Radiated Aerodynamic Noise Generated by High-Speed Tracked Vehicles

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The origins and manifestations of aerodynamic noise generated by high-speed tracked vehicles are discussed, and examples of measurements on magnetically levitated and wheeled trains are used to illustrate the significance of this noise. Sound-source location measurements with microphone arrays and the difficulties encountered in predicting aeronoise are also discussed.

Some press reports have described the sound produced by a magnetically levitated (maglev) vehicle traveling at high-speeds as "wind noise." Without further qualification, however, this description lends itself to gross misinterpretation. "Wind noises" can be as gentle as the whisper of a spring breeze or as awesome as the roar of a tornado, but neither extreme bears any resemblance to the sound emitted by a passing vehicle. As shall be demonstrated, the level of wind noise, or aerodynamic noise, generated by the passage of a high-speed vehicle lies within the accustomed range of wayside levels produced by conventional trains. Indeed, a well-designed high-speed tracked vehicle will generate lower sound levels than does its conventional counterpart traveling at much lower speeds.

In Germany the phrase "high-speed tracked vehicles" refers to the electrically powered InterCity Express (ICE), the new generation of Deutsche Bahn (DB) trains, and the TRANSRAPID maglev TR 07, which has been certified for commercial operations but is not yet in regular service. The ICE carries passengers at speeds up to 250 km/hr which the DB plans to increase to 280 km/hr in 1995 and to 300 km/hr in the near future. The maglev TR 07 is designed for sustained operation at speeds up to 500 km/hr.

When the research and development of high-speed ground transport systems began in the 1970s, it appeared axiomatic to many people that higher speeds equal higher noise levels. To belie the logic of this equation, the DB, in cooperation with the German Ministry for Science and Technology, has invested heavily in seeking ways to reduce wayside noise levels. Since it was recognized early on that some of the important noise sources at speeds in excess of 250 km/hr would have flow-generated origins (*1,2*), the new high-speed vehicles were designed to minimize aerodynamic noise levels. As a result of these efforts, wayside noise levels generated by the ICE at 300 km/hr are comparable to those produced by average conventional InterCity trains traveling at speeds between 160 and 200 km/hr. And the maglev TR 07, which is significantly quieter than wheeled trains at corresponding speeds, generates noise levels at 400 km/hr that lie within the range of sound levels produced by conventional trains at much lower speeds.

Sound sources on railway trains can be grouped into three categories:

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1. On-board machinery (traction motor, air-conditioning units, etc.),
2. Wheel/rail (W/R) interactions, and
3. Aerodynamic interactions.

The first category is important generally only up to speeds of between 50 and 80 km/hr, whereas the second category is the principal source of wayside noise up to speeds of at least 220 km/hr. At higher speeds, aerodynamically generated forces begin vying with W/R interactions for dominance. One cannot specify any particular speed at which the former sound sources become more important than the latter because this speed depends on a number of factors, including the design of the vehicle, condition of the rails and wheels, use of wheel-noise absorbers or sound barriers, and the definition of wayside noise.

The three corresponding categories for maglev vehicles are

1. On-board machinery and magnetostrictive forces,
2. Vehicle/guideway interactions, and
3. Aerodynamic interactions.

In the following sections, the aerodynamically generated sound component will be discussed and examples to illustrate its significance will be given.

GENESIS AND MANIFESTATIONS OF AERODYNAMIC NOISE

The immediate cause of aerodynamic noise is flow interactions between the moving vehicle and the air. In this paper only the radiation field of aerodynamic noise will be discussed but there is also a near-field component that could cause cabin noise problems for maglev vehicles in particular. The fluid mechanical phenomena to be discussed have aeroacoustical consequences.

Aerodynamic Drag

Solid bodies traveling through the atmosphere encounter resistance to their motion. This resistance, called aerodynamic drag, can be considerable for tracked vehicles. Gawthrope (*3*) found that a conventional train uses up to 70 percent of the traction power available at the wheels to overcome aerodynamic drag. For a high-speed train operating at 300 km/hr, this figure could reach 90 percent (*4*).

