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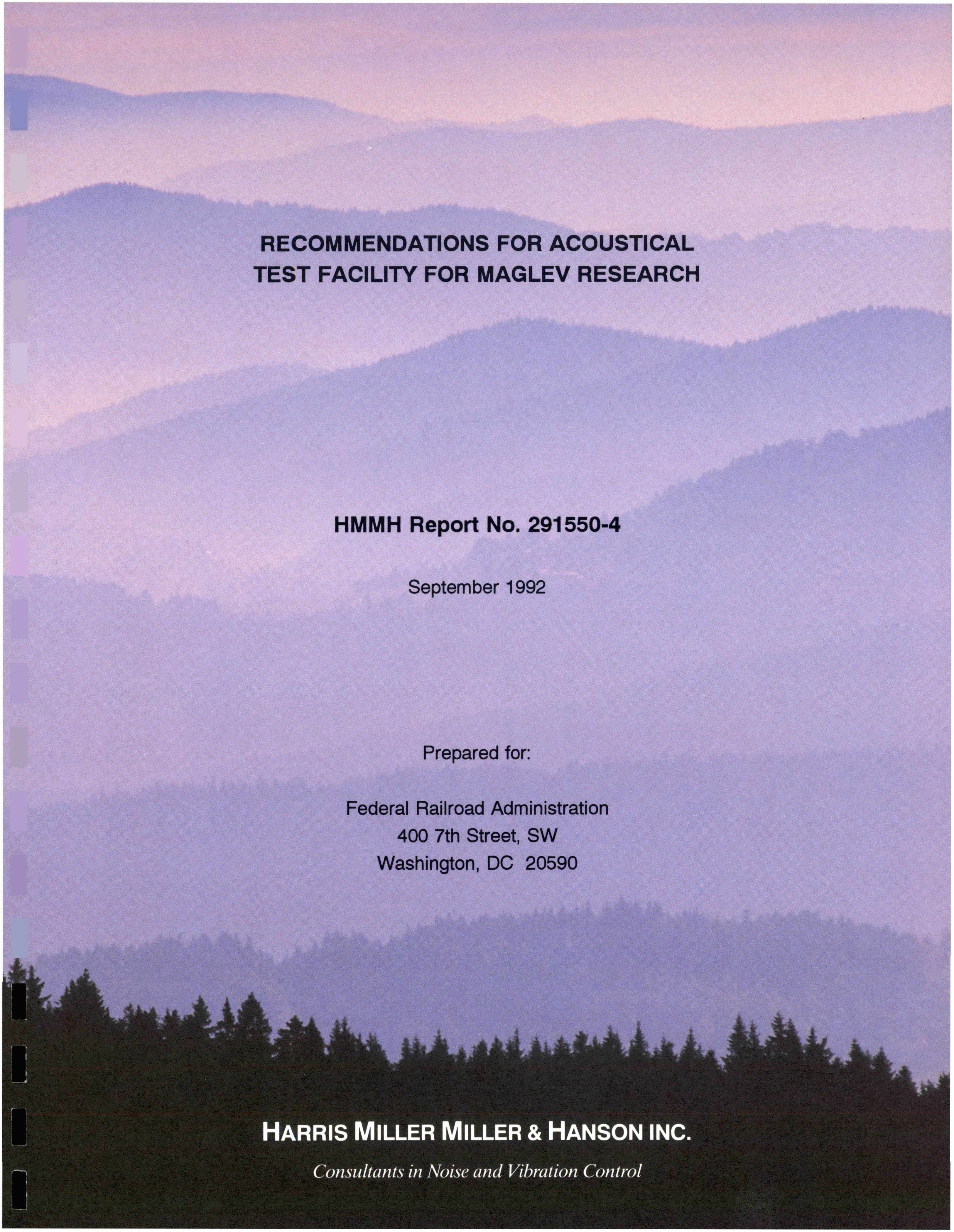

RECOMMENDATIONS FOR ACOUSTICAL TEST FACILITY FOR MAGLEV RESEARCH

HMMH Report No. 291550-4

September 1992

Prepared for:

Federal Railroad Administration
400 7th Street, SW
Washington, DC 20590

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TABLE OF CONTENTS

PREFACE

This report is the fourth of four reports to be prepared under U.S. Department of Transportation Contract # DTFR53-91-C-00074, "Noise from High Speed Magnetically Levitated Transportation Systems." The reports under this contract cover the following areas:

1. Characterization of Noise Sources
2. Noise Criteria for High Speed Maglev Systems
3. Design Guidelines based on Noise Considerations
4. Recommendations for Acoustic Test Facility for Maglev Research.

This report provides a summary of recommended acoustic test equipment and techniques which could be used in a U.S. test facility for maglev system development.

EXECUTIVE SUMMARY

Noise from high speed operations of a maglev system is a source of concern. The German and Japanese prototype maglev systems generate high noise levels at very high speeds. Without mitigation, a maglev system may encounter public opposition if introduced to the existing transportation system in the United States. Based on progress made by the aircraft industry there are many reasons to believe that the noise level can be brought to acceptable levels. In the case of maglev, however, research is needed to develop a better understanding of the mechanisms of aerodynamic sound generation associated with high speed operations.

A comprehensive acoustical test program should be an integral part of any full scale testing program undertaken as part of a U.S. maglev development. The primary benefit from an acoustical testing program will be a quieter maglev system. Secondary benefits include a better understanding of aeroacoustic sources and aerodynamic drag associated with high speed surface transportation systems.

Gaps in research to be filled by acoustical testing are listed in the table below, along with testing approaches to define maglev noise and vibration sources and to investigate mitigation methods.

ISSUES	TEST PROGRAMS
Aeroacoustic sources	Microphone array measurements Microphones mounted on vehicle surface
Interior noise sources	Sound intensity measurements
Vehicle structural radiation	Panel-mounted vibration transducers Microphones mounted on vehicle surface Near-field/far-field microphones
Guideway structural radiation	Sound intensity measurements Vibration power flow measurements
Vehicle/Guideway flow interaction	Scale model flow visualization Microphone array measurements
Noise barrier effectiveness	Multiple-point microphones
Boundary layer control	Scale model wind tunnel tests
Noise from rolling wheels	Scale model noise tests Full scale noise measurements in Japan
Noise from lifting surfaces	Scale model noise/wind tunnel tests
Active cancellation (Interior)	Multiple-point microphones Sound intensity measurements

Acoustical testing facilities should be included at a new test track facility to perform the foregoing research. The size and scope of such a test facility depends on the philosophy of the sponsors of the development program - whether the facility will be a support operation for tests at the test track only, or a center for acoustic research on a wide variety of high speed vehicles. Each of these approaches affects the type of staff and instrumentation for the facility, as well as the budget necessary to continue operations.

INTRODUCTION

Noise has been identified as a potential source of concern associated with the introduction of maglev to the existing transportation system in the United States.[1] The first operational maglev systems have been shown to generate high noise levels at very high speeds.[2] Although there has been only a limited amount of research devoted to noise control of maglev systems, there are many reasons to believe that the noise level can be brought to acceptable levels. Among the reasons for optimism is the progress made by the aircraft industry in research on airframe noise during the 1970's. For noise reduction to be accomplished in a similar manner for maglev, we must continue the research to develop a better understanding of the mechanisms of aerodynamic sound generation associated with high speed maglev operations.

