Helicopter noise experiments in an urban environment

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In two series of helicopter noise experiments, sound-pressure-level recordings were made on the ground while a helicopter flew over (i) an array of microphones placed in an open field, and (ii) a similar array placed in the center of a city street surrounded by tall buildings. For given helicopter altitude and airspeed, it was found that the flyover noise recorded in the street, although initially lower, built up rapidly as the aircraft approached such that the peak recorded noise was actually more intense than that recorded in the open field. This result is in qualitative accord with the results of previous laboratory scale-model experiments performed by Lyon and Pande. The differences between the two sets of field data are attributed in major part to the fact that a reverberant sound field builds up in the street during flyover. This enhancement is less pronounced for higher flight altitudes. A simple theory based on geometrical acoustics and statistical concepts is described that quantitatively explains the sound enhancement found for a helicopter flying over a city street.

Subject Classification: 28.55; 50.80; 20.30, 20.15.

INTRODUCTION

A general question which is of current interest in studies on noise abatement is: how does the noise heard by a listener in a city street differ from that heard under similar conditions in an open field? Recently, Lyon, Pande, and Kinney performed a series of model experiments which suggest that the noise in a city street from an aircraft passing overhead is enhanced relative to that heard in an open field.[1,2] The present paper describes a series of field experiments which confirm the existence of the enhancement and gives a simple theory which quantitatively explains it.

I. DESCRIPTION OF EXPERIMENTS

Two separate sets of field experiments were performed: (i) an open-field experiment, and (ii) an urban experiment. The same aircraft was used in both experiments; a U. S. Coast Guard Sikorsky[a] HH-3F (a twin turbine, amphibious, search and rescue helicopter).

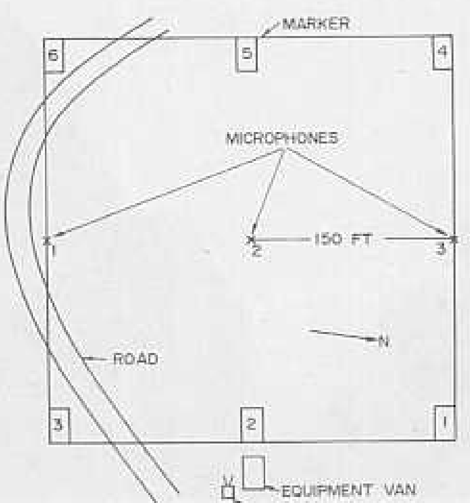

FIG. 1. Diagram showing experimental layout for open-field experiment at Otis Air Force Base.

The open-field experiment was performed at Otis Air Force Base in Bourne, Massachusetts, on a small field near the on-base Coast Guard Station. The DOT/TSC mobile noise laboratory van and panel truck were used for the data collection.[4,5] A line of three Brüel & Kjær 4134 microphones and an array of six markers were set up in a 300-ft square pattern in the field. Figure 1 shows a diagram of the field and of the experimental layout. Before takeoff, the pilot was told to fly over each of the three microphones separately in a direction perpendicular to the line of microphones and at altitudes of 200, 300, and 400 ft. The flyover noise from the helicopter that was detected by the three microphones was recorded on three separate channels of a Hewlett-Packard 3960A four-track instrumentation recorder while the fourth channel was used to record the time code generated by a Datum time code generator/reader model 9300. This time code was recorded on one channel of a Nagra IV-S stereo tape recorder while verbal comments, including reports of the helicopter's position as it flew over, were recorded on the other channel. Another set of comments, including reports of indicated altitude and airspeed, were recorded on a Nagra IV monaural tape recorder by an observer riding in the helicopter. In addition, a Robot photographic recording system (made by Robot-Foto, Düsseldorf, Germany) was set up overlooking the site and the sky above it. This system consisted of a time control unit, inset clock and counter, and an automatic camera with a wide-angle lens. The camera took photographs at 1-sec intervals and the inset clock was synchronized with the time code generator. Figure 2 shows a representative photograph of the helicopter flying over the site. The camera and time code generator were used to correlate the noise from the helicopter with its position relative to the locations of the microphones.

