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# FLIGHT-EFFECTS ON PREDICTED FAN FLY-BY NOISE

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## ABSTRACT

A paper study was made of the impact on PNLT (Perceived Noise Level, Tone corrected) and fly-by EPNL (Effective Perceived Noise Level) when forward motion reduces the noise generated by the bypass fan of an aircraft engine. Calculated noise spectra for a typical subsonic tip speed fan designed for blade passage frequency (BPF) tone cutoff were translated in frequency by systematically varying the BPF from 0.5 to 8 kHz. Two cases of predicted flight-effects on fan source noise were considered: (1) reduced BPF tone level of 8 dB and (2) reduced broadband noise levels of about 2 dB in addition to reduced tone level. The maximum reduction in PNLT of the noise as emitted from the fan occurred when the BPF was at 4 kHz where the reductions were 7.4 and 10.0 dB for cases (1) and (2), respectively. The maximum reduction in EPNL of the noise as received during a 500-foot altitude fly-by occurred when the BPF was at 2.5 kHz where the reductions were 5.0 and 7.8 dB for cases (1) and (2), respectively. A factor of two change in tone frequency gave about one-half the maximum EPNL reduction.

STAR Category 07

# INTRODUCTION

The noise generated by the bypass fan of an aircraft engine in flight is known to often be reduced or altered compared with that generated during ground-static operation. Such flight-effects on fan source noise are attributed to the cleaner (less distorted) inflow that occurs during flight. Considerable effort has been expended to evaluate and understand these fan source noise changes because of the impact flight-effects can have on the development of quieter aircraft engines. From what is known now (ref. 1-6), the most important flight-effect occurs with a fan stage designed for cutoff of the blade passage tone caused by rotor/stator interactions. The tone level for such a fan is significantly reduced during flight compared with that observed during ground-static tests. The tone reduction may also be accompanied by a reduction in broadband noise although the degree of the broadband noise change is still uncertain. Although these flight effects often appear dramatic, the impact of the source noise change on perceived noise of an aircraft has received relatively little attention. The purpose of this study was to evaluate the reduction in fly-by perceived noise that can be attributed to flight-effects on fan source noise and, in particular, to examine the sensitivity of the noise reduction to changes in frequency of the blade passage tone.

The evaluation was made with the aid of a fan noise prediction method that typifies the noise of low tip-speed, tone cutoff fans tested at NASA-Lewis. A computer program of the prediction method that included an aircraft fly-by noise routine was used for the numerical calculations. Noise predictions were made for a low tip speed fan for which the blade passage frequency was systematically varied from 0.5 to 8 kHz. Two cases of flight-effects on fan noise were considered: (1) reduced blade passage tone level of 8 dB for the noise radiation from the fan inlet (2) the reduced tone level accompanied by reduced broadband noise levels of about 2 dB for the noise radiating from both the inlet and exhaust ducts. The effects of these noise reductions on perceived noise are presented and discussed as a function of the frequency of the blade passage tone. The fan source noise, defined as the noise at a 100-foot radius without atmospheric attenuation, is considered first. Both perceived noise level (PNL) and tone corrected perceived noise level (PNLT) reductions in source noise are discussed. The fly-by calculations for the noise from the fan alone are then presented. The fly-by noise is characterized by the Effective Perceived Noise Level (EPNL) for a 200-foot altitude fly-by at a velocity of 200 ft/sec with the fixed observer at a 500-foot sideline distance from the plane of the flight path. The computations of fly-by EPNL include the effects of atmospheric attenuation, Doppler frequency shift, dynamic amplification and ground-effects.

## METHOD OF ANALYSIS

The basic objective of the method of analysis was to simply translate in frequency the noise spectra for ground-static and flight operation expected from a typical subsonic tip speed fan designed for BPF tone cutoff and to evaluate the impact of the frequency translation on perceived noise levels.

The analysis was performed with the aid of an aircraft noise prediction computer program developed at NASA-Lewis for in-house applications.

The computer program generally consists of aircraft engine noise prediction procedures for various engine components and is capable of performing fly-by noise calculations. For this study the predicted noise was limited to that of the bypass fan of an aircraft engine. The fan noise prediction method used in the computer program is that developed at NASA-Lewis for the Aircraft Noise Prediction Program (ANOPP) Office located at NASA-Langley and reported in reference 8. The method is based on the average performance of a series of quiet fans tested statically at NASA-Lewis. Free-field one-third-octave band noise levels are predicted as a function of the design parameters and operating variables of the fan. Incorporated in the prediction method is an adjustment that attempts to account for the reduction in noise that has been observed when the fan is in flight.

The present study was made for a low tip-speed, single-stage fan operated at 80% of its design speed. Design values consist of an 1150 ft/sec tip-speed, 850 lb/sec flow rate and 1.4 pressure ratio. The fan is comparable to that used in Engine A of the NASA Quiet Engine Program (ref. 7). At 80% of design speed the tip speed is 920 ft/sec and the pressure ratio is 1.3. The tip speed and pressure ratio at 80 percent of design are representative of those for fans in present wide body CTOL aircraft during approach and in STOL aircraft during takeoff. The fan was assumed to have no inlet guide vanes and to have a rotor/stator blade number ratio so that the blade passage tone due to rotor stator interactions is cutoff. Experience has shown that the cutoff phenomenon is evident in flight but is masked by the tone noise caused by inflow distortions during ground-static tests.

In order to explore the effects on perceived noise of both tone and broadband noise reductions due to flight, calculations were made for two versions of the fan. They consist of a nominal one-chord and two-chord spacings of the rotor and stator. The predicted noise levels for ground-static operation in reference 8 is identical for the two versions of the fan. The predicted flight noise, however, differs in that the broadband noise as well as tone noise is reduced by flight with a two-chord spacing whereas only the tone is reduced when the spacing is one chord. Hereafter in the noise calculations, reference will not be made to the two versions of the fan but simply to flight-effects consisting of (1) tone alone reduction and (2) tone-an-broadband noise reductions.

