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Noise and Detectability Characteristics of Small-Scale Remotely Piloted Vehicle Propellers

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Several small-scale propeller configurations applicable to a conceptual remotely piloted vehicle (RPV) aircraft were designed, fabricated, and tested to determine their performance, acoustic, and detectability characteristics. The tests were conducted in static and simulated forward flight conditions in a wind tunnel. Propellers tested included tractor, pusher, and ducted configurations. The acoustic data obtained were used to determine the slant range and altitude of no detection of each propeller configuration. The acoustic and detectability characteristics of small-scale RPV propellers were found to be significantly different from those of the large-scale propellers. An increase in forward velocity resulted in a significant drop in the SPL's at higher harmonics of blade passage frequency. As expected, tip speed had a very strong effect on noise and detectability in forward flight. It was found that most of the propellers tested would be detected at one of the first few harmonics (mostly first or second) of their blade passage frequency. Of the propellers tested at the design values of thrust and tip speed, three-bladed propellers were generally less detectable than either two- or four-bladed propellers for most of the forward velocities considered. Pusher and ducted propellers were found to be more detectable than their tractor and open counterparts.

Introduction

MANY lightweight aircraft and a few present-day RPV's use propellers as their means of propulsion. It has been well known that on a propeller-driven aircraft the propeller is a primary source of noise. The noise radiated by a propeller is therefore of importance both from the civil point of view as regards annoyance and from the military viewpoint as regards detectability. The primary objective of the effort leading to this paper was to develop noise and detectability trending data of small, low noise propellers (minimum detection) applicable to a conceptual RPV aircraft. Propellers used in RPV's of interest here are smaller (1-2 ft in diameter) than those used in the conventional aircraft. Extensive research has been done in the past to quiet propellers, but most of this work was aimed at quieting large-scale propellers (diameter of 6 ft or greater).

Scientists[1,2] over the years have tried to design "quiet propellers" without adversely affecting their performance. It was established that the most powerful single factor affecting the noise level of a propeller is its tip speed. It was also found that at a given tip speed such factors as blade loading and blade geometry can be significant as far as noise reduction is concerned. A trend study conducted by Barry et al.[3] using noise detectability methods showed that for low noise levels, and therefore minimum detectability, propellers should operate at the lowest possible tip speed, have a wide blade chord, have a larger diameter than that required for performance and have from three to five blades; four blades are the apparent optimum. Until recently, most of the research work conducted on propeller noise has been based on static test data, as the methodologies available for the propeller noise prediction were scarce. Recent test data taken during a flyover[4] show that the harmonic and broadband noise is significantly lower in flyover than at the static condition, which may be due to relief of blade loading in forward flight and to different inflow conditions. It is therefore imperative that the effects of forward flight be taken into account in any noise/detectability study of propellers.

While most of the noise reduction studies to date have been confined to large-scale propellers used in general aviation aircraft, a few researchers tried to study the noise characteristics of small-scale propellers (1-2 ft in diameter) based on an extension of ideas used for large-scale propeller noise studies. Hoehne and Luce[5] have investigated the noise characteristics of small-scale propellers and found that a decrease in noise could be obtained by operating at larger blade angles, lower revolutions per minute, and smaller diameter, but at a penalty in propulsive efficiency. The noise characteristics of small propellers with and without forward flight simulation were also examined by Grosche and Stiewitt.[6] Based on the noise measurements, they have shown that low forward velocities of less than 60 ft/s reduce the rotational (harmonic) noise and high-frequency broadband noise of the propeller by up to 20 dB compared to static tests.

This paper presents the results of a systematic investigation of the noise and aural detectability characteristics of small-scale RPV propellers. Based on the effects of various parameters on noise observed for large-scale propellers, several propeller configurations with changes in the diameter, blade number, blade planform shape, and twist distribution were designed and fabricated. Various propeller configurations were tested in the static operating condition and at different forward flight velocities simulated in a wind tunnel. The acoustic data obtained were reduced to determine the aural detection distances, and the propeller configurations with the least aural detectability were then determined.

Design and Fabrication of Test Equipment

All propeller configurations were designed to develop 4 thrust horsepower (thp) at a cruise speed of 75 knots at 4000 ft

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Table 1 Characteristics of different blade designs

Blade design designation	Blade diameter, in.	Airfoil section used	Taper ratio, $C_{r/R}=0.15$ / $C_{r/R}=1.0$	Activity factor	Amount of twist, deg	Remarks
BD1	20	NACA 230XX	2.3	133	36	Optimum performance design, linear chord distribution
BD2	26	NACA 230XX	2.9	88	34	Optimum performance design, linear chord distribution
BD3	20	NACA 230XX	2.0	193	25	Low noise design, linear chord and twist distributions
BD4	26	NACA 230XX	2.0	193	25	Low noise design, linear chord and twist distributions

altitude and 95°F. Two propellers of 20 and 26 in. diameter, each with four blades, were designed to provide optimum performance. The design of the optimum performance propellers was based on Theodorsen's[7] theory. The propeller rotational speeds were chosen consistent with the RPV engine power curves. A rotational speed of 4500 rpm was chosen for the larger diameter (26-in.) propeller. Since it was decided that both the large and the small diameter propellers should have the same design tip speed, 510 ft/s, the smaller diameter (20-in.) propeller had a design rpm of 5850. NACA 230 series airfoil sections were chosen for the blades. In addition to these propellers, two low noise propellers with the same diameter, tip speed, and operating conditions as the optimum performance propellers were also designed. Since the survivability is one of the most important considerations of propeller RPV's, the slant range detection distance was chosen to be the determining criterion for the design of low noise propellers. Three prediction programs, a performance prediction program, a noise prediction program,[8] and an aural detectability program[9] were used in the design of low noise propellers. Results of trending data of large-scale quiet propeller studies were used as guidelines in arriving at these low noise propeller designs. The characteristics of the four-blade designs (two optimum performance designs and two low noise designs) are given in Table 1. Several sets of these blade designs were fabricated so that propeller configurations with at least six blades of each design could be tested. The pitch angles of the blades during the tests were changed manually by a system of mating location holes in the hub socket and blade shank and a location pin.

