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SMALL AIRCRAFT PROPELLER NOISE WITH DUCTED PROPELLER

R. Duane Oleson*
United Technologies Corporation
Sikorsky Aircraft
West Palm Beach, FL 33410

Howard Patrick†
Embry-Riddle Aeronautical University
Daytona Beach, FL 32114

Abstract

The purpose of this paper was to document the results of initial testing of various configurations of a ducted propeller apparatus. The apparatus was designed based on a combination of acoustic principles and a desire to be able to apply the knowledge gained to a practical application such as an ultralight aircraft in an effort to reduce the overall noise levels emitted. The apparatus consisted of a 35 horsepower ultralight engine, a four bladed ultralight propeller, and a duct constructed of a foam core covered with fiberglass. Initial evaluations compared noise levels from the apparatus both with and without the shroud in place, as well as various engine silencer configurations. The data gathered proved the apparatus was actually about 6 dB louder with the shroud than without the shroud as a result of strong rotor-stator interactions. Based on the initial evaluations, this apparatus demonstrated its potential for further testing and acoustical work in the principles of rotor-stator interactions, short duct acoustics, and active noise control applications with the long range goal being to reduce the acoustic emissions from propeller driven aircraft.

Introduction

With more emphasis these days being placed on the noise levels emitted from small aircraft, new methods to reduce these levels have been receiving attention. The advancement of active noise control (ANC) technology within the past decade, along with successful results using ANC to reduce noise levels from a propeller in a long duct prompted further examination into the feasibility of using ANC to effectively lower the external propeller noise emitted from a general aviation aircraft.[1] As a next step, a test apparatus which was in many aspects identical or very similar to the type of ducted propeller that would be used on a small airplane, was designed and constructed. Although the test apparatus was initially intended as a platform for testing ANC, it became apparent after its completion that it could serve as a tool for research into other areas of acoustics as well as ANC, such as duct acoustics, rotor-stator interaction tones, and engine exhaust noise. This paper highlights some of the initial test results, which when used in conjunction with on-going research might hopefully be used towards lowering levels of noise emitted from aircraft flying overhead.

Apparatus and Procedures

The apparatus used for the evaluation consisted of a small two-cylinder, two-cycle gasoline aircraft engine with a four bladed, composite aircraft propeller. A duct (also referred to as a shroud) was designed and constructed which fit around the propeller. The test apparatus was easily modified which allowed for operation using various engine silencer configurations, operation with or without the duct, and various rotor - stator blade combinations. (Currently, with the duct in place, the apparatus has only been run using a four bladed propeller with three stator vanes.) The apparatus was designed such that with only some small modifications, the engine, propeller, and duct could be fitted onto an ultralight type aircraft for in-flight testing at some future time.

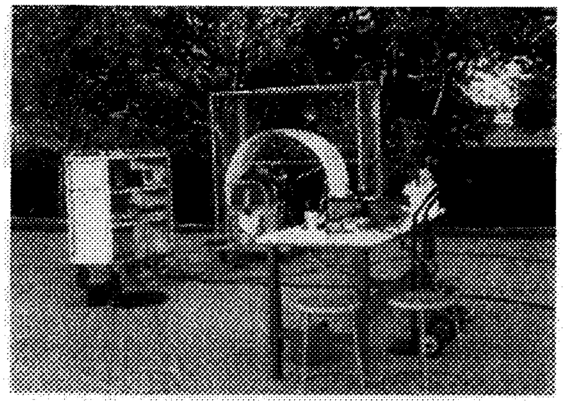

Figure 1. Complete Setup Ready to Run

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* Test Engineer, Developmental Flight Center

† Associate Professor, Aerospace Engineering Dept., Senior Member, AIAA.

Note: Work contained herein was performed at ERAU, prior to author's employment at Sikorsky Aircraft.

The apparatus was mounted to a cart which could be easily moved around. This was important, since all the acoustical testing was performed outdoors which provided the best freefield conditions. The complete setup, including the instrumentation rack and the shroud are shown in Figure 1. Note that the apparatus consists of a pusher configuration with the engine mounted in front of the propeller.

A ducted propeller system was chosen for the evaluation, since it was felt that there was good potential for reducing overall noise levels through use of a duct. In addition to reducing the noise due to elimination of the tip vortices, the duct could provide a platform for implementing active noise control techniques to reduce the levels of noise emitted from the duct. The use of a duct was not without its drawbacks though. Acoustically speaking, the use of stator vanes in the duct resulted in the introduction of rotor - stator interaction tones which needed to be evaluated to determine their strength. In theory, if the number of stator vanes had been more than double the amount of rotor blades,. all of the interaction tones would have decayed before exiting the duct.

