THE KINEMATIC SOUND SCREEN: AN EFFECTIVE SOLUTION TO HIGHWAY NOISE ABATEMENT

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Simple barriers of earthwork or solid construction have been widely used to reduce traffic noise levels in neighborhoods adjacent to urban freeways. The Kinematic Sound Screen is a new concept in noise barrier design. It consists of a series of hollow, triangular-shaped columns acting as Helmholtz resonators. The spacing between columns permits the motorist to "see through" the barrier at highway speeds while at the same time screening the traffic from the view of observers in nearby residential areas. Laboratory testing of Kinematic Sound Screen panels demonstrated that an approximate 15-dB attenuation in transmitted noise levels can be achieved with this approach, which is comparable to that obtained with conventional, solid barriers. A full-scale sound screen has been constructed along a freeway in Phoenix, Arizona, and field evaluation of this prototype demonstrated that attenuation of greater than 10 dB is achievable using a 12-ft high screen with greater attenuation possible. The Kinematic Sound Screen offers a promising alternative to conventional barriers along future urban freeways.

•BEGINNING in July 1972 the Federal Highway Administration Policy and Procedures Memorandum (PPM) 90-2 made it necessary for the highway design engineer to consider noise abatement measures on all new highway construction projects. The stated purpose of PPM 90-2 is to reduce the effects of traffic noise by the greatest possible extent without neglecting other important considerations. Section 136(b) of the Federal-Aid Highway Act of 1970 requires not only that noise be fully considered but also that other economic, social, and environmental effects be considered and that "final decisions on highway projects (be made) in the best overall public interest taking into condideration the need for fast, safe and efficient transportation, public services and the cost of eliminating or minimizing such adverse effects."

At this point, the following questions are pertinent:

1. Just how stringent are these standards imposed on new highway construction by PPM 90-2?
2. What measures are available to enable the design engineer to comply with these standards?

The noise standards specified in PPM 90-2 require in part that the sound levels experienced at the exteriors of schools, parks, and residences near proposed highways not exceed 70 dBA (70 A-weighted decibels) more than 10 percent of the time during the worst hour of the day. The magnitude of the noise abatement problem is shown in Figure 1, which depicts the noise levels that are exceeded more than 10 percent of the time (designated as L_{10}) for a typical four-lane highway, assuming moderate traffic flow. Note that, for sections of such a highway, some type of noise abatement measure is required if residences, schools, or parks are within 250 ft of the nearest lane of traffic.

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Figure 1 also indicates some methods for attenuating (or reducing) the sound levels produced by nearby highway traffic for buildings at various distances from the highway. It is clear that the most effective attenuation is achieved through the use of barriers and that the higher the barrier is the more effective it is in reducing the sound level. This is due in part to the fact that a large portion of the noise produced by diesel trucks is emitted from the exhaust stack at heights of 10 to 15 ft above the roadway. Thus, low barriers do not attenuate exhaust stack noises to any appreciable extent.

Solid barriers can be thought of as a "plate" having elastic properties and known thickness. Such barriers affect a sound field in two ways: diffraction and transmission of sound waves over and through the barrier and reflection of sound waves off the face of the barrier. Figure 2 shows the action of these influences on a typical sound wave striking a barrier. As might be expected, the objective in barrier design is to keep the sum of the diffracted component (L_D) and the transmitted component (L_T) as small as possible with respect to the incident sound energy level (L_I). As will be shown, this objective can be achieved with only limited success using solid upright barriers.

Maekawa (1) developed a mathematical model for the performance of acoustic barriers. His research indicated that the noise attenuation of a solid barrier is directly proportional to a factor δ, where $\delta = A + B - C$ as shown in Figure 3.

It is clear from this model that, the greater is the angle AB (i.e., the higher the barrier relative to the observer and source), the greater will be the effective attenuation of a given solid barrier.

Maekawa also demonstrated, however, that barrier attenuation is inversely proportional to the wavelength (λ) of the incident sound waves. Thus, long wavelengths of 4 to 10 ft are relatively unaffected by solid barriers because they are easily diffracted over the top except for wall heights greater than 25 ft. Because the apparent sound level at any given time is slightly greater than the level of the loudest sound present, this means that the overall effectiveness of any simple barrier is limited by its ability to screen out low-frequency sounds. In practice, this limit is approximately 15 dB for simple barriers less than 25 ft high (2). When it is recognized that traffic noise levels peak in the frequency range of 125 to 250 Hz (3), the true limitation of simple barriers as traffic noise attenuators can be appreciated.