An appropriate test stand to test various propeller configurations (tractor, pusher, and ducted configurations) statically in a semianechoic test cell as well as in a wind tunnel was designed and fabricated. The thrust and torque of the propeller configurations were measured with the help of a thrust load cell and a torque meter, respectively. Two axisymmetric ducts to be used in combination with the optimum performance and low noise propellers were designed using a numerical computation method developed by Kaskel et al.[10] The axisymmetric ducts were also designed such that the duct-propeller combination developed about 4 thp at the design cruise speed of 75 knots.

The test equipment fabricated had the capability of testing various propellers and propeller-duct configurations in the tractor and pusher modes. In addition, it also had the capability of testing two multibladed (two or three blades) propellers with axial separation (called spaced propeller configuration) and two multibladed propellers with axial separation and with variable blade-to-blade phasing between the blades in different planes (called phased propellers).

Performance and Noise Tests/Data Reduction

The aim of the tests was to obtain sufficient performance and acoustic data of various propeller configurations in the static and simulated forward flight conditions so that propeller configurations with low detectability characteristics could be determined.

Static Tests

For static tests, the propeller test stand was mounted in a semianechoic test cell at the University of Maryland. The test chamber was lined with acoustic foam and was contoured such that it could fit in the test section of the University of Maryland wind tunnel in which the forward flight tests were conducted. Noise measurements were made on a semicircle (in the same horizontal plane as the propeller hub) having a 5-ft radius with its center at the center of the propeller hub. A microphone was mounted on a pivot arm of a mechanical linkage system, which was driven by a remotely controlled motor located on the drive table at the foot of the linkage. Noise measurements were generally taken for at least seven angular locations of the microphone on the semicircle. The propeller noise signal from the microphone, after amplification and signal conditioning, was recorded on an FM tape recorder (tape speed 60 in./s) and paralleled to a narrow-band and ⅓-octave-band spectral analyzers for on-line spectral analysis. Performance measurements consisted of recording of thrust load cell readings suitably displayed on a digital transducer indicator and power input to the drive motor.

Prior to the static tests, background noise data were recorded with the drive motor running and it was concluded that the background noise was not a significant factor in the static tests. The test procedure consisted of recording performance and acoustic data at the designated operating conditions for various propeller configurations operating in the tractor mode. For most of the static tests, the operating condition was a design thrust value of 18 lb (which results in 4 thp at a cruise speed of 75 knots) at the design tip speed of 510 ft/s. Some propeller configurations were also tested at off-design values of thrust and tip speed. Propeller configurations tested in the static condition included conventional free propellers with four different blade designs and blade numbers varying from two to six, a few ducted configurations, and a few spaced/phased configurations.

Wind Tunnel Tests

These were conducted in the University of Maryland wind tunnel, the test section of which was lined with acoustic foam to minimize acoustic reflections off the walls. The propeller test stand was mounted on the six-component balance system located in the floor of the test section. The acoustic measurement system was the same as the one used in static tests except that the microphone was equipped with a wind screen bullet cone. The performance measurement system was also similar to that used in static tests except that a torque meter was installed between the drive motor and the drive shaft to obtain the torque required by the propeller. As was done in the static tests, the selected propeller configurations were mounted on the test stand and the performance and acoustic data were taken simultaneously at the designated operating conditions.

Most propeller configurations were tested at four different forward velocities, 15, 50, 70, and 91 ft/s, and at a design thrust value of 18 lb and a design tip speed of 510 ft/s. Although all propeller configurations were designed to develop 18 lb of thrust at a cruise speed of 127 ft/s (75 knots), excessive background tunnel noise prevented testing at that speed. Propellers tested in the tractor mode at the design conditions included configurations with all four different blade designs and blade numbers ranging from two to four. Propellers with BD3 blade design (small diameter, low noise design) were also tested at two more tip speeds (340 and 576 ft/s) and two more thrust values of approximately 27 and 36 lb. These additional tests were conducted to provide the necessary trending data. A few propeller configurations were also tested in the pusher mode at the design conditions. Wind tunnel tests were conducted in two stages. In the first stage, only a selected group of propellers was tested at a forward velocity of 91 ft/s. The second stage of tests was more extensive in that they included a larger number of propeller configurations and forward velocities. However, the second stage of tests which was conducted at a latter time included testing of only tractor configurations.

Data Reduction

The performance data (the thrust and power or torque absorbed) were reduced to obtain the propulsion efficiencies of the various propeller configurations. In the case of static tests, figure of merit was used as a measure of the efficiency of the propeller configurations. The acoustic data (pressure-time history) of each propeller configuration were analyzed to obtain narrow-band and ⅓-octave-band spectra. Most of the narrow-band spectra were obtained for a bandwidth of 10 Hz over a frequency range of 0-2.5 kHz. The spectral data were used to obtain the detection distances of the propeller configurations.

Two types of aural detection distances were computed for each propeller configuration. The first one was the altitude of no detection and is defined as the altitude above which an aircraft can fly without being aurally detected on the ground. The second one was the slant range detection distance and is defined as the greatest distance in the direction of flight from the aircraft flying at a given altitude to a point on the ground at which it is aurally detected. The directivity pattern of the aircraft noise plays an important role in the determination of these detection distances. The SPL's in the forward quadrant of the propeller determine the slant range while the SPL's in and about the plane of the propeller determine the altitude of no detection. Ambient noise spectra (see Fig. 1) representative of the battlefield noise were used in the determination of the detection distances.

The altitude of no detection of each propeller configuration was determined using a method given in Ref. 11. The method uses the given propeller noise spectrum and a detection level spectrum is determined for a specified detection and false alarm rates and a given ambient noise spectrum as detailed in Ref. 12. A 50% detection rate and 1% false alarm rate were used in the computation of altitudes of no detection. The ⅓-octave-band spectral data were used in the determination of altitudes of no detection.