To perform the evaluation, noise samples were recorded, from which frequency spectra were plotted to analyze the noise samples. Farfield noise samples were taken at 30° intervals around the entire front end of the apparatus and continued around the intake side and behind the apparatus to a azmuthal angle of 150° (Figure 2), beyond which further measurements were impractical due to propeller wake interference as well as limitations in the physical surroundings. Frequency spectra of the noise samples were used to identify the major components of the noise at the various azimuths. Overall sound pressure levels (OASPL's) were also measured at all locations which provided a means of comparing the levels of total noise emitted using the various configurations. Measurements were made at a 4 foot height above an acoustically hard asphalt surface.

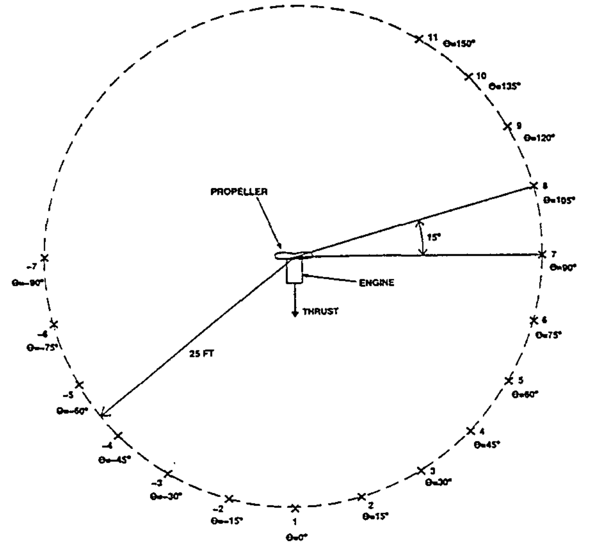

Figure 2. Sound Measurement Locations As a Function of Azimuthal Angle at 25 Feet

Theoretical Noise Distribution

In the unshrouded configuration, there were two primary sources of noise: the engine noise and the propeller noise. The engine had two monopole sources, one at the intake and one at the exhaust. However, since the distance between the two sources was very small when compared to the distance at which measurements were made (1 ft compared to 25 ft), the engine noise was considered as one monopole source.

The propeller noise under static conditions was composed of two components. The first was the loading noise, which was a dipole source. The strength of the dipole source thus was based on the amount of thrust and torque the propeller was creating. The second component was the thickness noise, which was a monopole source, and was caused be the propeller displacing the air. These two components resulted in the theoretical directivity pattern shown in the middle drawing of Figure 3.[2]

Upon combining the two noise patterns, the overall noise emitted from this setup was expected to resemble that in Figure 3. This assumed, however, that the two sources were emitting noise completely independent of one another and did not take into consideration the additional noise due to interactions between the sources as well as phase effects between tones of identical frequencies. Certainly, the sources were not completely independent of one another, so the actual results were not expected to look exactly like the theoretical solution. Still, similarities were found between the theoretical solution and the measured data which confirmed that the assumption made was not completely unjustifiable.

Results

The results are broken into three sections - noise without the shroud, noise with the shroud, and engine noise. All measurements were made at a distance of 25 feet from the center of the propeller. The engine was rotating at approximately 2400 RPM.

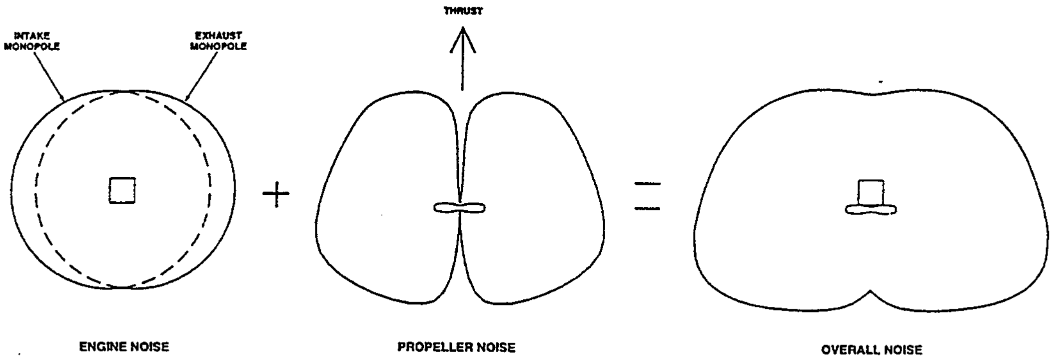

Figure 3. Predicted Directivity Pattern From Apparatus

Noise Without the Shroud

OASPL Tones The OASPL's ranged between 98.5 and 104.6 dB. It will be shown shortly, that for most of the angular (θ) positions recorded, the most significant tone was due to propeller noise, indicating that for these positions, the largest contributor to the level of OASPL was propeller noise. Certainly though, the engine noise was not low enough to be negligible and actually did appear as the dominant tone at some of the angular positions around the exhaust side of the engine.