Typical one-third-octave band spectra obtained from the prediction method are shown in figure 1. The frequency of the blade passage tone is 2.4 kHz for this illustration. The spectra shown are at a 100-foot radius from the fan and without atmospheric attenuation effects which, if included, would not be very significant at this distance. The spectra, therefore, characterize the predicted fan source noise. For ground-static noise, the spectrum for the forward gradient exhibits a prominent blade passage frequency (BPF) tone whereas for the aft quadrant the tone level is below that of its harmonic. This low resultant tone level in the aft noise is a property of tone-cutoff fans that has been noted in ground-static tests (ref. 9). Figure 1 shows that predicted flight-effects are most prominent for the noise propagating from the fan inlet. With tone-alone effects, the tone level is reduced 8 dB in the forward quadrant but there is no change in aft quadrant.

With tone-and-broadband noise effects, the predicted forward quadrant tone reduction is somewhat more than 8 dB, but the tone harmonics as well as the broadband noise for both the fore and aft noise appear reduced by a constant level. In effect, the spectra for the two conditions of flight-effects can be considered identical except that the levels for tone-and-broadband effects are about 2 dB lower than those for tone-alone effects. In reality, observed changes in broadband noise (refs. 5, 6 and 10) are more complex than those predicted here but a more accurate model remains to be developed.

The far-field directivities obtained from the prediction method (ref. 8) are shown in figure 2. The PNL and PNLT levels are shown for the same conditions used for figure 1 where the BPF is 2.5 kHz. The levels of both PNL and PNLT for the forward quadrant are higher than those for the aft quadrant. The balance between peak fore and aft levels can influence the perceived noise reductions obtainable from flight effects on fan noise in that high aft noise levels can limit the maximum reduction possible. For this fan, where fore noise generally is dominant, the aft noise will not seriously limit the reduction in maximum perceived noise levels caused by reductions in forward quadrant noise.

As illustrated in figure 3, the frequency of the blade passage tone was systematically varied by one-third octave frequency increments from 0.5 to 8 kHz. In effect, the noise levels were maintained constant and the spectrum was simply translated in frequency in a sequence of 12 increments. PNL and PNLT, which are weighted levels, will vary with such frequency translations of a given spectrum. The reductions in PNL and PNLT due to flight effects,therefore, will also depend on the position of the spectrum in the frequency plane. The importance of this frequency dependent weighting procedure alone will first be demonstrated by presenting PNL and PNLT reductions obtained in the noise at a 100-foot radius from the fan without the effects of atmospheric attenuations. Such calculations demonstrate the effect of flight on source noise or the noise as it is perceived in close proximity to the fan.

Fly-by noise calculations were made that included the effects of atmospheric attenuation, Doppler frequency shift, dynamic amplification and ground-effects. The fly-by calculations were made for the condition shown in figure 4. It is a 200-foot altitude fly-by at 200 ft/sec with a fixed observer at a 500-foot sideline distance from the flight plane. These are the fly-by conditions commonly used for STOL aircraft noise studies and they are used here to show the effects of the assumed spectral changes in fly-by noise. During fly-by the Doppler frequency shift amounted to several one-third-octave bands. Band splitting was not used in the calculations as a tone progressively shifted from one band to another. Abrupt changes in PNL and PNLT values, therefore, were encountered along the flight path because of the discrete nature of the conversions and corrections used to calculate perceived noise and the large differences in atmospheric attenuation between one-third-octave bands at high frequencies.

The fly-by EPNL values were calculated in general conformance with FAR-36 although the exact rules were not followed. As indicated in figure 4, noise levels for the observer were predicted at ½ sec. intervals in flight time rather than those observed at ½ sec. intervals on the ground as specified in FAR-36. The calculations were made for a range of 1200 feet (6 sec.) before and after the point of closest approach to the observer and

PNLT was evaluated at each interval position. EPNL was obtained from a numerical integration of the PNLT time history when PNLT was not more than 10 dB below the maximum value of PNLT. Exceptions regarding the 90 dB PNLT value specified in FAR-36 were neglected.

## RESULTS AND DISCUSSION

The source noise, defined as the free-field noise at a 100-foot radius without atmospheric attenuation, will be discussed first and the effects of flight on the perceived noise in close proximity to the fan will be shown. The fly-by noise as perceived by a fixed ground observed will then be presented and discussed.

### Source Noise

Figure 5 shows the peak fore and aft levels of PNL and PNLT as functions of blade passage tone frequency for ground-static and flight conditions. The curves for the two assumed flight effects are nearly identical except for a level displacement of about 2 dB. This behavior can be attributed to the similar and nearly identical spectral shapes for the two cases with only the spectrum levels differing. It can also be observed in figure 5 that the aft noise was not altered by flight-effects without a broadband noise change. Flight-effects had the most pronounced effect on forward quadrant noise and at blade passage frequencies greater than 2 kHz. Incidentally, the irregular behavior with frequency was caused by the conversion process to perceived noise and not by computational problems.

The reductions in PNL and PNLT caused by flight-effects on source noise are shown in figure 6. The solid lines represent results of calculations using inlet radiated noise only while the dashed curves include the consideration of aft radiated noise. For the case where tones alone are affected by flight, figure 6(a), the maximum reductions were 7.4 and

5.2 dB for PNLT and PNL, respectively. The maximum reduction in PNLT occurred when the spectrum was located with the tone at a frequency of 4 kz. The PNL reduction exhibited no distinct maximum and were high from 4 to 8 kHz. Below 2 kHz the PNL reduction was less than 1 dB and the dashed line indicates that aft noise was higher than forward noise. The PNLT reduction below 2 kHz was relatively constant at 3 dB. Most of the 3 dB reduction is accounted for by the tone correction factor that is independent of tone frequency in this region. The variations in PNL and PNLT reductions with tone frequency when both tone and broadband noise are reduced, figure 6(b), are similar to those for tone alone reductions except that the levels are higher. The peak reductions were 10.0 and 7.0 dB for PNLT and PNL, respectively. As indicated in figure 6, the aft noise in some cases controlled and limited the reduction in PNL.

