Abstract

The feasibility of attenuating propeller farfield noise is demonstrated by means of superimposing exhaust noise from the piston-engine with the very propeller noise so as to produce a destructive interference. Both the propeller noise and the engine exhaust noise signatures consist of a succession of periodic signals with "positive" and "negative" pressure parts. The problem is therefore the "adjustment" of the propeller sound signal so that it is precisely in anti-phase with the exhaust noise signal. A potentially promising way to achieve such an objective lies in the adjustment of the relative circumferential position of the propeller blades to the crank shaft such that - at any particular observer position on the ground - "sound" and "anti-sound" would combine to produce a reduced level.

To substantiate this concept a theoretical and experimental study was initiated. In order to support the theoretical findings, flight tests with a Cessna T 207 aircraft were executed. A special flange was inserted between the propeller and the drive shaft. The flange could be rotated in steps, thus shifting the phase of the sound waves as radiated from the propeller with respect to those of the engine exhaust. Acoustic measurements with a wing-mounted microphone indicated the feasibility of the concept in the near-field of the aircraft, where A-weighted overall level differences between 3 and 4 dB were observed. Flyover noise tests on the farfield effects using a microphone on the ground indicated a noise reduction potential from 4 to 6 dB between particularly good and bad relative propeller blade positions.

INTRODUCTION

The concept of active sound attenuation as first published in the early thirties by Lueg [1] used an "artificially" produced sound to counteract unwanted noise. The reactive suppression in the near-field of a primary source has been parti-cularly investigated by Nelson et al. [2, 3]. The attenuation of a sound field radiated by a point source by using an adjacent monopole source as a simple example of the active control of sound has been discussed more recently by FFowcs Williams [4]. A practical use of this concept was demonstrated by Chaplin [5] who succeeded in reducing the periodic sound as radiated by the exhaust of an internal combustion piston engine. A proposal to reduce the noise of overflying propeller driven aeroplanes using anti-noise loudspeakers or sirens installed under the wings was made by Bscchor in 1973 [6]. Most of these concepts however relate to stationary problems where the source does not move with respect to the receiver.

Active noise attenuation by destructive interference of the sound radiation from a primary and from a secondary acoustic source has thus long been recognized as a promising means to reduce the noise especially of low-frequency sources. To reduce the noise of a piston-engine powered propeller aeroplane one might consider the propeller to represent a primary source whose radiative field is to be appropriately superimposed with the sound field of the engine exhaust as the secondary source.

Within a theoretical and experimental study a method was developed and its feasibility demonstrated to attenuate the rotational (harmonic) noise from overflying aeroplanes by adjusting the propeller noise in anti-phase to engine noise. A reduced overall acoustic power output can be achieved by appropriately arranging the secondary source (piston-engine), whose strength is allowed to differ in magnitude from the primary source (propeller). It is important to point out that, when a noise source is moving or another source is added, then the result is a complex acoustic radiation pattern. In most cases this pattern is distinctly different from that of a source at rest in a free field. Static acoustic measurements made for the purpose of characterising the source behaviour or of understanding the very noise generating mecha-
nisms must accordingly be corrected for motion and the effect of interference. The need to make such corrections and the accurate prediction of noise from moving individual sources (or of systems of sources) from first principles requires a thorough quantitative understanding of these effects. It is important to realize that kinematic and dynamic effects of forward motion and interference of sound from the sources play a significant role in the measurement and prediction of noise from aircraft.

In this paper some theoretical results on the influence of the proximity of sources and of their motion on the radiation from acoustic monopole and dipole sources are presented and experimental findings are reported on propeller and exhaust noise interference effects during flight. Parts of this work are based on earlier studies by the author and one of his collaborators (7, 8, 9, 10).

THEORETICAL CONSIDERATIONS
Calculation of the Intensity
Radiation Pattern

The sound field of a propeller driven aerofoil may be derived by superimposing propeller noise and engine exhaust noise. The sources of both these harmonic noises produce again a harmonic noise pattern with a certain amount of higher frequency components. In order to use the sound sources in an efficient manner for purposes of destructive interference, pressure amplitudes of equal magnitude and good phase matching of the sources are an important prerequisite.