The urban experiment was performed on a section of Summer Street in South Boston, Massachusetts, using

FIG. 2. Photograph of helicopter flying over the open-field site taken by the Robot camera.

the same helicopter and recording equipment as were used in the open-field experiment. The site chosen was a straight section of the street 100 ft wide flanked by buildings of roughly the same height (120 ft or so) on both sides. It is of interest to note that this same site was used for experiments performed by Wiener, Malme, and Gogos[6] on the propagation of ground-level-generated sound in urban areas. Three microphones were set up in a row along the centerline of the street and were spaced the same distance apart as they were in the open field experiment. Figure 3 shows a map of the urban site indicating the microphone locations and the general layout of the street. Before takeoff, the pilot was told to fly along the centerline of the street to familiarize himself with the microphone array and then to make several passes across the street over each of the three microphones separately at 200, 300, and 400 ft. As in the open-field experiment, the flyover noise detected by the microphones was recorded on three channels of the HP 3960A tape recorder while a time code was recorded on the fourth channel. Also, one person stood in the street and reported on the helicopter's position while another person rode on board and recorded indicated altitude and airspeed. The Robot camera was placed at the extreme south end of the street with a field of view encompassing the equipment, the buildings, and the sky above. Figure 4 shows a representative photograph taken by the camera during a flyover. As before, the camera and time code generator were used to correlate the flyover noise from the helicopter with its position relative to the microphones in the street.

II. EXPERIMENTAL RESULTS

To date, the analysis of these experimental results has concentrated on determining the existence and magnitude of the urban noise enhancement. The occurrence of this enhancement was readily supported by the noise recordings. Figure 5 shows two sample plots derived from the data of A-weighted sound-pressure

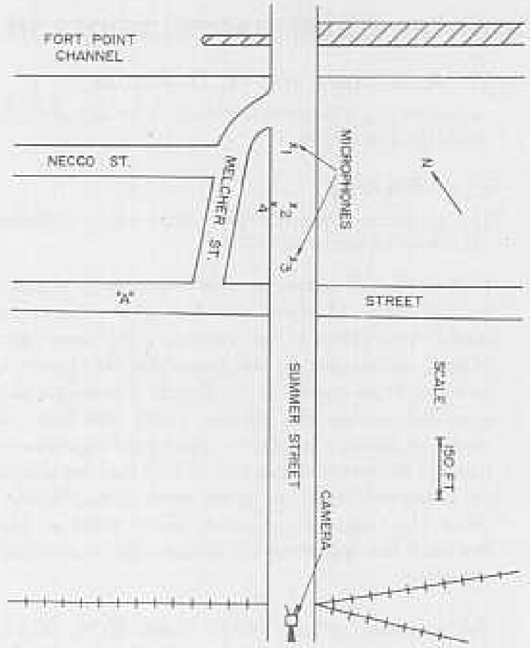

FIG. 3. Map of the urban experimental site indicating the microphone location.

level versus helicopter position relative to a microphone (denoted by "LISTENER" in the figure) for a pass made at 200 ft over the center microphone in the open-field experiment (plot denoted by "OPEN FIELD SPL") and for a pass made at 200 ft over the center microphone in the urban experiment (plot denoted by "URBAN SPL"). The difference (sound enhancement) between the peak levels of the two plots indicated in the figure is 8 dBA. For all such combinations of data corresponding to flyovers made at 200 ft over the center microphones in both series of experiments, the differences between the peak levels measured in the urban experiment and those measured in the open-field experiment varied from 5 to 8 dBA with an average

FIG. 4. Photograph of helicopter flying over the urban site taken by the Robot camera.