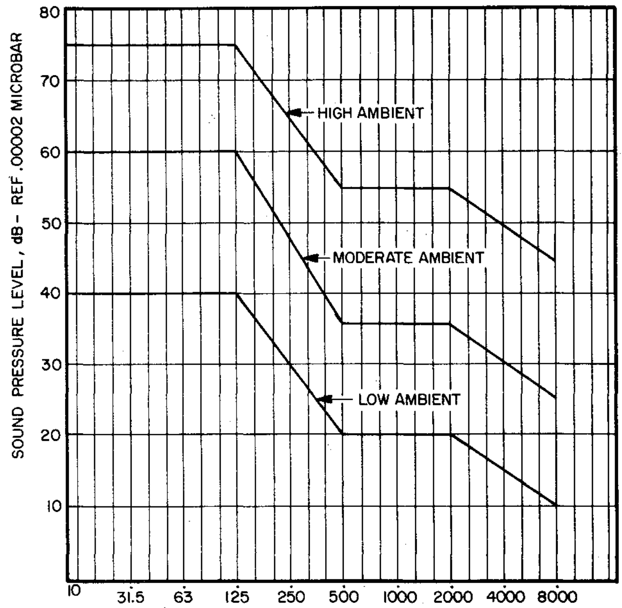

Fig. 1 Ambient noise levels.

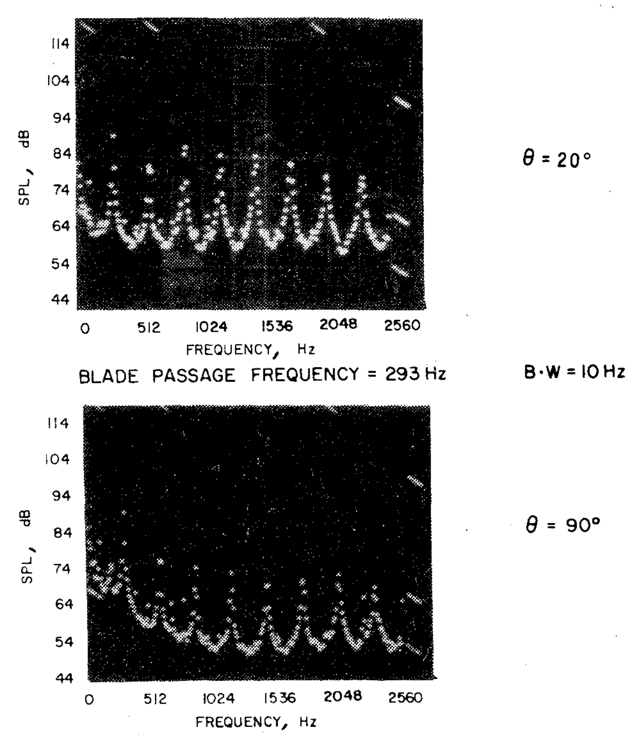

Fig. 2 Narrow-band spectra for three-bladed propeller (BD3 design)—static tests.

For the specified ambient noise spectrum and flight conditions, the slant range detection distances were obtained using a computer program developed by Abrahamson.[9] The program computes a slant range detection distance using Ollerhead's detectability criterion.[13] The output of the program consists of a slant range spectrum which gives the detection distances for various frequency bands. For each detection distance, the probability of detection is also given. The slant range distance for a given frequency band is taken as the distance for which the probability of detection is 50%. The peak value of the slant ranges over all the frequency bands is taken as the slant range detection distance of the propeller configuration for the direction θ, where θ is the

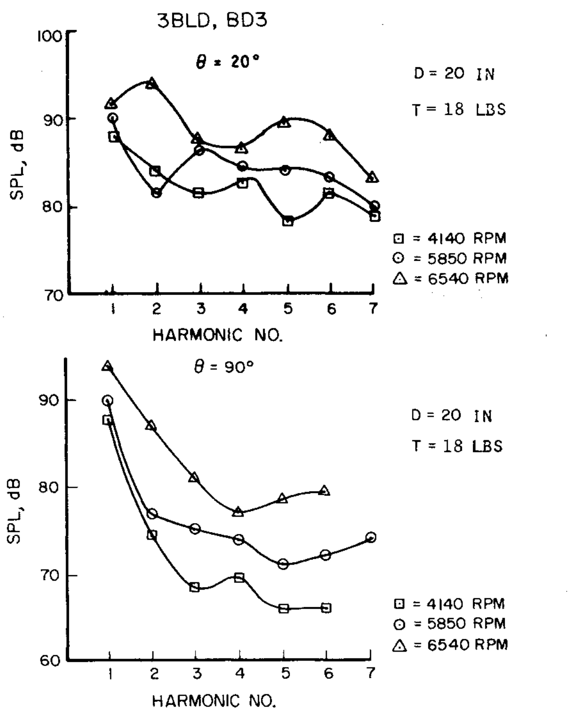

Fig. 3 Effect of tip speed on the noise at harmonics of blade passage frequency—static tests.

angular location, from the thrust axis, of the microphone whose acoustic data are used as input to the computer program. The effect of forward directivity was taken into account in the determination of the slant range detection distances of propeller configurations. Slant ranges of all propeller configurations were obtained for a flight altitude of 1000 ft using their narrow-band spectral data as input to the computer program.

Discussion of Results

The performance, acoustic, and detectability characteristics of various propeller configurations tested in static and simulated forward flight (wind tunnel tests) are discussed below.

Static Tests

The propellers tested in the static condition can be broadly classified into two categories: free propellers and ducted propellers. A three-bladed propeller with BD3 blade design (low noise design) is considered here to illustrate the performance and general acoustic characteristics of free propellers. The performance characteristics were predictable and it was found that the tip speed is a more important performance parameter than thrust.