Following Gutin’s classical theory for propeller noise (steady blade forces in a rotating reference frame) and using an approximation by Goldstein [11] in which directivity and phase information are preserved, and furthermore assuming a monopole for the engine exhaust orifice, the normalized intensity in the far-field may be expressed as:

\[ I' = \frac{1}{2\pi} \frac{F_n}{4nB^2} (\sin \theta)^2 (\cos \theta + c_f)^2 + \frac{2}{4nB^2} + \frac{2}{4nB^2} F_n (\sin \theta) \frac{B}{4nB^2} (\cos \theta + c_f) \cos \theta \]

\[ \theta = 2n(e \cos(\phi - \phi') \sin \theta + a' \cos \theta) - nB(\phi - \phi' - \phi_0) \]

(in this case no individual phase shifting of the higher harmonics of the engine exhaust noise is made). Here, \( n \) and \( B \) are the higher harmonic order and the number of blades, respectively, \( \phi_0 = \phi - \phi_f \) is the ratio of the engine exhaust and propeller velocity potentials and \( c_f \) is a factor which is usually somewhat less than unity (\( c_f = 0.9 \)), thus not signifi-

\[ F_n = \frac{1}{2n} \int_0^1 \frac{1}{(\sin \theta)^2 (\cos \theta + c_f)^2} d\theta \]

and from Fig. 1.

\[ \text{Fig. 1 Coordinates of Propeller and Exhaust Relative Positions for establishing an Acoustic Model; (Sources in Motion)} \]

The intensity \( I' \) was normalized with

\[ I' = \frac{1}{\rho K_n B^2} \frac{1}{2\pi^2} \]

\( \rho \) being the density, \( K_n \) the wave number related to the \( nB \) order of harmonics and \( \omega \) the radian frequency of the sources, respectively. For simplicity the intensities of the propeller and engine exhaust sound were assumed to be equal. As in the case of a source near a wall (image source) this superposition of the sound fields causes a complicated intensity radiation pattern showing a number of lobes.

The number of lobes in the propeller plane depends on the term \( nB \theta \) in eq. (1). In case of a 3-blade propeller the intensity radiation pattern consists of e.g. three maxima for the first and of fifteen maxima for the fifth harmonic (Fig. 2). The lobes differ in shape since the angles between the maxima are different. The orientation of the interference pattern in the propeller plane with regard to a symmetric axis depends on the
phase difference between propeller sound and exhaust noise. It may vary as a result of an azimuthal displacement of the propeller relative to the crank shaft. An orientation of the narrowly spaced lobes towards the ground is disadvantageous and should be avoided (as illustrated in Fig. 3/right half on the 5th harmonic pattern).

Local Interferences

According to classical calculation examples dealing with elementary sources it is desirable to replace the cosine argument \( \theta \) in the third summation part of eq. (1) by a suitable value of \( \Delta \phi \) in the argument to give a value of \( \cos \theta = -1 \). This would result in a reduction of the intensity maximum

\[
\Delta I'_{\text{max}} = - \frac{E_n}{\pi} \Theta_R (\sin \phi) nB (\cos \phi + \phi')
\]

To reduce the sound radiation towards the ground it is even more important to specifically adjust the interference pattern as described in the following: The maximum intensity lobes forming the largest aperture angle \( \Delta \phi_{\text{max}} \) can be positioned symmetrically to the vertical axis. This causes a 'zone-of-silence'-aperture underneath the aeroplane. This maximum angle can be opened up still further by certain additional steps (to be explained further down). The propagation distances for the sound waves which are oriented in the direction of these maxima, are now much larger before they hit the ground. The sound pressure level difference for the spreading reduction compared with a vertical radiation is

\[
\Delta L_p = 20 \log (\cos \phi)
\]

(see Fig. 2).

The nB maxima in eq. (1) appear at the angles \( \phi_{\text{max}}^{(n)} \) on the circumference, when the argument of the cosine term is an integer multiple of \( 2\pi \).

\[
2\pi [e' \cos (\phi_{\text{max}}^{(n)} - \phi_A) \sin \phi + a' \cos \phi] - nB (\phi_{\text{max}}^{(n)} - \phi - \frac{\pi}{2}) = 2m \pi
\]

where \( m \) is a natural number which sequentially designates the successive maxima.