During the development of a US maglev system, a full scale testing program will be undertaken at either a test track or a useful transportation corridor to be determined. A comprehensive acoustical test program should be an integral part of any full scale testing program. The primary benefit from an acoustical testing program will be a quieter maglev system, one that will be compatible with urban and suburban land uses. Existing systems will definitely need additional noise reduction to meet environmental noise criteria in residential areas.[3]

Secondary benefits include a better understanding of aeroacoustic sources and aerodynamic drag associated with high speed surface transportation systems. Aeroacoustic research could especially benefit because never before has there been an opportunity to study aerodynamic noise on a land-based high speed vehicle that is not dominated by propulsion noise. In addition to acoustics, aerodynamic design of the vehicle could be directly affected by the findings. For example, experience gained from acoustical testing of the TransRapid TR06 led to an improved aerodynamic shape of the TR07.[4] In that case, acoustical scanning of the vehicle passby at speed revealed locations of sources of intense noise associated with flow disturbances. Subsequent scale model testing in a wind tunnel confirmed regions of vortex shedding near the nose as a result of shape. Modifications of the nose shape were undertaken, resulting in less noise and less drag.

Aerodynamic testing is often carried out using scale models in wind tunnels instead of costly full scale testing programs at test tracks. In some cases the acoustic testing can also be carried out using scale models in wind tunnels. As discussed in Section 1 of this report, however, there are some tests that can only be performed in full scale.

Gaps in research that could be filled by acoustical testing, full scale and scale model, during any major maglev testing program are discussed in the first section of this report. The second section describes some of the testing approaches that could be used in research activities to define maglev noise and vibration sources and to investigate mitigation methods. Finally, we present a description of the kind of acoustical testing facilities that should be included at a new test track facility.

1. NEED FOR ACOUSTICAL ANALYSIS CAPABILITIES

The first two tasks in this contract quantified the potential environmental noise problems associated with the introduction of a high speed maglev system in an urban or suburban setting. Because maglev has a great potential to serve as an alternative to aircraft as a short haul carrier between cities, the mode will of necessity be placed in densely populated areas. Consequently, noise control will be a major part of the design/development process for maglev. Before design guidelines for noise control can be developed with confidence for a new maglev system, the following issues should be resolved through an acoustic test program.

- What are the key aeroacoustic sources for each speed range?
- How much of the sound radiation generated by the boundary layer can be attributed to vehicle structure?
- How effective are boundary layer control methods in reducing noise?
- How much noise is generated by the vehicle flow interaction with guideway structure?
- How much sound is radiated from the guideway structure?
- What is the screening effect of guideway side walls?
- How much noise is generated by guide wheels rolling on guideway surfaces at low speed?
- How much noise will be generated by lifting surfaces if they are employed for guidance purposes?
- How effective is active sound cancellation for maglev interior noise?

Approaches to investigating the foregoing issues are discussed in Section 2. This section discusses why these acoustical research issues are likely to be important during the development program.

1.1 Identification of Noise Sources

The aircraft industry made great progress in controlling jet engine noise after many years of research on noise generation mechanisms. However, research on airframe noise sources is proceeding slowly. Much of the airframe noise control research considered to be so important in the 1970's has been discontinued as a result of funding cutbacks in the 1980's, according to Crighton.[5] Unfortunately, it is the airframe noise sources that are key to understanding the noise generation mechanisms associated with maglev. As shown in Figure 1, noise sources originate from the magnetic propulsion system, mechanical/structural interactions and aerodynamic forces. Defining the contributions from each source makes a difference in determining the appropriate design mitigation measures. The first report prepared under this contract summarized what is known about the noise levels and sources associated with high speed maglev operations.

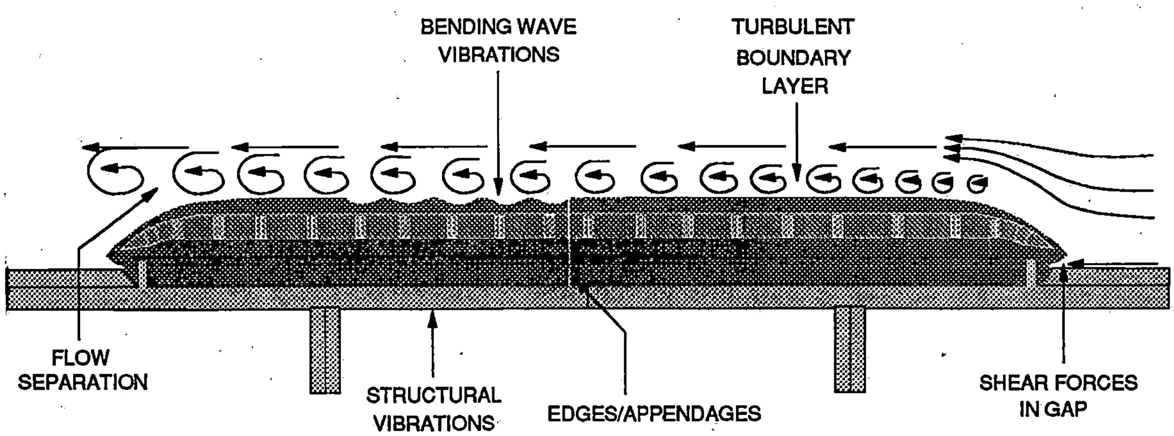

Figure 1. Maglev Noise Sources

One of the points emphasized in the Task 1 Report is that the sound generating mechanisms associated with a high speed vehicle are complex. Many different mechanisms can result in similar noise characteristics. Researchers without access to an experimental vehicle have little definitive data with which to work; often just the maximum passby level in A-weighted sound level. Consequently many of the hypotheses about dominant sources are based on circumstantial evidence. For example, the noise vs. speed curve from measurements of the TransRapid TR07 shown in Figure 2 can be approximated by three straight lines in different speed regimes with slopes proportional to velocity to the third, sixth and eighth powers, labeled A, B, and C, respectively. These three noise vs. speed relationships correspond to:

(A) noise from guideway structures (velocity to the third power),

(B) noise from vortex shedding and vehicle body radiation (velocity to the sixth power),

(C) noise from the turbulent boundary layer (velocity to the eighth power).

The straight lines shown in Figure 2 are not unique. Others could be drawn to approximate the same data because the actual sources that are dominant in each regime are not actually known.

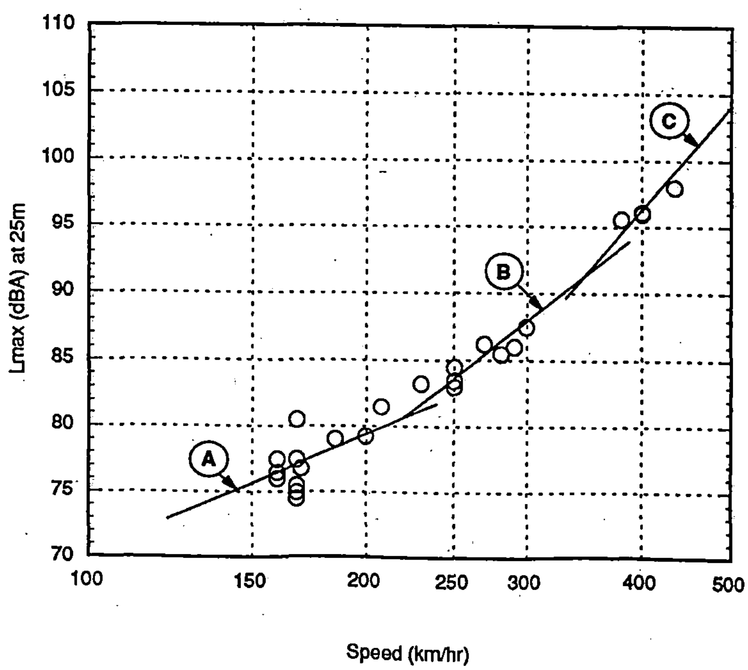

Figure 2. Measured Noise of TR07 with Straight Line Approximations

1.2 Design Input

The shape and structure of the vehicle and guideway are developed during the system design phase. An understanding of the basic noise generation mechanisms will enable designers to include noise control features in the initial design of the system instead of having to employ retrofit treatments later. Modifying an existing vehicle or guideway structure to solve a noise problem is expensive and often adds undesired weight to the system. Furthermore, since many of the airflow disturbances that generate noise are also sources of increased drag, a design that results in low noise may also result in low drag. The following subsections discuss how an acoustic testing program could provide input to the design process of a new maglev system.