The aerodynamic drag of a body comprises three components: (*a*) skin-friction drag caused by viscous shear in the layer of air adjacent to the body, (*b*) form or pressure drag due to the modified pressure distribution around the body, and (*c*) induced drag when the body has nonzero lift. Since tracked vehicles generally have a zero or very low, positive or negative, lift coefficient, induced drag plays a very minor role at best in establishing their total aerodynamic drag, and this component shall be ignored. Of the first two components, skin-friction drag is usually slightly larger than pressure drag for tracked vehicles (*3*). Taken together, these first two components are called profile drag.

The viscous nature of air is the underlying cause of profile drag, and it is absent if the fluid is inviscid. Thus, bodies having zero lift traveling through inviscid fluid experience no resistance to their motion, and no mechanism exists for generating flow-induced noise. When the fluid is air, however, drag forces do act on the moving body, and it radiates noise. Although the facts that the body experiences drag and sound is generated are simply observations, it shall be assumed that a causal relationship exists between them (i.e., aerodynamic drag produces aerodynamic noise). If only 10^{-6} of the mechanical power dissipated by aerodynamic drag were to be converted into acoustic power, a 60-m-long vehicle traveling at a speed of 300 km/hr would generate a sound level greater than 80 dB at a point 25 m from the vehicle.

This probable causal relationship was studied by Revell et al. in their investigations of airframe noise (*5,6*). They found that the root-mean square (rms) sound pressure $\tilde{p}$ is related to the aerodynamic drag coefficient C_x of a structural element of the aircraft by

$$\tilde{p}^2 \sim C_x^n \tag{1}$$

where n has a value of 3 for most components, including the fuselage. Therefore, if a tracked vehicle is relatively "clean" in an aerodynamic sense, Equation 1 tells us that a decrease in the drag coefficient produces a corresponding decrease in the rms sound pressure of aerodynamically generated noise.

A vehicle's aerodynamic drag is strongly affected by crosswinds. Gawthrope (*3*) writes that even the "wind on a typical breezy day could easily increase drag by 20 percent."

Turbulent Boundary Layer

The viscosity of air must be taken into account when considering the behavior of an airflow close to the surface of a solid body. One of the boundary conditions of fluid mechanics is the "no-slip" condition. If there is relative motion between a viscous fluid and a solid body, the no-slip condition requires that the fluid particles in direct contact with the body have zero velocity relative to the body. To simplify the discussion, consider a fluid moving with free-stream velocity U_0 interacting with a stationary body. At the body's surface, the fluid velocity is zero, whereas at some distance from the surface the fluid has to attain its free-stream velocity. Therefore, within a layer of fluid adjacent to the surface, there must be a velocity gradient with its accompanying shear stresses. This layer of fluid is called the boundary layer.

The boundary layer on the vehicle begins at the stagnation point on the tip of the nose, at which the flow velocity is zero, and moves around the convex surface in a generally downstream direction. Initially the airflow is laminar, but within a short distance of the stagnation point the flow undergoes transition to turbulence. The chaotic motion of fluid within a turbulent-boundary layer (TBL) produces pressure fluctuations on the vehicle's surface. These pressure fluctuations will be discussed later.

Flow Separation

To satisfy the continuity equation, the air adjacent to the surface of the nose, but not in direct contact with it, accelerates along the convex surface. Depending on the geometry of the head shape, the accelerating air can rapidly attain speeds that are up to 60 percent higher than U_0. The accelerating air flow on the head produces a favorable pressure gradient (i.e., $dp/d\xi < 0$, where p is pressure and ξ is distance along the head). A pressure gradient is favorable when it inhibits the separation of the boundary layer. When the air reaches the region of constant head width, the flow decelerates, thereby creating an adverse pressure gradient (i.e., $dp/d\xi > 0$). In this region, the thickness of the boundary layer increases more rapidly with ξ than it did in the region of favorable pressure gradient. Both the wall shear stress and the adverse pressure gradient suck off momentum from the flow, thereby causing it to decelerate further. The boundary layer can then often no longer maintain itself on the surface and separation occurs. If the air flow in the region of separation can be considered two-dimensional, the line of flow separation coincides with the disappearance of the wall shear stress and the beginning of a region in which the flow reverses itself. On the front of a full-size moving vehicle, however, the air flow is often three-dimensional, and boundary-layer separation can occur without the shear stresses going to zero or the flow reversing itself (*7*).