The dimensionless distances \( e' \) and \( a' \) are now expressed as \( e' = e n B / c = e_n B \) and \( a' = a n B / c = a_n B \). Now eq. (2) may be rewritten in an implicit form

\[
\phi_{\text{max}} = 2\pi [e \cos (\phi_{\text{max}} - \phi_A) \sin \phi + a \cos \phi] - \frac{\pi}{B} + \frac{1}{2} \Delta \phi
\]

The term \( 2\pi a \cos \phi \) causes a rotation of the interference pattern during the flyover. If this rotation is to be avoided, with regard to the closer spaced maxima.
of the higher order harmonics, the distance a between engine exhaust and propeller plane must be minimized. The term

$$2\pi e_a \cos(\theta_{max} - \theta_a) \sin\theta$$

describes a deformation of the circumferential distribution of the maximum values from the interference pattern. It is obvious that the circular position \(\theta_a\) of the engine exhaust has separated the entire lobed pattern into two semi-circles. One of them - included between the angles

-180° + \(\theta_a\) and \(\theta_a\) - contains growing angles, the other semi-circle contains the contractions of the angles between the lobes. In order to put the particular pattern (with increases of angles) towards the ground, the attitude of the exhaust should therefore assume an angle of \(\theta_a = 90°\). Furthermore, to achieve a symmetrical adjustment of the largest aperture angle \(\Delta\theta_{max}\) between two maxima during the flyover a value of

$$\Delta\theta_{max} = \theta_{max} - \theta_{max}$$

using eq. (3) is formed, i.e.

$$\Delta\theta_{max} = 2\pi [e_a \cos(\theta_{max} - \theta_a) - \cos(\theta_{max} - \theta_a) \sin\theta + \frac{1}{nB}]$$

(4)

For a distance between engine exhaust and axis of rotation \(e_a = 0\), eq. (4) in the overflight position \(\sin\theta = 1\) yields an equidistant distribution of the maxima \(\Delta\theta_{max} = 2\pi /nB\). With respect to an increase of the angle between two maximum lobes \(\Delta\theta_{max}'\), it is more advantageous to optimize the distance \(e_a\) of the exhaust to the axis to ensure an increase of this angle instead of setting \(e_a = 0\).

After optimization of \(e_a\), the maximum achievable angles \(\Delta\theta_{max}\) for a certain rotational speed can be determined. An exact adjustment of those \(\Delta\theta_{max}\) for all phases of both sources which are symmetrical to the vertical axis can be carried out by "tuning" the phase difference \(\Delta\phi\) on the propeller shaft.

With some precautions, such as

- eliminating \(a\) to avoid changes of the signal distances to the receiver on ground during flight,
- setting exhaust orientation \(\theta_a = 90°\) to direct the particular best-suited angle with increased angles between the lobes towards the ground, and
- adjusting the phase difference at a value of \(\Delta\phi = -30°\) (which means that angle spreadings of the interference patterns are symmetrical toward the ground)

the following very promising results may be achieved.

Example:

Assume the following conditions:

- \(e = 1.25\) m;
- \(a = 0\) m;
- \(\theta_a = 90°\);
- \(\Delta\phi = -30°\); and
- a rotational speed range from 2500 to 2600 RPM.

Although these conditions may not be actually realized in practice, beneficial spreading angles \(\Delta\phi_{max}\) as well as substantial noise level reductions \(\Delta Lp\) are computed. For the

fundamental: \(\Delta\phi_{max} = 225.6°; \Delta Lp \approx 0\)

no components to the ground

5th harmonic: \(\Delta\phi_{max} = 126°; \Delta Lp = -6.9\) dB

10th harmonic: \(\Delta\phi_{max} = 99.4°; \Delta Lp = -3.8\) dB

As shown in this example and in Fig. 3, slight changes of the position of the exhaust and the adjustment of phase differences result in large spreadings of the angles between the lobes with considerable reductions of the noise radiation towards the ground.