To illustrate the general acoustic characteristics, narrow-band spectra corresponding to the azimuth locations $\theta = 20$ deg (representative of the data in the forward direction and therefore a measure of slant range) and $\theta = 90$ deg

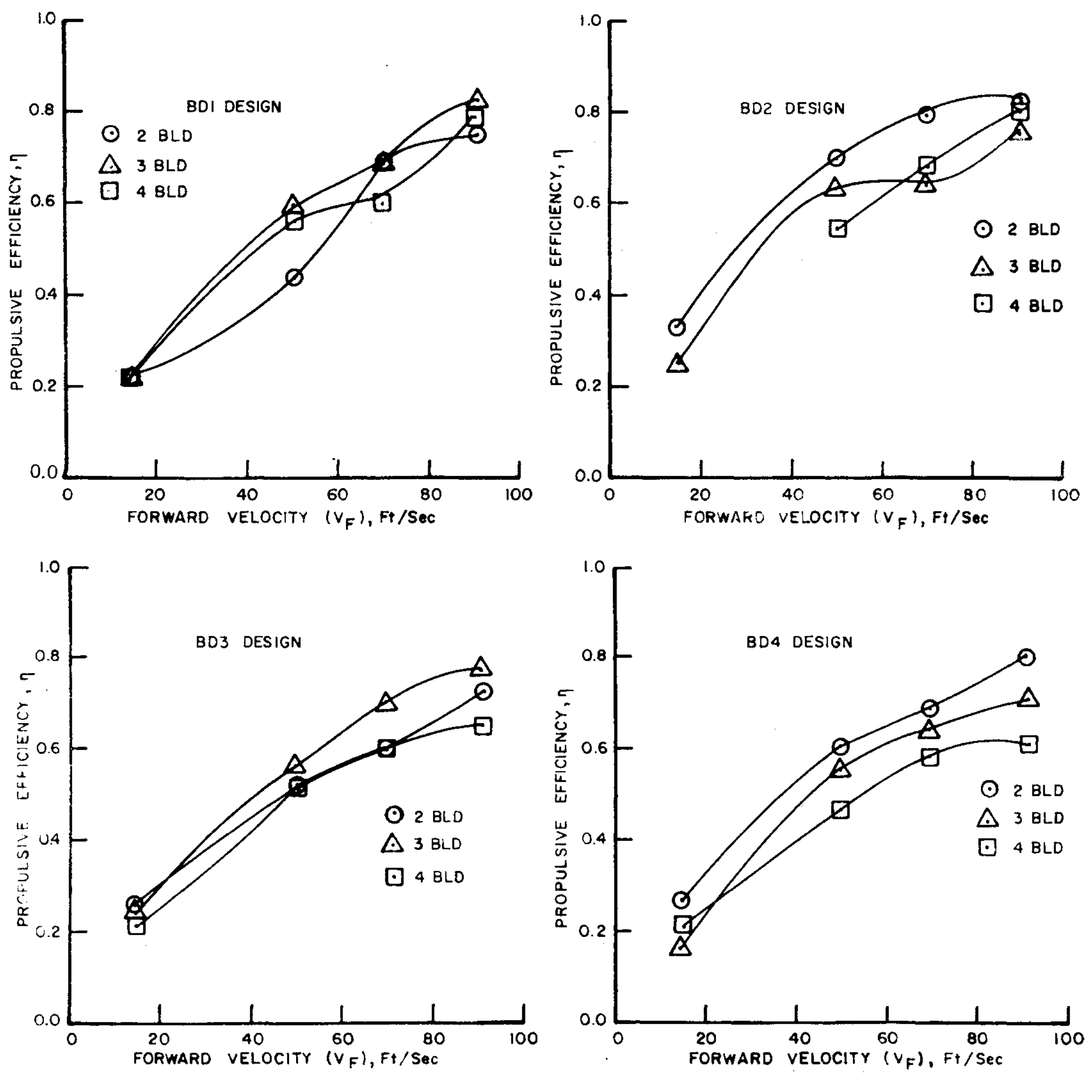

Fig. 4 Performance characteristics of tractor propeller configurations tested at design tip speed and design thrust.

(representative of the data in and about the plane of the propeller and therefore a measure of altitude of no detection) are considered here. It is to be noted that θ is the angle between the thrust axis and the microphone. Figure 2 gives the narrow-band spectra (10 Hz bandwidth) of the three-bladed BD3 propeller for $\theta = 20$ and 90 deg at the design values of thrust and tip speed. The peaks of SPL's (tones) in these spectra occur at integer multiples of blade passage frequency (293 Hz). For $\theta = 20$ deg, Fig. 2 shows the existence of relatively high SPL's at higher harmonics of blade passage frequency. These are probably due to the combination of unsteady aerodynamic loads on the propeller blades and the interaction of the propeller with inflow turbulence. For $\theta = 90$ deg, there is relatively a large difference in SPL's between the first harmonic and the higher harmonics of blade passage frequency (see Fig. 2) suggesting that the steady loads (which usually contribute to the lower harmonic noise) are the dominant sources of rotational noise in the plane of the propeller. However, the levels of the higher harmonic tones in the plane of the propeller are much lower than those at $\theta = 20$ deg, indicating a strong directivity. Figure 3 shows the effect of rotational speeds on the harmonic levels of the three-bladed BD3 propeller at the design thrust value. As expected, the SPL's at most of the harmonics increased with the tip speed. It was also found that the tip speed had a stronger effect than thrust on the acoustic characteristics of these RPV propeller configurations. The acoustic characteristics of the three-bladed BD3 propeller are representative of other configurations tested in the static condition.

For ducted propellers tested in static condition, the performance data showed that the thrust augmentation expected of ducts did not occur. It is believed that the low velocity inflow may have separated from the duct surface ahead of the propeller plane, preventing the thrust augmentation from being realized. Also the tip clearances were found to be larger than the design values. The acoustic characteristics in general showed the existence of higher broadband noise indicated by the rise in the floor level of the spectra at higher frequencies. For $\theta = 90$ deg, the SPL's at higher harmonics for the ducted propellers are 6-9 dB higher than those of the free propellers. Unlike free propellers, the data showed a relatively more uniform directivity pattern for the ducted propellers.