The reductions in source noise observed with changes in blade passage frequency essentially reflect the weighting factors and calculation procedures used to calculate PNL and PNLT. Considering how the weighting factors vary with frequency, the reduction was expected to decrease at high tone frequencies. The calculated reductions, however, did not exhibit a significant decrease at high tone frequencies.

## Fly-By Noise

Typical time histories of the noise observed at a fixed sideline position during fly-by are shown in figure 7. The PNLT values of the noise are shown because the time histories of PNLT are numerically integrated to compute the Effective Perceived Noise Level (EPNL). For a simulated fly-by using noise predicted for ground-static operation, the maximum PNLT is shown to be up to 10 dB higher prior to than after the time of closest approach. With flight-effects these two peak levels are more nearly equal. Flight-effects involving only the tones do not alter the aft noise since no aft noise reduction of the tones was assumed. Flight-effects with and without broadband noise changes exhibit time histories that essentially differ only by a constant. For the 5 kHz tone result in figure 7 abrupt level changes are evident at a time of about 4 seconds. The abrupt changes can be attributed to the calculation procedures in that a 1/3-octave-band Doppler shift in spectrum frequencies occurs at this time. The change in atmospheric attenuation and perceived level weighting accompanying the frequency shift cause the abrupt changes.

The EPNL values for these fly-by evaluations are shown as a function of tone frequency in figure 8. The levels for the three cases are shown to be relatively constant for tone frequencies up to about 2 kHz and then decrease rapidly. The differences in the levels of the three curves are the significant results of this study.

The reductions in EPNL caused by flight-effects are shown as a function of tone frequency in figure 9. The maximum reduction is 5 dB when tone alone is affected by flight. The maximum reduction increases to 7.8 dB when both tones and broadband noise are affected. Both of the peak reductions occur when the spectrum was located with a blade passage frequency at 2.5 kHz. The reduction is about one-half the maximum value for either a 2:1 increase or decrease in tone frequency. At very low frequencies, however, the reduction approaches a constant level. This constant level is about the same as that noted in figure 6 for the PNLT reductions in source noise. The EPNL reductions, however, begin to increase from this constant level at a lower tone frequency than that for the source noise in figure 6.

A significant difference between the EPNL reductions of figure 9 and the source noise reductions of figure 6 is that the EPNL reductions are significantly decreased at high tone frequencies. This decrease, not noted in the source noise, is the result of both atmospheric attenuation and the Doppler shift in frequency and not simply a result of perceived noise weighting factors. The large atmospheric attenuation at high frequencies makes the tone less important regarding the EPNL value. The Doppler increase in tone frequency during the approach to the observer further reduces the impact of the tone on EPNL. At high tone frequencies, therefore, tone reductions caused by flight-effects can have an insignificant effect on EPNL.

This study of flight-effects on fan fly-by noise was made with the blade passage tone level 8 dB lower in flight than during ground-static operations. The tone level for the predicted fan forward quadrant noise is approximately 15 dB above the broadband level in the one-third octave spectra. It is possible, therefore, with complete tone cutoff that a tone reduction of 15 dB could occur during flight. Figure 10 shows the effect on perceived noise reduction when the tone reduction is varied. The curves are for a tone frequency of 2.5 kHz. Maximum EPNL reduction, as shown in figure 9, was obtained at this tone frequency. Figure 10 indicates that the EPNL reduction would not have been greater with a tone reduction larger than 8 dB. The PNLT on which EPNL is based is shown to attain its maximum reduction with a tone reduction of about 7 dB. The curves level off for large tone reductions because the second harmonic of the blade passage tone is the dominant tone in this region and controls the PNLT evaluation. The results of this study, therefore, are believed to be indicative of the reduction in perceived fan noise that can be expected whenever a substantial reduction in blade passage tone level occurs during flight and aft fan noise does not dominate the far-field directivity. The results must also be qualified by the specific spectra used for the evaluation and particularly with regard to the level of the second harmonic of the BPF tone in the spectra.

## SUMMARY OF RESULTS

Perceived noise reductions caused by flight-effects on fan source noise were evaluated using the calculated noise levels obtained from a previously developed fan noise prediction method that included assumed flight effects on the noise. The analysis was made for a low tip-speed fan having blade passage frequency (BPF) tone cutoff design features. The tone frequency was varied from 0.5 to 8 kHz in one-third-octave frequency increments which, in effect, resulted in a frequency translation of the entire fan noise spectrum. Flight-effects consisted of (1) reduction in tones alone and (2) reductions in tones and broadband noise. Reductions in the perceived noise level (PNL) and tone corrected perceived noise level (PNLT) were calculated for the fan source noise defined as the free-field noise level without atmospheric attenuation at a 100-foot radius from the fan. Reductions in the Effective Perceived Noise Level (EPNL) of the fan noise alone were calculated for a 200 ft/sec fly-by at an altitude of 200 feet and with the fixed ground observer at a 500-foot sideline distance from the flight plane. The fly-by noise calculation included the effects of atmospheric attenuation, Doppler frequency shift, dynamic amplification and ground effects. The following table summarizes the maximum noise reductions obtained and the tone frequencies for these maxima.

