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TURBULENCE SPECTRA IN THE NOISE SOURCE REGIONS OF THE
FLOW AROUND COMPLEX SURFACES

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SUMMARY

The complex turbulent flow around three complex surfaces was measured in detail with a hot wire. The measured data include extensive spatial surveys of the mean velocity and turbulence intensity and measurements of the turbulence spectra and scale length at many locations. This paper completes the publication of the turbulence data by reporting a summary of the turbulence spectra that were measured within the noise source locations of the flow.

The results suggest some useful simplifications in modeling the very complex turbulent flow around complex surfaces for aeroacoustic predictive models. The turbulence spectra also show that noise data from scale models of moderate size can be accurately scaled up to full size.

INTRODUCTION

The noise generated by a turbulent airstream passing over the wings and flaps of conventional- and short-takeoff-and-landing (CTOL and STOL) aircraft and other complex surfaces is of practical interest. A number of these surfaces have been studied acoustically in detail. However, the complex turbulent flow around these complex surfaces has neither been measured in detail nor related to the measured acoustic data. The authors, in a previous paper (ref. 1), reported on the turbulence and mean flow parameters that affect the noise level and radiation pattern of three vastly different complex surfaces. An approximate acoustic analogy model was used to estimate the size and location of the volume and surface noise sources. The three surfaces and related noise source contours are reproduced from reference 1 in the three figures in this report.

This short report completes the publication of the turbulence data by reporting a summary of the extensive turbulence spectra that were measured within the noise source regions. These data and the accompanying discussion will suggest some simplifications that will be helpful in applying a basic aeroacoustic theory to the complex flows around complex surfaces. They will also aid in scaling up acoustic data from small models of these surfaces to the full-scale configuration.

BRIEF DISCUSSION OF APPLICABLE BASIC AEROACOUSTIC THEORY

The state of the art in analytically describing the complex turbulent flow around complex surfaces and the resulting noise emission is summarized

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here. Fundamental theories exist for the noise produced by simple flows around simple surfaces. These theories describe the following: the small-chord airfoil, the infinite plate with intense turbulent flow over a leading or trailing edge or with no edges in intense turbulence, and the simple subsonic jet (see the appendix of ref. 1, and ref. 2, for details). The theory for the small-chord airfoil is the nearest to predicting the entire noise emission (i.e., spectra at all angles) without resorting to empiricism (ref. 3). Some fundamental theories only predict, in a simple way, the radiation pattern (e.g., ref. 4). There are of course a large number of semiempirical theories that give more complete predictions (e.g., ref. 5).

The noise generated by the complex turbulent flows around complex surfaces, such as the three surfaces sketched in figures 1 to 3, has certainly not been described by a fundamental theory. Indeed, the mean flow and the details of the turbulence have not even been accurately described by an analytical model. Again, a number of semiempirical theories give a fairly complete description of a range of surface geometries (refs. 6 and 7). A more fundamental model is desirable because it should be able to handle a greater range of configurations. A number of simplifications are required in order to measure and analytically describe the details of these complex flows in a tractable manner. Although some of the simplifications used herein may appear to be extreme, they will not affect the basic conclusions reached.

The simplifying assumptions are as follows:

(1) The spatial gradients of the parameters describing the flow and turbulence are small enough so that single values of the parameters can be used within each source region of the flow. The longitudinal parameters are mean velocity U_1 , rms turbulence velocity \tilde{u}_1 , and integral scale length l_1 . Furthermore, the noise reaching a point in the far field is the sum of the noise from all of the volume elements that make up the noise source regions. Therefore, the effect on the resulting far-field noise of even large local deviations from single values of the turbulence parameters would tend to be washed out. We shall show later that this is probably a good approximation.

(2) The longitudinal turbulence spectra can be adequately measured by a single wire (normal to the velocity vector) in the manner of Laurence (ref. 8). He found that in external turbulent shear flows two-wire correlations for l_1 agreed with single-wire measurements of l_1 , where the peak value of the longitudinal turbulence energy F_{1p} was used instead of the conventional value at zero wavelength. The length scale, using the terminology of reference 9, is

$$l_1 = \frac{\pi}{2} R_5 F_{1p} \quad (1)$$

This single-wire technique makes detailed turbulence measurements in the noise source regions near the complex surfaces tractable.