Shown in Figure 4 is the measured OASPL directivity pattern for the unshrouded propeller. Upon examination of this curve, it is evident that noise levels are lowest at the positions inline with the propeller plane with levels of 98.5 dB on the exhaust side (θ = -90°) and 99.0 dB on the intake side (θ = 90°). The highest noise level is noted at θ = 45°, where the OASPL is 104.6 dB. Interestingly, this does not appear to be symmetrical as at θ = -45°, the OASPL is only 101.4 dB and shows no significant increase in noise anywhere in this region.

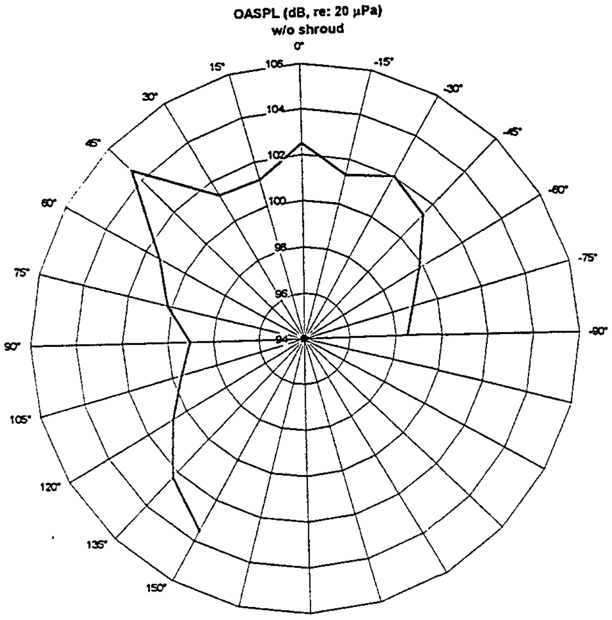

Figure 4. Measured Directivity Pattern Without Shroud

Other than the 45° positions, the acoustical noise field appears to be fairly symmetrical from the θ = -90° position, around the front of the apparatus to the θ = 90° position. From θ = 90° around to θ = 150°, the OASPL is on the rise which follows the lobe pattern behind the plane of rotation predicted by the theoretical solution. Unfortunately, due to physical limitations, measurements beyond 150° were not able to be taken, so it could not be determined if 150° was the high point of this lobe or not.

Propeller Tones Inspection of the spectra shown in Figure 5 reveals that the engine tones labeled nE, can be clearly distinguished from the propeller tones labeled nP, where n is the harmonic number. The propeller was powered through a transmission with a gear ratio of 2.53:1 which resulted in separation of the propeller and engine tones. Using the spectra, an attempt is made to plot the directionality field of just the propeller BPF which appears as a tone located at approximately 160 Hz. This tone can be seen clearly on the power spectrum curves for all positions, and in all but a couple positions, is the dominate tone. An example of the power spectrum is provided in Figure 5 in which the tone at 160 Hz can be seen to be 5 dB greater than any of the other tones (peaks).