1.2.1 Noise Control

Minimizing noise from a new maglev system requires incorporation of noise control during the design phase. Two examples illustrate how an understanding of the basic mechanisms of noise generation could be worked into the system. First is the turbulent boundary layer interaction with the vehicle surface which may be responsible for the rapid rise in noise with speed, e.g., proportional to velocity to the sixth and eighth powers. An issue to be resolved is whether the surface panel response is a major contributor to the sound radiation. A measurement program to determine the role played by panel vibration would be valuable. If it turns out that vibrations of the vehicle skin are important, then a reasonable noise control method is to add damping material to the surface skin. If not, then the added weight of the damping material would be unnecessary.

A more refined approach to the problem of vehicle surface radiation is based on aeroacoustic theory. Turbulent boundary layers contain quasi-random pressure fluctuations; the pressure spectrum shows some characteristic peaks, one of which corresponds to the effective convection velocity of the turbulent field. These pressure fluctuations in turbulent flow over a flat infinite plate surface, either rigid or compliant, theoretically radiates sound inefficiently (quadrupole radiation), but if the flow excites the structure and there are non-uniformities in the surface, the surface radiates sound quite efficiently (dipole radiation). Non-uniformities include stiffeners and ribs supporting the surface panels, abrupt terminations as in edges, surface curvature and roughness elements.[6] The design implications of the theory are in the spacing of ribs supporting light weight panels, as well as the materials and dimensions of the panels. It is a given that a maglev vehicle should weigh as little as possible. A light weight skin system tends to vibrate easily in resonant modes and if the turbulent boundary layer excites the panels at resonance, then they tend to radiate more sound. However, by knowing the modal characteristics of the vehicle structure along with the frequency characteristics of the turbulent boundary layer, the designer can fine tune the vehicle structure such that frequencies of resonant modes of panels do not coincide with peak frequencies of pressure fluctuations occurring in the boundary layer. In this way the designer maintains a light weight design, but avoids sound radiation from vehicle surface panel response.

A second example is the potential use of lifting surfaces for vehicle guidance and control. Vortex shedding from trailing edges and ends of lifting surfaces are major noise generators on fixed wing aircraft. If such aerodynamic control surfaces are incorporated into the design of a future maglev vehicle, as proposed for some concepts, it is likely that significant noise radiation will result. Airframe research has resulted in noise control treatments at the leading and trailing edges that could be incorporated in the design.[5] Some treatments discussed by Crighton (Reference 5) and in the Task 3 Report of this contract include boundary layer suction and perforated and slotted edges.

Other noise control measures should be tested as part of the acoustical testing program. Among these are noise barriers, boundary layer controls, and active sound cancellation. Measurements of noise on the Japanese MLU002 maglev vehicle indicate that this vehicle radiates about 5 dBA less noise to the 25 meter wayside reference position than does the German TR07 at 300 Km/hr. A possible explanation for the lower noise level is that the side wall and closed deck guideway configuration acts as an effective noise barrier for wayside noise. Our Task 3 guidelines report gives an estimated 5 dB reduction for a noise barrier in a screened configuration.

The dominant aeroacoustic sources all relate to actions of the boundary layer such as vortex shedding, turbulence and separation. Therefore noise control methods should focus on keeping the boundary layer attached to the vehicle surface and as smooth as possible. One of the controls which shows promise for noise reduction is boundary layer suction to keep the boundary layer attached to the vehicle sides. The excess air could be ejected at the rear of the vehicle to compensate for the pressure deficit at that part of the vehicle, thereby reducing form drag.

Active sound cancellation is always under consideration as a new noise control method. The basic principle of this method is that since they are made up of periodic pressure fluctuations above and below atmospheric pressure, sound waves can be canceled out by introducing pressures of the opposite sign. The key to sound cancellation is the word "periodic." Before a sound wave of opposite sign can be introduced, the initial wave must be sampled so that a pressure generator (loudspeaker) can be set up to produce the necessary sound. Most of the external sounds from a high speed vehicle are not periodic, however. Little progress has been made on reducing broadband noise by this method.

Interior vehicle noise patterns are often characterized by tones generated by electronic equipment, air conditioning fans and other equipment with periodic operating characteristics. Active sound cancellation has been successfully applied to interiors of automobiles, trucks and locomotives. It could be useful in developing a quiet maglev system since many of the operational characteristics of maglev are likely to generate interior sound spectra with tones.

1.2.2 Drag Reduction

Minimizing aerodynamic drag is among the design goals of the maglev system development program. Measurement of noise can help meet that goal. Sources of aerodynamic noise are regions of unsteady airflow over the maglev vehicle and its guideway. Unsteady airflow over the surface of a vehicle is also associated with increased drag. As a maglev vehicle moves through air, the boundary layer of air adjacent to the vehicle starts out smoothly at the nose (laminar flow) but gradually changes to unsteady fluctuations (turbulent flow) where the nose section transitions to the parallel side body and roof of the train. Depending on the body curvature associated with forward sections of the vehicle, the transition to turbulent boundary layer flow can be gradual or intermittent. If intermittent, the flow is unsteady, with intermittent vortex shedding which draws energy from the smooth forward motion of the vehicle thereby increasing drag. Thus it is important that aeroacoustic and aerodynamic testing should be carried out in concert during development phases of a new maglev system.

A case which demonstrates how acoustical testing can lead to aerodynamic improvements occurred during the development of the TransRapid TR07.[4] Extensive acoustical measurements were conducted to locate noise sources on the prior generation model TR06. Among the measurements at the Emsland test track performed by the developers, Messerschmitt-Bolkow-Blohm Gmbh (MBB), were a series of acoustic scans using a microphone array system (microphone array systems described later in this report). The results of the scan represented by Figure 3 indicated locations of high noise levels at a specific region near the nose of the train and at gaps between car body and magnet sections (called "bogies") and between the two cars of the train. The shaded contours superimposed over a sketch of the vehicle in Figure 3 represent regions in which the sound pressure level is uniform within a few decibels. Wind tunnel tests confirmed that the dark region at the base of the nose section corresponds to an area of intense flow separation at a crease between the vehicle body and the bogie fairings. Design changes from these investigations resulted in a redesigned nose section, smooth fairings between the car body and the bogies and elastic fairings at the joints between car bodies.