The momentum in the vehicle's boundary layer is usually high enough for the separated flow to reattach itself at a short distance downstream, thereby forming a separation bubble. As mentioned earlier, crosswinds can modify the boundary layer on a vehicle, particularly on its head shape. For example, wind gusts could trigger an incipient flow separation. The shape of a vehicle's head is a very important parameter for reducing the probability that a boundary-layer flow separation will occur (*4*), but because of difficulties in the manufacturing process or operational reasons, head shapes are often less than optimal. In a numerical study of flow over a head designed for a maglev vehicle, Siclari et al. (*8*) found that the flow separated on the nose and produced vortices that were swept downstream along the sides of the vehicle.

A different kind of separation occurs when vortices are shed on structural elements of the vehicle (i.e., on salient or trailing edges, axles, cut-outs, pantographs, etc.). Vortex shedding is a very important source of aerodynamic noise on high-speed vehicles.

Noise Sources on High-Speed Vehicles

According to Gutin's principle (*9*), fluctuating forces acting on a surface generate sound regardless of the origin of such forces. Strong sound sources are generated within regions of TBL flow separation. Although rms fluctuating pressures (i.e., forces) within such a region can be 20 or more times higher than those beneath an attached TBL (*10*), the principal source of noise may be the time rate of change of pressure rather than the fluctuations per se. Other strong sources of pressure fluctuations and sound are generated by vortex shedding from edges and protuberances. The pressure fluctuations within an attached TBL are also fluctuating forces acting on a surface and, as such, also generate sound. The specific sound power generated by these fluctuating forces is, however, relatively weak, and the author is not aware of any unambiguous laboratory measurements of TBL sound. Because TBL noise is a strong function of flow speed, however, it is conceivable that a very large surface such as that on a 200-m-long maglev vehicle traveling at very high speed could generate a TBL sound power that would substantially contribute to wayside noise levels. Model calculations (*11*) indicate that TBL noise could be important at speeds over 400 km/hr, but this prognosis has not yet been verified directly.

Fluctuating forces generate sound having a dipole pattern. A couplet of such forces lying side by side with their fluctuations 180 degrees out of phase produces a lateral quadrupole, whereas when the two fluctuating out-of-phase forces lie end to end, they form a longitudinal quadrupole. On a flat, smooth, infinite, rigid surface, sound generated by the pressure fluctuations in a TBL would combine with sound reflected from the surface to produce such longitudinal quadrupoles. Relative to an acoustic wavelength of TBL noise, however, the width of a vehicle is not large, and dipole noise is more likely to be important.

Sound generated by aerodynamic sources is proportional to flow speed raised to a power, namely,

$$\tilde{p}^2 \sim U^\alpha \tag{2}$$

where α depends on the source, flow speed U, and whether or not the sound is A-weighted. The Mach number of a flow is $M = U/c$, where c is the local sound speed. For $M << 1$, α equals 6 for dipoles and 8 for quadrupoles. Sound generated by W/R and vehicle/guideway interactions can also be represented by Equation 2 if we let $\alpha \approx 3$ for A-weight sound. For machinery noise, α can be taken as ≈1 (*11,12*).

Since α equals at least 6 for aerodynamic sound (trailing edge noise where $\alpha \approx 5$ is an exception) and 3 for noise generated by W/R and vehicle/guideway interactions, there must be some speed at which the sound power level produced aerodynamically equals that due to W/R or vehicle/guideway interactions. This speed is called the upper acoustical transition speed U_{t_2}. The problem is to determine whether βU_{t_2}, when $\beta \approx 0.8$, lies within the range of operating speeds for each type of vehicle.

The peak frequencies of vortex-shedding sound are proportional to the local flow speed. Although the peak frequencies of sound generated by a TBL flow separation or surface-pressure fluctuations also increase with flow speed, their dependence on it is more complicated. For cavity noise, peak frequencies do not generally exhibit this dependence on flow speed. When the surfaces of the rails are smooth and free of corrugations, the results of many array measurements have shown that the peak frequencies of W/R noise are independent of train speed. The levels of the higher-frequency peaks tend to increase at a slightly higher rate with increasing speed than do the levels of the lower-frequency peaks, but the frequencies themselves remain essentially constant.