MAXIMUM NOISE REDUCTIONS

| FLIGHT-EFFECTS | Fan Source Noise 100-Ft Radius | | | | Fan Fly-By Noise (500-Ft Sideline) | |
|---|---|---|---|---|---|---|
| | PNL | | PNLT | | EPNL | |
| | ΔdB | BPF kHz | ΔdB | BPF kHz | ΔdB | BPF kHz |
| Tones Alone | 5.0-5.2 | 4-8 | 7.4 | 4 | 5.0 | 2.5 |
| Tones and Broadband Noise | 6.8-7.0 | 4-8 | 10.0 | 4 | 7.8 | 2.5 |

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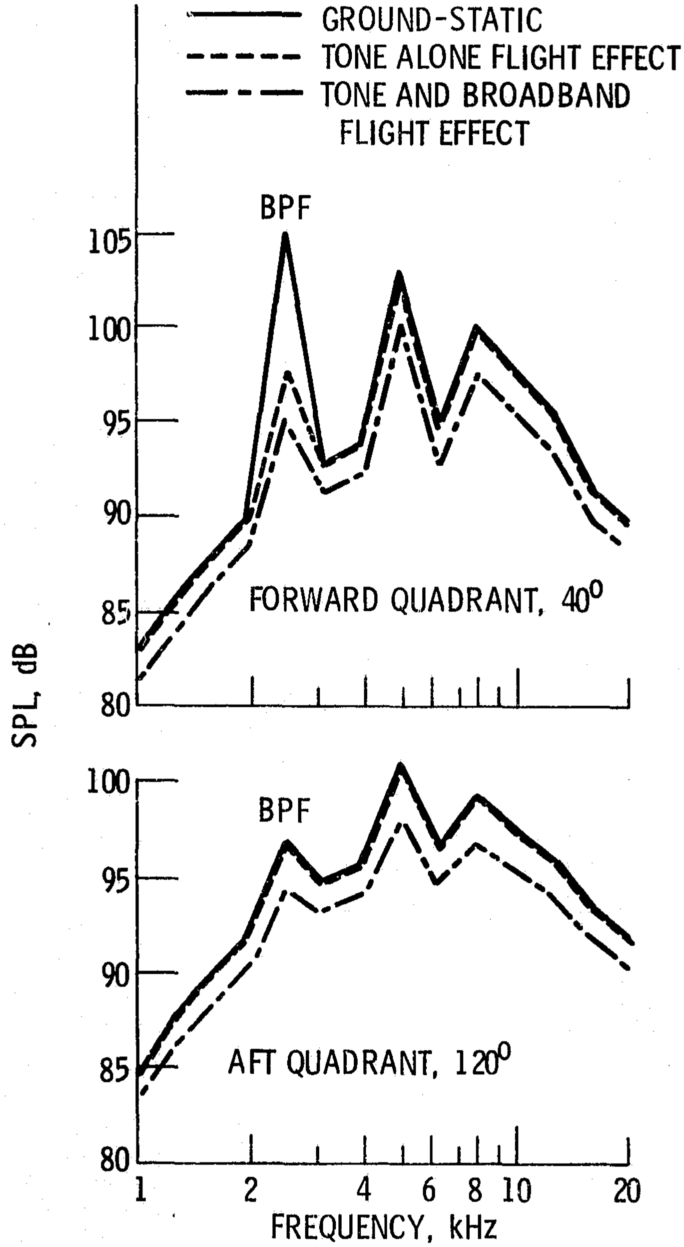
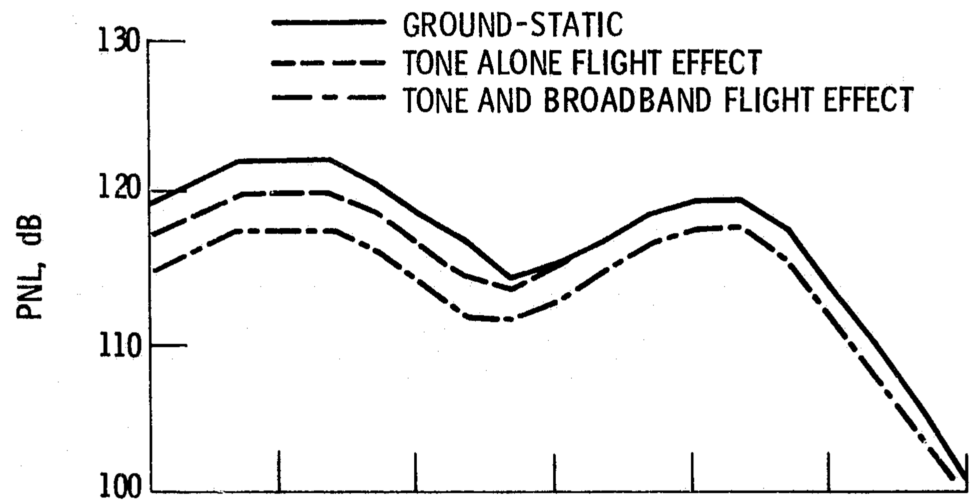
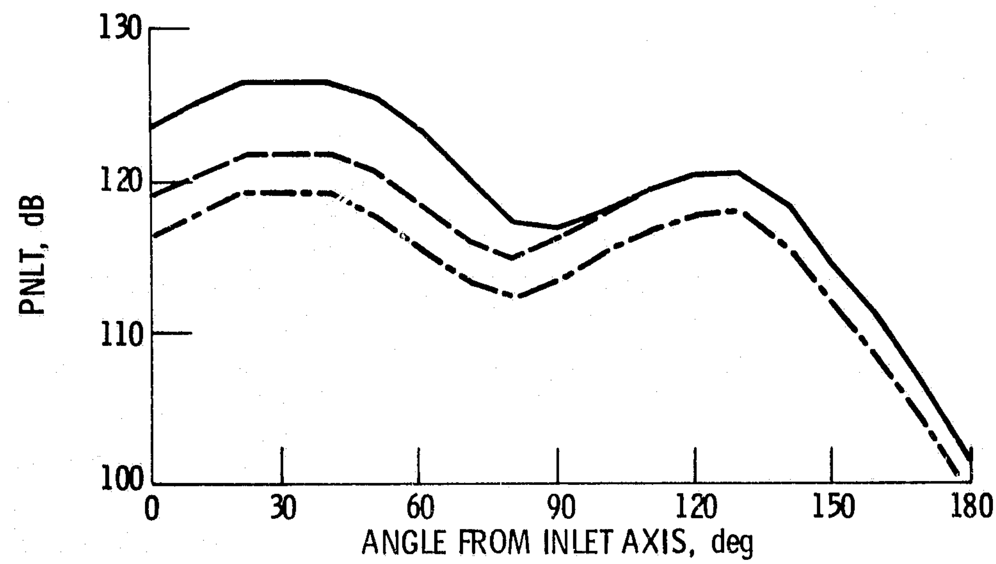



Figure 1. - Typical 1/3-octave-band spectra characterizing fan noise during ground-static and flight operation. 100 ft radius. No atmospheric attenuation.