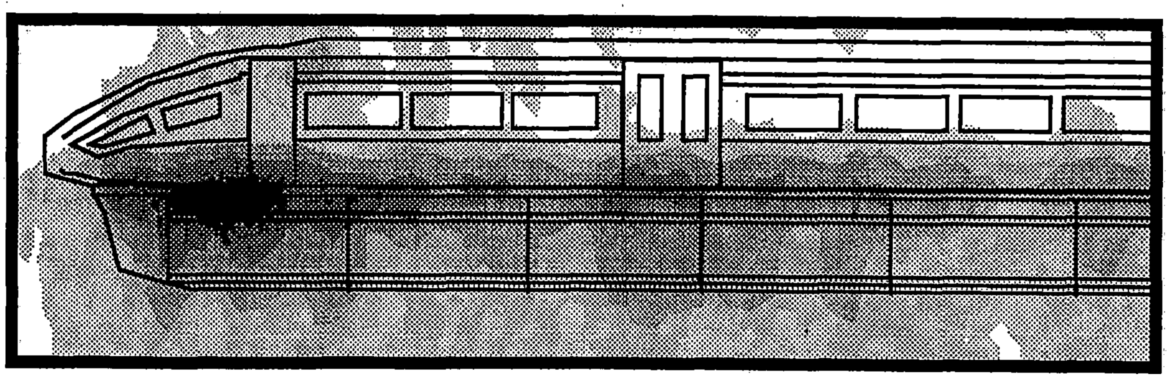

Figure 3. Locations of TR06 Sound Sources from Microphone Array Analysis

1.2.3 Guideway Structure

Noise from the guideway structure can be generated in several ways, three of which are:

- structural vibrations of girders or deck caused by vehicle dynamic loading,
- structural vibrations caused by magnet pole reactions, and
- aerodynamic interaction between vehicle and structure.

A noise measurement program will provide useful design input to identify the cause of structural noise in all three cases.

Structure-borne Noise As a train passes over guideway segments, each section oscillates as it is loaded and unloaded. Low frequency vibrations of the deck structure and the supporting beams generate low frequency sounds which may prove to be annoying to nearby residents. The guideway structure is subjected to another source of vibration at the same time -- the dynamic loads associated with magnetic pole passing. Every magnetic pole that supports the vehicle weight has a transient load during the vehicle passby. The sequential loading of magnets results in oscillating loads on the structure, resulting in dynamic response at the forcing frequency and the natural modes of vibration.

For the case of noise radiation from structural vibrations, the source of sound can be determined by a series of measurements combining vibration transducers and near field microphones. Locating the sources of guideway noise, dynamic loading or magnetic pole vibration, and treating them in the initial design can be especially important due to the relatively high cost of the guideway component of a maglev system. Knowing whether steel beams require damping treatment before being used in a given alignment could be an important factor in estimating the weight and cost of a system. It is better to have this input at the onset of the design process than after the structure is built. Retrofitting a noisy steel guideway is costly.

Aerodynamic Noise Air being dragged along with the vehicle and being pushed aside as a vehicle passes, encounters the fixed guideway structure. Obstructions to the freely flowing air cause disturbance in the flow which can result in noise generated from vortices. Evenly spaced openings, poles or structural members are the potential source of periodic vortex shedding as a vehicle moves along the guideway. The result could be similar to a very large siren. Depending on the passby rate, the sound generated by this source could be in the frequency range of audibility showing up as a tone superimposed on the sound radiated by guideway vibrations. Since tonal sounds tend to cause greater annoyance than broadband noise, a guideway system with periodic vortex shedding characteristics should be avoided. Noise measurements should be able to identify the source of any tone that occurs and changes in the design could be specified.

1.3 Scale model vs full scale testing

A comprehensive research program on noise from high speed vehicles can take place both in the laboratory and at a test track, depending on the nature of the sound source. Some kinds of testing are best performed in a scale model facility where design changes can be made easily and cheaply. Other kinds of research are impossible to perform on less than full scale and require the prototype vehicle to operate up to speed on a test track. Some of the advantages of each type of testing are summarized in this section.

Scale Model Testing Scale model wind tunnel testing is a standard experimental tool in the field of aerodynamics. Based on the principle of dynamical similarity, airflow around a scale model is the same as for the full scale prototype provided that the dimensionless Reynolds number is the same.*

The primary advantage of scale model testing is that it allows one to economically study the relationships among key parameters and to evaluate the effects of design changes. Because they are of a size that can be handled easily, scale models save time in construction and measurement. Experiments can be undertaken in a controlled environment that is conducive to obtaining the desired information. For example, boundary layer separation and reattachment points on a maglev vehicle can be determined through flow visualization means in a wind tunnel.

As discussed in Section 1.2.2, several important changes in the shape of the forward section of TransRapid 06 were made as a result of wind tunnel tests of a 1:25 scale model. A region of vortex shedding in a sharp crease near the nose was observed by flow visualization techniques. The crease was filled in on the model to eliminate the source of vortex

* Reynolds number, Re =LU/ν, where L = representative length of model (m), U = velocity (m/sec), ν = kinematic viscosity of fluid (m^2/ sec).

shedding. Further wind tunnel testing led to refinements in the nose shape to reduce flow perturbations causing drag. Implementing and testing these changes on a full scale model would have been time consuming and costly.

Where investigations of aerodynamic flow around the vehicle are expected to lead to identification of aeroacoustic sources, a laboratory with the appropriate low-noise, low-turbulence wind tunnel is most suitable. Aeroacoustic phenomena that are fluid related, such as sound from vortex shedding from rigid structures, can be successfully scaled provided both the Reynolds number and the Strouhal number are the same as full scale.** Sound pressure spectra under these conditions will be acoustically similar to the full scale situation, provided the frequency is adjusted by the scale factor.

More complicated, however, is the case of modeling sound radiation from vibrating structures and panels. Two wave-bearing media, the air and the structure, are involved. Acoustic scaling in air is well understood. The important phenomena associated with sound waves, such as reflection, scattering and absorption, are related simply by the geometric scale factor. However, the structure is more complicated. It supports a number of different types of waves: bending waves, compressional waves and torsional waves. Bending waves tend to be the most important for sound radiation, but the other types are important for modeling the correct behavior at boundaries, such as panel supports. In order for scale models to be useful, the behavior of all wave types in the structure and the associated sound radiation should be the same in the scale model at the scale frequency as occurs in the full scale prototype at full scale frequency.

Fortunately, the equivalency of scale-model and full-size testing is achieved under the following conditions:

- model and prototype materials and their surrounding fluids (air) are the same,
- loss factor (measure of damping) of structural material is independent of frequency,
- linear dimensions of model are 1/n times the full scale dimensions, and

** Strouhal number, $S = fL/U$, where f = acoustic frequency (sec^{-1}), L = characteristic length (m), and U = velocity (m/sec).

- all vibration and acoustic measurements are made at n times the full scale frequency.

It turns out that all the key parameters necessary to define structural sound radiation can be measured on a scale model that is a 1/n-size replica of the full size structure. Among the key variables that can be measured are:

- Mechanical power input
- Amplitude and modal structure of the vibration field
- Reflection of waves at structural joints
- Directivity of sound radiation
- Radiation efficiency, and
- Shielding and diffraction effects.

Under the foregoing conditions, the amplitude of vibration velocity and the amplitude of the radiated sound pressure from the model will be the same as the full scale if the input force on the model at scaled frequency is $1/n^2$ times that of the full scale input force. Scale models work well for panels and structures excited by point or localized forces. For example, a scale model of the guideway structure could be used to estimate the sound radiation from various beam configurations. Unfortunately, scale models do not work out as well for panels excited by turbulent boundary layers where the size and strengths of the turbulent eddies are difficult to scale down to miniature dimensions.

<u>Full Scale Testing</u> As mentioned above, scale model testing would be the ideal method of aerodynamic noise testing except for one important fact. Dynamic response of structural elements associated with a vehicle skin does not scale in the same proportions as the fluid dynamics when the real materials are used in air. Consequently, in order to determine the contribution of the structure to aeroacoustic noise from a maglev vehicle, testing must be carried out on full scale components in wind tunnels or on the prototype vehicles.

Moreover, the structure-borne transmission of interior noise sources are difficult to model. Vibration isolation and damping parameters are complex to model on less than full scale. Components can be made up and tested to optimize treatments before they are installed in the full scale vehicle, but even then they need to be tested in the full scale configuration.