**EXPERIMENTAL ASPECTS**

**Test Aeroplane**

Near-field noise experiments were conducted on a Cessna T 207 airplane, equipped with a Teledyne Continental six-cylinder, four-stroke turbo-charged piston engine of 212 kW rated power and a McCauley three-blade variable-pitch propeller of 2.03 m diameter (Fig. 4). The aircraft was typically flown in level flight at constant flight speeds of 60 m/s. Additional near-field noise experiments were performed with a Hartzell two-
blade variable-pitch propeller of 2.03 m diameter.

The aircraft was equipped with a wing-mounted microphone M1 for fixed-position near-field noise studies. Measurements with such airplane-attached microphones are inherently free from ground-reflections and cross-wind effects, which necessarily occur in flyover ground-based measurements. Moreover, there is no Doppler-effect, allowing the gathering of accurate base-line data. In contrast to wind tunnel tests on isolated propellers, however, the very propeller noise is "contaminated" with engine noise contributions. Therefore, the aeroplane was equipped with a microphone M2 close to the engine-exhaust orifice to allow an identification and quantification of the engine noise.

**Engine Noise Characteristics**

As shown in Fig. 5, top, the signature of the four-stroke engine at constant rotational speed and torque exhibits a succession of signals of characteristic shape and amplitude. Each signal corresponds to one working cycle of a piston. The individual engine pressure signals consist of "positive" and "negative" components, as evident from the pressure-time histories from the six-cylinder engine shown in the Figure. Each engine pressure signal has its own characteristics, affected by the combustion processes, and the propagation within the cylinder outlets and in the exhaust system. The very propeller wake may to some extent also affect the exhaust noise, its effect however being minimal. Considering a longer sequence of 3.5 working cycles (Fig. 5, bottom), one may observe that each of the six individually formed signals belonging to any particular cycle are repeated in a time span corresponding to two revolutions (= one firing cycle of the four-stroke engine). This becomes more obvious still, if signals with identical numbers are considered. The distance in time between these signals corresponds to \( t_c = 2 \cdot 60/n = 46 \text{ ms} \) for a rotational speed of \( n = 2600 \text{ RPM} \), related to a sequential time between two firings \( t_c = 2 \cdot 60/2 \cdot n = 7.7 \text{ ms} \), where \( z \) is the number of cylinders. Signals of identical number show an identical shape.

In contrast to the propeller noise signals, the time span from one signal to the next is not the same. This is a consequence of the particular shape of the exhaust system of the turbo-charged engine (Fig. 6). The exhaust system of the same engine without turbo-charger consists however of two simple pipes (Fig. 7).

![Fig. 5 Engine Exhaust Sound Pressure Signatures](image)

![Fig. 6 Exhaust System of the Continental Turbo-charged Engine](image)

**Propeller Noise Characteristics**

As shown in Fig. 8, at blade helical tip-Mach-numbers \( MH^* \) greater than 0.7 the pressure-time history signal of a rotating propeller consists of a sequence of distinct impulses. They possess "posi-
tive" and "negative" parts, each one "im-
pulse" corresponding to one each blade 
for one propeller revolution. This Figure 
shows data for a constant $M/H = 0.83$ for 
microphone position M1. M1 is located 4 m 
from the propeller axis to the leeward 
side, 1 m aft of the propeller-plane. At 
a speed of 60 m/s this microphone meas-
ures noise signals that were propagating 
in the plane of rotation. It is obvious, 
that the positive components exhibit an 
approximate saw-tooth shape. In contrast,
at the normal speed of the propeller, a 
relatively narrow peak pressure pulse is 
formed on the negative pressure side.

At moderate tip Mach numbers, rotating 
blades produce both monopole (thickness) 
and dipole (thrust and torque related 
loading) type noise. The sound field from 
rotating blades is periodically in time 
with $60/B\cdot n$, where $B$ is the number of 
blades and $n$ is the shaft speed. At a 
constant rotational speed the time span 
between two signals is constant and can 
be exactly calculated.