INITIAL CONCEPT DEVELOPMENT

It is precisely the state of affairs just described that led to consideration of alternatives to conventional solid noise barriers in 1970. At that time, the Engineering Corporation of America was commissioned to study the environmental effects of a section of proposed freeway running through an established residential neighborhood in Phoenix, Arizona. Cursory analysis of the expected noise levels in the adjacent community after freeway construction indicated that some type of noise abatement measure along the edge of the roadway would be desirable. Our research into the attenuation qualities of solid barriers indicated that, at best, the overall sound level could only be reduced about 15 dB using this approach. When the poor aesthetic and environmental impact of such a barrier was considered, we began to search for a viable alternative that would present a pleasing architectural appearance and at the same time equal or exceed the attenuation qualities of conventional barriers.

A major objection to the use of conventional solid barriers is their inherent opacity, which is highly confining and potentially hazardous for the motorist, especially in view of the extreme wall heights required to reach an appreciable attenuation level. Therefore, the possibility of using transparent plastic panels was explored. However, no measurements relating the effective attenuation of plexiglass barriers to conventional solid barriers have been reported. Also, maintenance would be a frequent and costly consideration.

The beginnings of a feasible solution to this barrier problem became evident when it was decided to investigate the possibilities of using the principles of Edison's Kinetoscope in this application. The Kinetoscope is a forerunner of the modern movie projector. It consists of a film strip transported in front of a light source. A rotating shutter containing a single aperture is rotated rapidly such that 46 times a second the aperture is precisely positioned over an individual frame. The effect of motion depended on spinning the shutter rapidly in synchronization with advance of sequential frames on the film strip. It was apparent that apertures in a barrier might permit the surrounding countryside to be viewed in similar fashion as a continuous panorama for observers passing by closely spaced apertures at highway speeds.

Thus, the obvious physical characteristic that distinguished the Kinematic Sound Screen from conventional barriers was established. From its original conception to the present time, the screen has consisted of a series of triangular-shaped columns separated by narrow apertures as shown in Figure 4.

At this point, it was necessary to consider methods for improving the sound attenuation qualities of the Kinematic Sound Screen. The objective at this point was to compensate for the sound transmission characteristics of the apertures through proper design of the triangular columns separating the apertures.

Rayleigh (4) established the side branch as having a damping effect on sounds transmitted through tubes. In the case of the sound screen, the analog to Rayleigh's side branch is the Helmholtz resonator. The Helmholtz resonator consists of a chamber with an orifice that couples the air inside the chamber to the air outside. The Helmholtz resonator was adapted for the sound screen by hollowing out the triangular columns between the apertures as shown in Figure 5.

Note that each triangular column incorporates two orifices. These orifices (or absorption slits) are located adjacent to the apertures on both sides of the column. As an incident sound wave strikes the front faces of the columns, it is compressed as it proceeds through what is, in effect, an acoustic horn toward the aperture. When a given wave reaches the absorption slit openings, a large portion of its energy is expended in moving the column of air in the orifice to the resonating chambers. The resulting sound waves in the chamber bounce off the walls, scattering and losing energy. Eventually, some portion of the original sound energy is passed back out of the chamber as a reflected wave. Thus, the sound screen permits only a small portion of the incident sound energy to be passed through the apertures between columns. The remainder is dissipated through heat in the Helmholtz chambers or is reflected back toward the source.

ACOUSTIC PROPERTIES OF THE SOUND SCREEN

If we consider each hollow column of the sound screen to be a Helmholtz resonator acting as a side branch, then the ratio of the power transmitted into the chamber to that of the incident wave is given by the standard formula:

$$\alpha_b = \frac{\frac{\rho_0 C}{A} R_b}{\left(\frac{\rho_0 C}{2A} + R_b\right)^2 + X_b^2} \tag{1}$$

where

ρ_0 = density of air at STP,
C = speed of sound in air at STP,
A = cross-sectional area of cavity orifice,
R_b = acoustic resistance of the resonating chamber = $\rho_0 CK^2/2\pi = \rho_0 A/2\pi L'V$,
L' = effective length of orifice neck,
V = volume of chamber,
X_b = acoustic reactance of the resonating chamber = $\rho_0\left(\frac{\omega L'}{\pi A^2} - \frac{V}{\rho_0^2 C^4 \omega}\right)$, and
ω = frequency of incident sound wave.