Most important aerodynamic sound sources on high-speed vehicles have peak frequencies lying below 1,000 Hz. Consequently, when this sound is A-weighted, the sound pressures are attenuated in such a way that the lower the frequency, the greater the attenuation. The effect on the speed exponent α when vortex-shedding sound is A-weighted is illustrated in Figure 1. Sound produced by vortex shedding has a dipole radiation pattern, and, hence, $\alpha = 6$ when the sound is unweighted. The three peaks in the figure represent vortex-shedding sound generated speeds of 100, 200, and 400 km/hr (200, 400, and 800 Hz peaks, repectively). The increase of sound level with increasing speed is represented by a speed exponent of 6 for unweighted sound; when it is A-weighted, however, α can range from 6 to about 8, depending on frequency and, hence, speed.

Two other effects that influence sound emitted by moving sources are (*a*) the well-known Doppler frequency shift and (*b*) convective augmentation of the sound pressure. This augmentation is slightly different for point sources than it is for line or surface distributions of sources. Since the important sound sources on a tracked vehicle are all dipole-like, the increase of level due to convective augmentation shall be approximated with an expression similar to what one would obtain for a point dipole:

$$\Delta = -20 \log(1 - M^2) \tag{3}$$

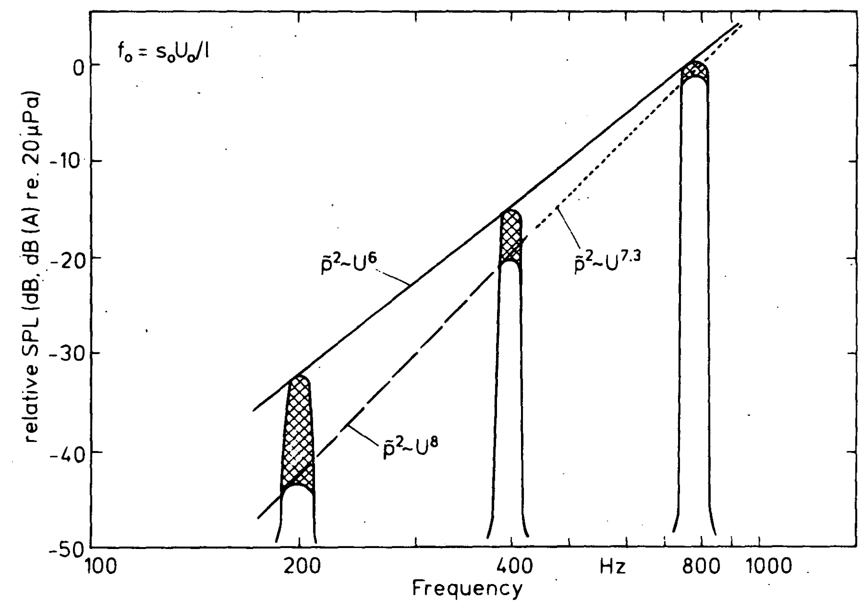

FIGURE 1 Simplified example showing effect of A-weighting on vortex-shedding sound.

Wind Tunnel Measurements

An important parameter for many flow-generated sound sources is the Reynolds number, defined as $Re_d = Ud/\nu$ where d is some dimension of the body and ν is the kinematic viscosity of the fluid. For example, skin-friction drag, vortex shedding from certain bodies including rods having circular cross sections, and the properties of a boundary layer and where it undergoes transition to turbulence are dependent on Reynolds number. Aeroacoustical measurements on scale models in an open-jet wind tunnel can help identify locations of probable aeronoise sources, but if these sources depend on the Reynolds number, erroneous conclusions could be drawn. Although Reynolds-number scaling of even a single railway car is impossible in most wind tunnel facilities, subcomponents of a train, such as the pantograph or structural elements in the bogie region, can often be scaled by using oversize scale models. The measured frequencies and sound levels can then be adjusted to represent the values that they would have on the full-scale component.

EVIDENCE FOR IMPORTANCE OF AERODYNAMIC SOUND

All single-microphone results in this section are given in pass-by sound pressure levels $L_{eq,p}$ which are simply equivalent sound pressure levels averaged over the time of passage.