Narrow-band analysis of signal sequen-
ces, as represented in Fig. 8, shows that 
the distinct negative pressure part of 
the signals are responsible for a spec-
trum with substantial higher frequency 
content, which largely determine the A-
weighted level. A "narrowing" of the ne-
gative pressure peaks thus causes the A-
weighted level to increase.

**Superposition of Signals**
in the **Time Domain**

For the typical aeroplanes the phase 
angle between propeller sound and engine 
noise is in no way optimized; the time of 
the emission of the acoustic sound waves 
from the propeller and from the engine 
exhaust are not adjusted to result in mi-
imum sound radiation (and often, after 
an overhaul, the propeller is put back on 
the crank shaft in a different circum-
ferential position). In practice, the 
signal sequences of engine and propeller 
are propagating with a fixed time delay 
just as chance would have it. Moreover, 
in the process of measuring flyover noise 
of two sources separated by a certain 
distance, the ensuing sound waves are 
continuously shifted with respect to a 
stationary observer on the ground. It is 
of interest, therefore, to determine in 
advance, and prior to any actual flyover 
noise testing, how the combined signal 
changes after a propeller was adjusted in 
different circumferential positions.

A computer-simulation was carried out 
by shifting two series of propeller noise 
signals and engine exhaust noise signals 
in small incremental steps and adding their pressures. Fig. 9 shows a typical 
result with two series of signals as 
measured on the test aeroplane Cessna T 
207 in flight. The signals of the two 
concurrent sound sources are plotted on 
the top of the Figure, the propeller 
oise (left) and the exhaust noise of the 
engine (right) as measured at microphone 
M1 position (see Fig. 4).

In this procedure the exhaust signal, 
originally measured at position M2 (see 
Fig. 4) was attenuated to correspond to 
the sound pressures at microphone posi-
tion M1.
Inspecting the signals obtained in the anti-phase superposition, it is obvious that not each individual pattern is reduced at the same rate. As the computer simulation was carried out with measured values, this might be due to the form of the (ring-shaped) collecting-pipe of the exhaust (see Fig. 6) of the turbo-charged engine. Although the distribution of the ignition points over the working cycle is symmetrically, the resulting ignition pressures are not equally spaced in time. This is however an important requirement for matching exactly all propeller and exhaust patterns. A thorough matching would be possible, if an exhaust pipe was used like that of Cessna 207 A, where three cylinder outlets on each side of the engine are reduced to one common exhaust pipe (see Fig. 7). Corresponding observations have already been made under actual measuring conditions, as reported in the Section below.

**Combinations of Propeller-Blade and Engine-Cylinder Numbers**

As mentioned before it is mandatory that a sound pressure signal from one cylinder coincides with a sound signal emitted by one propeller blade. This is the case, for example, with a 4-cylinder four-stroke engine in connection with a two-blade propeller, but also with a 4-cylinder two-stroke engine in connection with a four-blade propeller. In contrast, with a 6-cylinder four-stroke engine having a two-blade propeller, only one blade sound signal is available for three cylinder sound signals. There would still be a small noise reduction.

In general, the number of the propeller-blades B and the number of the cylinder ignitions per revolution of the propeller shaft C must yield an integer ratio. A ratio of B/C = 1 is to be preferred, where maximum noise reduction would be achieved. Table 1 presents the ratios B/C of the number of the propeller-blade noise pressure signals to the number of the engine cylinder noise pressure signals per revolution of the propeller for different engine/propeller combinations with and without gears. A noise reduction for each blade pressure signal occurs when the magnitude of the ratio B/C is equal to 1. Other ratios - smaller or larger than 1 - would result in a less good reduction. Again, B/C = 1 would provide an optimum result. For attenuation of half of the blade pressure signals the characteristic value B/C = 2 gives an average result. The characteristic value B/C = 1/2 indicates that, for attenuating one blade pressure signal, two cylinder pressure signals are available in correct anti phase.

| Table 1. Combinations of Propeller and Exhaust Sound Pressure Impulses for Typical Aeroplanes to result in Characteristic Values B/C: |
|---|---|---|---|---|---|---|---|
| B being the number of blade sound pressure impulses per revolution of propeller shaft; | C being the number of cylinder sound pressure impulses per revolution of propeller shaft |
| 4-stroke | 2-stroke |
| drive direct | direct | reduction 2:1 |
| cyl. | 4 | 6 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| B | 2 | 3 | 2 | 3 | 4 | 2 | 4 | 6 | 8 |
| C | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |

The sequential times between two signals of the propeller and engine sound-field may be estimated from the left or right hand parts of the following equations; if
the signals have to be matched to achieve attenuation then the two equations must be satisfied:

\[
\frac{1}{B} \cdot n_p = \frac{2}{Z} \cdot n_M \\
\frac{1}{B} \cdot n_p = \frac{1}{Z} \cdot n_M
\]

for four-stroke engines

for two-stroke engines

with \( B \) being the number of blades, \( Z \) the number of cylinders, \( n_p \) and \( n_M \) the RPMs of the propeller and engine, respectively.

If a reduction gear of an even number-ratio \( r = n_M / n_p \) is used then \( n_M \) must be substituted by \( n_M = r \cdot n_p \) in the equations.

**FLIGHT TESTS**

**In-Flight Measurements**

**Phase Shifting Device**

The purpose of the test flights has been to show whether positive and negative parts from the propeller sound pressure interfere with those of reverse sign from the engine exhaust. In this case similar results to those achieved from the computer simulation are to be expected. These in-flight experiments were not specifically directed towards generating global reductions of sound in space but rather to test the occurrence of a directional attenuation underneath the aeroplane. Therefore, it was considered primarily important to investigate the interference effects - such as attenuations or reinforcements - in the direction of the wing tip microphone for an optimisation of the superposition of sound pressures. Fig. 10 schematically illustrates the overlapping sound fields close to the aeroplane and the microphone positions at the tip of the wing as well as close to the engine exhaust.

To carry out experiments on active attenuation of sound fields near an aeroplane the aircraft was now equipped with a special flange inserted between crankshaft and propeller as shown at the top of Fig. 11. This special flange consists of two discs, each of them being mounted to the propeller and the drive shaft by bolts. To shift the phase of the sound waves, as radiated from the propeller in relation to those from the engine exhaust, the two discs could be rotated stepwise against each other (see bottom of Fig. 11).

Fig. 11 Special Flange on Test Aeroplane

The change of the two discs of the flange for the subsequent adjustment could then be done on the ground with the engine stopped. The smallest angle between both discs is 7.5°. This corresponds to a
shift of the sound fields by 0.48 ms at a propeller rotational speed of 2600 RPM. Fig. 12 shows the changes of the phase angle between the crank shaft and the propeller. Those changes accomplished an overlapping "dial-sector" between two blades amounting to 120°. Thus, 16 posi-

![Diagram of propeller blades and rotation]

Fig. 12 Phase-Shift Adjustment between Crank Shaft and Propeller

tions, each of 7.5°, had to be adjusted. It might be helpful to note some important time intervals referring to an engine speed of n = 2600 RPM:

- length of the working cycle of the engine

\[ t_A = \frac{2 \cdot 60}{n} = 46 \text{ ms} \]

- time for one shaft revolution

\[ t_W = \frac{60}{n} = 23 \text{ ms} \]

- time between two blade sound patterns

\[ t_p = \frac{60}{B \cdot n} = 7.7 \text{ ms} \]

- time between two cylinder sound patterns

\[ t_z = \frac{2 \cdot 60}{2 \cdot n} = 7.7 \text{ ms} \]

- lower limit of angular change corresponding to a time shift

\[ t = \frac{60}{16 \cdot B \cdot n} = 0.48 \text{ ms} \]

Experimental Results

Fig. 13 shows the overall sound pressure patterns as measured at microphone M1 and changing the relative positions between the two discs. These changes demonstrate the effect of superposition of sound pressures from a specified blade and one specified piston at different phase shifts. On each trace, the sound pressure pattern from the engine exhaust (broken lines) is indicated. Changing the adjustment settings - from No. 1 to No. 17 - the exhaust trace now changes its position relative to the overall pressure patterns. In this way the effect of individual phase shifts can be followed. Deformations of the overall patterns - like a "thickening" with positions 15 and 17, amplifications with positions 3 and 17, attenuations with positions 5, 9 and 13 - are produced by different phase shifts between propeller and exhaust sound waves.