APPARATUS AND PROCEDURE

Hot-wire surveys were made in the turbulent flows around the three complex surfaces shown by the sketches in figures 1 to 3. The effective size of all of the nozzles was 5.2 cm. Most of the measurements were made in the

plane through the nozzle center (plane of symmetry), where there is no spanwise mean flow. A tuft was used to align the wire normal to the mean velocity vector at other spanwise measurement locations. Most of the measurements were taken with a single wire to obtain longitudinal mean flow and turbulence data (U_1 , \tilde{u}_1 , and ℓ_1 and normalized spectra). The measurement locations are denoted in the sketches by small circles within the flow region. A few measurements were taken with X wires of the transverse turbulence velocity u_2 and its spectrum; the locations where this was done are denoted in the sketches by small squares. The data measurements, the procedures, and the data reduction follow standard practice; for more detail refer to references 1 and 9.

RESULTS AND DISCUSSION

Magnitude and Location of Source Regions

The main purposes of this study were to make detailed turbulence spectra measurements within the noise source regions and to see what these data suggest. Before proceeding any further, the relative magnitude, size, and location of the noise sources must be determined. This can be done by using the simplifying assumptions stated previously and the simple acoustic analogy model described in reference 1. This model is described briefly here so that the reader will have a better physical understanding of the noise sources. From reference 1 the noise amplitude in the far field is the sum of the contributions from the volume and surface noise sources at each point within the turbulent flow field. The amplitude of the volume and noise sources at each point in the flow I are given by the following equations:

Volume sources (source always present wherever there is turbulence)

$$I \propto V_n^8 \left(\frac{\tilde{u}_1}{V_n} \right)^8 \frac{1}{\ell_1} \quad (2)$$

Surface sources (surfaces with edges immersed in significant turbulence)

$$I \propto V_n^a \left(\frac{U_1}{V_n} \right)^{a-2} \left(\frac{\tilde{u}_1}{V_n} \right)^2 \left(\frac{1}{\ell_1} \right) \left(\frac{r_0}{\ell_1} \right)^{-3} \quad (3)$$

where a is 6 for very small-chord airfoils, $c/\ell_1 < 1$; a is 5 for very large-chord airfoils, $c/\ell_1 > 10$; V_n is the nozzle jet velocity; and r_0/ℓ_1 is the distance from the edge of the surface to a given point within the turbulent flow field. These equations show that the magnitude of the volume and surface sources at each point in the flow depends primarily on the mean velocity and the turbulence intensity \tilde{u}_1/V_n there. The resulting noise source regions are shown by contours on the sketches in each figure. These constant-noise-source contours were copied from reference 1. The surface source is only strong near an edge, where r_0/ℓ_1 is large.

A radiation pattern is associated with each source as a factor multiplying I. It depends on the geometry and the local mean flow in the source region. For example, the volume sources of the configurations in figures 1 and 2 would be mainly radiated in the downstream direction. A velocity power law of V_n^8 or better would be expected in that direction, especially for the over-the-wing configuration, where the volume source is dominant over the surface source. In contrast, the three-flap configuration is dominated by the surface source and the chord length is relatively small. Therefore, the V_n^6 velocity power law would be expected at every angle. The velocity power law results noted in the figures qualitatively show how the pattern varies with geometry and mean flow.

Magnitude of Parameters Within Source Regions

It was suggested before that each source region might be adequately described by single values of the turbulence parameters, thereby providing a simple quantitative description of the whole complex turbulent flow around the complex surfaces. Values of these single parameters were obtained by merely comparing the noise source regions to the contour plots in reference 1 for \tilde{u}_1/V_n and U_1/V_n and the point values of l_1 . Table I shows the range of values of these parameters that occurred within the strong source regions (i.e., typically within the -5-dB contours for the volume surface sources).

Single values of the turbulence parameters could be used for each source region because the range of the values for \tilde{u}_1/V_n and U_1/V_n is sufficiently small. The scale length variation is much larger, but the effect of the scale length on the magnitude is weak. Therefore, a single value could be used.