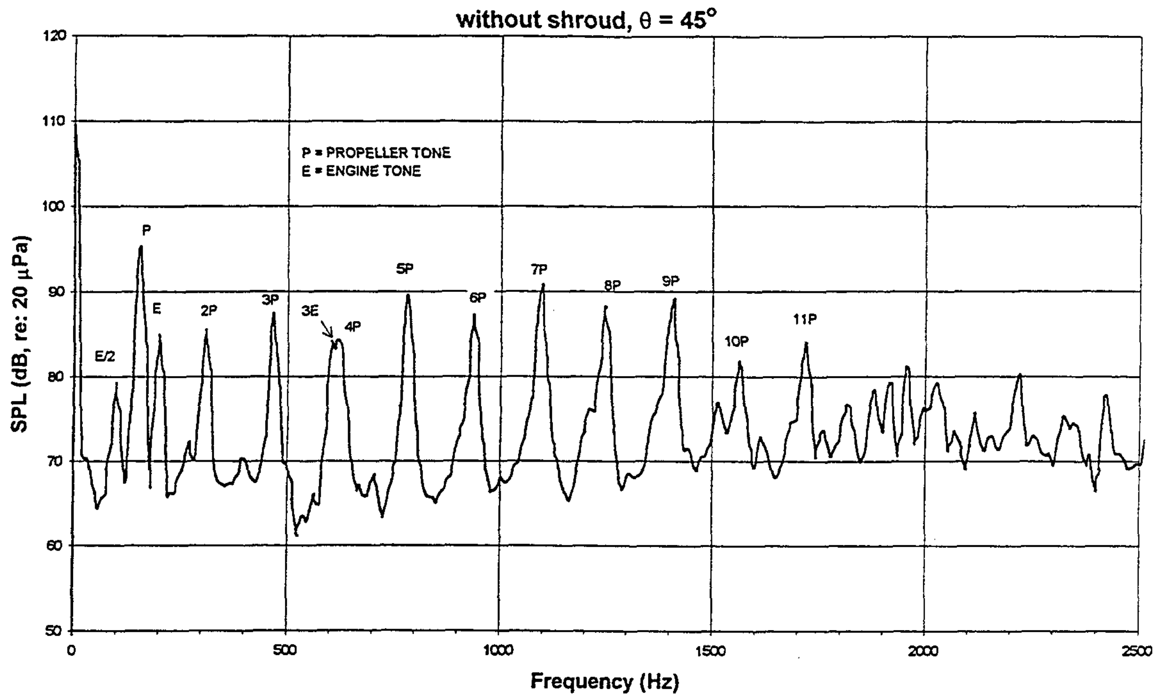

Figure 5. Spectrum Plot Without Shroud

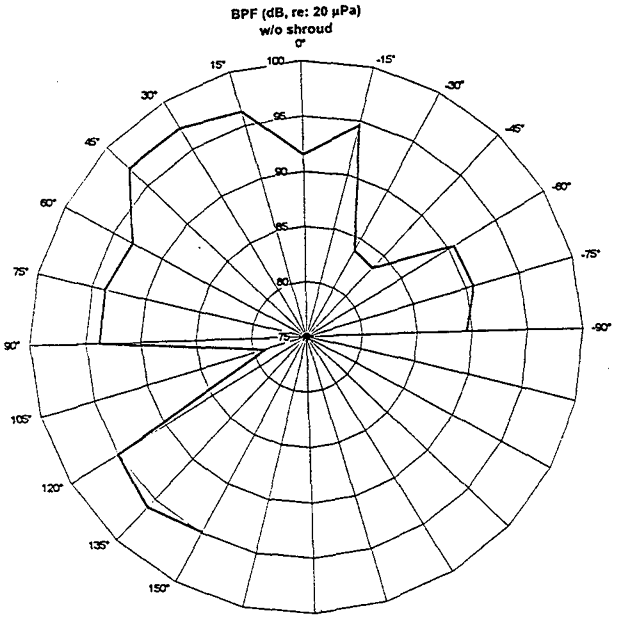

Figure 6. Directivity Pattern of BPF Tone at 160 Hz Without Shroud

By plotting only the BPF levels recorded at each theta position, the effect of the fundamental propeller tone on the OASPL field is shown in Figure 6. From this plot, the directivity field tends to appear somewhat lopsided. The propeller noise looks to be more significant on the intake side of the engine than on the exhaust side. Normally, for an ideal case, propeller noise is expected to be symmetrical along the centerline. Most likely, this asymmetry is a result of turbulence which is shed off the engine. With the engine and propeller setup in a pusher configuration, the resulting inflow into the propeller is not an even distribution, and as a result, the pressure distribution over the disk area was not symmetrical, leading to asymmetrical acoustic emissions.[3]

__Engine Tones__ The fundamental engine tone occurs at 200 Hz. When plotted out in a similar fashion to the BPF and presented in Figure 7, two separate monopole sources are clearly depicted, one due to exhaust noise and one due to intake noise. It appears as though the monopole sources are close enough to actually cancel out parts of one another, giving the directivity pattern the look of a dipole as shown in Figure 7. This is noted because of the significant drops in levels of noise in the region between θ = 0° and θ = 60° where the two monopole sources overlap one another. Overall, the exhaust noise levels are approximately four to five dB higher than the intake noise levels.

Higher harmonics of engine noise seem to be limited to only the third harmonic at most azimuthal positions. The second harmonic appears almost non - existent as does the harmonics above the third.

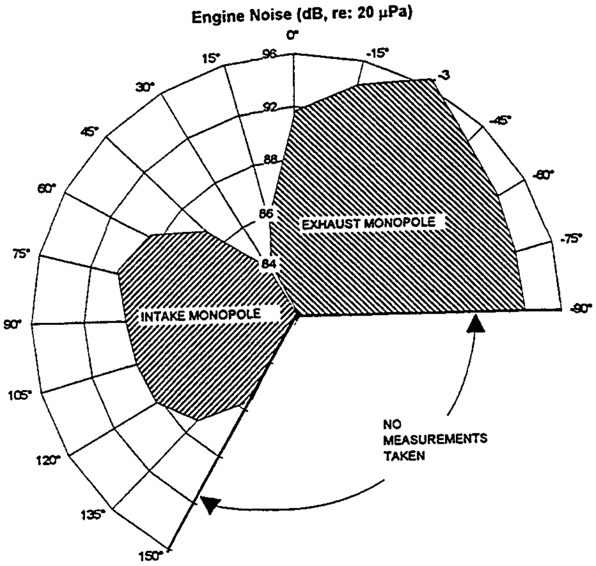

Figure 7. Directivity Pattern of Engine Tone at 200 Hz

Noise With Shroud

The same measurements previously discussed were taken with the shroud in place. Of primary interest was the OASPL measurements which provided a direct comparison to the unshrouded configuration. Also of importance were the power spectra, which proved to be most insightful when analyzing the propulsion system noise with the shroud in place. With the propeller blades passing within about one half an inch behind the trailing edge of the stator vanes, it was assumed that strong interaction tones would be observed between the propeller and stators. In fact, this was the case. Other factors thought to influence the overall noise included shroud shielding, duct acoustical emissions, and an increase in propeller efficiency due to a reduction in tip vortices. The gap between propeller tip and shroud was approximately 1/8 of an inch.