Wind Tunnel Tests

Performance Characteristics

The performance characteristics of all of the propeller configurations were obtained in terms of their propulsive efficiencies at various tunnel velocities considered. Figure 4 shows the performance curves of tractor propellers with all four different blade designs tested at the design values of thrust and tip speed. As shown, optimum performance propellers (blade designs BD1 and BD2) have generally higher values of propulsive efficiencies than those of low noise propeller designs (BD3 and BD4). Optimum performance blade designs have lower activity factors, higher twists, and a larger taper ratio (see Table 1) than their acoustic counterparts. Among the tractor propellers tested, the two-bladed BD2 propeller had generally the highest propulsive efficiencies at the forward velocities considered. It was found that at a forward velocity of 91 ft/s, the pusher configurations were less efficient (by about 6-8%) than their tractor counterparts. Also the ducted propellers tested in either the tractor or pusher mode were found to be less efficient (by as much as 9%) than their free (or nonducted) counterparts. Lack of thrust augmentation and the presence of nonuniform tip clearance around the azimuth probably contributed to the poor efficiencies of the ducted propellers.

Acoustic Characteristics

The general acoustic characteristics of propellers tested in simulated forward flight are illustrated by the narrow-band spectra of a representative configuration (three-bladed BD3

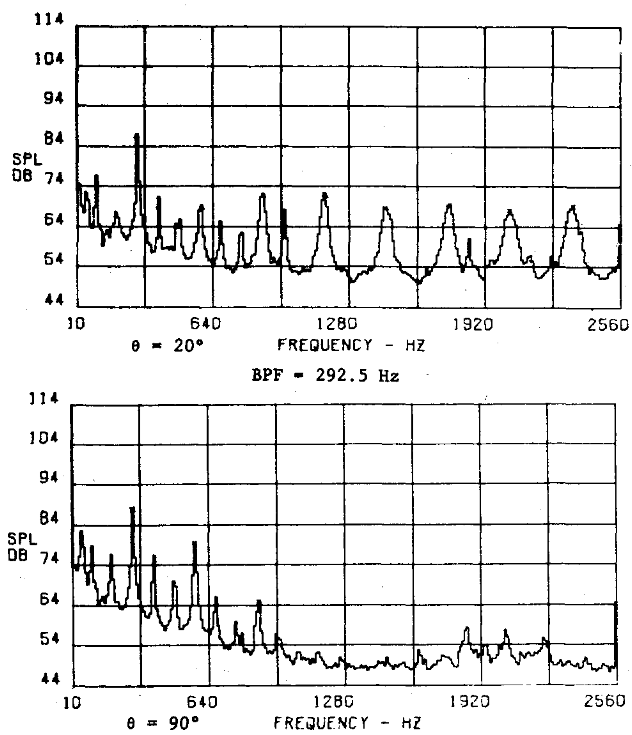

Fig. 5 Narrow-band spectra of the three-bladed BD3 propeller at a forward velocity of 15 ft/s.

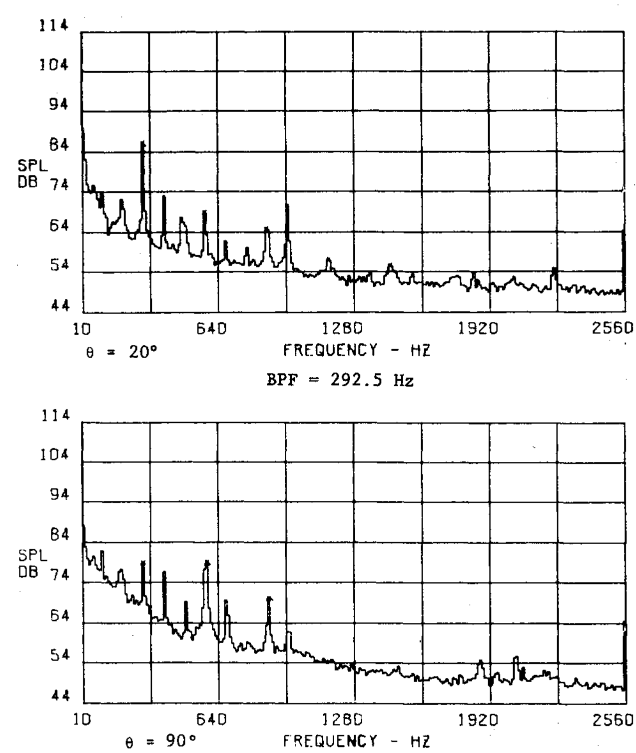

Fig. 6 Narrow-band spectra of the three-bladed BD3 propeller at a forward velocity of 50 ft/s.

propeller) for microphone locations $\theta = 20$ and 90 deg. Figure 5 gives the narrow-band spectra of the three-bladed BD3 propeller tested at a forward velocity 15 ft/s at the design values of thrust and tip speed. A comparison of these spectra with those obtained in static tests (see Fig. 2) shows that while the SPL's at the first few harmonics of blade passage frequency remained almost the same, the SPL's at higher harmonics of blade passage frequency were much lower (by about 10-15 dB) for 15 ft/s than those for the static condition. This significant drop in higher harmonics SPL's could be due

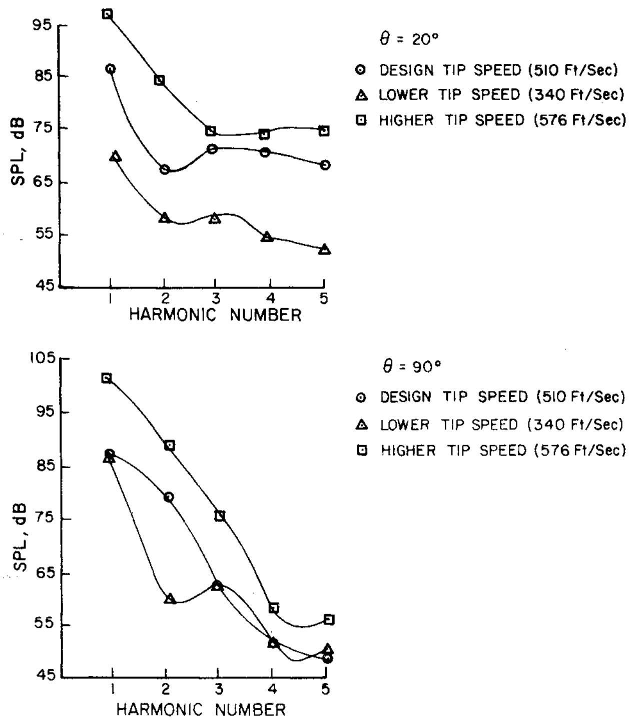

Fig. 7 Effect of tip speed on a three-bladed BD3 propeller at a forward velocity of 15 ft/s.