Turbulence Spectral Measurements

Longitudinal turbulence spectra $F_1 < R_5 k_1 >$ were measured at many locations in the turbulent flow around the three surfaces. A representative sample of these spectra is plotted in figures 1 to 3. These spectra have been normalized by a vertical shift so that the peak energies coincide as defined by equation (4).

$$\frac{4F_1 < k_1 R_5 >}{F_{1P}} \quad (4)$$

where R_5 is a constant set here at the hydraulic radius of the nozzles ($R_5 = 2.6$ cm). The wave number at the peak k_e was used to normalize the frequency according to equation (5).

$$\frac{k_1}{k_e} = \frac{2\pi f}{U_1} \left(\frac{4l_1}{3} \right) = \frac{2\pi}{3} (R_5 k_1) F_{1P} \quad (5)$$

where

$$k_1 = \frac{2\pi f}{U_1} \quad (6a)$$

and

$$\frac{1}{k_e} = \frac{4\ell_1}{3} \quad (6b)$$

The spectra in the three figures were measured at a large number of points in the flow. For example, the spectrum marked with solid circles in figure 2 was measured (as the sketch shows) at a point well downstream of the trailing edge.

Examination of the three figures reveals that there are basically two types of spectra: The spectra associated with the open symbols have no definite peak except at zero frequency; the spectra associated with the solid symbols have a definite peak. In most cases the peaked spectra occurred within the secondary turbulent mixing region of the flow coming off the trailing edge of the surface.

Discussion of the Spectra

Having described the spectral data, we now discuss the significance of the spectral results. In particular, what simplifications are suggested that would permit improvements in aeroacoustic analytical models? And finally, what do these results suggest with regard to scaling up acoustic data from small-scale models?

Simplifications in aeroacoustic models. - Above $k_1/k_e = 1$ nearly all of the longitudinal spectra were within ± 1 dB of the Kolmogoroff law ($k_1^{5/3}$) or the exponential law (k_1^2). These laws are for the nonviscous inertial sub-range. The k_1^7 law applies where viscous effects dominate (ref. 10). These laws also describe the limited number of transverse spectra measured.

We must now relate the turbulence spectra to the acoustic spectra for this model size (5.2-cm nozzle). The normalized frequency k_1/k_e is related to the Strouhal number used in acoustics fd_n/V_n .

$$\frac{k_1}{k_e} = \frac{2\pi f}{U_1} \frac{1}{k_e} = \frac{8\pi}{3} \left(\frac{\ell_1}{d_n} \right) \left(\frac{V_n}{U_1} \right) \left(\frac{fd_n}{V_n} \right) \quad (7)$$

where d_n and V_n are the nozzle diameter and velocity, respectively, and U_1 is the local mean velocity. Equation (7) is then evaluated approximately by using typical values for ℓ_1/d_n and \tilde{u}_1/V_n from table I:

$$\frac{k_1}{k_e} \cong 5 \left(\frac{fd_n}{V_n} \right) \quad (8)$$

For a velocity range of 120 to 240 m/sec the normalized frequency k_1/k_e range would be from 0.4 to 40 for an acoustic frequency range of 200 to 40 000 Hz.

Within this range nearly all of the normalized turbulence spectra on the three plots collapse together (within ± 1 dB). In other words, a single normalized turbulence spectrum describes all of the points within the source regions, over the range of the acoustic data for the model ($0.4 < k_1/k_e < 40$).

But what about the few points where there is a very peaked spectrum that does not match the single universal spectrum. A unique characteristic in the turbulence spectral data permits a good check on the previous claim that single values of \tilde{u}_1/V_n , l_1/d_n , and U_1/V_n and a single curve for the normalized spectra will describe the turbulent flow for complex surfaces adequately for acoustic modeling purposes. A large region of the flow for the model over-the-wing configuration (fig. 2) had a strong peak that persisted at higher velocities. Indeed, the turbulence spectrum described by the solid triangles was the most peaked spectrum observed. Spanwise spectral measurements show that this region was about half a nozzle width wide. Such a large region must surely generate a noticeable peak in the far-field acoustic spectra. Nevertheless there was no evidence of even a weak peak in the acoustic spectra near the frequency of this peak. In other words, the noise emitted from other points in the source regions, with somewhat different turbulence parameters, was enough to swamp out this peculiar peaked source region. This result again suggests that little would be gained by modeling the turbulent flow in detail; single values of the turbulence parameters are sufficient for each source region. This does not mean that peaked acoustic spectra cannot occur. A small cylinder has a region of intense highly correlated turbulence in its near wake; it produces a very peaked acoustic spectrum (ref. 3). But keep in mind that peaked turbulence spectra would become less peaked as the size of the surface or velocity (i.e., Reynolds number) was increased (ref. 8).

