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AN OBSERVATION ON TONE CUT-OFF IN STATIC TEST

DATA FROM JET ENGINE FANS

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SUMMARY

The far-field acoustic data for eight full-scale fans tested at a NASA-Lewis outdoor facility are analyzed for the effect of a "cut-off" design feature where the number of rotor and stator blades are proportioned so that the blade passage tone will not propagate. Inlet flow distortions, prevalent during static testing, interact with the rotor to generate tones that generally mask this cut-off phenomenon. In this study distortion tone properties previously evaluated are used to analyze the tones propagating from the aft fan duct. The analyzed data clearly differentiate the fans that are and are not cut-off.

INTRODUCTION

A variety of jet engine fan stages have been designed that incorporate the cut-off principle prescribed by the Tyler-Sofrin theory (ref. 1). According to this theory, the blade-passage tone caused by rotor-stator interactions will not propagate to the far-field from either the inlet or aft ducts of a fan when the number of blades and vanes are properly selected. However, the acoustic results from ground static tests for cut-off fans usually exhibit a strong propagating blade-passage tone. The practicality of cut-off in fan design has been challenged because of such results. Recently, however, the cut-off phenomenon was clearly evident in the noise generated during actual flight by fans that exhibited strong blade-passage tones during ground static tests (refs. 2 and 3). This difference between static and flight behavior is attributed to inlet flow distortions that occur during static testing but are absent during flight. The inflow for static tests differs from that during flight in that nearby structures and obstacles, ground vortices and flow separation in a flight type inlet can readily distort the inflow during static tests. Pockets of free air turbulence, which elongate when drawn into an inlet during

static tests, can also give an inflow distortion of considerable duration during static tests (ref. 4). The interaction of the rotor with such inflow distortions will generate blade-passage tones regardless of whether the rotor-stator interaction tones are cut-off.

The purpose of this report is to present an observation and data analysis concerning a difference in the tones generated during static tests by fans which are and are not designed for cut-off. The acoustic data used for this purpose are those acquired from the Lewis full-scale-fan outdoor acoustic test facility. The observation concerns eight 1.83-meter (6-ft) diameter quiet fans previously described (ref. 5). These fans have no inlet guide vanes and a relatively large rotor-stator spacing and were tested in the un-suppressed configurations. The far-field noise for these fans was measured over a 160° arc from the inlet axis, with noise propagating from both the inlet and aft ducts. The specific noise data to be used are the one-third octave sound power spectra of the noise propagating from the inlet and from the aft ducts. These power spectra were approximated by integration over the inlet and aft quadrants of the measured radiation pattern.

CUT-OFF OBSERVATION

The recent identification of inflow distortions as a common source of blade-passage tones in static tests has prompted a reevaluation of the Lewis data concerning cut-off design features. The rotor-distortion tones generally were suspected of masking the cut-off phenomenon, particularly in the case of inlet noise, because the tones from such a source would freely propagate from the inlet duct. The rotor and stator, however, could obstruct the aft propagation. It was reasoned that cut-off, therefore, might not be completely masked for the aft duct. Pursuing this concept, the inlet and aft noise were examined for differences caused by cut-off. The differences observed are illustrated in figure 1, which compares the sound power spectra for the inlet and aft noise for two fans - one designed for cut-off and the other not so designed.

The difference in the spectra for the two cases is the power level of the fundamental blade-passage tone (BPT) relative to the harmonics. Without cut-off (fig. 1(a)) the fundamental tone level is higher than that of the harmonics in both the inlet and aft noise spectra. The effect of cut-off on inlet and aft noise is shown in figure 1(b). The aft spectrum exhibits a fundamental tone level which is lower than that of the second harmonic ($2 \times \text{BPF}$), whereas the inlet spectrum is similar to that without cut-off. Figure 1, therefore, suggests that cut-off is partially effective in reducing the fundamental tone propagation from the aft duct. This deduction was verified by comparisons between other fans and at other fan speeds, although the presence of cut-off was not always as clearly evident as figure 1 shows it.

DISCUSSION AND ANALYSIS

The observation of cut-off illustrated in figure 1 provides a basis for analyzing the Lewis data for the effect of cut-off. Some qualitative properties of the tone levels and harmonic fall-off rates, however, are useful in performing the analysis.

The level of the distortion tones in the Lewis facility was tentatively established during the development of a tone prediction procedure (ref. 6). The level of the fundamental tone for distortion-rotor tones appears to be equal to that of the rotor-stator tone that is not designed to be cut-off. The significance of this result is that for a fan not designed for cut-off, the inlet distortions cause about a 3-decibel increase in the fundamental tone level emanating from the inlet. The aft noise is relatively insensitive to inlet distortions for a fan not designed for cut-off.