2. RECOMMENDED ACOUSTICAL TESTING PROCEDURES

Several noise and vibration measurement techniques exist to determine the behavior of sound sources. New methods are being developed as improved instrumentation becomes available. This section is by no means an encyclopedia of all the possible measurement and analysis methods available to study aeroacoustic sources. Here we review currently available methods that should be a part of the maglev noise research program, especially the full scale testing of a prototype vehicle. Like the first generation German and Japanese maglev programs, the US effort will develop a prototype and will improve it by testing. Both exterior and interior noise measurements will be part of the testing program to identify noise sources.

2.1 Noise measurements

2.1.1 Exterior diagnostic tools

Exterior moving vehicle noise measurements are made with one or more microphones mounted at specified locations from the path of the passing vehicle. For vehicles on fixed guideways, the path is determined, thereby simplifying the description of the location of the vehicle with respect to the measurement point. Depending on the purpose of the measurement, the noise will be received by a single microphone or a set of multiple microphones.

Single point microphone - A single microphone is usually employed when the data are to be used for complying with vehicle noise specifications, enforcement of noise emission regulations, noise monitoring for environmental assessments, and general noise descriptions of the envrionment. The advantage of a single microphone measurement is simplicity. Nothing more elaborate is necessary when a general description of the noise environment is required because a single point receiver represents the noise exposure of an observer at the microphone location. The disadvantage of the single microphone in the case of a fast moving vehicle is that it integrates the effect of all the sound sources and therefore can not be used as a method for localizing individual sound sources. Moreover, the frequency content of the data is smeared by the Doppler effect***, unless corrections are made during post-processing the data. Therefore, the single point microphone has limited use in diagnostic work concerning a moving vehicle.

There are methods of using single point microphones for focusing on sound sources. The familiar "shotgun microphone," used in enhancing televised sporting events, employs a dished receiver to focus sounds coming from one small source to a microphone located at the focal point of the dish. Such a receiver could be useful in diagnostic work to locate sound sources on fixed structures, like the guideway, but a number of disadvantages are associated with the "dish" for use with fast moving vehicles. It has a relatively limited frequency response for a given dish shape: for investigating sources with a wide frequency range, the shape of the reflector must be changed, or a number of different units must be used. For focussing on a particular spot, the entire dish must be swiveled to follow the course of the moving vehicle requiring a complex mechanism. Even then, only one spot at a time can be followed for a given passby. The difficulties of using the dished microphone make it unworkable for diagnosing sound sources on the high speed maglev vehicle. However, it does have potential application in determining sound generation from particular sections of the guideway as the vehicle passes or as the guideway is driven by a controlled source of vibration.

Another single point microphone technique for measuring noise sources on the guideway is the sound intensity probe described in the section on "Interior diagnostic tools." Radiation of sound from vibrating structures can be diagnosed by this method using steady state forcing vibrations. Although transient vibrations from a moving vehicle are the actual source, structure-borne sound measurements are more easily analyzed using continuous vibration sources, such as a shaker.

*** The Doppler frequency shift is the continuous change in frequency of sound emitted by a moving vehicle as it approaches and then recedes from a fixed observer. The mathematical expression for the effect is $\mathbf{f} = \mathbf{f_s}/(1 - \mathbf{M_s} \cos \Theta)$ where **f** is the observed frequency, $\mathbf{f_s}$ is the emitted frequency from the moving source, M is the Mach number and Θ is the angle between the forward vector of the vehicle motion and the vector from the sound source to the receiver. For example, when a moving vehicle is approaching the receiver, the angle Θ is less than 90 degrees and the observed frequency is greater than that actually emitted. At $\Theta = 90$ degrees, the source is perpendicularly opposite the receiver and the observed frequency is true. Similarly, at Θ greater than 90 degrees, when the vehicle is receding from the observer, the observed frequency is lower than that emitted.

Multiple microphones - A useful technique for diagnosing sound sources is to measure and record the sound at several locations around the vehicle simultaneously. Placement of microphones equidistant on a vertical plane around a source is commonly used to determine directivity in that plane and in the case of a line source like a maglev train, the sound power. Other than the complexity of setting up, calibrating and recording sound on a multiple channel tape recorder, sound power and directivity measurements are rather straightforward in that no attempt is made to correlate the signals of the various microphones. The energy average over the period of the passby is sufficient.

Microphone arrays - Microphone arrays can be used to both localize the sound sources and to correct for the Dopler frequency shift associated with a high speed moving vehicle. Arrays have been successfully applied in Germany and Japan for the identification of sound sources on high speed trains.[7,8,9] For a linear array, a line of equally spaced omnidirectional and phase-matched microphones is pointed toward the passing vehicle. The signals generated by sound pressure waves received by each microphone are recorded on individual channels of a multi-channel tape recorder (Figure 4). The sensitivity of the array depends on the angle of the approaching sound waves and a number of other factors, such as the number of microphones, their spacing, the acoustic frequency and the weighting factor multiplying the signal from each microphone (called "shading"). Summing the output of all the microphones results in a beam pattern where the group of microphones has an increased sensitivity to sounds coming from a small area, much like the "shotgun microphone" described above. By shading the microphones at the ends of the array, the beam pattern is narrowed in the center so that waves from off the beam axis have less effect. The utility of the array is that the beam of maximum sensitivity can be electronically steered to pick up sounds emanating from a wide angle in the plane of the array, similar to a searchlight. In fact, a German promotional publication recently called its microphone array, "Die akustische Taschenlampe" - the acoustical flashlight. The "searching" is done during post processing of the recorded data; the array is "steered" by the technique of controlled phase delay between each channel (Figure 5). Correlating the location of the moving vehicle with the direction of the beam is important. A dedicated channel of the tape recorder is used to record position information of the moving vehicle, such as the time of crossing a light beam.

Discrimination among wavelengths by an array depends on the distance between microphones. Different microphone separations must be used for investigation of different frequency ranges. Since a linear array can only be steered in the plane defined by its physical axis and its acoustic axis, longitudinally spaced sound sources can be located only by a horizontal array and the vertical distribution of sound sources can be located only by a vertical array. With two axes used simultaneously in a crossed array, a mapping of sound sources over the surface of a moving vehicle can be obtained, as shown in Figure 1. Crossed arrays are now in use in both Germany and Japan [10].