To achieve attenuations of the sound pressure levels the relative phase shifts between the sound pressures should be like those with positions 5, 9 and 13, of course. Positions like 15, 17 and 3 yield unwantedly higher levels. To illustrate the potential inherent in such superpositions two arrangements of measured pressures are shown in Fig. 14. Here, on top two measured propeller pressure patterns of virtual identical shape (—) after superposition with engine exhaust patterns (—–) produce quite different peak-to-peak amplitudes and shapes (bottom of the Figure): in-phase left trace and out of phase right trace. The pronounced negative pressure part of the pattern (left) - which predominantly affects the tonal content of the spectrum - is attenuated (right).

Flyover Measurements

Subsequent to the near-field noise mea-
surement on the test aeroplane itself, flyover measurements were executed to check whether observed near-field effects in the noise field would extend to the ground.

As mentioned before, the pressure pulses of the turbo-charged engine of the test aeroplane are not equally spaced in time during any given working cycle. If an exact destructive interference of all sound impulses from the propeller is to be achieved, then the requirement of

\[ \Delta t = \frac{\Delta \tau_\epsilon}{v_\epsilon} \cos \theta \]  

in order to achieve this effect, the distance between engine exhaust and propeller plane must be as small as possible. This minimum distance is 0.7 m for the test aeroplane, in which case alternating pressure attenuations and reinforcements would result in a rotation of the interference pattern.

More precisely: a relative change of the time difference \( \Delta t \) between two distinct impulses from propeller and engine exhaust noise as measured on the ground does indeed occur (Fig. 15). This time difference now consists of two parts, as can be shown by a model (see Fig. 1) using two monopole sources in motion of the same frequency. The distance between the two sources is assumed to be \( a \), their constant velocity \( v_\epsilon \). If source \( Q_1 \) is emitting a time \( \Delta \tau_\epsilon \) later than source \( Q_1 \), then the difference of the sound rays to a receiver on the ground is

\[ S_1 - S_2 = a \cos \theta + v_\epsilon \Delta \tau_\epsilon \cos \theta \].

From this equation the difference \( \Delta t \) can be extracted,

\[ \Delta t = \Delta \tau_\epsilon (1 - M_F \cos \theta) - a \cos \theta / c \],

where \( M_F \) is the flight Mach-number, \( c \) the velocity of the sound and \( \theta \) the emission angle, respectively.

Measurements and Data Evaluation

The flight speed of the aeroplane has again been held constant at about \( v_\epsilon = 60 \text{m/s} \). The test flights were directed both upwind and downwind. The flight height was \( h = 150 \text{m} \). Two constant shaft speed settings \( n_\epsilon = 2500 \text{RPM} \) and \( n_\epsilon = 2600 \text{RPM} \) were employed. The recording of the sound signals began 500 m ahead of the flyover position and were stopped 500 m after microphone flyover. After each of the test flight series had been completed the azimuthal propeller/shaft-position was changed.

During flyover, the aeroplane was photographed in the overhead-position. Simultaneously the camera click was recorded on a separate channel of the multi-channel tape recorder. With this impulse the relative position of the aeroplane and the sound impulses on the tape could be correlated.

The data evaluation of the sound signals received on the ground was performed with a 2-channel FFT-Analyzer both for time signatures and narrow band frequency spectra. The overhead position photographs were used to determine flight height and lateral deviation of the aeroplane for correction of the sound pressure.

Characteristics of the Sound Pressure Time-Histories

In order to determine the components of both the propeller and engine exhaust pressure, time-increments of 80 ms length

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Fig. 14 Top: Superimposed Propeller- and Exhaust-Sound Pressure Pattern In-Phase (left), Out-of-Phase (right)  
Bottom: Overall Sound Pressure Pattern

equal distances is to be strictly observed. Therefore, measurements as presented in the following yield interferences of single impulses only as observed during the in-flight tests.