A universal normalized turbulence spectrum would tend to produce a universal acoustic spectrum at 90° from the direction of the mean flow through the source region. The 90° was selected to remove mean velocity effects. Normalized acoustic spectra from these types of complex surfaces do indeed tend to collapse together.

Scaling up acoustic data from a model. - Examination of fundamental aero-acoustic theories for jet and surface noise indicates that small-scale-model acoustic data can be simply scaled up to full scale (at the same V_n). Scaling requires that the square of the ratio of model diameter to microphone radius $(d_n/R)^2$, the ambient temperature, and the attenuation be accounted for and also that the model and full-scale Strouhal number fd_n/V_n and normalized turbulence spectra be the same. The normalized turbulence spectra for the model and full-scale configurations will agree if viscous effects are not important. The three plots show that viscous effects are only important above a normalized frequency of $k_1/k_e = 100$, where the turbulence spectral law changes from $k_1^{-5/3}$ (nonviscous) to k_1^{-7} (viscous effects dominate). Corresponding to $k_1/k_e = 100$ is a Strouhal number of about 20. Because this is much higher than the upper limit of the acoustic model data, acoustic model data with a 5-cm nozzle are safely below the viscous-dominated region. Full-scale data may be a problem because the acoustic data go up to 20 kHz. But these data are also below the viscous region because the transition (nonviscous to viscous) increases with the Reynolds number to the 0.75 power (ref. 9).

Recent comparisons of scaled-up model data from complex surfaces agreed within 1 to 2 dB with full-scale data, except at low velocities, where the internal engine fan noise affected the full-scale noise at high frequency.

CONCLUDING REMARKS

The results given in this report suggest some useful simplifications in modeling the complex turbulent flow around complex surfaces for aeroacoustic predictive models. Even with these simplifications the authors believe that the state of the art in applying fundamental aeroacoustic theory to complex surfaces is not sufficiently advanced to predict the noise emission without considerable empiricism. On the other hand, noise data from scale models can be simply and accurately scaled up. Therefore until significant improvements are made in applying fundamental aeroacoustic theory and in modeling the complex turbulent flow for use in these theories, it is simpler and more accurate to measure the noise from a small-scale model and scale up the data.

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APPENDIX - SYMBOLS

a	exponent in eq. (3)
c	airfoil chord length, m
d_n	nozzle diameter, m
$F_1 \langle k_1 R_5 \rangle$	turbulence energy in narrow frequency band 6 Hz wide
F_{1p}	peak value of turbulence energy spectrum
f	frequency, Hz
I	sound intensity
k_e	wave number at peak value of turbulence energy
k_1	wave number, $k_1 = 2\pi f/U_1$
l_1	longitudinal integral length scale, m
R	microphone radius, m
R_5	normalizing size, taken here as hydraulic radius of nozzle
r_0	distance from edge of surface to point within flow field, m
U_1	local longitudinal mean velocity, m/sec
\tilde{u}_1	root-mean-square component of longitudinal turbulence velocity, m/sec
V_n	nozzle velocity, m/sec

TABLE I. - RANGE OF VALUES OF \tilde{u}_1/V_n , U_1/V_n , and l_1
WITHIN STRONG SOURCE REGIONS (≥ -5 dB)^a

Configuration	Surface sources	Volume sources
Slotless wing	Trailing-edge region: $0.12 < \tilde{u}_1/V_n < 0.14$ $0.6 < U_1/V_n < 0.8$ $? < l_1 < 1.8$ cm	Trailing-edge region: $0.14 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $0.9 < l_1 < 1.9$ cm Impingement region: $0.15 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $1.5 < l_1 < 1.8$ cm
Over the wing	Trailing edge: $0.1 < \tilde{u}_1/V_n < 0.13$ $0.8 < U_1/V_n < 0.9$ $? < l_1 < ?$	Near trailing edge: $0.16 < \tilde{u}_1/V_n < 0.18$ $0.4 < U_1/V_n < 0.6$ $1.3 < l_1 < 1.4$ cm
3-Flap	Trailing edge of last flap: $0.1 < \tilde{u}_1/V_n < 0.12$ $0.5 < U_1/V_n < 0.7$ $0.7 < l_1 < 1.0$ cm Between flaps: $0.1 < \tilde{u}_1/V_n < 0.13$ $0.6 < U_1/V_n < 0.8$ $1.6 < l_1 < 1.8$ cm	Above trailing edge: $0.15 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $0.9 < l_1 < 1.4$ cm