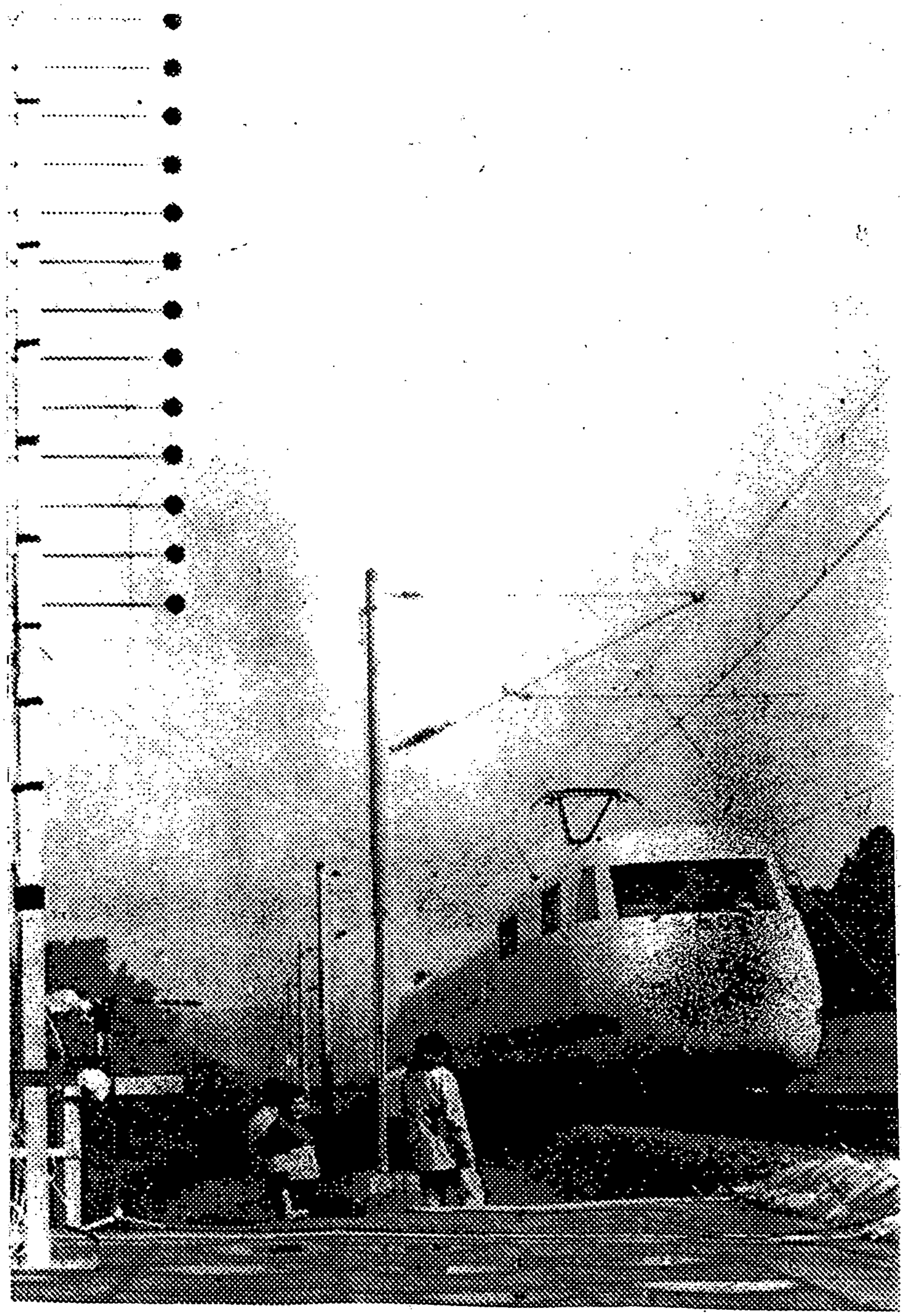

Figure 4. Linear Microphone Array (from Ref. 9)

The crossed array is the among the first tools that should be developed for the U.S. Maglev Acoustical Test Facility. The state of the art of digital electronics has advanced a great deal since the first linear arrays were built in Germany in 1978. The ability to scan the surface of a fast moving vehicle and mapping the noise sources on a color monitor will be useful for both noise control and aerodynamic analysis.

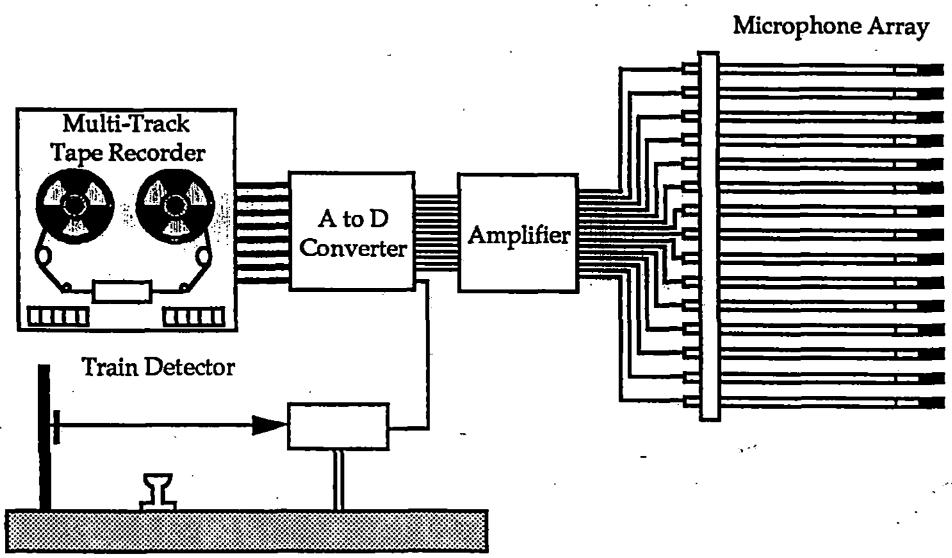

Figure 5. Schematic of Microphone Array System

2.1.2 Interior diagnostic tools

Sound intensity - A recently developed acoustical measurement technique involving multiple microphones is measurement of sound intensity. By measuring and integrating the sound pressure gradient and velocity by closely spaced phase matched microphones, the sound intensity vector (magnitude and direction) can be mapped in the vicinity of a sound source.[11] This technique proves to be especially valuable in identifying and locating sound sources (Figure 6). By moving the sound intensity probe over the surface and mapping the results onto a grid, regions of high sound intensity can be identified as sources. Further, the direction of the energy flow can be mapped through the use of the probe's directivity pattern.

Application of sound intensity appears to be confined to fixed sources, due to the time it takes to map out the isointensity contours and vectors. Sound intensity measurements could be used to determine sources of interior noise of a moving vehicle, however, provided steady state conditions can be established for long enough to scan the appropriate surfaces.

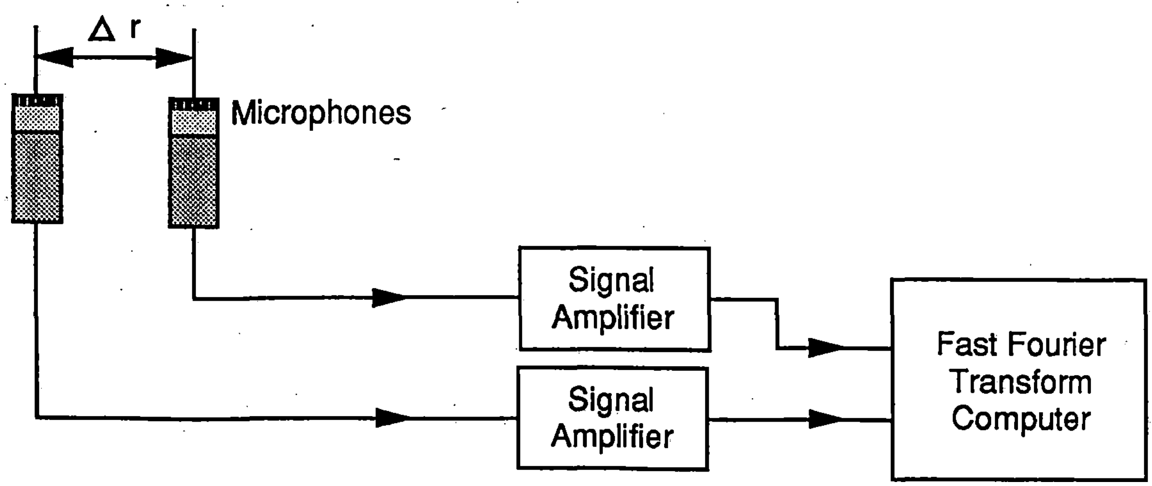

Figure 6. Schematic of Sound Intensity System

2.2 Vibration measurements

An acoustical test facility needs to be well equipped with a vibration measurement capability since sound radiation from vibration of solid structures is an important part of the overall noise problem. Both the guideway and the vehicle body require vibration measurements in order to understand the basic noise generating mechanisms.