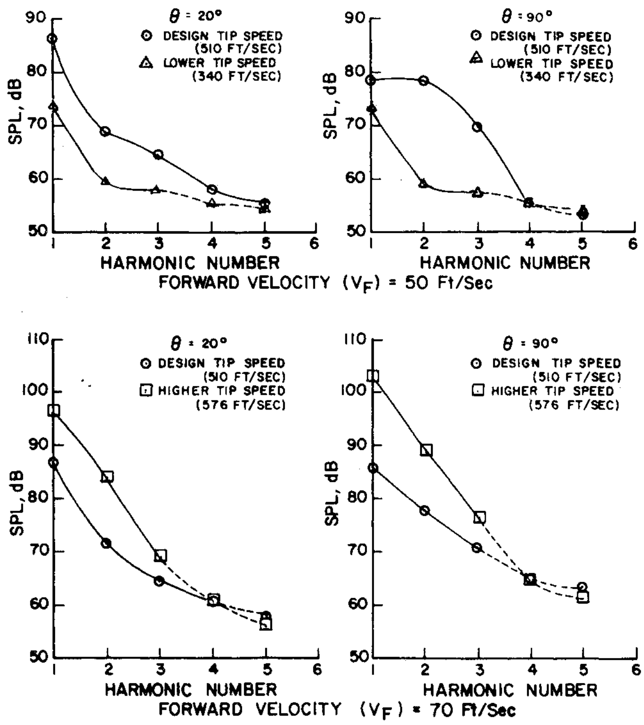

Fig. 8 Effect of tip speed on a three-bladed BD3 propeller.

to a relatively more uniform inflow and less wake interaction at 15 ft/s than that at the static condition. Also, at 15 ft/s, the higher harmonic peaks for $\theta = 20$ deg were quite broad (see Fig. 5), indicating the presence of a strong broadband noise component. Figure 6 shows the narrow-band spectra of the three-bladed propeller configuration at a tunnel velocity of 50 ft/s. The higher harmonic SPL's for 50 ft/s are substantially lower than those for 15 ft/s. It is believed that as forward velocity increases, there will be more uniform inflow and less wake interaction resulting in a drop of higher harmonic SPL's. This could not be confirmed by the tests at higher test tunnel speeds of 70 and 91 ft/s because the excessive tunnel background noise at these speeds masked the propeller noise signal. Full-scale flight tests[4] do show a decrease in higher harmonic levels with an increase in flight speed. This trend is at least partially confirmed by the present tunnel tests. The SPL's at the first two or three harmonics of blade passage frequency, where, as will be shown later, a propeller is most likely detected, showed only a little variation with forward speed. It was also found that the directivity pattern of the propeller was not significantly affected by the changes in forward velocity.

The general acoustic characteristics discussed above are fairly typical of the tractor propeller configurations tested in the wind tunnel at the design conditions of tip speed and thrust. A few pusher configurations showed a substantial increase in higher harmonic SPL's compared to those of the corresponding tractor configurations. It was also found that the ducted propeller was much noisier than its free counterpart. Acoustic trends (the effect of such parameters as the blade design, blade radius, blade number, tip speed, and thrust on the acoustic characteristics) of the propellers tested in the tunnel are discussed below at two forward velocities: 15 ft/s, which is representative of low speed forward flight, and 70 ft/s, which is representative of moderate speed forward flight. The effects are shown in terms of the narrow-band SPL's at the first five harmonics.

Effect of blade design: The total effect of such paramenters as blade activity factor, taper ratio, and twist was identified as the effect of blade design. It is believed, however, that the blade activity factor (blade chord) plays the most significant role among these parameters. It was found that the blade design did not have a strong effect on the SPL's. However, propellers with the BD3 blade design (wider chord blades) had slightly higher SPL's (about 2-3 dB) than those with BD1 blade design. Unlike the trends observed for large-scale propellers in the literature, propellers with wider chord and lower twist blades had slightly higher SPL's, at least at the lower harmonics of blade passage frequency.

Effect of diameter: The effect of blade radius was obtained by comparing the acoustic data of propellers with blade designs BD3 and BD4 tested at the design conditions. At a forward velocity of 15 ft/s, the larger diameter propeller (BD4) had higher SPL's for both $\theta = 20$ and 90 deg. The effect was similar at other tunnel velocities but not as strong. The trend observed for these small-scale RPV propellers is different from that of the larger-scale propellers where the larger diameter propellers were less noisy.

Effect of blade number: An increase in the blade number generally resulted in a decrease in the harmonic SPL's at the forward velocities considered. The effect of the blade number was stronger for the noise in the plane of the propeller ($\theta = 90$ deg) than in the forward direction.

Effect of tip speed: Propellers with the BD3 blade design were tested at three different tip speeds. Figure 7 shows the effect of tip speed at the tunnel speed of 15 ft/s and design thrust value of 18 lb. As expected, tip speed had a strong effect on SPL's at various harmonics of blade passage frequency. Figure 8 shows the effect of tip speed at higher forward velocities, where the dashed lines indicate that the acoustic data in question may have been contaminated by the tunnel background noise. It can generally be concluded that the tip speed had a significant effect on the acoustic characteristics of small-scale RPV propellers in forward flight, at least in the range of tip speeds considered.

Effect of thrust: In the range of thrust values considered (18-36 lb) for a given tip speed, an increase in the thrust value resulted in a moderate increase in harmonic SPL's, though the amount of increase seems to depend on parameters such as blade number and forward velocity.

Thus, as far as acoustic characteristics of RPV propellers in forward flight are concerned, tip speed is found to be a very strong parameter. Parameters such as blade radius, activity factor, and blade number have a relatively weaker effect on the noise output. Also, the acoustic trends observed in small-scale RPV propellers were not necessarily the same as those previously observed in large-scale propellers.