Figure 2 shows two sets of wayside noise levels (*13*) for the four coaches on a dedicated TGV-Atlantique (TGV-A) operated by the French National Railway. The data were measured with a microphone positioned 25 m lateral to the centerline of the track and at the height of the rails (6 m above the local ground). One set of measurements was made under free-field conditions, whereas the boundary conditions for the second set involved a 2-m-high conventional sound barrier. From the measuring station, only about 20 percent of the coach bodies were visible above the barrier.

If an average frequency of about 2,000 Hz for W/R noise is assumed, the effect of the sound barrier can be estimated with expressions given elsewhere (*14*). For a line of incoherent sound sources located just below the wheel axles, Kurze and Beranek [Fig. 7.9 (*14*)] indicate that the barrier should provide an excess attenuation of W/R noise of about 14 dB. For a speed of 160 km/hr, a speed at which aerodynamic noise is relatively insignificant, Figure 2 shows that the barrier does indeed afford an excess attenuation of approximately 14 dB. The attenuation of sound by a barrier is frequency dependent: the higher the noise frequency, the greater the excess attenuation up to a maximum of about 24 dB for a practical barrier (*14*).

As train speed increases, the levels of the peak frequencies of W/R noise also increase, the higher-frequency peaks at a slightly higher rate than the lower-frequency peaks, but the frequencies themselves remain essentially constant. Because the peak frequencies are invariant, the excess attenuation attributable to the barrier should also remain constant as vehicle speed increases. But, as can be seen in Figure 2, the excess attenuation decreases as train speed increases. This behavior implies the existence of additional sound sources whose importance increases progressively with increasing train speed. These additional sources are generated by flow interactions with structural elements of the coaches in the bogie regions. Because the peak frequencies of this flow-generated sound are substantially lower than those of W/R noise, the excess attenuation of sound provided by the barrier at higher speeds is less than it was at lower ones where the level of aeronoise is negligible. In addition, the higher speed exponent of aerodynamic sound sources means that the rate of increase of intensity with speed for aeronoise is significantly greater than it is for W/R noise. Therefore, the net effect on the curve of wayside noise level is that its slope increases with increasing train speed.

Other results that demonstrate the presence of aerodynamic noise are given in Figure 3. All measurements were made 25 m from the centerline of the track or guideway. Results are shown for a two-

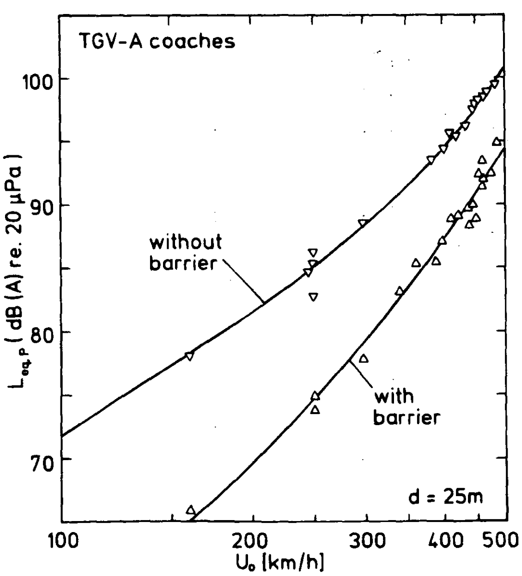

FIGURE 2 Wayside noise levels for TGV-A with and without sound barrier (*13*).

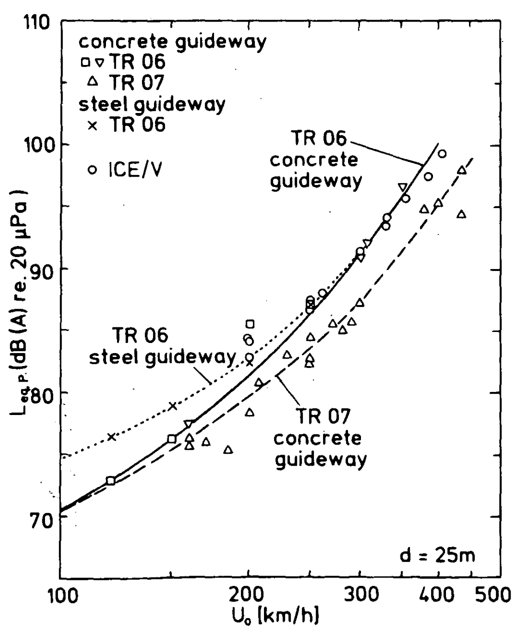

FIGURE 3 Wayside noise levels for TR 06 and TR 07 (*15*) and ICE/V.