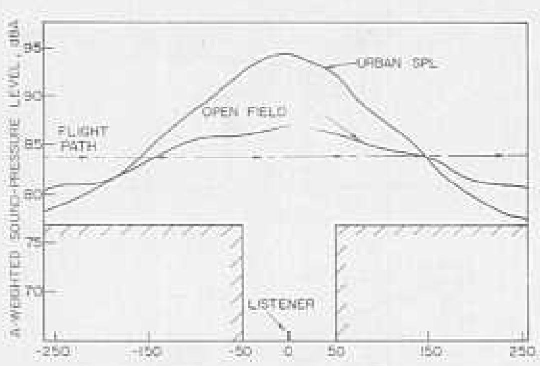

FIG. 5. Two sample plots of A-weighted sound-pressure level versus helicopter position relative to microphone position (LISTENER) for a pass made at 200 ft over the center microphone in the open-field experiment (OPEN FIELD SPL) and for a pass made at 200 ft over the center microphone in the urban experiment (URBAN SPL).

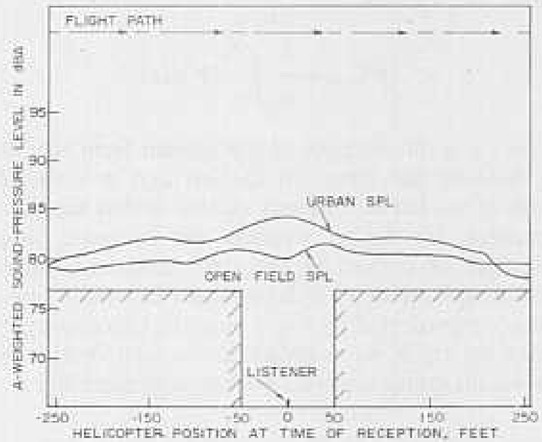

FIG. 7. Sample plots of A-weighted sound-pressure level similar to those shown in Figs. 5 and 6, but for a flight altitude of 400 ft.

difference or sound enhancement of 6.75 dBA. For a flight altitude of 300 ft, these differences varied from 4 to 6 dBA with an average of 5 dBA. Finally, for 400 ft, the sound enhancements varied from 3 to 6 dBA, with an average of 4.5 dBA. Figures 6 and 7 give similar comparisons of open-field and urban data for flight altitudes of 300 and 400 ft, respectively. The sound enhancement indicated in Fig. 6 is 5 dBA while that indicated in Fig. 7 is 4 dBA. One may note that, as might be expected, the sound-pressure levels for both the open-field and urban experiments decrease with increasing flight altitude, and that, in addition, the relative enhancement also decreases.

III. THEORY

A relatively simple expression which explains the observed effects of buildings on the SPL from low-flying aircraft may be derived from fundamental notions analogous to those commonly used in room acoustics.[7] consider a point source of sound [Fig. 8(a)] located directly above or above and to the side of a street flanked by tall buildings. The source is assumed to be omnidirectional such that very near the source the acoustic pressure is given by the wave equation's solution for a point source in an unbounded medium

$$p \approx \frac{f(t-R/c)}{R}, \tag{1}$$

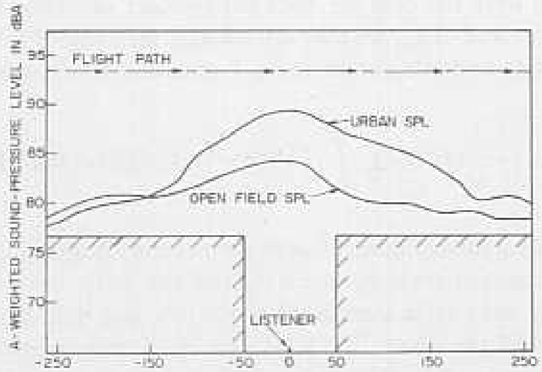

FIG. 6. Sample plots of A-weighted sound-pressure level similar to those shown in Fig. 5, but for a flight altitude of 300 ft.

where $f(t)$ is a function characteristic of the source and R is the net distance from the source. Then, if diffraction is ignored, the pressure detected by a listener between the buildings and somewhat above the street is given by

$$p = \sum_n \frac{f(t-R_n/c)}{R_n}, \tag{2}$$

where the sum is over all straight or crooked ray paths which connect the source to the listener, and which are constructed according to the laws of geometrical acoustics (equal angles of incidence and reflection, etc.). The walls and street are assumed for simplicity to be perfectly reflecting. The parameter R_n is the length of the path (which may include several reflections) connecting source and listener.