A wide variety of vibration measurement techniques are available to the researcher. In general the method is based on a surface mounted transducer that converts motion of the vibrating surface to electrical signals which are amplified and recorded on magnetic tape. After calibration against a standard, the recorded signals are analyzed for overall vibration levels, for frequency band levels, for various motion descriptors (acceleration, velocity or displacement), as required. This section is not intended as a primer on vibration measurement techniques. Summaries of vibration measurement methods can be found in handbooks on acoustical measurements and noise control.[12] A typical measurement system is shown in Figure 7.

Guideway structureborne noise - The guideway has a major effect on the noise radiated from a maglev system at low and medium speeds.[2] Guideways with undamped steel girders are measured to be about 5 dBA noisier than an all-concrete guideway for passbys of maglev vehicles. Despite their propensity for being noisier, steel structures are generally preferred over concrete for reasons of cost or ease of fabrication. A measurement program designed to identify the sources of structureborne noise radiation could result in development of quieter guideways, especially those made of steel. Such a program would involve correlation of noise radiated and the vibration of key components of the structure.

Vibration measurements play a key role in developing noise control from structures since the intensity of sound produced by a vibrating surface is proportional to the mean square velocity of that surface. Measurements of the amplitude and modal pattern of the vibration field together with the mechanical power flow through the structure are fundamental to determining the sources of noise in guideway structures.

Vehicle structure - The vehicle skin vibrates under the fluctuating pressure loading of the turbulent boundary layer at high speed. How much these vibrations contribute to the radiated noise at high speed is unknown. As discussed in Section 1, this is one of the most pressing of the source questions. If it could be determined whether the structural radiation is significant, then the structural design could be altered accordingly. An experiment combining measurements of vibration, near field sound pressure and wall pressure at the vehicle skin under turbulent boundary layer loading could serve to answer the question.

Such a measurement program might, for example, measure the vibration response of the vehicle skin while at the same time measuring the pressure fluctuations of the boundary layer adjacent to the skin. The vibrations of the panel would be determined by attaching many light weight accelerometers to the interior surface of a panel of the vehicle skin. Data would be analyzed to determine the modal structure of the panel and to correlate the information with the pressure field caused by the turbulent boundary layer outside the panel.

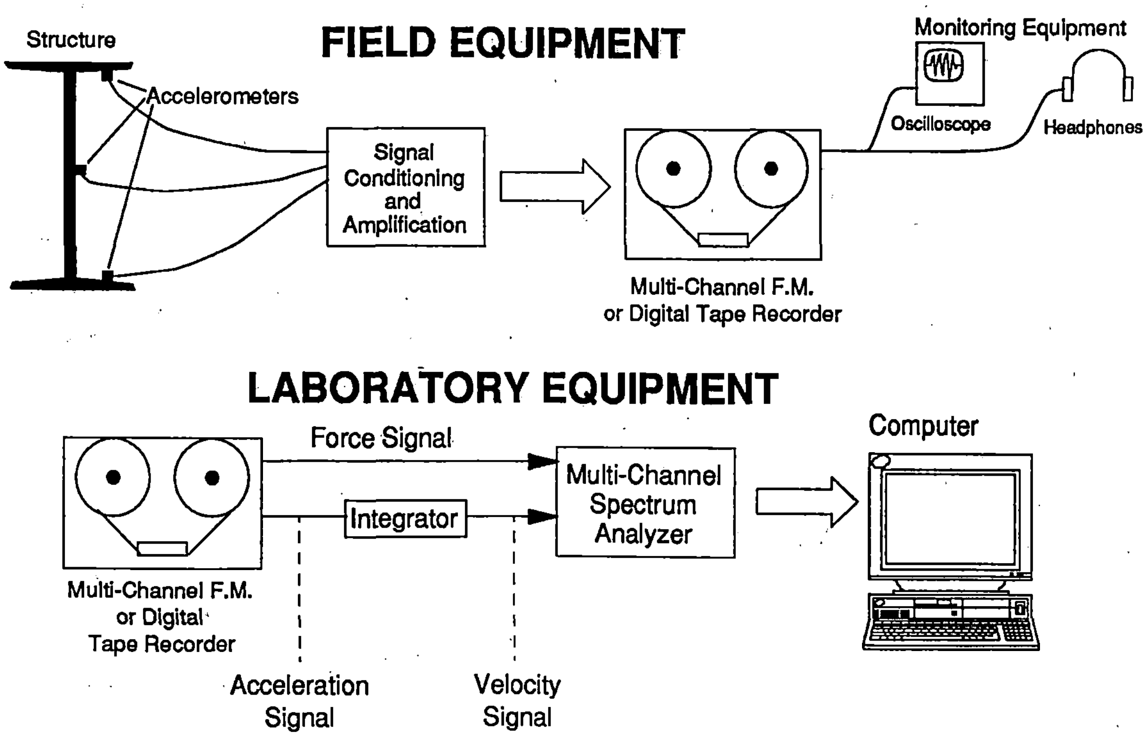

Figure 7. Schematic of Vibration Measurement System

2.3 Recommended Tests to Fill Research Gaps

In Section 1 we listed key noise issues that need to be resolved through an acoustic test program. In Section 2, we describe various noise and vibration measurement methods at the researcher's disposal. This subsection puts the two together in a table as a guideline for a future acoustical test program.

Table 1. Recommended Tests to Resolve Maglev Noise Issues

ISSUES	TEST PROGRAMS
Aeroacoustic sources	Microphone array measurements Microphones mounted on vehicle surface
Interior noise sources	Sound intensity measurements
Vehicle structural radiation	Panel-mounted vibration transducers Microphones mounted on vehicle surface Near-field/far-field microphones
Guideway structural radiation	Sound intensity measurements Vibration power flow measurements
Vehicle/Guideway flow interaction	Scale model flow visualization Microphone array measurements
Noise barrier effectiveness	Multiple-point microphones
Boundary layer control	Scale model wind tunnel tests
Noise from rolling wheels	Scale model noise tests Full scale noise measurements in Japan
Noise from lifting surfaces	Scale model noise/wind tunnel tests
Active cancellation (Interior)	Multiple-point microphones Sound intensity measurements

3. RECOMMENDED ACOUSTICAL TEST FACILITY

An acoustical test facility at the maglev test track will be important to conduct testing during the development stage of prototype vehicles. The size and scope of such a test facility depends on the philosophy of the sponsors of the development program - whether the facility will be a support operation for tests at the test track only, or a center for acoustic research on a wide variety of high speed vehicles. Each of these approaches affects the type of staff and instrumentation for the facility, as well as the budget necessary to continue operations.

3.1 Staff

The staffing requirements depend on how acoustic testing associated with the maglev program will be directed:

- test track's own personnel,
- system developer, or
- outside contractors and research institutions.

Either of the first two approaches requires that the staffing be highly trained, research-oriented professionals in the field of acoustics and capable of conducting independent research and noise control developments. The facility would thus become an acoustic research center for control of noise and vibration from high speed vehicles. The third approach would also require highly trained staff, but since the ideas for fundamental research would come from outside the facility, the staff would take on a support function, such as technicians and data analysts.

Research Facility - A complete research facility concentrating on aeroacoustics would require a major investment and ongoing commitment on the part of funding agencies. In order to justify the investment, there needs to be a demonstrated necessity that the problem is of continuing national importance. Although it is beyond the scope of this report to demonstrate a national need beyond the maglev development program, there is at present no coordinated research program in aeroacoustics of surface vehicles. There is a need for a focus point for such research and locating a research facility at the maglev test track could provide that focus.