Detectability Characteristics

The detection distances, slant range, and altitude of no detection of propeller configurations were computed for a temperature of 59°F and a relative humidity of 60% using the low ambient noise spectrum (see Fig. 1). It is believed that the trends of detection distances with other ambient noise spectra of Fig. 1 would be similar. It was found that because of higher SPL's of ambient noise at lower frequencies, and higher atmospheric absorption of the noise signal at higher frequencies, and because detection distances depend on the difference in SPL's between the propeller noise signal and the ambient noise, the detection would normally occur in the mid-frequency range ($200 \leq f \leq 1000$ Hz). In fact, computations showed that most of the propellers would be detected at the first, second, or third harmonic of the blade passage frequency. Detectability trend data to be discussed below closely followed the acoustic trend data of the lower harmonic SPL's.

Effect of forward velocity: It was found that the forward velocity had a significant effect on the slant ranges as well as altitudes of no detection of various propeller configurations, though the degree of effect seems to depend on the type of the propeller and its parameters such as blade design, blade number, etc. An examination of the slant range detection distance of various tractor propellers showed that there were essentially two types of propellers: one, in which the slant range at the high forward velocity of 91 ft/s is approximately equal to that at the low forward velocity of 15 ft/s; and the other in which the slant ranges at the two extremities of the forward velocities are quite different. In some cases, such as a two-bladed BD4 propeller, the slant ranges remained almost constant with forward velocity. Of all the propellers tested at the design conditions, the three-bladed BD3 propeller had the least slant range (4800 ft) at 91 ft/s. For this configuration, the slant range decreased with forward velocity. Unlike the slant range, the altitude of no detection of each propeller is determined by the lower harmonic SPL's in and near the plane of the propeller. Because of the strong directivity of most of the propellers tested, the effects of forward velocity on slant range and altitude of no detection were not necessarily the same. Of all the propellers tested at the design conditions, the three-bladed BD1 propeller had the lowest altitude of no detection (3500 ft) at 91 ft/s. Figure 9 shows the effect of forward velocity on detection distances of four propellers (one for each blade design) tested at the design values of thrust and tip speed.

Effect of blade design: The effect is similar to the one found with acoustic data. Of the two-, three-, and four-bladed tractor propellers tested at the design conditions, propellers with wider blade chords (BD3 design) were generally more detectable than those with the narrower chords (BD1 design) at most of the forward velocities considered (see Fig. 10), though the degree of detectability seems to depend on such parameters as blade number and diameter. This trend is different from that reported in Ref. 3 where wider chord blades were found to be less detectable.

Effect of diameter: Figure 10 shows that for a three-bladed propeller, an increase in diameter (from BD3 to BD4) resulted in a significant increase in the slant range at all of the forward velocities except at 15 ft/s. As far as the altitude of no detection is concerned, the trend is reversed between the low and high forward velocities, with the larger diameter propellers being more detectable at high forward velocities.

Effect of blade number: It was found that among the propellers tested at the design conditions, three-bladed propellers were generally less detectable than either two- or four-bladed propellers at most of the forward velocities considered.

Effect of tip speed: As expected, tip speed had a very strong effect on the detection distances. Figure 11 shows the effect of tip speed on the detection distances of a three-bladed BD3 propeller tested at the design thrust value. According to Fig. 11, a 13% increase in the tip speed from the design value of 510 ft/s resulted in an increase in slant range anywhere from

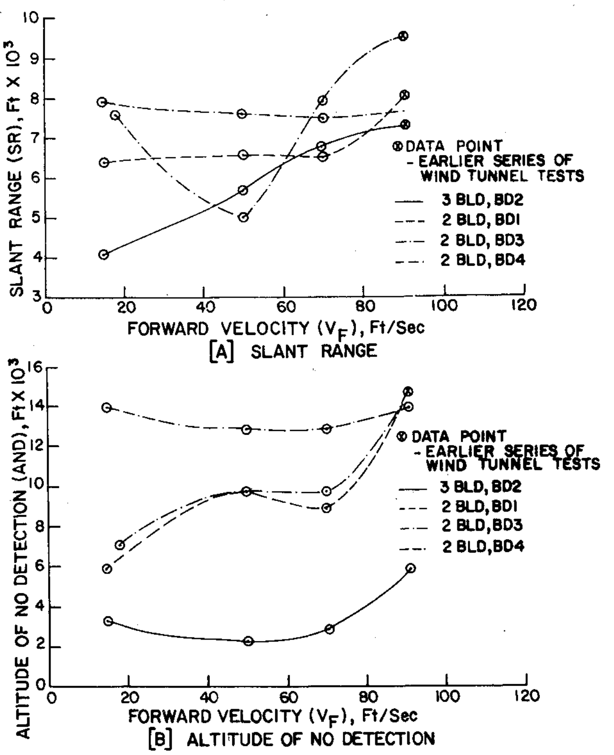

Fig. 9 Effect of forward velocity on the detection distances.

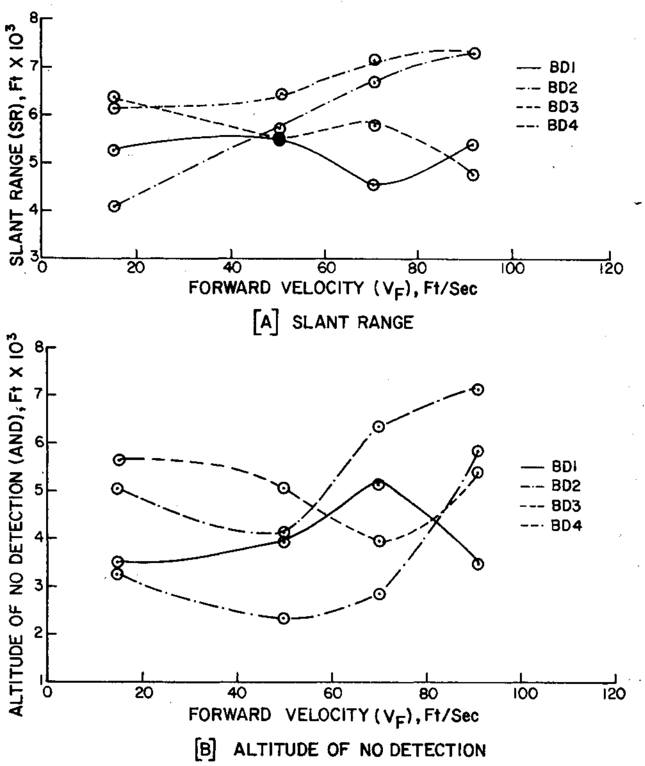

Fig. 10 Effect of blade design/diameter on the detection distances of a three-bladed propeller.