Therefore, the preceding formula reduces to

$$\alpha_b = \frac{C}{2\pi L'V} \Big/ \left(\frac{C}{2A} + \frac{A}{2\pi L'V}\right)^2 + \left(\frac{\omega L'}{\pi A^2} - \frac{V}{\rho_0 \omega C^4}\right)^2 \tag{2}$$

For values of $V < 10^8\ cm^3$, as in the case of the sound screen, the term $V/\rho_o\omega C^4$ becomes insignificant. For hardware design purposes, then, the formula can be expressed as

$$\alpha_b \cong \frac{C}{2\pi L'V} \bigg/ \left(\frac{C}{2A} + \frac{A}{2\pi L'V}\right)^2 + \left(\frac{\omega L'}{\pi A^2}\right)^2 \tag{3}$$

Therefore, maximum dissipation of energy in each Helmholtz resonating chamber can be achieved by adjusting the values for orifice area (A), orifice neck length (L′), and chamber volume (V).

It is clear from Eq. 3 that chambers of a given volume and orifice configuration will be more efficient at some sound frequencies than at others because of the influence of the factor ω. Because the majority of traffic noises occur in the frequency band of 125 to 1,000 Hz, this feature offered the possibility for selectively tuning the resonating chambers for maximum absorption in the frequency band of interest. Maximum absorption occurs at the resonant frequency of a given chamber.

It should be noted that the density of the chamber walls is not an influencing factor in the calculation of absorption efficiency for the Helmholtz resonators. Early in the research effort it was thought that the chamber wall material might affect absorption. However, subsequent testing with a variety of construction materials confirms that the choice of material is of little significance, with one qualification. The validity of considering the Helmholtz resonating chambers as side branches is based on the assumption that the chamber walls behave acoustically in the same fashion as the walls of an acoustic pipe, that is, as high-density elastic plates. Therefore, it appears likely that the ultimate material selection will be from high-density nonfrangible material such as plywood, precast concrete, plastics, sheet metal (steel), or cast or extruded aluminum.

LABORATORY TESTING

Initial testing of the Kinematic Sound Screen concept was conducted using a small concrete box with a door on one side and a microphone placed inside. Three doors were used in the preliminary tests. The first consisted of a solid, 2-in. thick concrete panel, the second door was a similar panel having a ½-in. slot, and the third door contained a V-shaped depression in the face leading to a slot having the same dimensions as the slot in door number two. Testing with the unslotted door resulted in a transmission loss of sound into the chamber of approximately 30 dB. Testing of the other two doors indicated that transmission loss was approximately 15 dB for the slotted door and slightly greater for the door with the V-shaped slot. It was theorized that the difference in transmission between the slotted and V-shaped slotted configurations was due to the scattering effect of the acoustic horn produced by the V configuration. By coupling the horn to Helmholtz resonators, it was felt that a 25-dB attenuation in transmitted sound level could be achieved for the full-scale sound screen. This level is comparable to the noise attenuation of conventional solid barriers. The sound screen, however, would have the advantage of "see-through" characteristics.

On the basis of the preliminary test results, a laboratory research program was initiated with funding from the research division of the Arizona Highway Department. The objective of this program was to set up a sound laboratory and evaluate the sound transmission characteristics of prototype sound screen panels. The laboratory consisted of a dual anechoic chamber as shown in Figure 6 and included a precision sound measurement and recording system with calibrated accuracies complying with National Bureau of Standards requirements.

The sound input system consisted of a "pink" noise pseudorandom generator driving two preamplifiers. The signal was then passed through a spectrum shaper to eliminate equipment anomalies within the generating equipment and reproduced by means of a bank of matched loudspeakers. Sound level recordings were taken from calibrated microphones located in the source chamber and the receiver chamber, using a real-time audio spectrum analyzer to drive a precision x-y plotter.

Figure 1. Highway noise levels (dBA, L_{10}) at various distances from edge of four-lane highway.

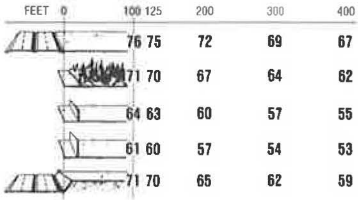


Figure 2. Acoustic effects of sound wave from line source impinging on barrier of finite thickness.