For the case of a minor research facility, the staffing would be made up of highly qualified professionals in the field of acoustics and noise control engineering, together with a support staff of technicians and analysts to conduct measurement programs, analyze the data and prepare test reports. Staff size depends on the extent of the funding and the scope of the program, but at a minimum the facility would need the following:

- Director - an internationally known and experienced research professional, with a Ph.D. and experience in both industry and academia,

- Acoustical Professionals - two or more acoustical engineers with advanced degrees, capable of conducting independent research programs and preparing publishing technical research papers,

- Technicians and Analysts - two or more technicians capable of conducting complex field measurement programs, instrument maintenance and record keeping, and one or more computer specialists with training in data analysis and programming,

- Administration - one executive secretary, one part-time word processor and one part-time librarian.

Support Operation - In the alternative that the test track operations would be offered as a facility for use by outside contractors and the developers of maglev vehicles, then the acoustical test facility would require a lesser staffing requirement. As a support facility, the staff would conduct measurements and analyze data in response to direction from outside contractors. Interpretation of the data and supervision of the data acquisition would be done by the professional staff of the sponsoring agency. Consequently, the staff could consist of the following:

- Facility coordinator - an acoustical professional with extensive background in noise control engineering and experimental testing procedures,

- Technicians and Analysts - two or more technicians capable of conducting complex field measurement programs, instrument maintenance and record keeping, and one computer specialist with training in data analysis and programming,

- Administration - one secretary and one part-time librarian.

3.2 Physical layout

The location of a maglev acoustic test facility in either case should be near the test track for easy access. At TransRapid's Emsland test track in Germany the acoustic laboratory is in the maintenance building in which the maglev vehicles are serviced. In that facility, laboratory set-up, equipment maintenance and storage and data reduction facilities are all located in a rather cramped space of 8 meters by 12 meters (estimated from observation). Space for an instrumented van is provided in the adjacent service bay shared with the maglev vehicle. Computer facilities are located in a separate building.

A good layout for an acoustical laboratory should include offices, computer peripherals, laboratory set-up, data reduction, equipment storage, document storage, and garage for instrumented van all in adjacent spaces to facilitate communication. The space needed for the entire facility depends on the scope of the activity, discussed above, but the minimum space needed is as follows:

• Offices - Director	3.5m x 4.5m
Staff	3.0m x 4.0m (each office)
Technician	3.5m x 4.5m (shared by two)
• Computer peripherals	3.0m x 4.0m
• Data reduction	3.5m x 4.5m
• Equipment set-up	5.0m x 8.0m
• Equipment maintenance and storage	3.5m x 4.5m
• Garage and loading area for van	4.5m x 10.0m

Total minimum space for a complete research laboratory, assuming two offices each for staff and technicians, is just under 200 square meters, not including amenities and common area. The reduced scale support facility discussed above would require about 175 square meters of working space.

3.3 Equipment

The equipment roster for a well-equipped acoustic test facility would be nearly identical for either type of mission, research facility or test support facility. Equipment would be required for:

- Noise measurements - sound level meters, microphones, calibrators, preamplifiers, supporting stands, cable, connectors, arrays, sound intensity equipment;
- Vibration measurements - accelerometers, calibrators, amplifiers, integrators, cables, connectors;
- Data acquisition and analysis - multi-channel digital audio tape recorders, analog-to-digital converters, frequency analyzers, filters, portable computers;
- Computer facilities - desk top computers with network, work station with access to main frame, laser printer, plotter, graphics work station;
- Instrumented van - high step van body, custom fitted work space, racks for instruments, built-in power supply for instruments, auxiliary heat, remote radio and telephone transmitter.

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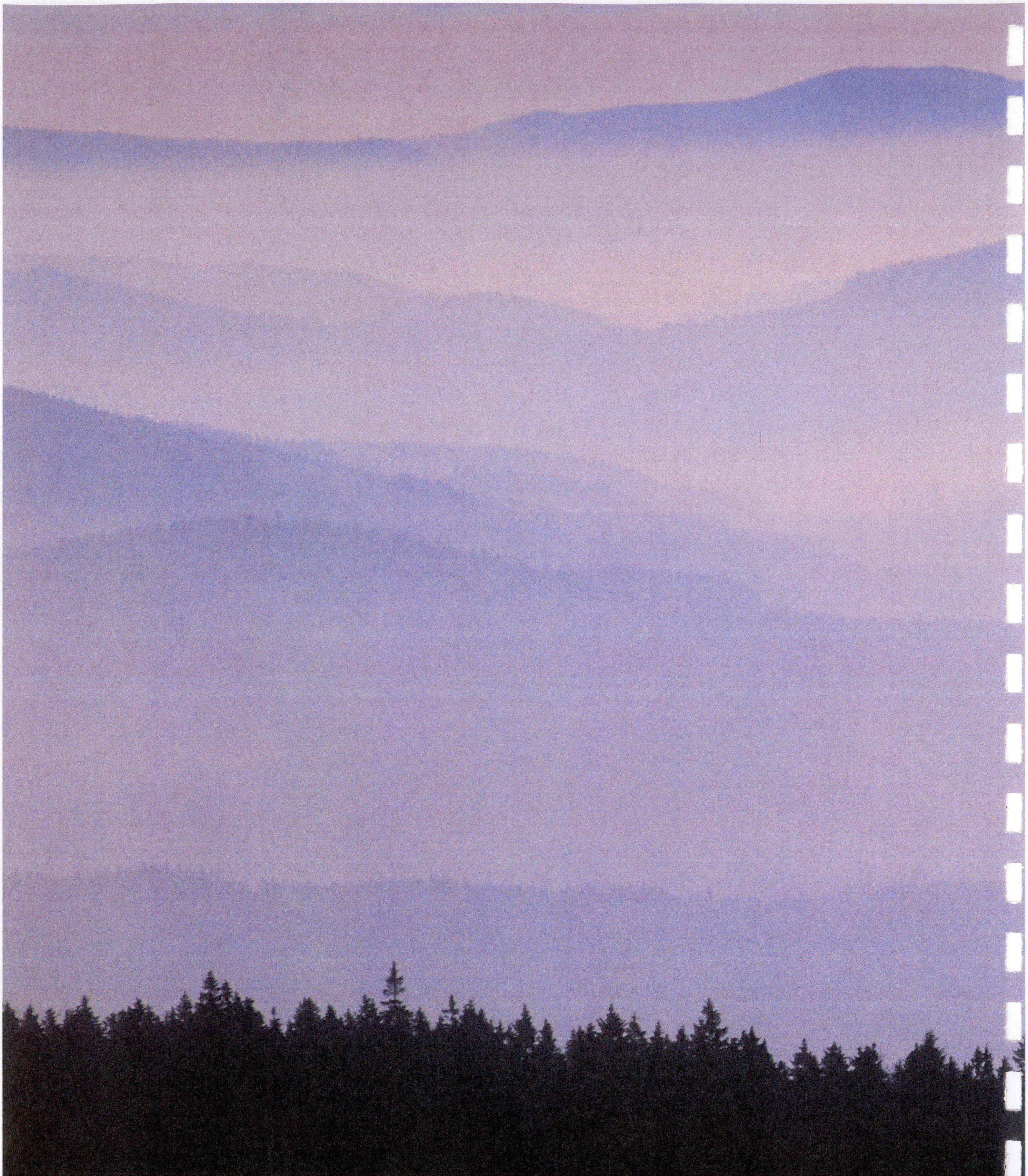

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