section TR 07 operating on a concrete guideway (*15*), a two-section older TR 06 maglev vehicle traveling on a steel and concrete guideway, and a two-coach ICE/V (test version of the ICE) operating on dedicated track. Results for the TR 06 on a steel guideway and some of those on the concrete guideway were measured by Korb and Largof of the firm IABG and are not generally available. The other results, for the TR 06 and those for the ICE/V, were measured by the DLR.

For the ICE/V, U_{t_2} is about 270 km/hr. Thus, according to Figure 3, if the only sound sources on the train were those generated aerodynamically, it would produce a sound level of approximately 85 dBA at 270 km/hr. Average conventional InterCity trains traveling at 160 km/hr have wayside noise levels that fall within the range of 84 to 93 dBA. The level of the aeronoise component generated by the ICE/V at 270 km/hr therefore lies within the lower eighth of this range of noise levels produced by conventional trains traveling at 160 km/hr.

For speeds below 265 km/hr, Figure 3 shows that the TR 06 operating on a steel guideway generates higher sound levels than it does on a concrete guideway at corresponding speeds. At speeds above 265 km/hr, however, the sound-level curves for the TR 06 on either type of guideway merge into one. The reasons for this behavior of the curves are that within the lower speed range, vehicle/guideway interactions are the principal sources of radiated noise, whereas at higher speeds, aerodynamic interactions become the dominant source of wayside noise. These latter sources depend only on the vehicle itself, and the guideway construction becomes irrelevant.

Figure 3 also shows that within the higher speed range, sound levels generated by the ICE/V are essentially identical to those produced by the TR 06 at corresponding speeds. It is interesting to note that the drag coefficients for the two-coach ICE/V and two-section TR 06 are approximately the same. The TR 07, with its improved aerodynamic shape and roughly 25 percent lower drag coefficient, generates correspondingly lower noise levels at speeds above 290 km/hr, where aerodynamic noise is dominant.

In comparing sound levels generated by the TR 06 and TR 07 when both vehicles are traveling on the same concrete guideway, it is seen that as speed decreases, vehicle/guideway interaction noise becomes progressively more important. At 100 km/hr, both vehicles generate essentially the same wayside noise levels. If the guideway were acoustically damped, both vehicles would produce significantly lower sound levels at lower speeds.

EXAMPLES OF SOUND SOURCES ON ICE/V

The results presented in this section were measured with linear line arrays of microphones. Since line arrays can resolve sound sources in only one spatial dimension, they were mounted in two mutually perpendicular positions on a ground plate along the wayside: in the wayside vertical (WV) position with the line of microphones perpendicular to the ground plate, and in the wayside horizontal (WH) position with the line of microphones parallel to the near rail. In the WH position the array can resolve sound sources lying along the longitudinal axis of the vehicle. The array beam can be swept in the direction of motion to track any point on the train, thereby increasing the bandwidth-time product and eliminating the effects of the Doppler frequency shift (*16*). In its WV position, the array can resolve sound sources lying at different heights on the vehicle. Figure 4 shows a large WV array, "large" being identified by the number 2, positioned to measure sound generated by flow interactions with the pantographs and associated equipment on the roof of the ICE/V. An array is said to be shaded (S) when the side lobes in its beam pattern are suppressed below the usual −13 dB relative to the main beam. The side lobes in our shaded array were 25 dB down. More details about the use of directional arrays for locating sound sources on moving vehicles can be found elsewhere (*16–18*).

The ICE/V comprised two power cars separated by two middle coaches. All wheels were equipped with disc brakes and noise absorbers that lower W/R noise levels by from 5 to 6 dB. For all measurements, the line of microphones was positioned at a distance of 5 m lateral to the near rail.