OASPL Measurements The directivity pattern of the OASPL with the shroud follows the same trends as the unshrouded case, although an increase in levels is evident. Increases in higher harmonics amount to approximately a six decibel increase in the overall sound pressure level. Upon examination of the directionality field in Figure 8 maximum OASPL's are observed at both $\theta = 45°$ and $\theta = -45°$ than with values of 110.1 dB and 111.3 dB, respectively. This varies only slightly from the pattern noted without the shroud, as a slightly higher noise level is seen around $\theta = -45°$ with the shroud. Behind the plane of rotation, $(90° < \theta < 150°)$ the levels of noise appear fairly constant, (within 2 dB's) indicating no distinct lobe at this position. This is in contrast to the unshrouded propeller which appears to have a distinct lobe at this location as can be seen by comparing the curves in Figure 4 and 8. Measurements beyond 150° would help to determine if this is the case.

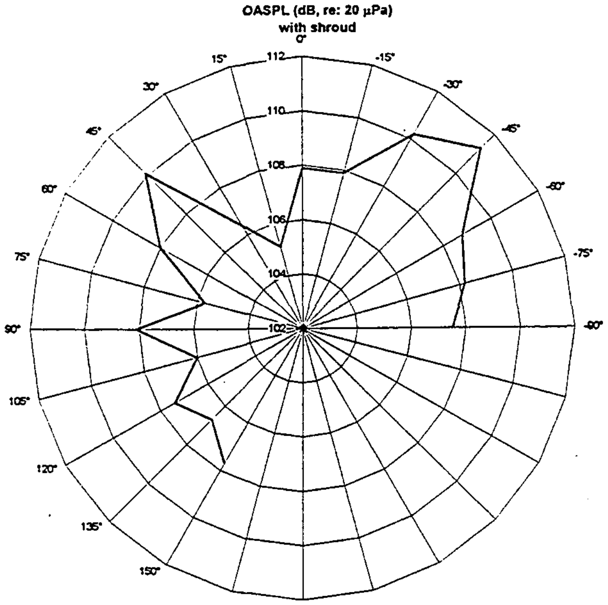

Figure 8. Measured Directivity Pattern With Shroud in Place

Rotor-Stator Interaction Tones Power-spectral analysis scans were performed in the same manner as for the unshrouded configuration. Again, all tones fall under one of two types: either rotor - stator interaction noise or engine noise, except for one unidentified tone at 520 Hz which appears in all the frequency scans with the shroud in place.

From examination of the power spectrum presented in Figure 9, the increase in OASPL can be attributed mostly to a set of distinct tones that occur at intervals of 160 Hz and higher. Notice that the tones appear at the same frequencies as the BPF and its corresponding harmonics, however, these tones are attributed more to rotor-stator interactions than the propeller harmonics.

Unlike the BPF and associated propeller harmonics, the fundamental rotor-stator interaction tone does not appear as the most significant tone. Instead, the highest level in the spectrum appears at around the 4th or 5th interval tone, and instead of the higher tones diminishing as they increase in frequency, they remain at fairly constant levels until a frequency