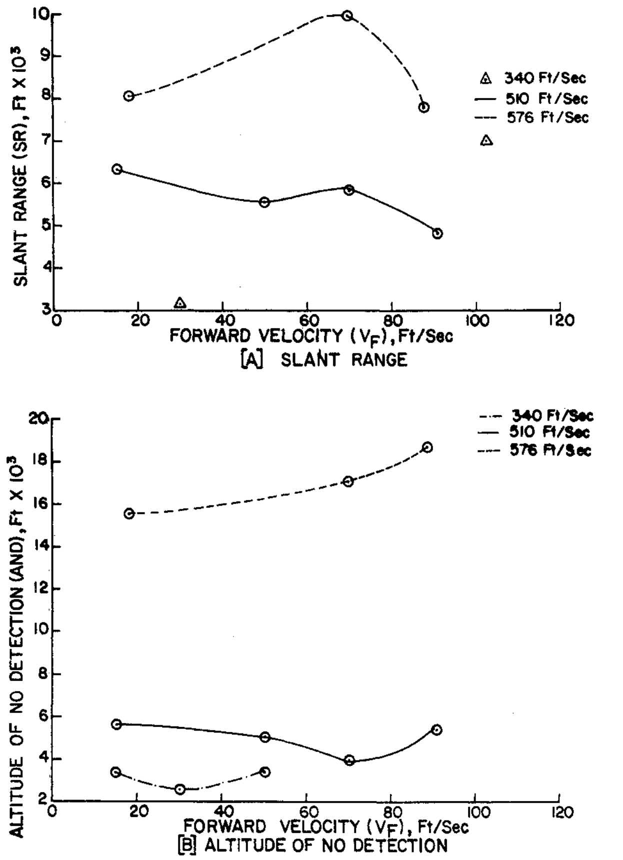

Fig. 11 Effect of tip speed on the detection distances of a three-bladed BD3 propeller.

30 to 70% depending upon the forward velocity. As far as altitude of no detection is concerned, the increases were higher with increase in tip speed, while a reduction in tip speed had comparatively smaller effect. Tip speed is one of the most potent parameters as far as the detectability of RPV's is concerned, though it has different degrees of effect on slant ranges and altitude of no detection.

Effect of thrust: An increase in thrust developed by propellers at a given tip speed increased their detectability though the amount of increase depended on such parameters as forward velocity and blade number.

In addition to the tractor propellers, a few propellers were also tested in the pusher mode in the first stage of wind tunnel tests as described earlier. It was found that pusher propeller configurations generally had higher slant ranges and altitudes of no detection than their tractor counterparts. No such clear trends could be established with the ducted propellers because of the limited data available. The investigation has shown that of the different tractor propellers tested at the design values of tip speed and thrust, three-bladed propellers had generally higher propulsive efficiencies and lower detection distances. It was found that the three-bladed BD1 propeller (an optimum performance design) was the best configuration considering both detectability and efficiency at most of the forward velocities considered. It is indeed encouraging to note that a propeller designed for optimum performance for a cruise speed of 127 ft/s had some of the lowest detection distances at most of the forward velocities considered. It is to be noted that the trend data of large-scale propellers were used as guidelines in the design of low noise propellers. However, these low noise designs were somewhat more noisy and detectable than the so-called optimum performance designs. This points out the inadequacy of large-scale propeller experience in the design of small-scale low noise RPV propellers.

Conclusions

On the basis of the results obtained in this investigation, it is concluded that the acoustic and detectability characteristics of small-scale RPV propellers are not necessarily the same as those of the large-scale propellers. This may have been due to either the low disk loading or the low operating Reynolds numbers of the RPV propellers investigated. It was found that the forward velocity has a significant effect on the acoustic characteristics as well as the detection distances of most of the RPV propeller configurations tested. It was also found, as expected, that such parameters as tip speed and thrust have a very strong effect on the detection distances and acoustic characteristics of RPV propellers. Ducted and pusher propeller configurations were generally more detectable and less efficient than their free and tractor counterparts, respectively. Most of the propellers tested had a very strong directivity in their acoustic radiation patterns.

General Remarks

Propellers for RPV's are generally characterized by small diameters (less than 3 ft) and low disk loadings (5-10 lb/ft^2). It would be highly desirable to develop a design method to help select high performance and low noise fixed-pitch propellers to be used in RPV's. A design method similar to those developed for large-scale propellers could be developed for determining the most efficient small-scale RPV propellers. However, such a design method requires extensive experimental performance data for RPV propellers which typically operate at Reynolds numbers of the order of 5×10^5/ft. The performance data obtained in this investigation are inadequate and are not amenable to the development of design charts similar to those developed for large-scale propellers. Most of the data in this investigation was obtained for a constant thrust condition. It is necessary to obtain extensive performance data covering a wide range of advance ratios and blade angles for the propellers investigated here to develop suitable design charts. It is also recognized that aural detectability plays an important role in the success of any RPV mission. Therefore it is necessary to obtain extensive acoustic data for these RPV propellers which can then be used to develop a detection distance data base. From the detection distance data base, it may be possible to develop suitable empirical relations which can be used in conjunction with performance charts to help select fixed-pitch RPV propellers with low detectability and high efficiency.

Despite the limitations, it is believed that the performance acoustic and detectability data obtained in this investigation are the first comprehensive data ever for small-scale RPV propellers and can be used in the selection of efficient propellers of low noise and aural detectability for RPV missions.

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