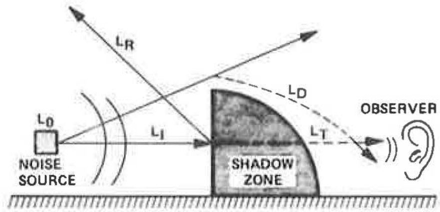


Figure 3. Significant distance relations for computing barrier attenuation.

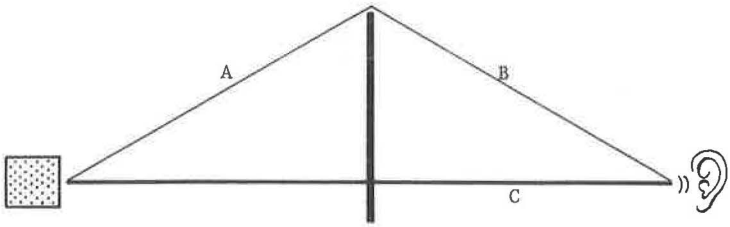


Figure 4. Optical design concept for Kinematic Sound Screen.

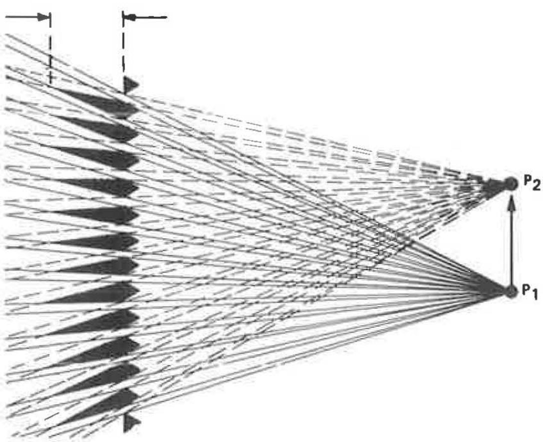


Figure 5. Acoustic design concept for Kinematic Sound Screen.

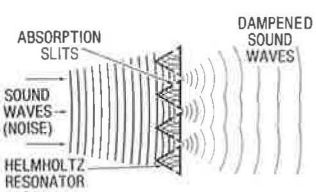
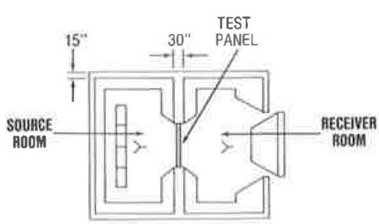


Figure 6. Layout of anechoic chamber.



Five test panels were fabricated and tested under this program. The physical characteristics of the panels are given in Table 1, and a typical test panel is shown in Figure 7.

The results of the initial testing for transmission losses through the sound screen panels were in the range of 17 to 20 dBA. Panels 2 and 3 were identical in construction except for material (concrete and wood respectively); however, the difference in measured attenuation was less than 1 dB. Hence, it was concluded that the construction material has no significant effect on the attenuation characteristics of the sound screen.

Of particular interest in this test series was the correlation between calculated resonant frequency and the frequency of maximum absorption. Without exception, maximum absorption occurred at or near the calculated resonant frequency. The absorption peaks were 10 to 15 dB greater than the average attenuation at other frequencies. Thus, the fundamental objective of selective tuning to reduce noise levels in specific frequency ranges appeared to be achievable.

Concurrent with the early laboratory tests, an evaluation of the optical properties of the sound screen was made using a pasteboard mock-up of the screen. It was discovered that the panel configuration used in the sound tests (that is, 6-in. wide columns with $\frac{1}{8}$-in. apertures between them) did not provide good resolution of the background when viewed by a passing motorist at freeway speeds. Alternate column widths of 1, 2, 3, and 4 in. were evaluated, the 1-in. width providing the best clarity. As a compromise between the optical features and the necessary minimum volume and strength characteristics desired in full-scale sound screens, the 3-in. column width was selected for further evaluation.

FIELD EVALUATION

At this point in the program, the sponsor requested that a 350-ft segment of 12-ft high sound screen be built along a Phoenix freeway to permit field evaluation of the concept.

Various materials were considered and evaluated for use in this full-scale screen, including plexiglass, sheet metal, concrete, and aluminum. On the basis of cost, availability, and ease of installation, the selected material was aluminum. The prototype sound screen was constructed in 4-ft sections, each 3 ft high, with a solid support column at the ends of each section. The hollow resonating chambers were formed as extruded segments 3 ft long and snap-fitted and glued to form a closed cavity. Cross-sectional views of the extrusions making up each column are shown in Figure 8.