^aWhere \tilde{u}_1 is root-mean-square component of turbulence velocity, V_n is nozzle velocity, U_1 is local mean velocity, and l_1 is integral scale length.

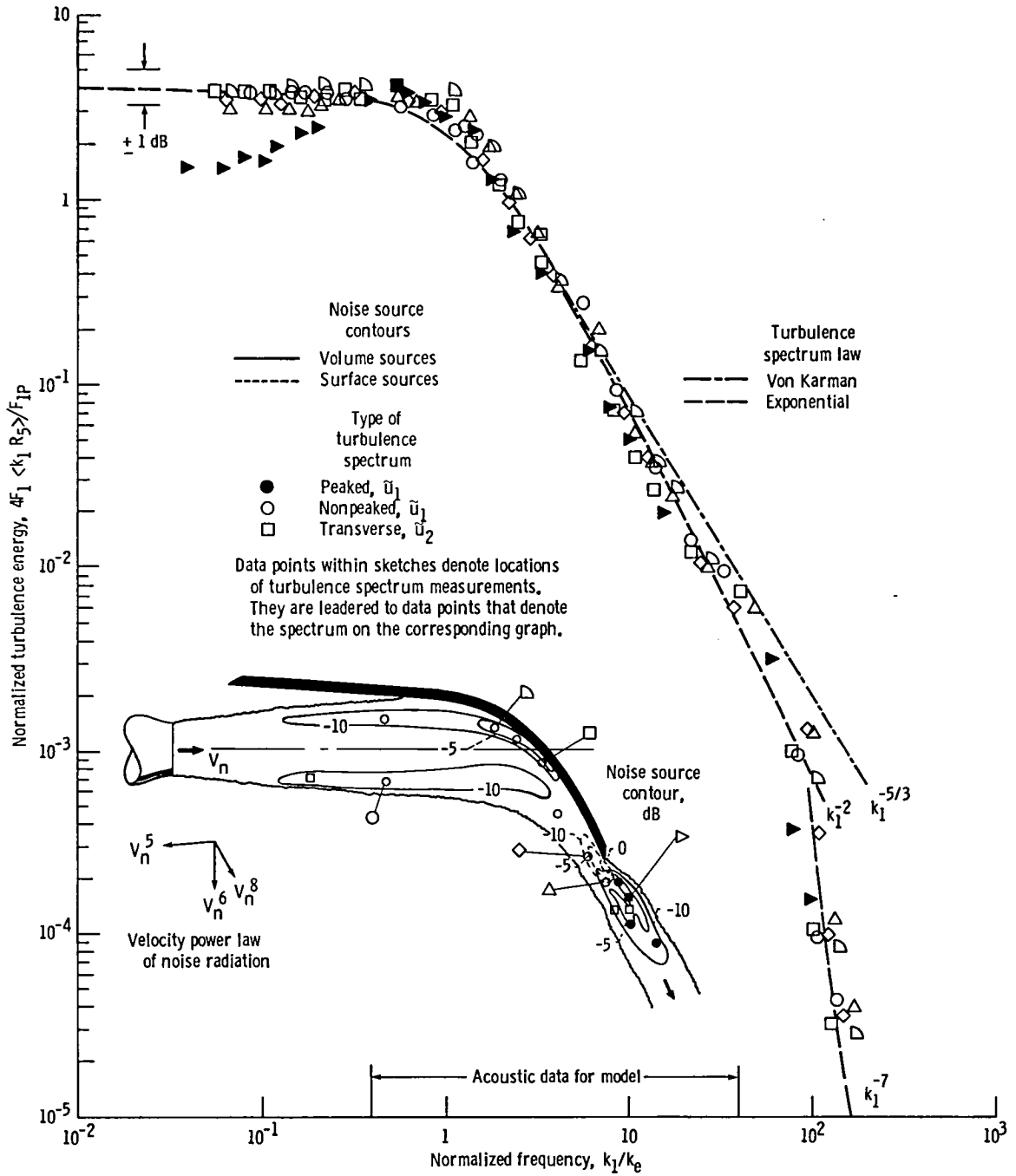


Figure 1. - Turbulence spectra in noise source regions of the slotless wing.