The source function $f(t)$ is assumed to be either periodic in time or a random function which is ergodic and, accordingly, also stationary.[8] Thus, we may speak of a time-averaged pressure squared at the listener location which, according to Eq. 2 above, is given by

$$\langle p^2\rangle_t = \sum_n \sum_m R_n^{-1} R_m^{-1} \langle f(t-R_n/c) f(t-R_m/c)\rangle_t, \tag{3}$$

where the brackets with the t subscript imply an average over time. The assumed nature of $f(t)$ guarantees that this average is independent of the choice of time origin providing that the averaging time is sufficiently long Thus, in particular, if $R_n = R_m$, one has

$$\langle f(t-R_n/c) f(t-R_n/c)\rangle_t = \langle f^2(t)\rangle_t \tag{4}$$

and Eq. 3 becomes

$$\langle p^2\rangle_t = \langle f^2(t)\rangle_t \sum_n R_n^{-2} + \sum \sum_{n\neq m} R_n^{-1} R_m^{-1} Q[(R_n - R_m)/c], \tag{5}$$

where

$$Q(\tau) = \langle f(t) f(t-\tau)\rangle_t \tag{6}$$

corresponds to the autocorrelation function of $f(t)$.

To simplify Eq. 5, we assume that source and listener have the same y coordinate, where y is distance along the center of the street, and ask for the mean expected $\langle p^2\rangle_t$ when the listener location is averaged across the street, i.e., we seek

$$\langle p^2\rangle_{t,x_L}=\frac{1}{w}\int_0^w \langle p^2\rangle_t dx_L, \tag{7}$$

where x_L is the distance of the listener from the building flanking the street on the left and w is the total width of the street. The expectation is that the derived expression for the x_L average will be much simpler than that for a given x_L and that, moreover, the variation of $\langle p^2\rangle_t$ with x_L will be small. In performing the average represented by Eq. 7 over the expression represented by Eq. 5, we assume that the contribution from the second group of terms ($n\neq m$) is negligible, i.e.,

$$\frac{1}{w}\int_0^w \sum_{n\neq m}\sum R_n^{-1}R_m^{-1}Q([R_n-R_m]/c)dx_L \tag{8}$$

is neglected, and hence,

$$\langle p^2\rangle_{t,x}=\frac{1}{w}\langle f^2(t)\rangle_t\int_0^w \sum_n R_n^{-2}dx_L. \tag{9}$$

The rationale for the neglect of Expression 8 is that for any realistic $Q(\tau)$ corresponding to aircraft noise one may expect that, as x_L varies from 0 to w, the term $Q[(R_n-R_m)/c]$ remains either negligibly small or else oscillates from positive to negative such that its average is negligible. If $f(t)$ is broad band, then $Q(\tau)$ is negligibly small when $\tau\gg 1/(\Delta f)$, where Δf is the bandwidth.[8] If $f(t)$ is narrow band, then $Q(\tau)$ oscillates with a period corresponding to the center frequency. Typically, we expect $|R_n-R_m|$ for $n\neq m$ to either be larger than $c/(\Delta f)$ for broad-band sound or, in the case of narrow-band sound, to change by several representative center-band wavelengths when the listener moves from one side of the street to the other. This seems plausible since the wavelengths of interest are comparable to 1 ft, while the building height and street width are comparable to 100 ft. Even the height of a listener's ear above the ground is substantially larger than a typical wavelength of interest.