(a) PERCEIVED NOISE LEVEL (PNL) DIRECTIVITY.




(b) TONE CORRECTED PERCEIVED NOISE LEVEL (PNLT) DIRECTIVITY.

Figure 2. - Typical perceived noise directivities characterizing fan noise during ground-static and flight operation. 2.5 kHz BPF. 100-ft radius. No atmospheric attenuation.

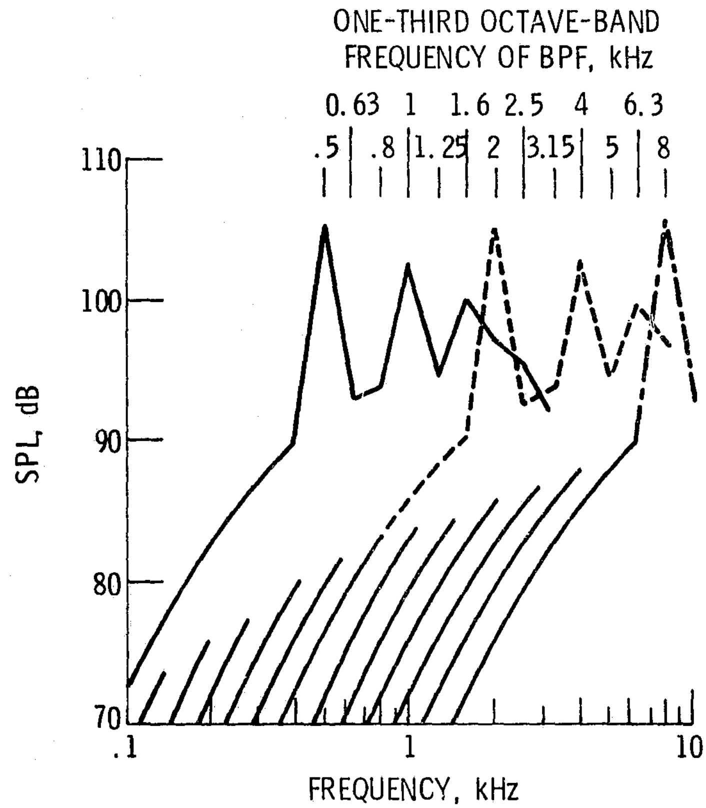



Figure 3. - Method of incrementing blade passage frequency (BPF).

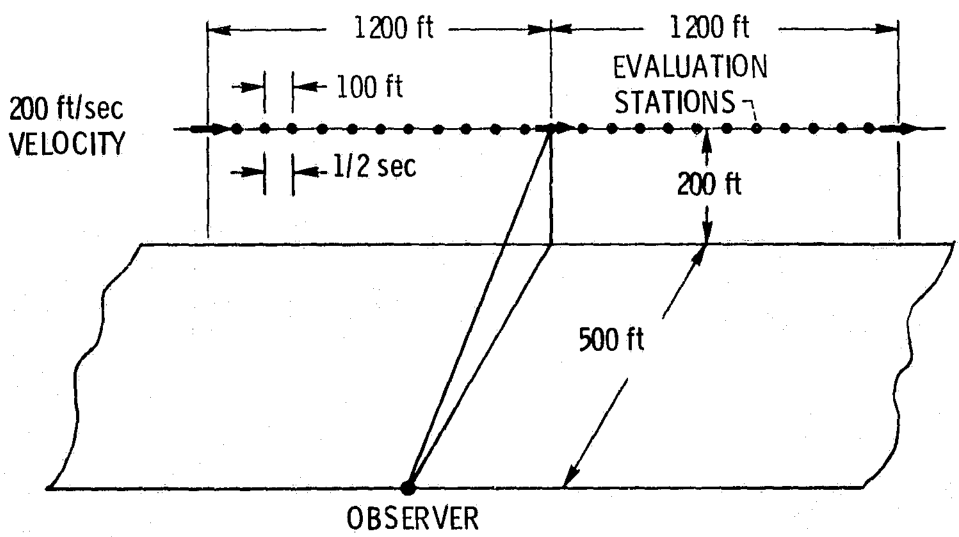



Figure 4. - Fly-by path.