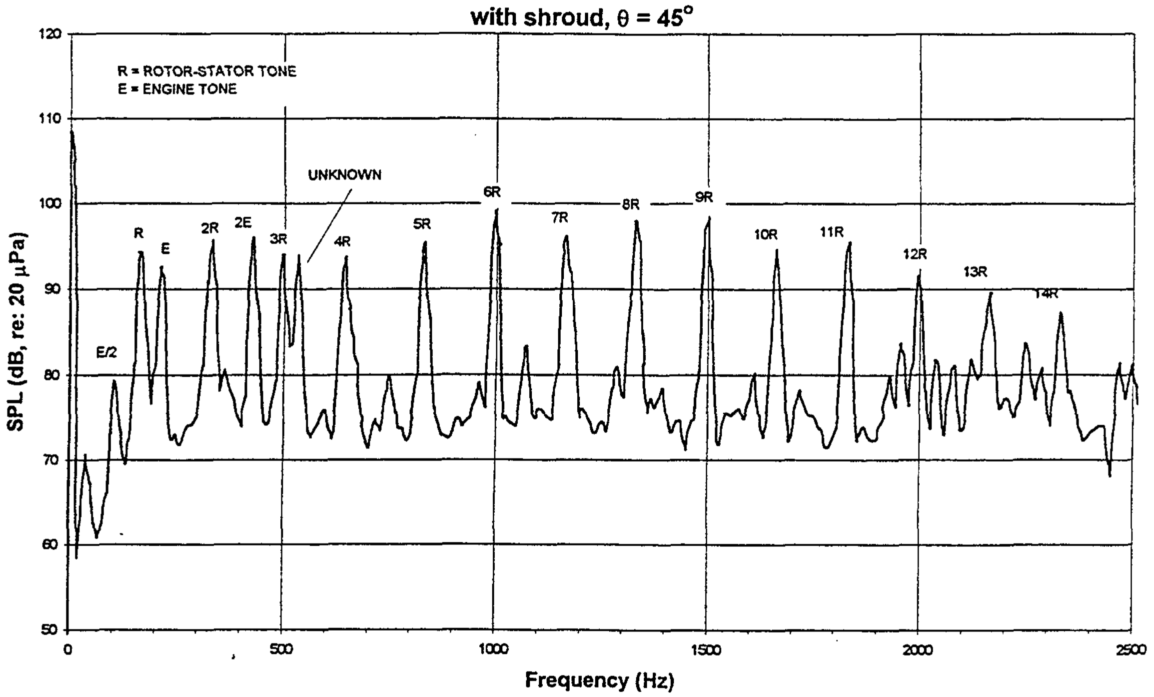

Figure 9. Spectrum Plot With Shroud

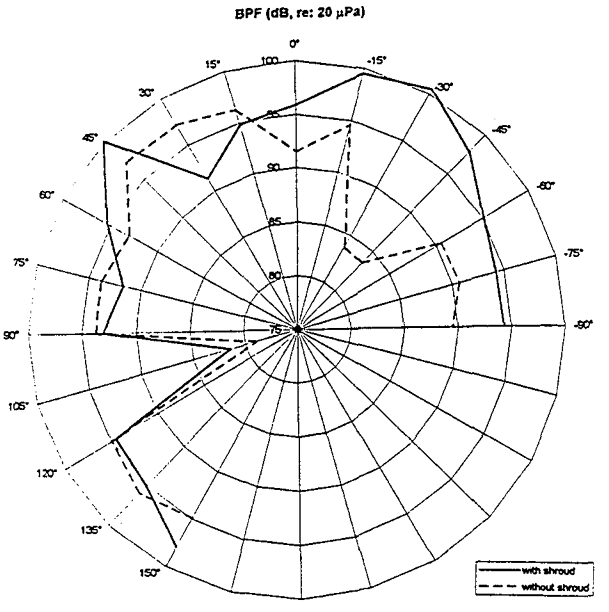

Figure 10. Comparison of Directivity Patterns at Blade Passing Frequency

of about 1,500 Hz, when they decay very rapidly. Further, a comparison of the BPF tone at 160 Hz between the unshrouded and shrouded configurations in Figure 10 shows differences in the directivity patterns. With the shroud in place, the directivity pattern of the 160 Hz tone does not exhibit the significant decreases on the engine exhaust side (-75° < θ < -15°) as does the 160 Hz BPF tone without the shroud.

By applying rotor-stator interaction concepts, the interaction tones for this apparatus can be accounted for in the power spectrum.[4] As an example, lets look at the fundamental tone (s = 1). Using standard notation,

$$\Omega = 40\ \text{Hz} \qquad B = 4 \qquad c = 1116\ \text{ft/s}$$

$$D = 54\ \text{in} \qquad V = 3 \qquad k = (0, \pm1, \pm2\ldots)$$

where:

$\Omega \Rightarrow$ rotational frequency of the propeller
$D \Rightarrow$ diameter of duct
$B \Rightarrow$ number of rotor blades
$V \Rightarrow$ number of stator blades
$c \Rightarrow$ speed of sound
$k \Rightarrow$ integer

For propagation of the tone to occur, Ω_m has to be greater than Ω, since Ω is subsonic. The rotational velocity of any particular mode is given by,

$$\Omega_m = \Omega \Big/ \left(1 + \frac{kV}{sB}\right) \qquad (1)$$

Table 1. Cutoff frequencies for mode m (hub to tip ratio = 0, radial mode = 0)

m	1	2	3	4	5	6	7	8
J_m	1.8412	3.0542	4.2012	5.3175	6.4156	7.5013	8.5778	9.6474
f^*_m (Hz)	145	242	332	420	507	592	677	762

and can be rewritten as in Eq. 2 to determine values of k.

$$-8/3 < k < 0. \qquad (2)$$

Integer values of k which satisfy Equation 2 are -1 and -2. Substituting these values of k into the previous equation and in Eq. 3,

$$m = sB + kV \qquad (3)$$

to determine the circumferential mode, corresponding modes of 1 and -2 and Ω_m's of 160 and -80 Hz respectively, are found. This indicates that for the fundamental tone, the only modes that are rotating at a faster speed than the propeller are 1 and -2. To determine if either of these modes might propagate, their corresponding cutoff frequencies must be found. The cutoff frequencies for circumferential modes 1 through 8, were determined using,

$$f^*_m = J_m c / \pi D \qquad (4)$$

and the corresponding Bessel functions for the modes, are presented in Table 1 for up to the eighth mode. In order to have sound propagation in the duct or shroud, the frequency of the tone has to be greater than its corresponding cutoff frequency, so propagation of the (1,0) mode can be seen to occur at 160 Hz, while decay of the (-2,0) mode will occur.