Significant sound pressure level attenuations on the ground require precise destructive superpositions of the sound waves over a sufficiently long time duration of a flyover. As shown previously,
were extracted. After identifying and numbering the individual noise impulses from the propeller and the engine exhaust, their development due to interference effects during the flight could be examined in detail.

Interference Process During Flight

The interference effects of overlapping sound pressures (attenuations and amplifications) measured in the near-field of the aeroplane had been shown in Fig. 13. A time sequence of sound pressure patterns as received by a ground microphone is shown in Fig. 15. This Figure displays impulses, which apparently are deformed in a "seemingly erratic" manner. A more detailed inspection of the patterns indicates however that every 6th impulse is affected in an individual way, such as being either attenuated or reinforced.

Presently it is supposed that these changes are due to engine exhaust noise. This appears likely because each of the 6 pulses of the engine noise is individually affected (see Fig. 5). Otherwise, a typical propeller noise pattern should consist of identically shaped pulses of equal spacing (see Fig. 8) as the propeller blades have the same shape and are equally spaced on the circumference of the propeller cup. The changes are certainly not being stochastic but rather corresponding to the working cycle of the 6-cylinder engine - cannot therefore be due to propeller irregularities. Fig. 16 shows a time sequence of the noise pressure pattern from a flyover for a shaft speed of \( n_s = 2600 \) RPM (top of Figure). Overlapping this interference pattern and engine exhaust pattern clearly demonstrates that the observed changes are due to the engine exhaust noise. An engine exhaust noise pattern measured at the time of emission on board of the aeroplane at the same RPM (center of Figure) is superimposed upon the ground-measured noise pattern utilizing the individual characteristic features of the two traces. Using this method, the correct phase shift for adjusting the two pressure-time-histories now yields the final result, as shown on the bottom of the Figure. Now it becomes quite obvious which particular time delays of the patterns yield in-phase caused reinforcements and out-of-phase caused attenuations.
CONCLUDING REMARKS

It has been demonstrated that arranging the sound fields of a propeller and the piston engine exhaust in anti-phase seems indeed a viable technique to reduce the flyover noise of propeller aeroplanes equipped with piston engines. As the experimental results obtained in the near- and far-field of an aeroplane - a Cessna T 207 - in flight are very encouraging, the application of this noise reducing technique to a more suitable test aeroplane is presently prepared. Thus far reductions in sound pressure level of 4 to 6 dB(A) were obtained. Higher noise level reductions seem possible with optimizing the relative positions (especially their distance) of the sound sources of the aeroplane. The requirement for an improvement, particularly as phase shifting of the two sources is concerned, can be readily accomplished.

Ground stationary experiments with a Cessna 207 A test aeroplane are also in a preparatory stage. This aeroplane is emitting sequences of equidistant sound impulses from propeller and exhaust, allowing a much finer adjustment of the relative source patterns.

Symbols

a     Distance between Propeller plane and exhaust in m
B     Number of propeller blades
C     speed of the sound in m/s
Df    Drag-thrust ratio
De    Propeller diameter in m
F     Distance of the exhaust to the propeller axis in m
Fn    Normalizing function
Knb   Wave number related to the nB-order harmonics
m     Natural number designating the maxima
MH    Helical blade tip Mach-number
Mf    Flight Mach-number
n     Propeller speed in RPM; harmonic order
r     Ratio of reduction
ta    Time span of the working cycle of the piston engine in ms
tz    Sequential time between two firings in ms
v     Airspeed in m/s
Z     Number of Cylinders of the piston engine
\( I' \) Normalized intensity
\( \Delta L_p \) Noise level reduction
\( d_{\phi} \) Phase shift angle
\( \phi_{max} \) Largest aperture angle
\( \phi \) Emission angle
\( \rho \) Density
\( \phi \) Circumferential orientation in the propeller plane
\( \phi_A \) Circumferential orientation of the engine exhaust orifice
\( \rho_A \) Exhaust orifice velocity potential
\( \phi_p \) Propeller velocity potential
\( \phi_R \) Ratio of the velocities potentials
\( \omega \) Radian frequency in 1/s

Subscripts

e     Emission
F     Flight
M     Engine
P     Propeller
W     One shaft revolution
Z     Cylinder

References