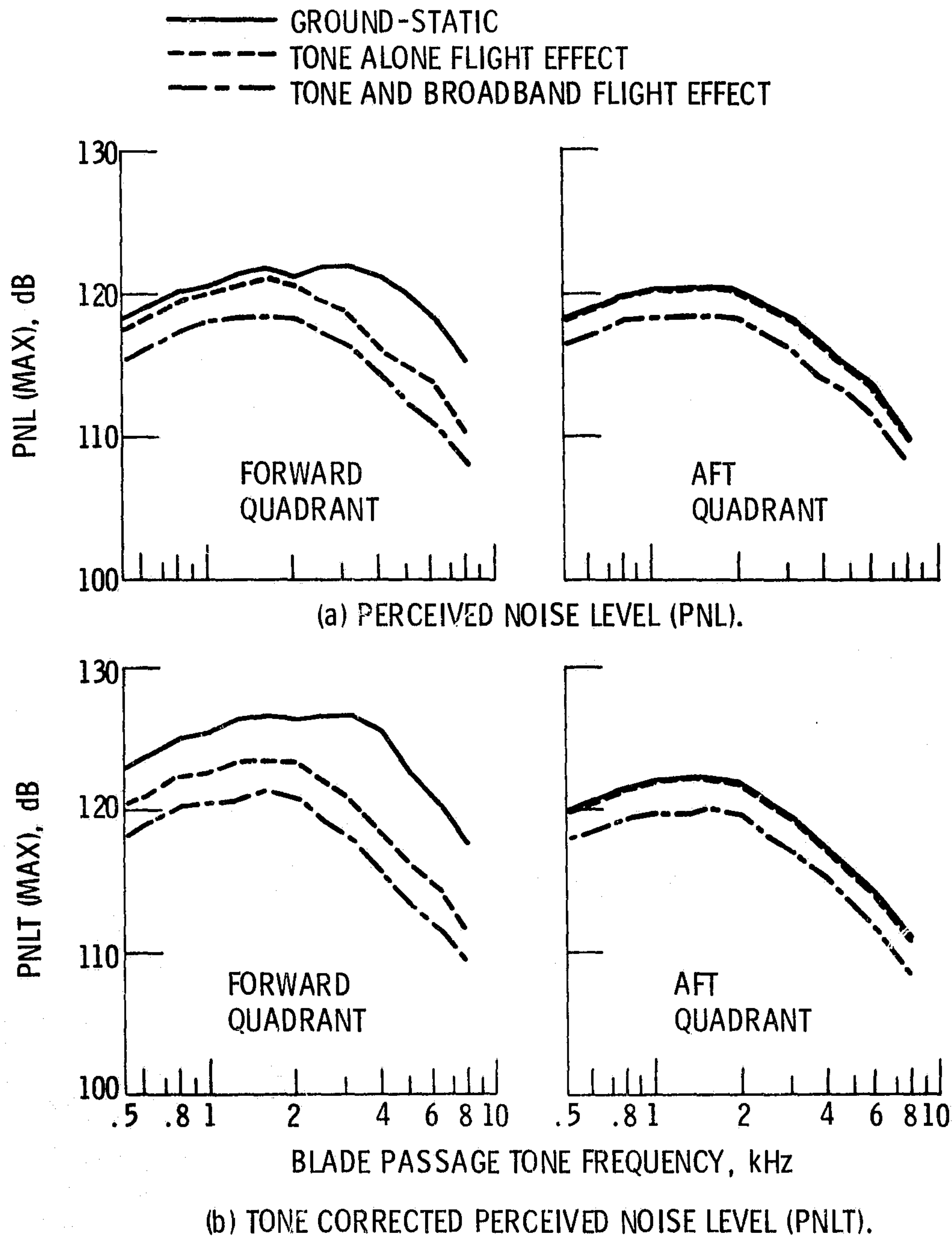
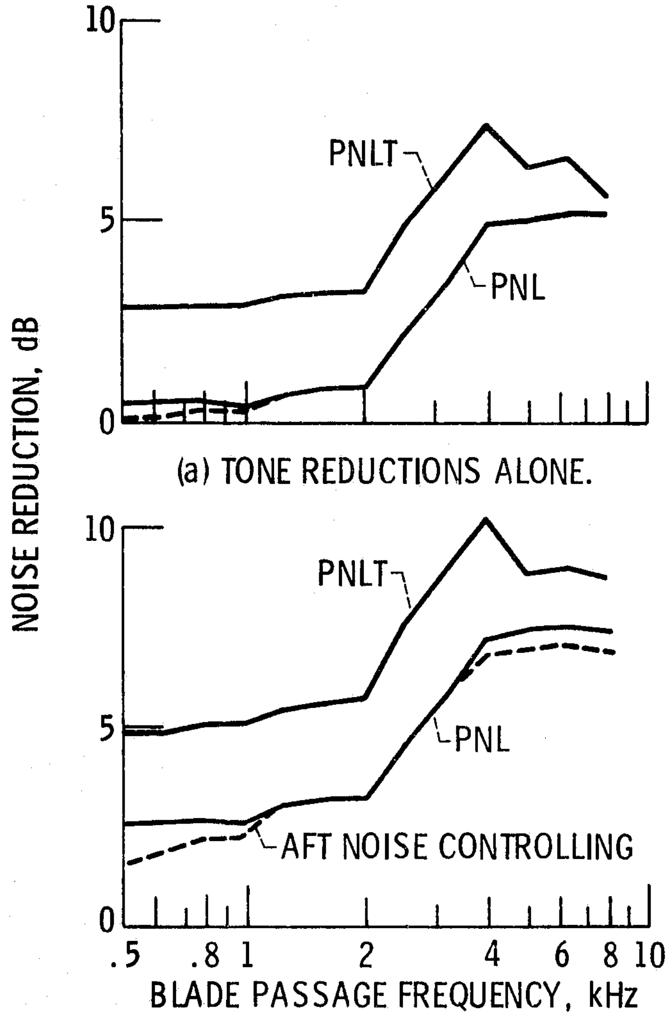



Figure 5. - Effect of blade passage frequency on maximum perceived levels of fan source noise. 100-ft radius. No atmospheric attenuation.




(b) TONE AND BROADBAND NOISE REDUCTIONS.

Figure 6. - Reduction in maximum perceived level of source due to flight-effects. 100-ft radius. No atmospheric attenuation.