(1,0): $f^*_{m=1} = 145$ Hz $< \Omega_m = 160$ Hz → Propagates

(-2,0): $f^*_{m=2} = 242$ Hz $> \Omega_m = 80$ Hz → Doesn't Propagate

Table 2. Possible propagating modes for shroud apparatus

possible k's	-1	-2
m lobes	1	-2
omega$_m$ (Hz)	160	-80
propogation ?	Yes	No

s = 1
tone = 160 Hz

possible k's	-1	-2	-3	-4	-5
m lobes	5	2	-1	-4	-7
omega$_m$ (Hz)	64	160	-320	-80	-45.7
propogation ?	No	No	Yes	No	No

s = 2
tone = 320 Hz

possible k's	-1	-2	-3	-4	-5	-6	-7
m lobes	9	6	3	0	-3	-6	-9
omega$_m$ (Hz)	53.33	80	160	p.w.	-160	-80	-53.3
propogation ?	No	No	No	Yes	No	No	No

s = 3
tone = 480 Hz

possible k's	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
m lobes	13	10	7	4	1	-2	-5	-8	-11	-14
omega$_m$ (Hz)	49.23	64	91.43	160	640	-320	-128	-80	-58.2	-45.7
propogation ?	No	No	No	No	Yes	Yes	No	No	No	No

s = 4
tone = 640 Hz

possible k's	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13
m lobes	17	14	11	8	5	2	-1	-4	-7	-10	-13	-16	-19
omega$_m$ (Hz)	47.06	57.14	72.73	100	160	400	-800	-200	-114	-80	-61.5	-50	-42.1
propogation ?	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No

s = 5
tone = 800 Hz

possible k's	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15
m lobes	21	18	15	12	9	6	3	0	-3	-6	-9	-12	-15	-18	-21
omega$_m$ (Hz)	45.71	53.33	64	80	106.7	160	320	p.w.	-320	-160	-107	-80	-64	-53.3	-45.7
propogation ?	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No

s = 6
tone = 960 Hz

p.w. = plane wave

In Table 2, the results of similar type of analysis performed on harmonics through s = 6 are shown. From these, frequencies through 960 Hz are accounted for and further analysis of higher harmonics produce similar results for the higher frequencies examined in the power-spectrum scans. By the ninth harmonic or so, corresponding to a frequency of 1,420 Hz, the effects start to weaken significantly and the majority of remaining tones can be neglected.

It should be mentioned, that every third harmonic (s = 3, 6, 9,...) there is no rotating pattern due to interaction tones. Instead, a plane wave is set up. This occurs whenever the blade harmonics are divisible by the number of stator blades. When this situation is set up, the interactions between the blade harmonics and the stators occur such that each stator is acted upon at the same exact time. The result is a strong tone at the particular blade harmonic. Details of the theory as well as more expermental results are presented in Reference 5.

Engine Tones The tones attributable to the engine with the shroud appear very similar to those without the shroud. Other than the shroud providing possible blockage effects at certain azimuthal angles, there is no further reasoning that the engine noise should differ due to the apparatus configuration.

Engine Noise

In the past two sections, the directivity patterns of the engine noise levels are plotted as a function of azimuthal angles. Results show the engine noise being generated by two monopole sources: one is the intake and the other is the exhaust. Since the engine noise is significant enough to affect the overall noise levels while testing, further investigation into the effectiveness of the silencers focusing on the intake and exhaust seems appropriate.

Recordings were taken at the azimuthal angle θ = 45°, at the standard distance of 25 ft from the engine. All recordings taken for this comparison were performed with the shroud removed. The four operating configurations measured were:

1) intake silencer on, secondary exhaust muffler on
2) intake silencer off, secondary exhaust muffler on
3) intake silencer on, secondary exhaust muffler off
4) intake silencer off, secondary exhaust muffler off

"Intake silencer off" indicates the entire intake silencer and air filter were removed. Essentially noise was free to propagate out of the carburetor throat into the open atmosphere uninhibited. "Secondary exhaust muffler off" indicates removal of the additional muffler, or "after-muffler" which was placed in series with the main muffler. Due to the nature of a two - stroke engine, testing with the main exhaust muffler removed was not feasible since it was needed for the engine to run properly.