The data from the Lewis tests were also examined with regard to the level of the tone harmonics for the rotor-distortion tones and for the rotor-stator tones. Although the findings are qualitative, it appears that on the average the fall-off rate in harmonic content with increasing harmonic order is generally much larger for the distortion-rotor tones than for the rotor-stator tones. The difference is roughly 10 decibels per harmonic for the distortion tones, compared with 3 decibels per harmonic for the rotor-stator tones. This tentative result evolved during the development of the tone prediction procedure by assuming various fall-off rates to fit the experimental data (ref. 6). The difference in fall-off rate is also partially based on rotor-stator spacing experiments performed on one cut-off fan (ref. 7). In the tests of reference 7 the expected reduction in rotor-stator interaction tone levels with increased spacing was observed only in the level of the harmonics. The results implied that the harmonics are dominated by rotor-stator interaction noise and are relatively free from inlet distortions effects.

The distortion tone level and harmonic fall-off rate properties can be used to express more quantitatively the observation of cut-off in the aft noise illustrated in figure 1. The harmonics in the aft noise spectra was presumed to be due only to rotor-stator interaction noise. The fundamental tone level of this rotor-stator interaction noise, when it is not cut-off, was projected to be 3 decibels higher than the observed second harmonic level. This projected level of the fundamental tone establishes its reference level. The difference between the observed level of the fundamental tone and this reference level provides a measure of the effectiveness of cut-off in reducing tone level. Figure 2 illustrates the procedure used in calculating this effective difference in fundamental tone levels.

The effective difference in tone level is expected to be a function of a theoretical cut-off ratio δ . The theoretical cut-off ratio is a quantity that can be calculated for each fan and operating condition. It is a measure of whether a tone should or should not

propagate. A tone should not propagate when the cut-off ratio is less than unity. An expression for δ for the lowest radial order of a spinning mode at the blade passage frequency for rotor-stator interactions is given by (ref. 8)

$$\delta = \frac{M_t B}{B - V} \left(\frac{1}{M^* \sqrt{1 - M_x^2}} \right)$$

where

B number of rotor blades

M_t Mach number of rotor tip

V number of stator vanes

M^* a theoretical cut-off Mach number (based on hub-tip ratio and model pattern)

M_x axial flow Mach number

For the case where M_t is supersonic, the rotor alone may generate a spinning mode that propagates. The cut-off ratio for this mode is evaluated by neglecting the stator vanes ($V = 0$).

Figure 3 shows the effective difference in fundamental tone level as a function of δ for the family of Lewis fans. The design speed value of the cut-off ratio for the fans are identified in the figure. All these fans were tested at underdesign rotational speeds. The experimental data are plotted as a function of the cut-off ratio calculated for these reduced speeds. Figure 3 shows a reduction in tone level when the calculated cut-off ratio is less than unity. Fans that are and are not operating with cut-off are clearly differentiated. The experimental results basically confirm the cut-off theory.

Theoretically, a relatively abrupt reduction in level should occur at a value of unity. The gradual and variable reduction with decreasing cut-off ratio observed in the experimental data partly reflects the propagation of a distortion tone from the aft duct. These distortion tones limit the amount of reduction that can be observed.