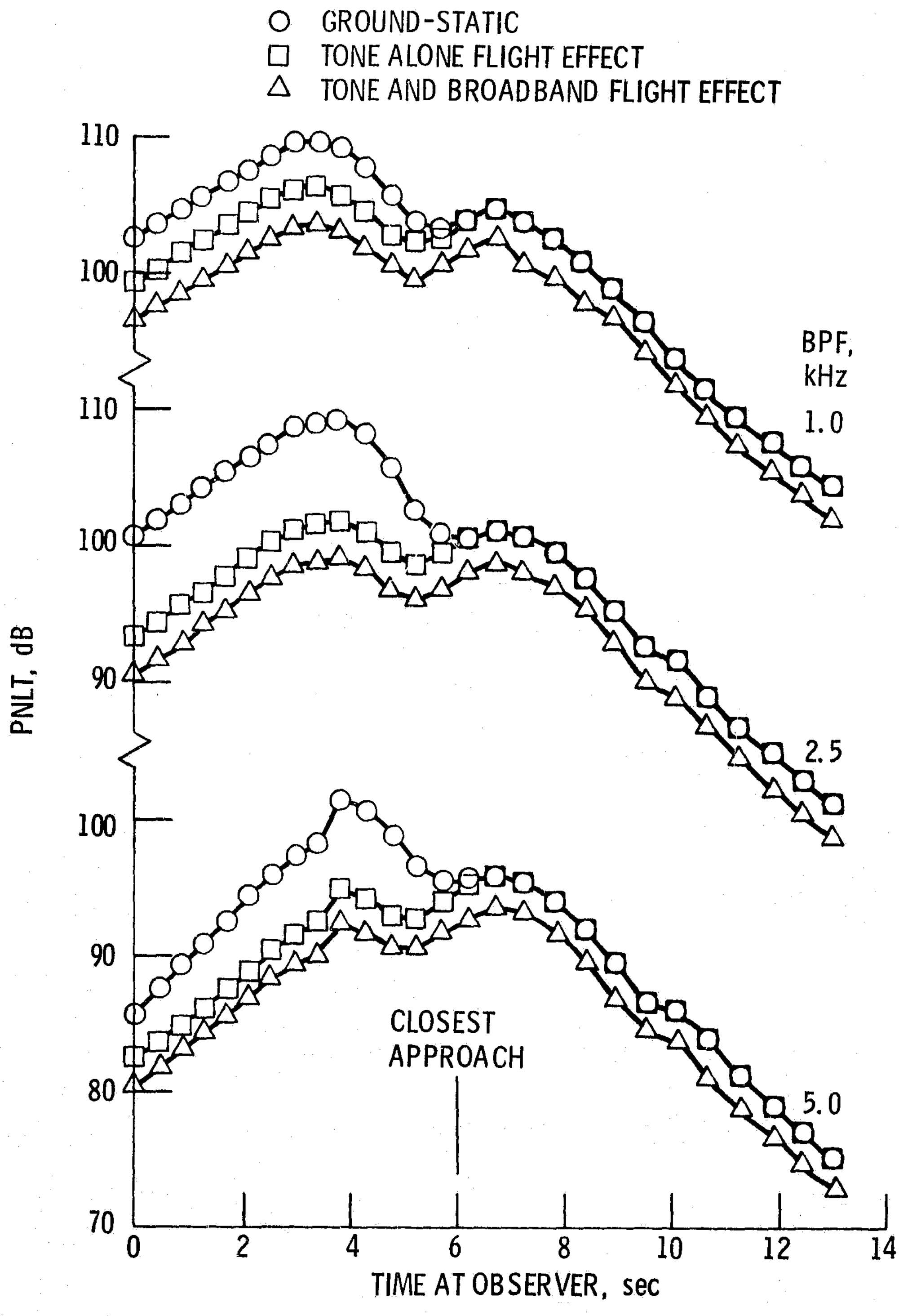



Figure 7. - Typical fly-by time histories of tone corrected perceived noise.

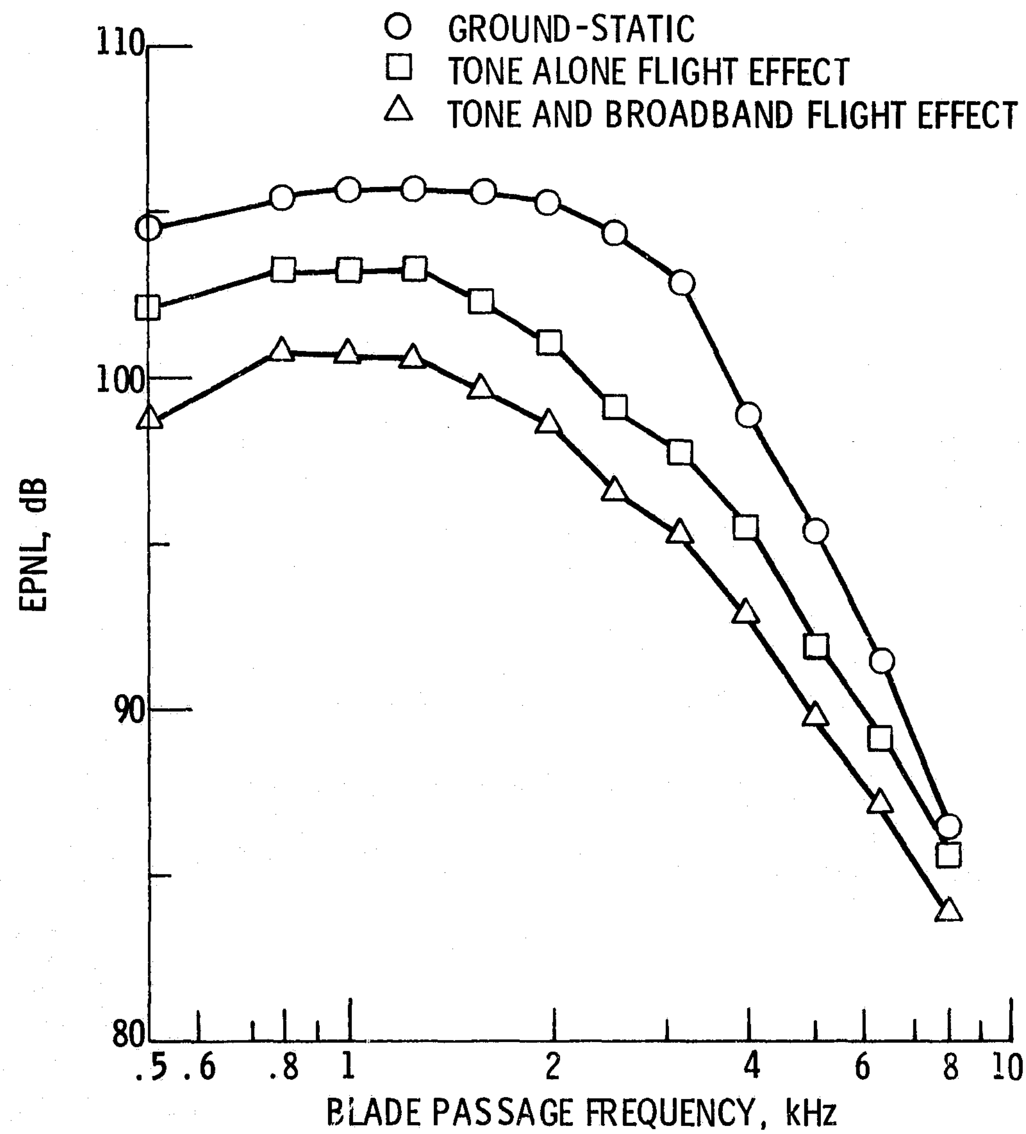



Figure 8. - Effect of blade passage frequency on fly-by EPNL (effective perceived noise level).