To facilitate the evaluation of the integral-sum combination in Eq. 9, it is convenient first to consider the ground to be nonreflecting (a restriction which we remove subsequently) and to associate an image listener (rather than image source) with each possible ray path. Any particular image listener may be located by drawing a straight line from the source in the same initial direction as the corresponding actual reflected ray path and continuing this path through the building walls until it reaches a point at the same height as the listener. One may note that all such image listeners lie on a straight horizontal line [see Fig. 8(b)] which is perpendicular to the street. If this line is divided into equal segments of length w starting with the section in the street proper, then in any such section there is at most one image listener. Note also that the rays connecting source-to-image listeners must intersect the building walls below their maximum height. This guarantees that there are only a finite number of image listeners. Let θ_n be the angle (between $-\pi/2$ and $\pi/2$) which a given ray from source-to-image listener initially makes with the vertical reckoned counterclockwise.

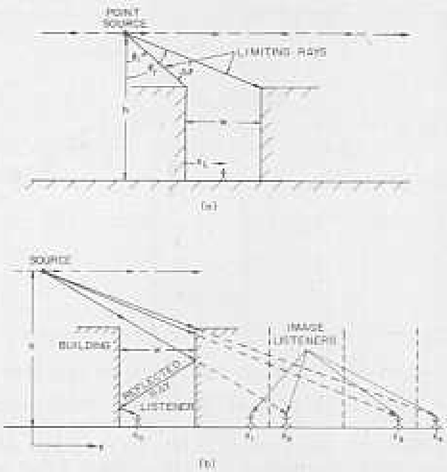

FIG. 8. (a) Diagram indicating definition of parameters used in the development of the theoretical model. Here h is height of sound source above street, w is street width, x_L is distance of listener from left side of street, and θ_i and θ_f are limits of range of initial directions of rays which eventually reach the street. (b) Diagram illustrating the concept of image listener. Each ray eventually reaching the listener at x_0 via one or more wall reflections has an initial direction pointing from source towards the corresponding image listener.

Then one may note that for fixed listener location any such θ_n should fall between values θ_i and θ_f which describe the limiting directions of the range of possible actual ray paths which eventually reach the street between the buildings.

Let x be distance along the line of image listeners with origin taken directly below the source and let h be the height of the source above this line (roughly the same as the height of the source above the street). Then, if x_n represents the coordinate along this line of the image (or actual) listener corresponding to the nth ray, one has $R_n^2=h^2+x_n^2$.

We next replace the sum over images by a sum over segments of length w along the x axis, the oth segment being the street proper. Since there is at most one image or real listener in each cell, we may denote the possible position of the image listener in the nth cell by $x_N(x_L)$ and delete all terms corresponding to cells which do not contain an image listener by putting in a suitable ramp function $U(\theta_N)$ which is zero unless $\theta_i<\theta_N<\theta_f$ (in which case it is unity), where θ_N is the initial direction of the ray which would go directly from the source to the possible image position. Since the limits of the sum over the cells are then independent of source location and of x_L, we may interchange the order of summation and integration in Eq. 9 such that it becomes

$$\langle p^2\rangle_{t,x}=\frac{1}{w}\langle f^2(t)\rangle_t\sum_N\int_0^w [h^2+x_N^2(x_L)]^{-1}U(\theta_N)dx_L. \tag{10}$$

The variable of integration in each of the integrals may be changed from x_L to $x=x_N$ and the limits on each such integration correspond to the left- and right-hand sides of the street. The total sum of all such integrals is just an integral over x from $-\infty$ to $+\infty$. The presence of the factor $U(\theta_N)$ implies that the integrand should be zero unless $\theta=\tan^{-1}(x/h)$ lies between θ_i and

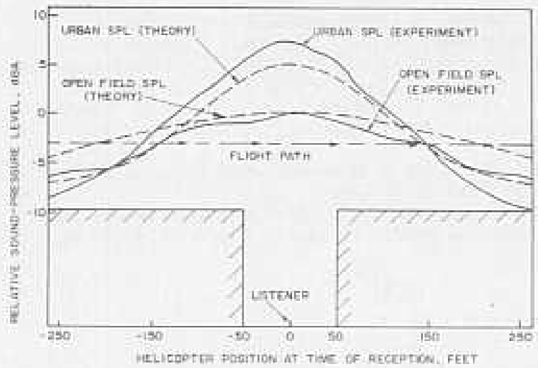

FIG. 9. Comparison of simplified theory of sound enhancement due to an urban environment with sample experimental data (solid lines) for helicopter flyovers at 200 ft above an open field and above Summer Street in South Boston. The sound-pressure levels are given relative to that recorded in the open field when the source is directly overhead. The source strength in the theoretical model has been selected such that it gives the same sound-pressure level as observed experimentally directly overhead in the open field. The (dashed) theoretical open-field SPL curve corresponds to spherical spreading. The urban SPL theoretical curve is based on the equation derived in the text.