CONCLUSIONS

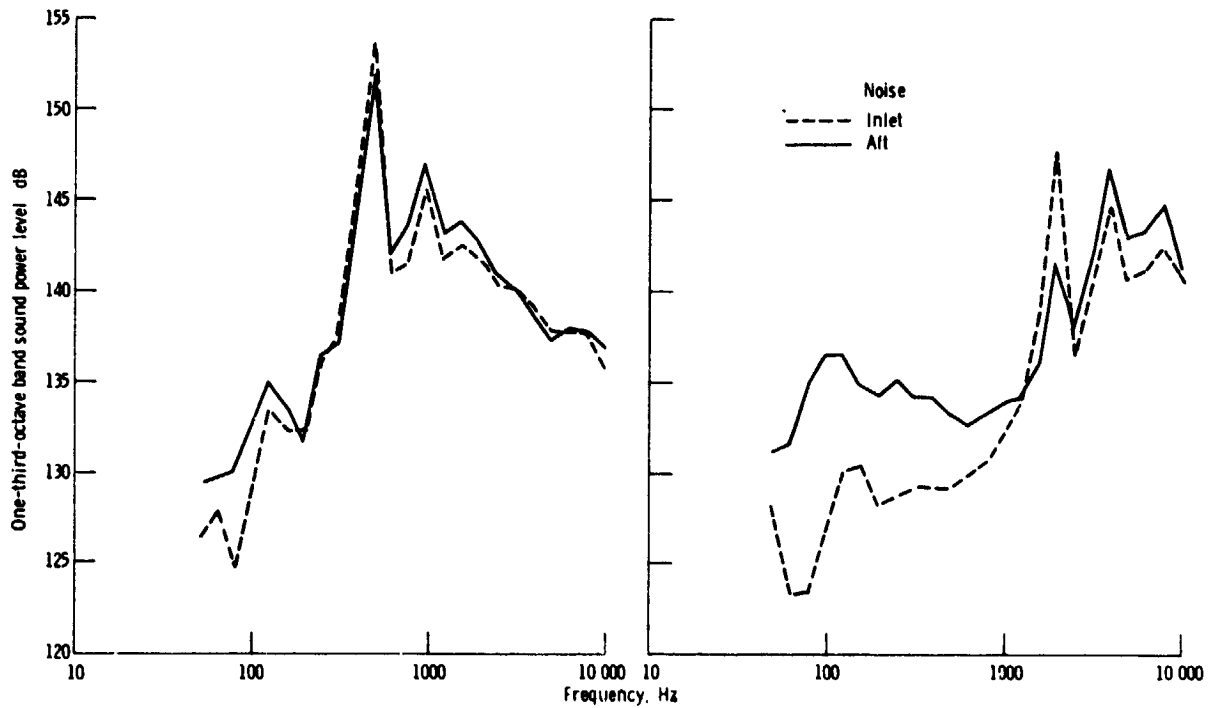
Tone cut-off does occur and can be identified in static test acoustic data that are contaminated by the effects of inlet flow distortions. The result confirms that

cut-off is a quiet fan design feature that can reduce the noise of operational aircraft engines.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 11, 1975,
505-03.

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(a) Without cut-off; fan: QF-9; fan speed, 86 percent of design.

(b) With cut-off; fan A; fan speed 80 percent of design

Figure 1. - Inlet and aft sound power level spectra from ground static tests for fans with and without tone cut-off design features.

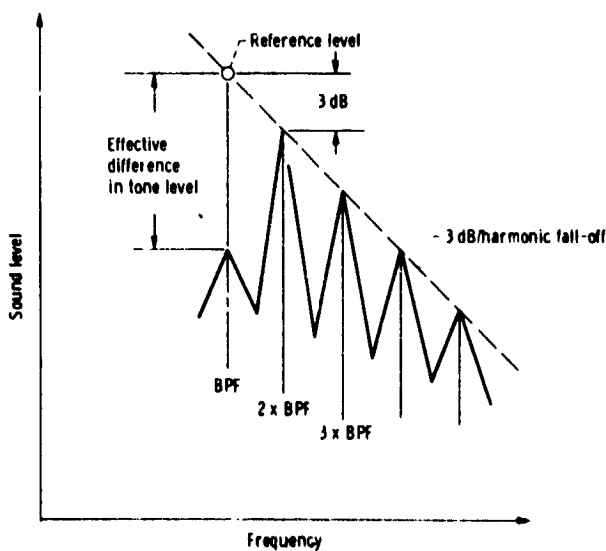


Figure 2. - Illustration of procedure used to establish reference level and effective difference in tone level of fundamental blade passage tone for aft propagating noise.

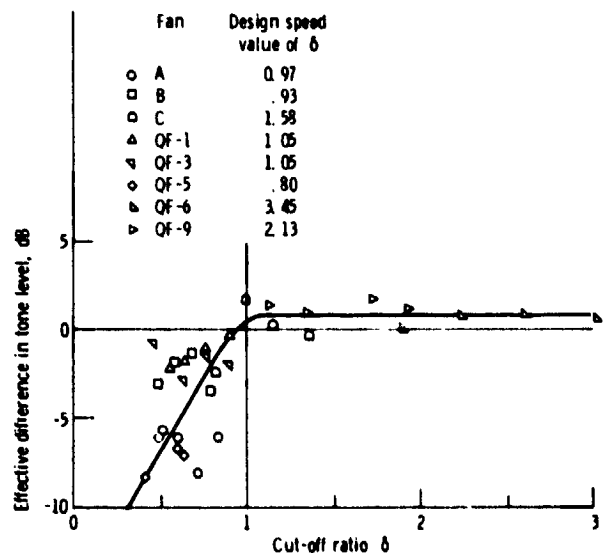


Figure 3. - Effect of cut-off ratio on effective difference of blade passage tone levels in aft radiated noise (Ground-static tests of NASA-Lewis fans.)