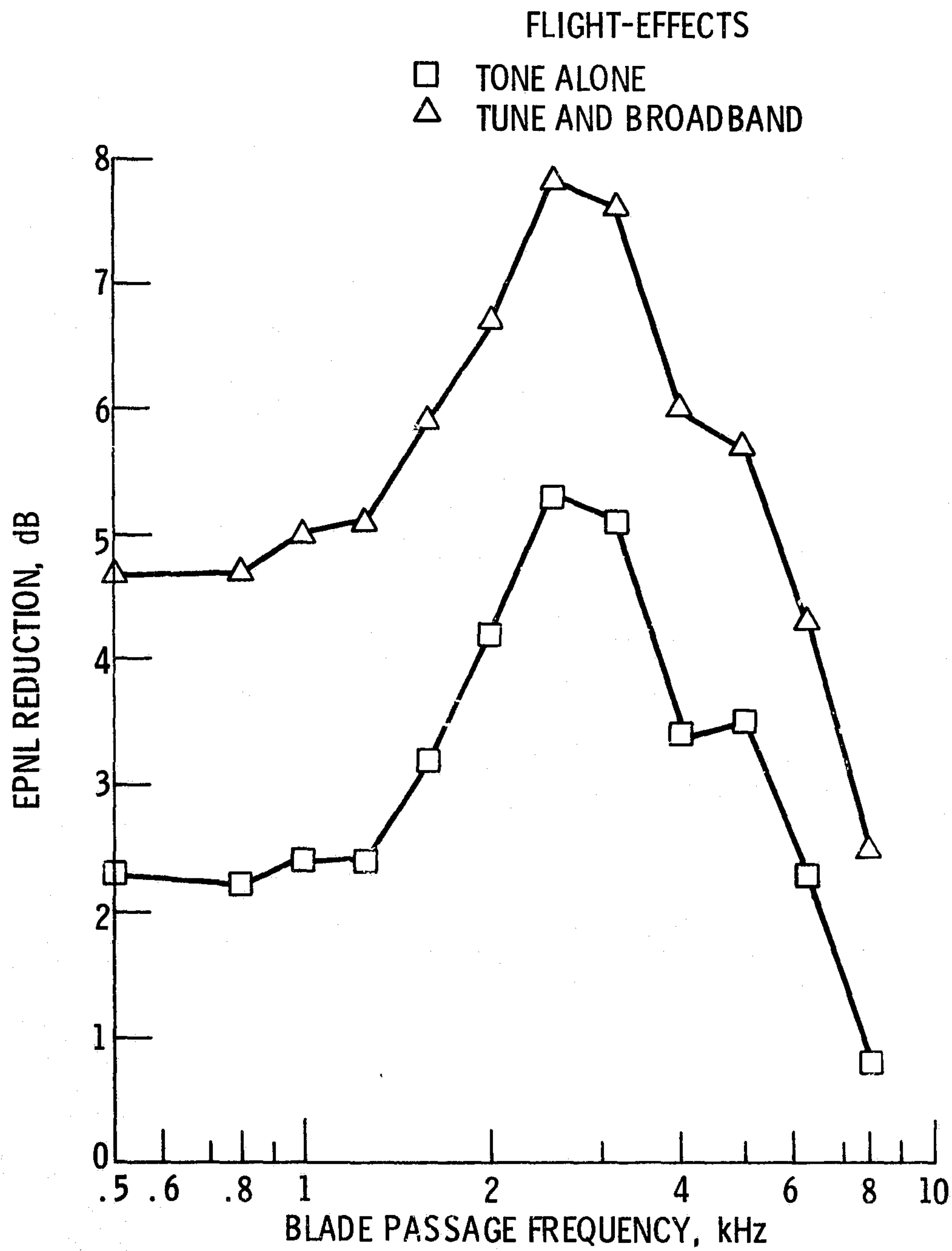



Figure 9. - Reduction in fly-by noise from flight-effects on fan noise.

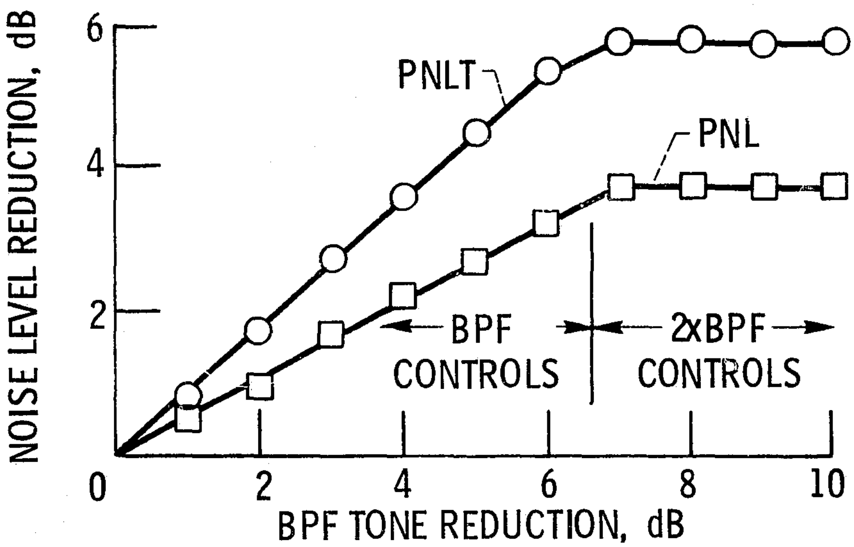



Figure 10. - Effect of BPF tone reduction on maximum perceived noise levels of fly-by noise for tone frequency of 2.5 kHz.