Figure 5 shows three superimposed time histories measured with the SWH2 array in the frequency range 300 to 1,200 Hz for pass-bys at 200, 250, and 300 km/hr. The hatched bars in the figure indicate the increase in sound levels for an increase in speed from 200 to 300 km/hr when α equals 3 and 6 (i.e., for W/R and aerodynamic dipole noise, respectively). As can be seen in the figure, the highest peak sound levels originate between 4 and 5 m downstream of the tip of the nose on the forward power car. The increase in these peak levels between 200 and 300 km/hr is obviously greater than the increase represented by the hatched bar for $\alpha = 6$. The actual speed exponent here is about 8, much greater than α for W/R noise. Measurements made with the SWV2 array show that what appears as a single peak level near the front of the train at each speed in Figure 5 actually comprises two sound sources, one of which is located 3 m above the rails and the other at about 0.5 m. The upper peak could be due to a local region of boundary-layer flow separation or near separation, whereas the lower peak level is most likely caused by vortex shedding from protuberances in the bogie region.

Figure 6 shows two superimposed scans measured in the frequency range 200 to 1,400 Hz with the SWV2H (H = high) array shown in Figure 4. These measurements, made at a train speed of 300 km/hr, were designed to study pantograph noise. As can be seen in Figure 6, a higher sound level is produced when the pantograph on the front power car is retracted than when the pantograph on the rear power car is raised. Although seemingly paradoxical, there is a simple explanation for these results. The boundary layer on the roof of the front power car is much thinner than it is on the rear power car. Consequently, the retracted pantograph and equipment on the leading power car are subjected to what is essentially the free-stream speed of the airflow. On the roof of the rear power car, on the other hand, only the upper part of the raised pantograph can interact with the free-stream velocity; the rest of the equipment lies within the thick boundary layer, where flow speeds are lower than they are in the free stream.

Figure 6 also shows a peak in the sound-level distribution on the side of the rear power car at a height of about 2.8 m above the rails. The inlet louvers for the automatic cooling fans are located at this height. The high noise level is probably due to vortex shedding on the louver vanes when air is drawn in by the fans.

CONCLUDING REMARKS

If wayside noise is defined by the peak sound level measured during a pass-by, the principal sound sources at high speeds usually are generated either by a separation or near separation of the boundary layer or by vortex shedding from the pantograph and its associated equipment. On the other hand, if the pass-by level is the pertinent

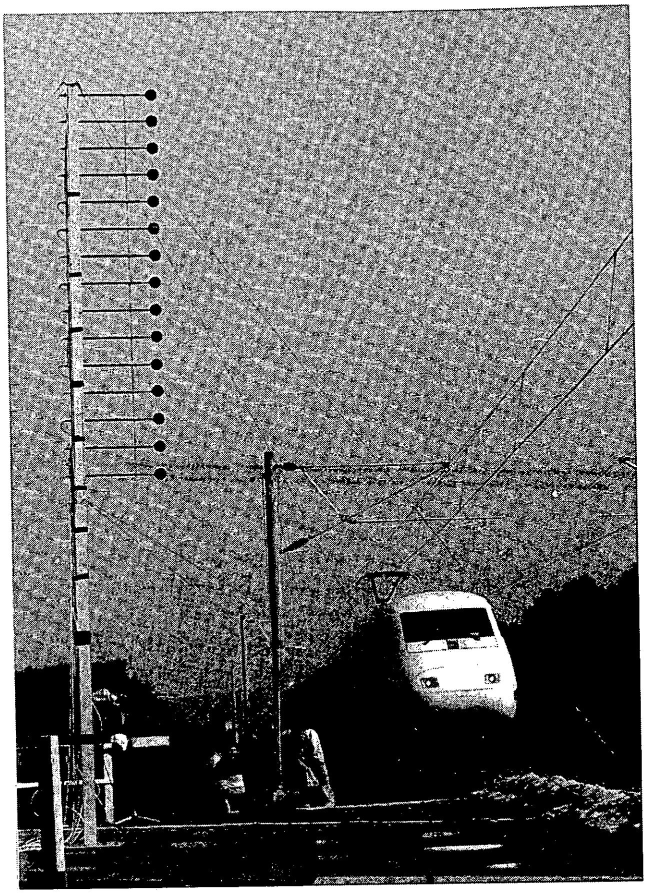

FIGURE 4 WV2H 15-microphone array designed to measure sound generated by flow interactions with equipment on roof of ICE/V.

measure of wayside noise, the important sources at high speeds are produced chiefly by vortex shedding from protuberances and edges distributed along the train, primarily in the bogie regions.

