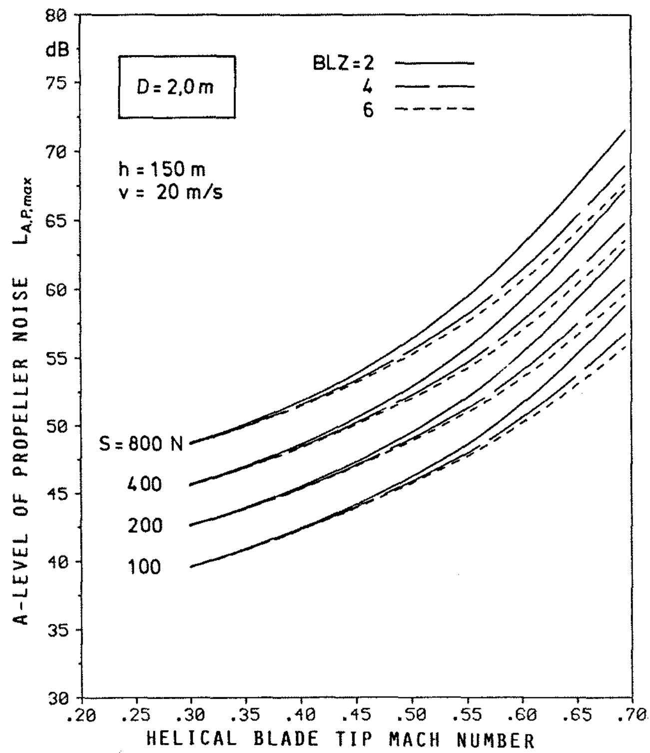

Fig. 24 Estimated A-weighted levels of total propeller noise vs. helical blade tip Mach number for a propeller diameter of 2.0 m and for various propeller thrusts and blade numbers

It should be pointed out that the levels as shown on the ordinates of Figs. 23 and 24 are free-field values. Since noise certification under ICAO-ANNEX-16 requires flyover noise being measured with a microphone 1.2 m above a grass surface, one may utilize the information in these figures and subtract 4 dB to account for the difference in microphone height, and add 6 dB to account for the free field condition; hence the current noise limits in the Federal Republic of Germany of 60 dB and 55 dB, respectively, would correspond to levels of 58 dB and 53 dB on the ordinate scales of Figs 23 and 24.

The levels as shown in these figures pertain to the propeller only. They would be strictly valid, if the engine contribution was at least 10 dB less than the propeller contribution. This assumption is, however, quite unrealistic. An ultralight aeroplane engine, even if well muffled, is more likely to contribute at least the same noise level as the propeller. In this case the permissible maximum propeller noise level must be lowered by another 3 dB.

Depending on the required propeller thrust, one may now go ahead and select an appropriate combination of blade number and tip speed. If the helical tip Mach number can be held below approximately 0.5, a further simplification is possible in representing ultralight aeroplane noise level vs. propeller-thrust, since now blade tip speed would be the only free parameter. Such a simplified representation appears in Fig. 25. Here the limit B1 pertains to an ultralight aeroplane, where the propeller dominates, and B2, where propeller and engine contribute equally. The tip speed corresponding to the noise limit can now be achieved with any combination of rotational speed and propeller diameter.

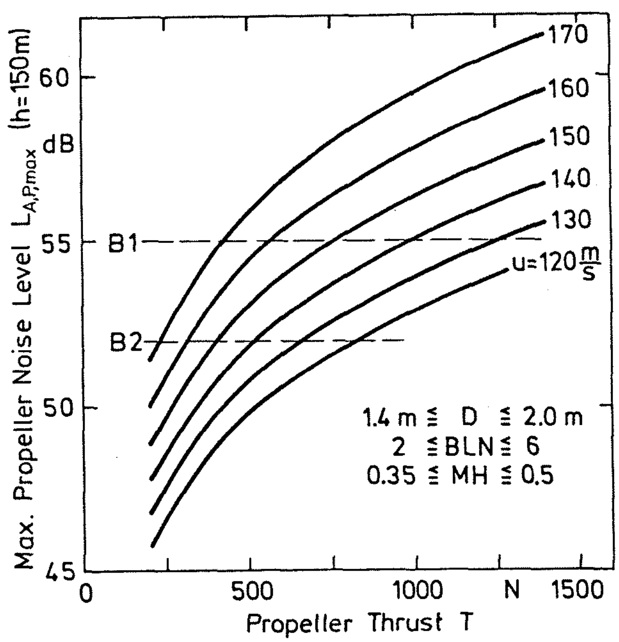

Fig. 25 Estimated maximum A-weighted flyover noise level as function of propeller thrust and blade tip speed;

boundaries B1 and B2 correspond to a noise limit of 55 dB (B1 to be applied if the propeller noise component dominates, B2 if propeller and engine noise are of equal magnitude)

6. CONCLUSIONS AND RECOMMENDATIONS

The results of this study are:

- Flight speed has no appreciable influence on propeller noise generation.

- Propellers with helical blade tip Mach-numbers below 0.5 radiate predominantly broadband noise; at higher Mach numbers harmonic noise components dominate.

- The A-weighted overall propeller-harmonic level rises linearly with approximately 12 dB, the overall propeller broadband noise with 6 dB, per one-tenth increase of the helical blade tip Mach number.

- At a given helical blade tip Mach number higher thrust loadings generate higher propeller noise.

- Distorted inflow increases propeller noise by 5 to 15 dB depending on the aerodynamic characteristics of the disturbance.

The stringent noise certification limit of L_A = 55 dB for current and future ultralight aeroplane designs in the Federal Republic of Germany can only be complied with if the aircraft is designed along the following guidelines:

- Configurations, where the inflow into the propeller rotational plane is highly distorted as a consequence of an upstream wing or strut, or of the position of the pilot in pusher-type ultralight aeroplanes must be excluded.

- The helical propeller blade tip Mach number should not significantly exceed a value of 0.45 if the engine noise is much less than the propeller noise, and of 0.40, if both noise components are of equal magnitude.

- The aircraft should have a very clean aerodynamic design to minimize ("noise-producing") thrust requirements.

- The engine must be fitted with an acoustically efficient exhaust muffler.

Following these guidelines should make it possible to design and construct a low-noise ultralight aeroplane which - in all likelihood - is not a "pain in the air", but rather a flight vehicle that would be acceptable to both the operator and the public.

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Acknowledgement

The support of the 'Umweltbundesamt' (German Federal Environmental Protection Agency) is highly appreciated. The authors also thank the staffs of the DFVLR Flugabteilung, Braunschweig, and of the DFVLR Hauptabteilung Windkanäle, Göttingen.