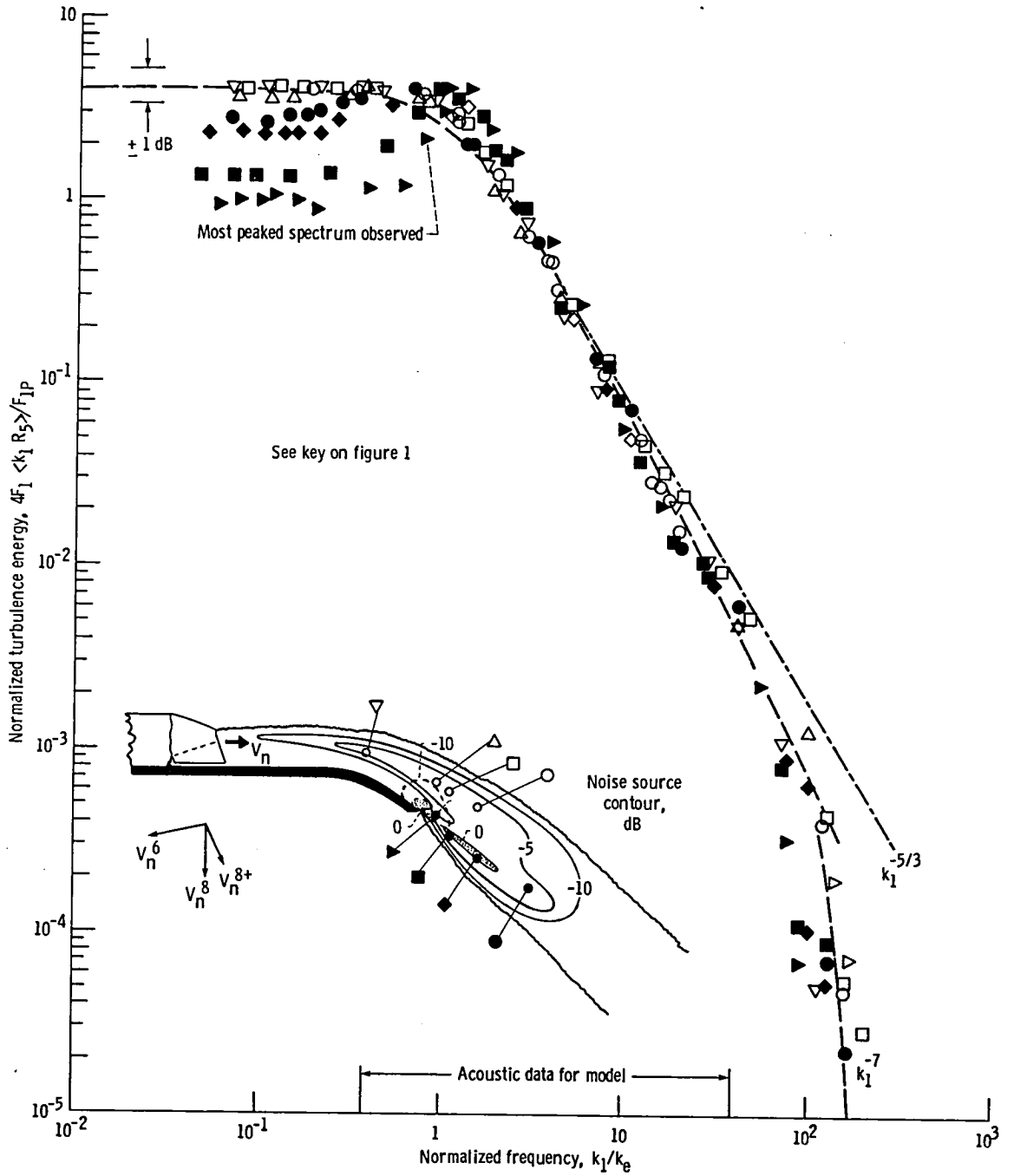


Figure 2 - Turbulence spectra in noise source regions of the over-the-wing configuration.