Based on initial testing of the apparatus without the intake silencer in place, it is felt that the impact of the intake silencer on the engine noise levels is greater than the impact of the after-muffler. Results presented in Figure 11 prove this conclusion where the power-spectrum of the farfield radiated noise for the different intake/exhaust mufflers are presented. The tone of interest is the fundamental engine tone at 200 Hz. From the two plots in Figure 11 with the intake muffler in place, the primary tone is not significant when compared to the overall levels of noise. Also, the second engine harmonic levels both

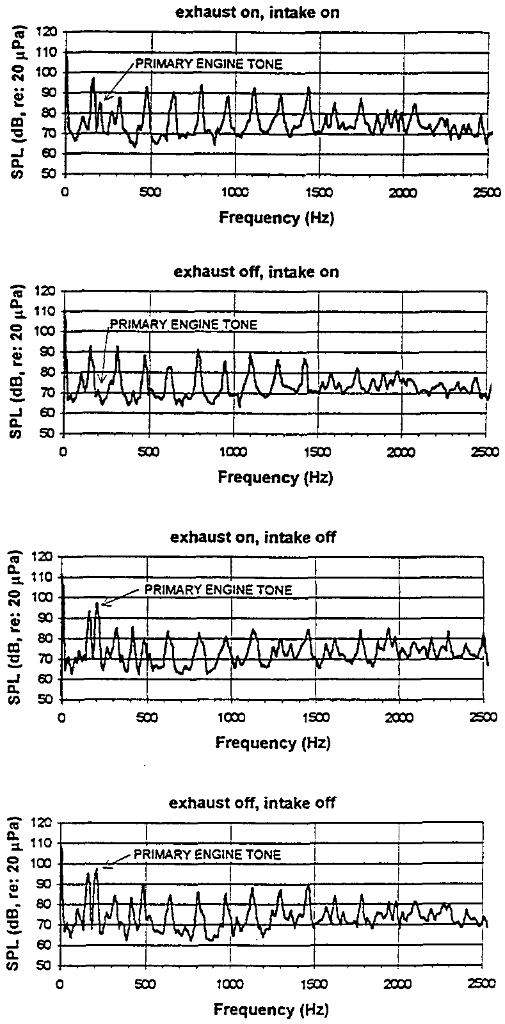

Figure 11. Spectrum Plots of Engine Noise Using Four Different Exhaust/Intake Configurations

indicate levels in the low 70 decibels. When these configurations are compared to those in which the intake silencer is removed in Figure 11, a large difference is noted in the tone at 200 Hz. With the intake silencer removed, the engine noise jumps up to levels of 97 dB from an average of 78 dB with the intake silencer installed. Corresponding to the increase in engine noise when the intake silencer is removed, is the OASPL which increases by about 2 dB. Without the intake silencers in place, the engine noise becomes the primary tone in the overall power-spectrum of noise.

A similar type comparison is attempted between the power-spectrum curves with the exhaust muffler installed and comparing these two curves with the exhaust off as shown, in Figure 11, indicates no significant differences between the various configurations. There are two explanations for this result. First, as the secondary muffler, the results will not be nearly as dramatic as they would have been had the primary exhaust muffler been removed. Second, all recordings of exhaust / intake noise are taken on the intake side of the engine, (θ = 45°) so there tends to be much more bias in the results, due to changes in the intake configuration than changes in the exhaust configuration. It is felt that any differences in engine noise due to exhaust configuration are probably overshadowed by the intake noise, so the only conclusion about the effectiveness of the after-muffler is that it is not effective enough to be noticed from the intake side of the engine.

Results do conclude the need for use of the intake silencer to avoid levels of engine noise that will affect the OASPL on the intake side.

Conclusions

For the unshrouded propeller, the OASPL is between 98.5 and 104.6 dB, with the highest levels exhibited at azimuthal angles of $\theta = 45°$ and $\theta = 150°$. The noise consists of propeller components and engine components which are separated using power-spectrum analysis. The propeller noise is greatest on the intake side of the apparatus. The lack of symmetry in the propeller noise between the intake side and the exhaust side is due primarily to non-uniformity in the intake velocity profile due to engine blockage. Propeller harmonics from the ultralight propeller are noticed up through the eleventh harmonic. The engine noise consists of two monopole sources as expected - the intake port and the exhaust port. Of these, the exhaust appears strongest, and at a few locations is measured to be greater than the propeller noise.

With the shroud installed, the OASPL increases by about 6 dB above the unshrouded propeller. The increase is due to an increase in levels of higher frequency tones which are attributed to rotor-stator interaction. The directionality pattern of the OASPL with the shroud seems to be more symmetrical than without the shroud; however, there also appears to be higher levels of standard deviation in the measurements.

Testing of various silencer configurations on the two-cycle engine concludes the need for the intake silencer to be in place when measuring the OASPL's emitted by the propeller. With the intake silencer, engine noise levels drop anywhere between 15 - 25 dB and OASPL decreases by 2 dB. Without the intake silencer, engine tones dominate the overall noise spectrum, which throws off attempts to measure the overall levels of propeller noise. Similar conclusions can not be drawn about the effectiveness of the secondary exhaust muffler.

The design and construction of this apparatus has opened the door for further work into the investigation of reducing noise in small aircraft. Further work has to be performed in the area of rotor-stator interaction tones. A theoretical analysis has shown the feasibility of reducing noise emitted through addition of more stator vanes, however, to get a complete understanding, additional propeller configurations should be tested.

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