The discussion of these sound sources has been phenomenological rather than analytical because the author elected to demonstrate the significance of this noise via measured results instead of mathematical analysis. If the problem of aerodynamic noise is tackled theoretically, the functional dependence of sound pressure on the various parameters can be established, but, since several of these are functions of both Reynolds number and the local geometry, the appropriate experimental values of these parameters must be incorporated into the analysis in order to calculate the radiated noise. When such values are available, this procedure can give satisfactory results for sound generated by flow interactions with individual structural elements having relatively simple geometries. However, it is difficult to apply this theoretical approach to ensembles of structural components, particularly if they have complicated geometries (e.g., the components in the bogie regions). A simpler method of obtaining an expression for predicting radiated noise is to combine information pertaining to the character of the sound sources with an empirical fit to measured sound levels.

The most accurate method of predicting whole-train time histories, pass-by sound levels, and so forth is with a computer model such as those described by Barsikow and Müller (*11,12*). In these models, the strength, location, and speed exponent of each sound source are taken from the results of measurements made with microphone arrays.

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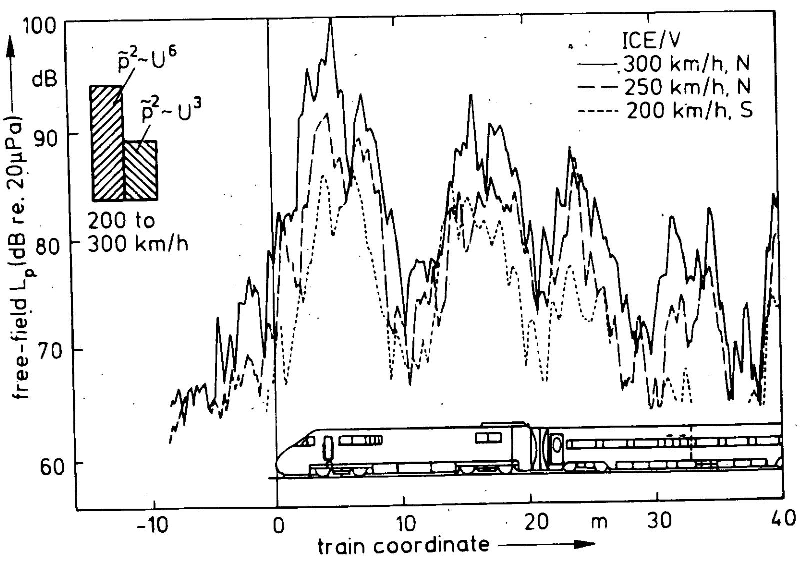

FIGURE 5 Radiated noise generated by ICE/V in frequency range 300 to 1,200 Hz, measured with SWH2 15-microphone array positioned 5 m from near rail; shaded bars indicate expected increases of sound level for aero- and W/R noise; L_p = SPL.

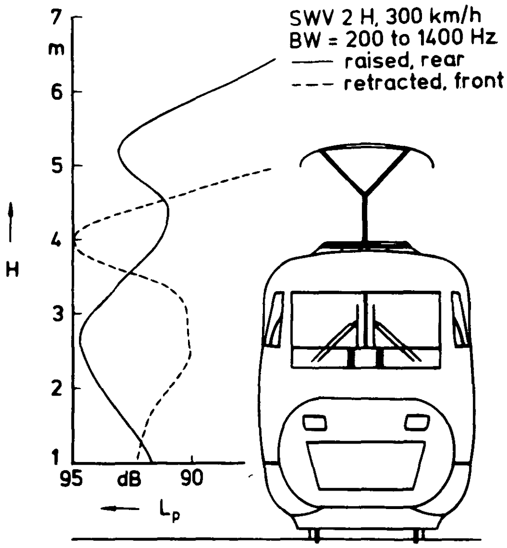

FIGURE 6 Scans on ICE/V power cars measured in frequency range 200 to 1,400 Hz with SWV2H 15-microphone array; H = height (m), L_p = SPL.

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