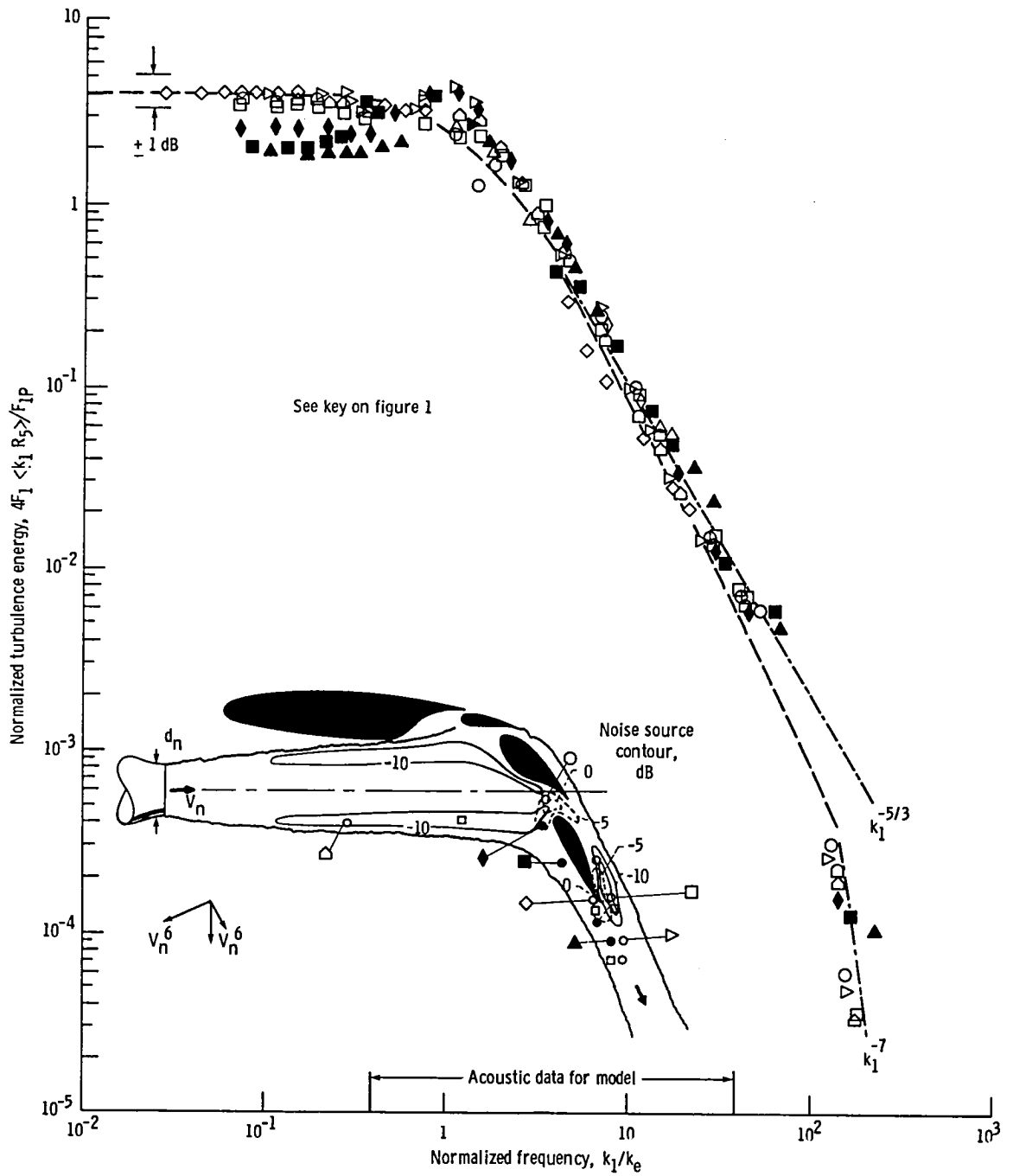


Figure 3. - Turbulence spectra in noise source regions of the three flaps.

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