θ_f. Thus, Eq. 10 becomes

$$\langle p^2\rangle_{t,x}=\frac{1}{w}\langle f^2(t)\rangle_t\int_{h\tan\theta_i}^{h\tan\theta_f}\frac{dx}{h^2+x^2}, \qquad (11)$$

which integrates to

$$\langle p^2\rangle_{t,x}=\frac{\langle f^2(t)\rangle_t}{hw}\Delta\theta, \qquad (12)$$

where $\Delta\theta=\theta_f-\theta_i$.

The presence of the ground for all cases of interest may be incorporated into the above expression by simply including a factor K, i.e.,

$$\langle p^2\rangle_{t,x}=K\frac{\langle f^2(t)\rangle_t}{hw}\Delta\theta, \qquad (13)$$

where K would be 4 (corresponding to a doubling of pressure) if the microphone were at ground level and the ground were perfectly reflecting. If the ground were perfectly absorbing, then K would be 1. In the more typical case of interest where the ground is nearly perfectly reflecting and the listener's ears are a moderate distance (5 ft) from the ground, the intensities of waves reflected from the ground on the average just add to the intensities of waves not yet having reached the ground, so that the more appropriate choice for K would be 2. In any event, once a choice for K has been made, the ratio of Eq. 13 to that which would be measured for a comparable listener position in an open field would be independent of K and also of the source function $\langle f^2(t)\rangle_t$.

In Fig. 9, the above theory is compared with some data taken during the field experiments for the case of a helicopter flying at 200 ft above the ground. The constant $K\langle f^2(t)\rangle_t$ in the theory is chosen such that the open-field prediction (simple spherical spreading) agrees identically with the open-field experimental data when the helicopter is directly overhead. The faster falloff with distance of the open-field experimental data compared to spherical spreading is presumably due to the fact that the theory ignores absorption. Vertical scales in the figure give the overpressures in dBA relative to that in the open field when the helicopter is directly overhead. Thus, the theoretical urban relative sound-pressure-level curve is given by (10) $\log_{10}(h\Delta\theta/w)$. Here h/w is taken as 2 and the building height is taken as $1.5w$.

One may note that the agreement between the theoretical and experimental urban SPLs in Fig. 9 is qualitatively good. While the theoretical curve falls about 3 dBA below the experimental curve when the helicopter is directly overhead; this is a discrepancy not wholly unexpected when one considers the actual variations in data taken under field conditions. A more representative sample of data (an extreme is presented in the figure) would give an enhancement somewhat smaller (about 1.5 dBA less) than plotted. The remaining 1.5-dBA discrepancy may or may not be real, but could possibly be explained by the fact that the theory gives a prediction for an average microphone location rather than specifically for a microphone in the center of the street. Since similar rays bouncing off of opposite walls from a source directly overhead would reach a center microphone exactly in phase, we would expect that the sound in the center of the street would be louder there than at an average location. The theoretical underestimation could conceivably be as much as 3 dBA.

One also notes that the theory explains the observed fact that the net enhancement of the sound in the street relative to that in the open field decreases with increasing altitude of flight. In particular, if the aircraft is directly overhead, Eq. 13 predicts enhancements of 5.0, 2.9, and 2.0 dBA when the aircraft is at altitudes of 200, 300, and 400 ft, respectively. The general trend is in agreement with the data represented in Figs. 5–7, although the theory apparently tends to consistently underestimate the peak enhancement by about 2 dBA when the microphone is in the center of the street.

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