It should be noted that the exterior view of the support columns is identical to that of the hollow Helmholtz cavities. This approach was selected to enhance the pleasing appearance of the sound screen from the motorist's point of view.

After the 3- by 4-ft sections were assembled off-site, they were then stacked at the construction site four tiers high on a concrete pad to provide a 12-ft barrier. The completed sound screen is shown in Figure 9.

Laboratory testing of these panels indicated that the attenuation of transmitted noise levels approached 15 dBA. Subsequently, tests were performed in the field with one microphone placed 5 ft in front of the screen and another placed approximately 15 ft behind the screen near the center of the 350-ft long section. The difference in sound levels between the front and back sides of the screen was considered to be the attenuation due to the sound screen. Although this testing demonstrated an overall noise reduction of approximately 10 dB, the greatest attenuation occurred in the higher frequency ranges. This corresponds well with the calculated resonant frequency for these panels, which was 798 Hz. The resonant frequency appears to act as a low-frequency threshold noise attenuation. Although noise absorption peaks at that frequency, there is a significantly diminished effect on lower frequencies. For this reason, it is desirable to design the Helmholtz chambers to resonate at as low a frequency as practicable.

Future testing planned for the Kinematic Sound Screen includes measuring the actual sound energy absorbed by the Helmholtz chambers at various frequencies. In addition, we plan to test panels without apertures (that is, solid screens with Helmholtz

Table 1. Physical characteristics of test panels.

Physical Data	Panel 1, Stucco	Panel 2, Continuously Poured Concrete	Panel 3, Plywood	Panel 4, Plywood	Panel 5, Plywood
Thickness (in.)	7	7	7	4¼	4
Weight (lb)	200	450	95	100	100
Aperture thickness (in.)	⅛	⅛	⅛	⅛	⅛
Angle of acoustic horn (deg)	47	52	52	71	76
Interior volume (cm^3)	1,945	2,999	2,999	1,105	1,029.7
Size of cavity opening (in.)	⅛	⅛	⅛	⅛	¼
Calculated resonant frequency (H_3)	359	316	316	500	725
Neck length (cm)	2.6	2.2	2.2	2.3	2.35
Neck area (cm^2)	21.37	21.37	21.37	21.37	42.60

Note: All panels were 2 by 4 ft.

Figure 7. Plywood test panel with ¼-in. cavity openings.

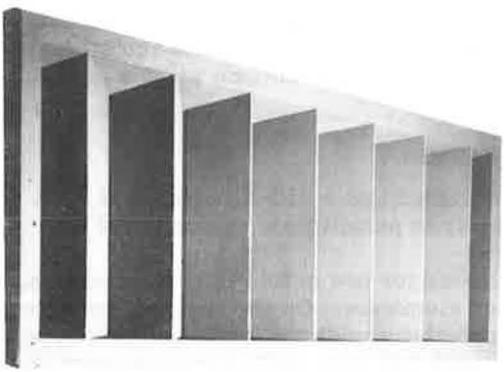


Figure 8. Cross-sectional views of aluminum extrusions used to construct full-scale Kinematic Sound Screen.

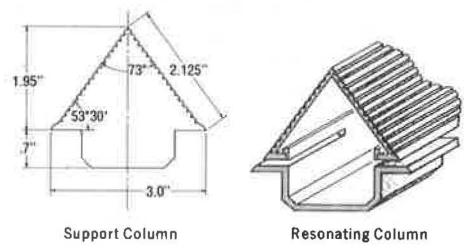


Figure 9. Full-scale Kinematic Sound Screen (aluminum construction).

resonators mounted on the front face) to determine the maximum attenuation that can be achieved with this concept.

CONCLUSIONS

In conclusion, the principle of the Kinematic Sound Screen is well supported by acoustic and optical theory. Testing, both in the laboratory and in the field, has demonstrated that the sound screen reduces transmitted noise levels by approximately 15 dB, with an overall reduction in traffic noise levels of more than 10 dB. With refinements in tuning the sound screen for the lower frequencies, it is anticipated that 15-dB attenuation can be achieved.

Thus, it appears that the Kinematic Sound Screen can provide the traffic noise attenuation required to ensure compliance with PPM 90-2 for adjacent schools, parks, and residences. Additionally, the unique "see-through" features of the Kinematic Sound Screen should make it popular with the motoring public and local residents alike.

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